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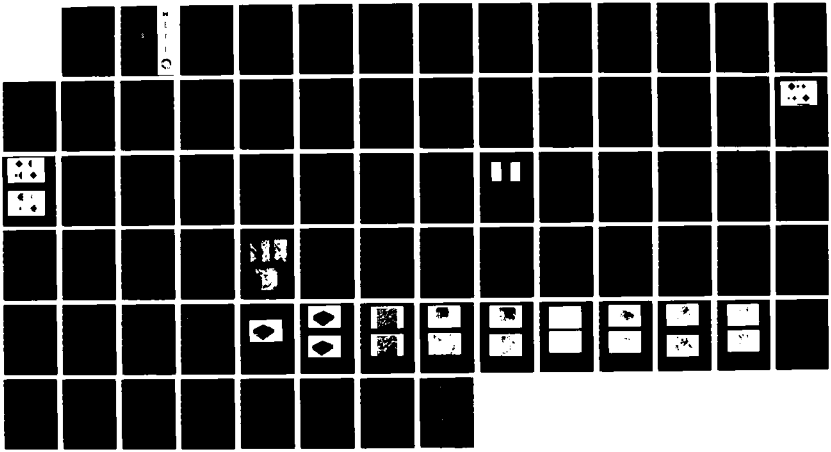

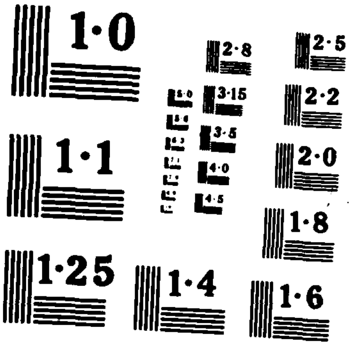
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A smart, mapping, charting and geodesy control generator, phase I

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March 1987

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87

A Smart
Mapping, Charting and Geodesy
Control Generator:
Phase I

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The real-time automated registration of multi-sensor imagery begins with the generation of control information. A specific application may require the registration of newly acquired data to an existing spatial database (absolute registration), or to other images of a series (relative registration). This study examines the the feasibility and upper-level design of a system capable of providing the control information required for a range of image registration tasks and image types. In general, the control generator we suggest will be guided by a spatial database maintaining information about the feature content of the area of interest. A rule-based query generator will extract candidate ground control optimized for the particular image type and geometry at hand.

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Summary

This document is the final report for Phase I of an investigation into the feasibility and design of a smart control generator for the purpose of automated image-to-map and image-to-image registration. The basic issues examined in this report are:

- Characteristics of a spatial database specific to the control generation task.
- The utility of various existing spatial data structures with respect to control generation.
- The top-level design of a prototype system to be used for further analysis and experimentation in automated control generation.

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Section 1

Introduction

Phase I was initially proposed to address the high-level concepts of an autonomous system for the registration of images and spatial map databases. The implementation of an autonomous image registration system on a digital computer has been one of the initial and continuing goals of research in the exploitation of remotely sensed data. Because the registration of multiple images is a prerequisite task of virtually any use of those images for map creation and updating or object detection and tracking, techniques that can aid a human operator, or actually accomplish the registration automatically, are of great importance.

The work done during Phase I was the result of a redirection of our efforts to concentrate on determining the feasibility of using a digital spatial database to support the generation of ground control in support of automated image registration procedures. Additionally, we outline the specific characteristics desirable in such a database. It was determined that questions of feature and image matching, and of the use of image data for registration control were not within the scope of Phase I.

The Smart Mapping, Charting and Geodesy (MC&G) Control Generator will extract ground control information from this spatial database system. For the current study it was assumed that the application was not in a real-time setting - typically operating in an interactive, operator-assisted environment. This is in contrast to a real-time application such as battlefield surveillance and management.

Our study of the use of feature information extracted from a spatial database leads us to conclude that such information, as it currently exists, is not adequate to the task of automated image registration. These existing databases of feature information are neither accurate nor complete enough to be relied on as a sole source of ground control. Even a complete and accurate spatial database would not be an appropriate source of control information for some registration tasks. Additional sources of control information will be necessary, particularly in a real-time setting. Possible sources for control leading to a refinement of the registration process include various dead-reckoning tools and image-to-image matching.

We find that, in general, the function of choosing candidate ground control information and methods is an aspect of autonomous registration that can potentially be automated with current technology. The characteristics of imagery and matching techniques that lead to control selection are knowledge of a sort that can be codified and manipulated with existing software techniques. Modeling of the location errors inherent in the various feature and matching techniques and in the coordinate transformations involved in registration can be performed to allow the determination of control appropriate for differing registration tasks.

The creation and maintenance of digital map databases is a subject of growing importance in both military and commercial endeavors. The use of various types of remotely sensed imagery in updating and exploiting such databases must begin with the currently labor-intensive and time consuming task of image registration. Thus, techniques to automate the control generation and registration processes will greatly enhance the utility of digital map databases for numerous applications. Among the existing and possible uses for large-scale map databases from remotely sensed data are:

Forestry and land management
Geological analysis and prospecting
Military applications (battlefield surveillance, target identification and tracking, etc.)
Municipal land-use planning
Scientific research (botany, oceanography, geology, planetology, etc.)

Virtually any use that has been found in the past for maps and map-correlated data will benefit from the eventual wide-spread existence of techniques for the automatic creation, updating and exploitation of digital map databases. Thus, the Smart Control Generator will be an essential part of a technology certain to be of great importance in the near and far future.

The Phase I effort is concerned primarily with a feasibility analysis of the registration of imagery not to other images, but to a digitally stored representation of the region or surface imaged. This representation is in the form of spatial databases or geographical information systems (GISs). Image registration requires that ground control points and features be extracted from the database containing the spatial representation and passed to additional software that will attempt to precisely locate those points and features in the actual image of interest. Thus, although our primary concern is to analyze the various techniques for digitally representing spatial data, actual implementation of such a system must attend to the specific feature identification and matching techniques to be used with the imagery in question.

Typically, the registration task begins with a human interpreter examining an image or map for features and patterns that s/he expects to be visible in the image to be registered. These expectations are based on accumulated experience with the imagery in question as well as the theoretical characteristics of the sensor technology. Additionally, knowledge of the sensor geometry and surface topography is used to constrain the area searched for ground control information. The purpose of a Smart Mapping, Charting and Geodesy (MC&G) Control Generator is to automate these reasoning processes. The human operator chooses ground control knowing that the mechanism for feature discovery and correlation will be human vision. Because in an autonomous image registration system these matching tasks will be implemented by the artificial (computer) analogues of human vision, the control generation system most account for the nature of those analogues.

The development of an automated control generation process basically requires the quantitative modeling of the registration procedure. The characteristics of the various aspects of the procedure must be known in order to predict the control features and methods most suitable to a given registration task. These aspects include the initial sensor position determining techniques, the storage of feature data, the matching procedures and the nature of the task. Characteristics about each of these aspects include the input data or situations required, their performance with respect to the specific task, their accuracies (and associated possibilities of introducing error), etc.. The process of developing a Smart MC&G Control Generator will require a system to accurately describe the automated registration process as it can be currently performed. Additionally, the system should retain the flexibility to permit consideration of advances in any and all of the various aspects of that process.

The database structure we find to be most appropriate to control generation has a highly-structured arc/node format. This provides advantages of storage space conservation and multiple levels of data organization. Some capabilities this database should exhibit include:

- geographical 'clustering' of features in physical memory;
- similar clustering of features according to their size;
- memory-resident operations to allow feature examination and modification with minimal disk access;
- object-oriented representation of features.

There exist spatial database systems that possess these attributes and others that make them suitable for further work with automated control generation. One of them, the Kork Geographical Information System from Kork Systems, Inc., is available to VEXCEL and is proposed as the database system to be used for further work in this area. Details about our examination of existing spatial database techniques will be discussed later.

The construction of a rule-based system for extracting relevant information from the database will require the greatest portion of the effort of implementing Smart MC&G Control Generation functions using spatial databases. It is possible only because the task of feature choice for ground control is well-constrained by the physical parameters of the sensors and image matching methods used. The control generator will also require an integrated elevation (terrain) modeling capability to aid in restricting the geographical region to be searched for control information and in the construction of simulated images. These functions will utilize existing three-dimensional data maintained in the spatial database. The creation and addition of new elevation data will not be an aspect of the initial development of a control generator.

Subsequent portions of this report will describe our work and the conclusions reached concerning the basic functionality needed for automatic control generation, the system components needed to implement the functions of the control generator, and the specific nature of a proposed prototype to be the central tool for further study in this area.

Section 2

Basic Functionality

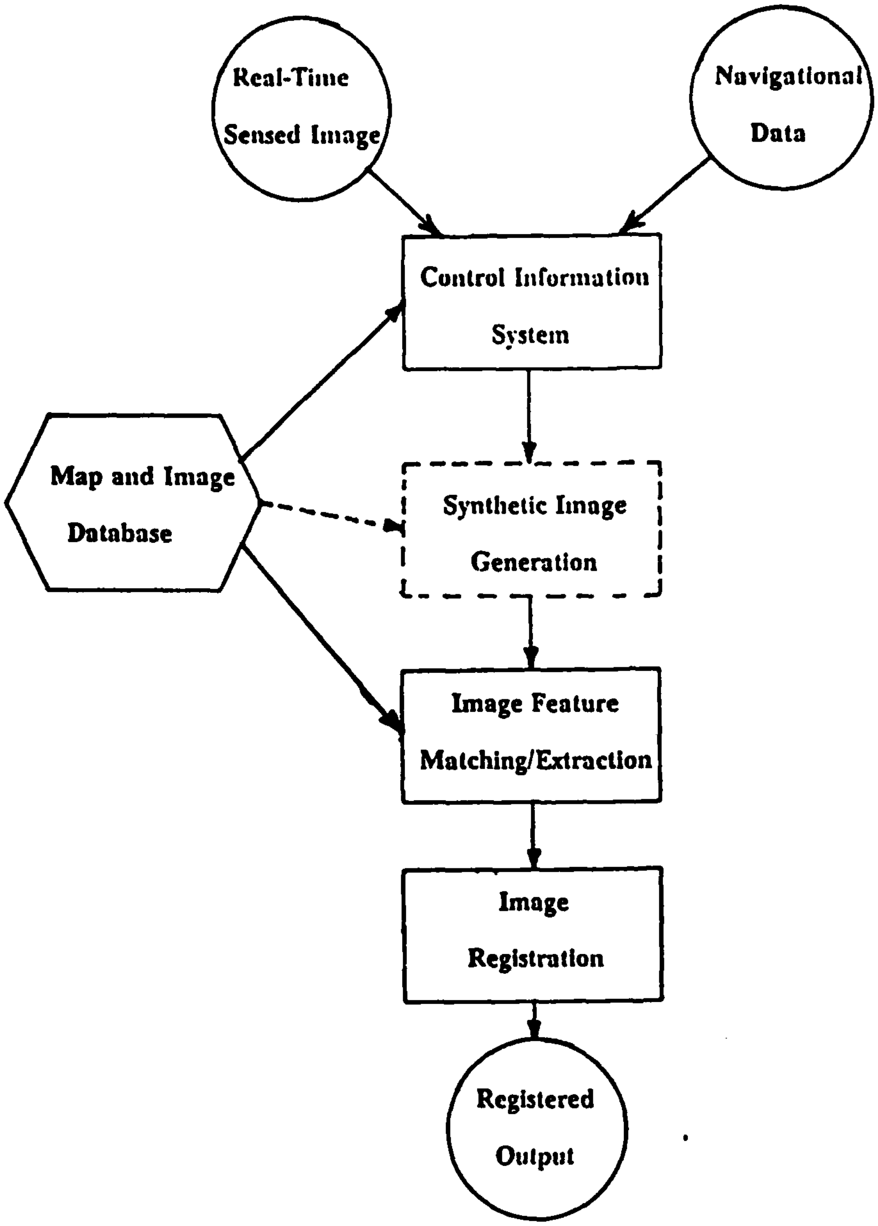
The functions of the Smart MC&G Control Generator fall into six basic areas:

- the geographical (feature) information itself. including attributes of those features;
- the image data itself (i.e. a library of image segments);
- the integration of initial sensor position and orientation information (i.e. data from dead-reckoning tools such as inertial navigation or global positioning systems);
- the intelligent querying of the information;
- the elevation (topographic) information processing;
- the evaluation and reporting of the discovered potential ground control points (including error estimation).

The first three of these items constitute the information to be managed, while the last three are the specific management functions to be performed for this application. The geographical information will initially be a digital representation of existing maps; specifically of the features present on the maps that are likely to appear in some image. This includes natural features such as streams, lakes and forests as well as cultural features like roads and buildings. The elevation modeling functions are considered separately because the need for their utilization in ground control generation is less common (and more expensive) than planimetric data. Image segments can be maintained in a companion database, or as objects in the GIS itself. These segments may be used as tools to predict and recall feature appearance during image matching procedures. Data from various dead-reckoning navigation and orientation systems can serve for coarse image correlation. This may be satisfactory in itself for some applications, or may be useful as an initial registration (subject to refinement) for other tasks.

The actual application of this data to automated image registration involves: first, the efficient search for ground control for the image of interest, and second, the estimation of the probable limits of error between the predicted and actual location of the ground control features in the image. A high-level diagram of the functions performed during automated image registration follows.

Functional Diagram



Note: Dashed lines indicate functions not always necessarily performed.

Section 3

Operational Scenario

What follows is an outline of some of the operations typically performed by the Smart MC&G Control Generator when given the task of reporting candidate ground control for a new image:

1) Image characteristics input to query generator
    - sensor type;
    - preliminary sensor geometry;
    - environment (weather).

2) Delineation of the search area by application of dead-reckoning information
    a) Inertial navigation, satellite ephemerides, or other *a priori* knowledge of the sensor position and orientation is used to eliminate geographical regions not visible to the sensor from consideration for ground control generation.
    b) This information is also used in the derivation of error limits between predicted and actual feature positions in the image.

3) Initial query generation
    a) sensor resolution + sensor range used to determine feature size range to be considered;
    b) sensor type + environment used to determine feature types and attributes to be searched for;
    c) look angle + altitude + average relief + image registration technique used to determine need to consider DEM.

4) If DEM required
    a) create DEM from GIS elevation data (if not already computed and maintained);
    b) create perspective view (with accuracy as specified by query generator in 3c above) to determine regions visible to sensor.

5) Extract all features of proper type/attribute within visible regions.

6) If image type and optimal matching process requires simulated image
    a) create simulated images of regions useful for image-to-simulated-image matching and registration.

7) Evaluate initial set of candidate control features
    a) secondary effects
        - orientation with respect to sensor/flightpath?
        - small features hidden? (refine DEM)
        - clutter;
    b) too few features (or poorly distributed)?
    c) relax parameters and re-query if necessary.

8) Calculate error limits of control points
    - from map accuracy + sensor resolution + sensor geometry accuracy.

9) Pass features, locations and error limits to image matching software.

The process described above illustrates the use of the major functions of the control generator. Other queries concerning ground control (e.g. additional information about a specific feature, additional features for refined registration, etc.) will utilize these functions under the control of the rule-based query generation and system control software.

Section 4

The Smart Mapping, Charting and Geodesy Control Generator

The Smart MC&G Control Generator comprises these three basic modules:

- the geographic information system (GIS);
    - feature data (map database),
    - image data (library of image segments),
- integrated digital elevation modeling (DEM) module;
- query generation and system control;
    - intelligent querying of GIS,
    - choice and coordination of image processing/matching techniques,
    - integration of dead-reckoning techniques,
    - reporting of candidate control and error estimates.

By separating the actual data storage and retrieval functions from the ground control query and analysis, the system is more easily upgraded as new feature and sensor types and attributes become relevant. Further, the implementation of the query generator as a distinct, rule-based system will allow the GIS to be used for other applications, requiring only that the appropriate rule-set be created.

The control generation system will be implemented using object-oriented programming techniques. The GIS will support feature storage and access as objects. Object-oriented programming, for example Smalltalk, has its roots in simulation, and consequently has as a fundamental structure the notion of "object". These objects can both constitute a representation of something, as well as actually do something. The former property corresponds to the notion of an "instance variable", while the latter corresponds to the notion of an "instance method". Each object has its own unique set of instance variables and instance methods.

Object-oriented programming also has the capacity for hierarchical classification. Objects belong to "classes", which in turn can be aggregated to form "superclasses", or subdivided into "subclasses". These classes, subclasses, and superclasses also have instance variables and instance methods. One of the conveniences of these hierarchical constructs is the property of "inheritance". Objects automatically inherit the instance variables and instance methods of the class to which they belong. Of course, these may be modified in individual cases, thereby retaining flexibility.

For the purposes of the map information database, individual features could be represented as objects. Classes of objects would correspond to real-world aggregations of objects that are appropriate to imaging. Instance variables of an object would correspond to those qualities or characteristics that are appropriate to imaging with a particular sensor type. Instance methods would correspond to particular methods of choosing control information or particular methods of forming synthetic images for a particular sensor type.

Therefore, for this particular application, object-oriented programming allows a convenient, flexible, and hierarchical definition of properties for map features which are complementary to the corresponding definition of imaging processes that are relevant to those properties.

Another consideration is that of extensibility. Any instance method will work on any object if the former is included in the latter's collection of instance methods, or "protocol". Therefore, one can define a new class and allow many existing methods to work for it by suitably defining its protocol. In this way, new map features can be added to the database and potentially be amenable to some of the previously-defined imaging and control information processes.

The remainder of this section will be devoted to a more detailed description of the three basic modules of the control generation system.

4.1 Geographic Information System

Clearly, the heart of the control generator is the database itself. The basic approach to registration that we consider could be called "map-guided". The existing map database is searched for possible ground control according to the current needs of the registration system at the time. Thus, the format of the database must be optimized for the sorts of queries most likely to be made. These queries can be divided into two classes:

- search by geometry;
- search by attribute(s).

Naturally, queries of the database will often, if not always, be some combination of these two types.

It should be clearly understood that the contents of the database may consist partially of terrain features that were automatically extracted from imagery. This is in addition to, or as opposed to, map-related data.

(a) Geometric Search

A common need will be a search for all features (perhaps with specified attributes) within a certain area or within a certain distance of a given point. This is a typical function of most Geographical Information Systems (GISs), and a number of techniques have been developed to facilitate this type of data manipulation. To speed the execution time of such queries, the digital representation of features near each other in the world should be "near" each other in the physical structure of the database. The purpose of this geographical clustering is to reduce the number of disk accesses needed to examine a given area.

Geographical clustering can be done by storing as a feature attribute the range (minimum and maximum) of coordinates spanned by each feature. A number of algorithms exist to sort these Minimum Bounding Rectangles (MBRs) so that all features within a given region can be quickly accessed. Among these is an extension of B-trees to more than one dimension, called an R-tree (for rectangular).

The use of differing sensor technologies (with differing resolutions) creates a requirement not so common to GISs. Depending on the sensor in use at any one time, features of different sizes will be of interest. It would therefore be advantageous to have features of similar size clustered within the database, once again for the purpose of speeding the search process. This size-related clustering would be subordinate to the geographical clustering described above. In such a system, one or several disk accesses would provide all the features of comparable extent within a given area.

(b) Attribute Search

The attributes associated with the features stored in the database will be used in two basic ways. First, they serve as keys in the initial search process. The control generator will initially (and perhaps subsequently) search for features with certain attributes within a specified region. Thus, the stored feature attributes become the primary filter for choosing candidate ground control. Other attributes may be used later for other purposes. These include analyzing the quality of the generated ground control and evaluating the limits of error in the preliminary position information sent to the image matching software.

There remains some question about the best place to store this attribute data. It could be stored in a separate database existing along-side (and keyed to) the GIS. This would minimize the size of the GIS, and optimize the purely geometric search aspects of the problem. However, it appears that most queries will involve a combination of geometric and attribute considerations. Thus, two distinct searches of the separate databases would typically be required for each query.

4.1.1 Spatial Database

A thorough study of existing and theoretical methods for the representation, storage and application of spatial information was an important component of the Phase I work.

The great emphasis that the generation of ground control places on lineal features (and lineal boundaries of areal features) implies that data representations that are optimized for manipulating point and lineal data as opposed to true areal representations are advantageous. It is for this reason that a number of areal representation schemes (such as quadtrees and their derivatives) are not optimal for this work. In those cases where areas of imagery are important to matching (as in actual image segments or in using windows from simulated imagery), there seems no need to maintain a representation of the image, because it is the image itself that is relevant.

The specific requirements of the control generator for memory space conservation, feature 'clustering' (geographic and attribute), rapid access and accurate database updating lead us to prefer a highly structured arc/node format. With such a format, points are represented by retaining their coordinates with respect to some reference frame. Lineal features are represented by a series of line segments, each of which is defined by the coordinates of its endpoints. Finally, the boundaries of areal features are represented as closed polygons, each side of which is a line segment defined as for lineal features.

The greatest advantage the use of a point/vector (or arc/node) format affords for map database management and ground control generation is the logical similarity between this representation and the likely ground control features present in maps and images. Ultimately, all registration processes rely on the identification of homologue points. Often, particularly in dealing with large-scale imagery, these points are derived from the more visible lineal or areal features in the image (e.g. intersections of lineal features or centroids of areal features). Existing (and probably future) digital representations of map information are composed of just such collections of points, lines and polygons as are used in arc/node-based GISs (e.g. DFAD).

The highly structured arc/node format will permit the GIS module to efficiently maintain three levels of data organization: spatial, topological and cartographic. It is at the cartographic level that each feature becomes more than simply a shape and location. The attributes that classify and describe a feature are part of the data object (representing that feature) manipulated at this logical level. It is at the cartographic level, with features as shape plus characteristics, that most human interaction with the data base will occur.

Operations that involve the geometric relationships between features will operate on the data at the topological level. The union, intersection, tests for inclusion, etc. of features can be done here without attention to their exact location, by applying topological rather than coordinate analysis. The physical extent of features is represented by nodes, edges, and faces at this level. These topological representations are created and updated from the cartographic data as a feature is added to the database. The many-to-many relationships inherent in geographic data (e.g. a road may cross many land areas, and a land area may contain many roads) is accommodated by links (pointers) between nodes, edges and faces at the topological level.

The combination of a feature's cartographic and topological representations is then geographically clustered. At this 'spatial' level of data organization, features are placed into physical storage (disk) with other features that are located in the same geographic area. This is important in order to speed searches for features within a given area. Additional data organization is done to put features of similar size 'near' each other in physical memory. This is relevant to the Smart MC&G problem because sensors of different types at different ranges will produce images of differing resolution. The data base will contain features visible from satellites, as well as small objects visible only from low altitudes. Clearly, the registration of no single image is likely to require both sorts of features.

A specific example of a spatial database that appears suited to further development of of automatic control generation is the Kork Geographical Information System (KGIS). This system allows for the clustering of features in physical memory as described above to increase the search performance of the database. It is an object oriented database, so that all information about the nature of each feature and the operations associated with that information are independent of the software external to the database itself. This permits the flexibility necessary for the alteration and experimentation that will be an important part of subsequent (Phase II) work on the Smart MC&G Control Generator.

The database structure we suggest for implementation of the Smart MC&G Control Generator is rather general. It reflects current work in spatial data handling, and requires little modification to be entirely well-suited to the image registration application we are discussing here. This is not surprising, as the data handling aspect of the problem is not particularly unusual or specific to control generation. The more specific aspects of the problem are addressed by the query generator that actually exploits the database, and the DEM software that must be integrated into it.

The integration of digital elevation data and modeling capabilities into the spatial database will be a significant project. This work is currently being performed at VEXCEL in an effort separate from the SBIR being reported on here. Our approach will be to provide each point of the terrain model in the database (KGIS) an elevation (z) coordinate as well as the planimetric (x and y) coordinates. The elevation of features not originally a part of the DEM can be (in some cases) interpolated from the grid of points that constitutes the DEM itself.

The major goal of all phases of the development of a Smart MC&G Control Generator is the discovery of data and processing techniques optimal for specific automated registration tasks. Quantitative modeling of the registration process in order to evaluate these control methods and features will be the basic tool by which the optimal combinations are found. The control system must be general enough to accommodate future advances in spatial database management (both in hardware and software), just as it must accommodate future image matching and feature extraction techniques. For this reason, the exact nature of the database system used for current work must be divorced from the control generator itself. The control generation system will present requests for feature or other data to the database management system. The exact format of the data within the database should not affect the control generator's choice of the data to be used for registration. Our conclusions about optimal spatial database design, and our choice of a specific existing system, are aimed at providing the best currently available foundation for immediate progress in quantitatively evaluating the components of the registration modeling process.

4.1.2 Image Segments

Small portions of images that contain examples of ground control features can be retained in the database system in order to facilitate later matching processes. These image segments can be useful for rapid registration in certain situations. For example, a well-defined feature present in an area that is periodically imaged with constant sensor type and geometry can in itself provide the needed control. In this case, simple areal correlation of an image segment containing the permanent feature with the appropriate region in the new image would be a rapid method of registration.

Another possible use of image segments arises in registering images that are part of a rapidly sampled time series (e.g. television-rate infrared images). An interest operator could be used to find and extract windows containing likely control features in the first of a series. Subsequent images in the series could then be registered by correlation with the windows extracted from earlier images.

The use of image segments for registration in these rather special cases would be managed by the control generator's query generation and control software. A library of image segments would be keyed to the corresponding features (where appropriate) in the spatial database.

4.2 Digital Elevation Modeling

The three-dimensional nature of the land surface to be represented in the GIS requires that elevation information be considered when generating ground control. Furthermore, the use of a variety of sensors, producing images with differing resolution and geometry, implies that the capability for rather detailed modeling of the terrain be an integral part of the control generating system. VEXCEL is currently engaged in development work to integrate elevation coordinate data and surface modeling capabilities into the Kork Geographical Information System.

One of the primary uses of a digital elevation model will be to calculate those regions of the area in question actually visible to the sensor. Registration of imagery from directly overhead will of course require little or no consideration of this shadowing effect. On the other hand, side-looking imagery, particularly from low altitudes, must interact strongly with the DEM component of the system. A second major use will be the creation of simulated images.

This software module will have the following capabilities:

- extract elevation data from GIS
- create digital elevation model of the necessary precision (may vary with respect to specific registration task)
- store/maintain this model in the GIS
- shadow analysis (perspective view) of region

Because of the computational expense involved in calculating a perspective view from a given DEM and sensor position, it may be applied only judiciously. In a dynamic processing setting one may "update" a previous DEM operation by adding relevant new DEM data, avoiding the need to re-compute the entire model. The control generation system must determine the need (and required accuracy) for consideration of elevation information based on the sensor in question and the ground relief of the terrain imaged.

4.2.1 Simulated SAR Imagery

The digital elevation model of a region will also be used to aid in creating a simulated radar image. Consideration of the sensor range, resolution, look angle, and platform heading in conjunction with the DEM and appropriate introduced noise produces an pseudo-image that can then be registered with the actual image. Since the simulated image is produced from a map-coordinate-based DEM, this provides geodetic control for the actual image. Recent work reported by Guindon and Maruyama indicates that this technique produces automatic registration of SAR imagery with accuracies comparable to those achieved manually [Guindon and Maruyama, 1986].

The simulation procedure used assumes that the radar backscatter (and thus, pixel intensity) is dependent only on the incidence angle. The results of their experimental work are shown in Table 1. The greatest consistency of the automated procedure with manual registration is found when large (64x64 pixel) windows, termed registration control points (RCPs), are extracted from the actual scene for comparison with the simulated image. Further, the use of adaptive filtering to reduce speckle also improves the registration.

Poor matches (i.e. low peak correlation values or failures to find a correlation peak within the interior of the RCP) tend to be associated with image areas that exhibit a small radiometric dynamic range. The selection of candidate control windows on the basis of observed gray-value variance would eliminate the need to calculate correlation values for these unlikely areas, thus increasing the efficiency of the registration process.

Summary of the performance measures for the 12 matching experiments.
Shown are RCP sizes 16 x 16, 32 x 32 etc; with the filtering options* for each

	16 x 16			32 x 32			48 x 48			64 x 64		
	NFL	7 x 7	11 x 11	NFL	7 x 7	11 x 11	NFL	7 x 7	11 x 11	NFL	7 x 7	11 x 11
Measure of internal consistency												
— pixel	3.0	2.7	2.7	2.5	2.2	2.1	1.7	1.6	1.6	1.8	1.5	1.5
— line	2.4	2.4	2.4	1.8	1.8	1.7	1.2	1.1	1.1	1.0	0.9	0.9
Measure of consistency with manual acquisition												
— pixel	3.0	2.8	2.7	2.6	2.3	2.3	1.8	1.8	1.7	1.9	1.6	1.6
— line	2.7	2.6	3.2	2.0	1.9	1.8	1.3	1.1	1.1	1.0	0.9	1.0
Number of failures	3	3	4	2	2	2	1	1	1	3	1	1
Median correlation coefficient of successful matches	0.60	0.63	0.67	0.61	0.60	0.70	0.64	0.71	0.71	0.64	0.72	0.71

---

*NFL = no prefiltering
7x7 = adaptive filtering 7x7 window
11x11 = adaptive filtering 11x11 window

TABLE 1

This table illustrates the use of simulated imagery for image registration. A simulated synthetic aperture radar image is created by using a digital elevation model. The pixel gray-values of the simulated image are determined by the incidence angle derived from an assumed sensor location and the DEM. Windows from the simulated and actual image are correlated to determine registration offsets. Because the simulated image is derived from a map-coordinate-based DEM, matching of the two images produces geodetic control for the actual radar image.

As might be expected, using larger windows for the correlation produces more accurate registration. Additionally, the use of filtering to reduce the effects of speckle improves the matching. Failures (inability to find a correlation peak) tend to appear in windows with little radiometric dynamic range. Thus, selection of windows based on observed gray-value variance should improve the entire process. (from Guindon and Maruyama, 1986)

4.2.2 Use of SAR Shadows

Another aspect of the generation of simulated SAR images from a DEM is the possibility of using radar shadows as features for image registration. The sequence of images below (Figures 1a, 1b, 2 and 3) illustrate the creation of shadow 'features' in a simulated SAR image [Domik, 1985]. Figure 1 shows the digital elevation model used, while Figure 2 indicates the portions of the scene illuminated given the sensor position used. In Figure 3 the simulated image is shown. Notice that features generated by the topography of the scene include bright areas due to radar lay-over as well as the shadow regions. These types of features will be more common in imagery sensed from a high look angle, and less important in images of regions more directly beneath the sensor.

4.3 Query Generator and System Control

The query generator is the component of the system that exploits the map database for the purpose of discovering likely ground control features. Knowledge of the characteristics of the sensors and image matching processes is utilized to guide the search of the database for ground control relevant to the current task. The choice of attribute data maintained by the Geographical Information System (GIS) will be driven by the specific character of the feature detection and image matching software, as well as by the exact nature of the sensing systems used. Choosing a GIS structure and programming techniques that emphasize code maintainability and reliability (i.e. structured, object-oriented code) will allow changing techniques in either of these areas to be easily accommodated.

In addition to accessing the database itself, this module will also perform overall system control functions. This includes such things as determining the need for DEM or simulated image construction, and the choice of rule and meta-rule subsets appropriate to specific image types and registration tasks.

The use of expert systems for maintaining and exploiting spatial databases was examined during Phase I. For the near future, the application of expert system techniques to Geographical Information Systems will be limited to small, precisely defined problem domains [Robinson, et al, 1986]. Fortunately, the evaluation of a digital map database for candidate ground control appears to be one such precisely defined domain.

This query generator will be a rule-based expert system, designed to automate the choices a human being would make if tasked with the problem of choosing initial ground control for differing image types. It communicates with the data itself only through the storage and retrieval protocols intrinsic to the GIS system. Thus, we avoid building dependence on each other into either module. Modification of the rules and meta-rules themselves will be necessary as new techniques (and new feature types) are developed.

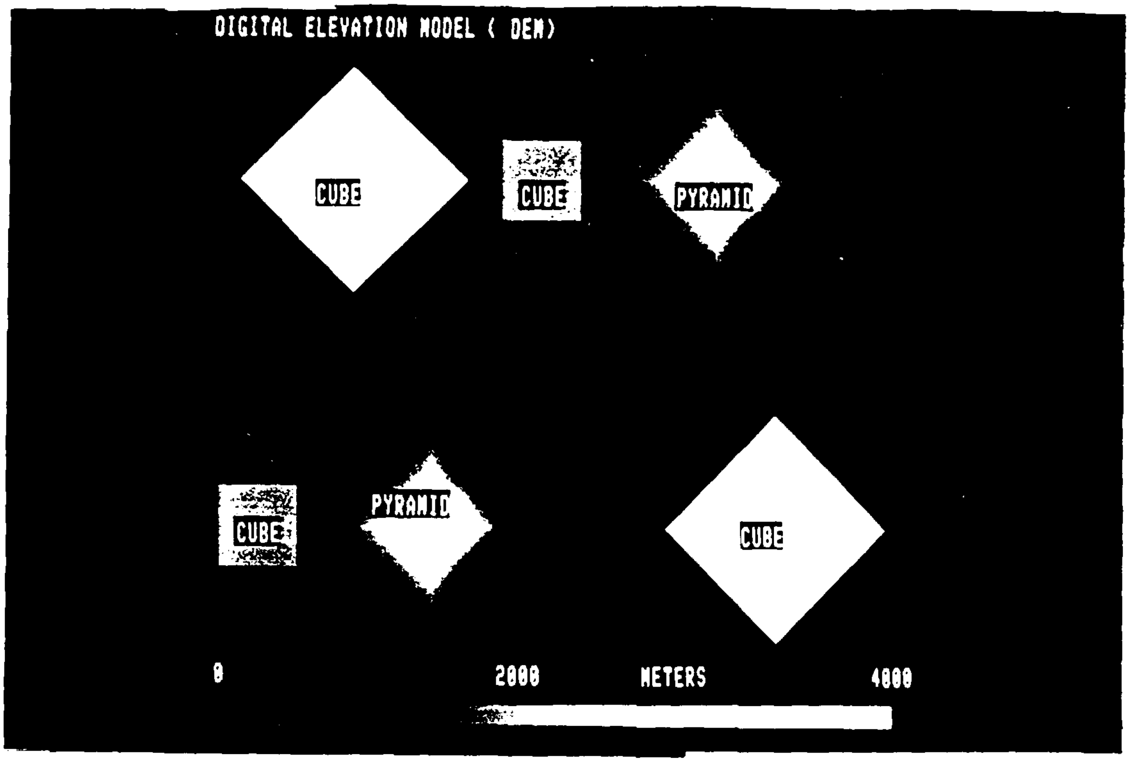
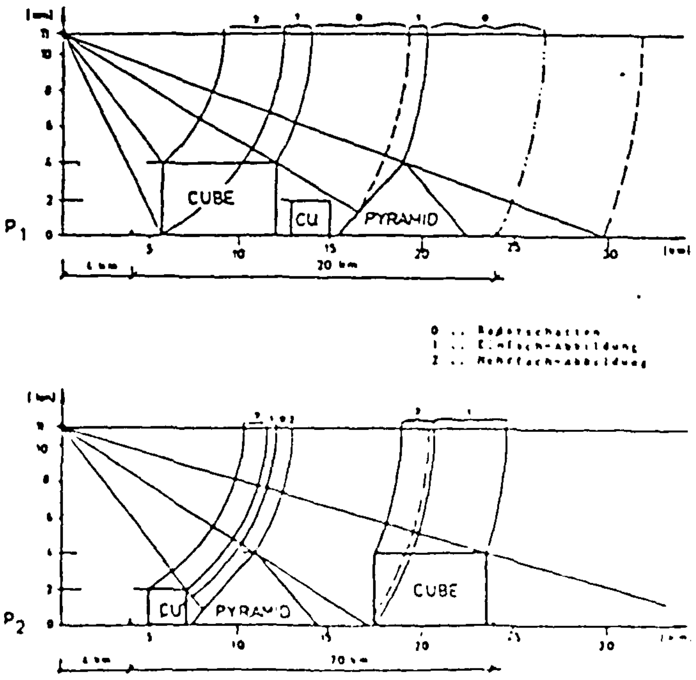


FIGURE 1

The digital elevation model used for an experiment with producing radar shadows in SAR imagery. Figure 1a (above) shows the model as seen from above. The lighter color indicates greater elevation. Figure 1b (below) provides a schematic of the model as seen from the side. The elevations in the model range from zero to four kilometers, while the sensor is placed at a height of 11 kilometers. The numbers (0,1,2) indicate regions in the slant range image in which a shadow, regularly illuminated region, and region of lay-over, respectively, would appear. (from Domik, 1985)



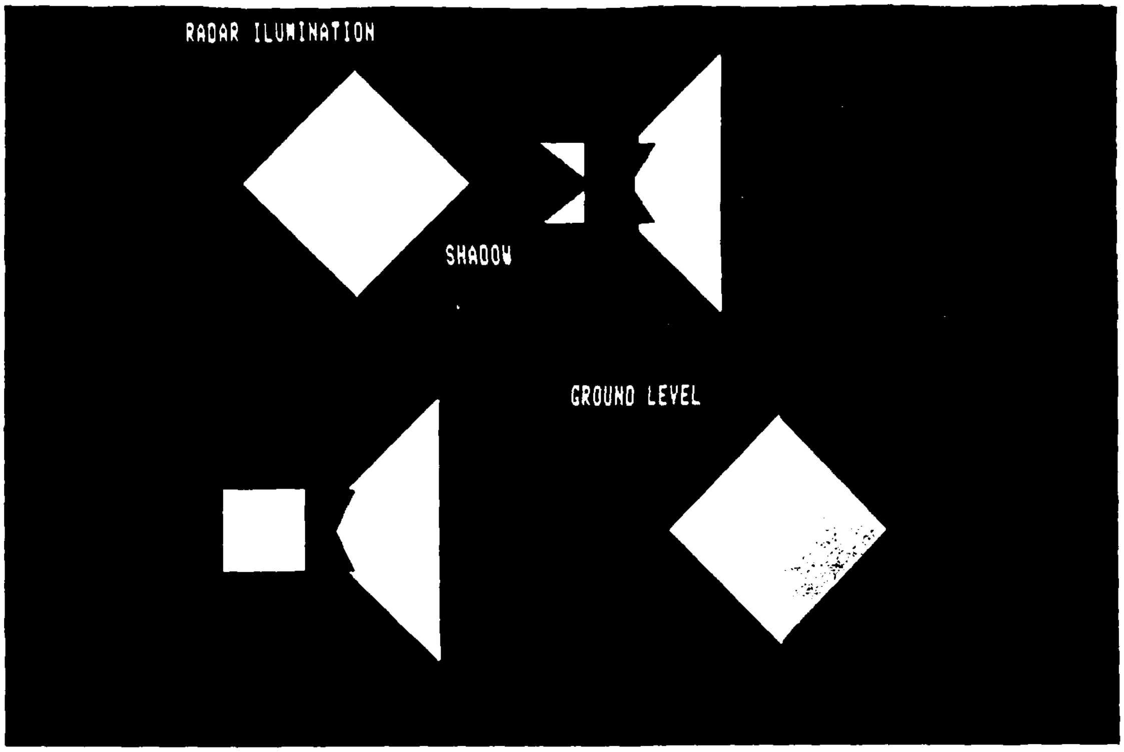


FIGURE 2

This figure illustrates the way in which the digital elevation model described in Figure 1 would be illuminated by a SAR sensor placed as shown in Figure 1b. (from Domik, 1985)

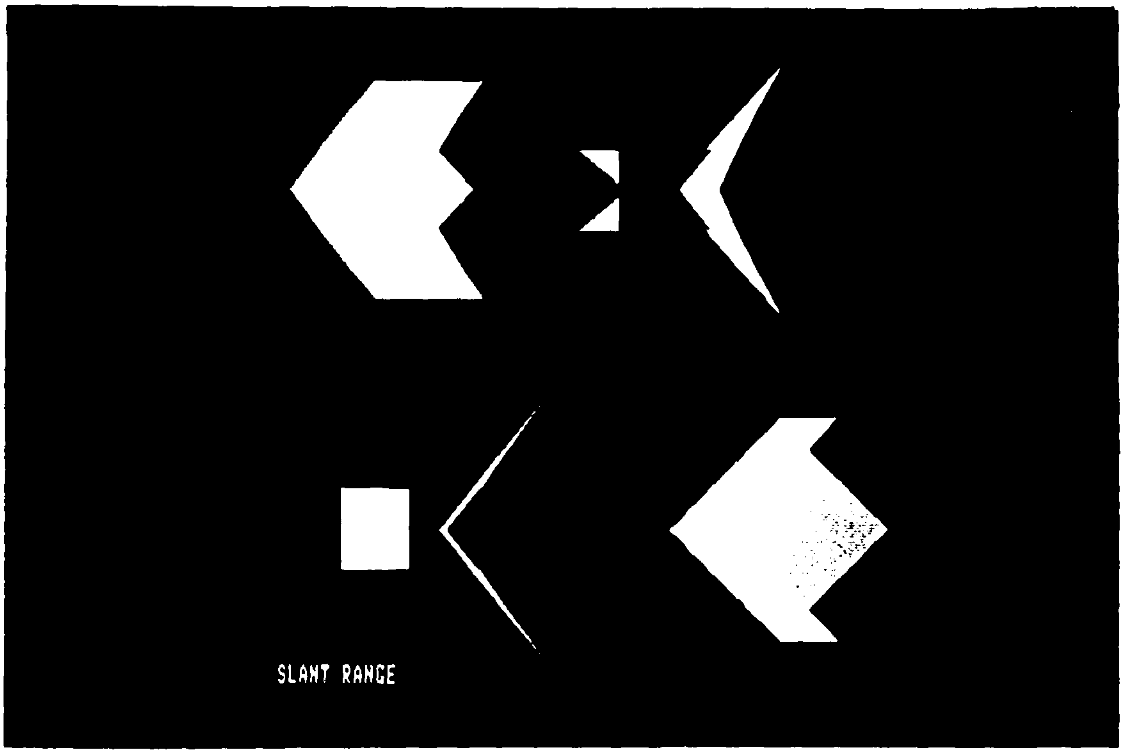


FIGURE 3

This is the simulated SAR image derived from the digital elevation model and sensor location described. Notice that regions of shadow, normal illumination and lay-over are all discernable. (from Domik, 1985)

At its most primitive level, this rule-based approach will allow the implementation of our understanding of map-guided ground control for a given sensor type. That is, as decisions are made concerning the utility of certain feature types or attributes, the query generator will be modified to reflect the importance to be given that feature type or attribute. Ultimately, however, the usefulness of the query generator will extend beyond this: comparisons of the relative utility of differing sensor types and image matching techniques in pursuit of various registration tasks will be efficient and accurate. Decisions concerning these relative strengths and weaknesses can then be incorporated into the rule set.

Three basic concepts of data representation and software implementation are important to the Smart Control Generator. The geographical data itself is represented in the previously discussed arc/node structure. This data type should not be confused with the object-oriented approach recommended for implementation of the database management system. The objects manipulated by the database may include geographical data represented in an arc/node data structure, but may also include attribute data and object processing routines that are not represented with such a structure. Finally, the query generation system that intelligently applies the functions of the database manager will encode the knowledge useful for control generation as a set of rules and meta-rules to direct the manipulation of the various objects maintained in the database.

4.3.1 Overview of Expertise for Control Information

The task of registering imagery with map data is an important problem. However, images and maps are quite different data formats. Images are sensor recordings of the received signatures of scatters of some type of electromagnetic radiation, whereas a map is some two-dimensional compilation of elevation and feature data by location. Maps are ususally at a very different scale than images, and are also much more sparse in detail. Consequently, registration cannot be performed on the basis of some local gray-value similarity corresponding to local scene similarity, as in image-to-image registration. Instead, registration can be attempted in two distinct ways. One way is by direct map-to-image matching. Another way is to produce a synthetic image from the map data that corresponds to some projected view similar to that of the real image, and then performing a registration between the real and synthetic images.

Direct map-to-image registration is performed on the basis of finding a correspondence between some identifiable map feature itself and its signature within the image. Such features are called control information. Such information is ideally in the form of distinguishable points, but often is in the form of identifiable line segments and contours, either open or closed. Because synthetic images contain less microstructure than real images, any matching between the real and synthetic image must proceed on the basis of the real and simulated signatures of map-recorded features. Therefore, control points are also important for the latter type of registration.

In order to attempt an automation of this type of registration, there must exist an automated process of choosing control information. Given some desired accuracy of registration, such an automated process must decide which features to select, how many, and with what spatial distribution. Examining the question of the feasibility of automating expertise for the selection of control information is the subject of this section.

The technology of expert systems is currently receiving a great deal of attention. Currently,however, there does not exist a large number of working expert systems which contain large knowledge bases containing hundreds or thousands of rules. This is because the process of distilling domain-specific expertise into a suitable format for automatic processing, such as rules, is tedious, time-consuming, and not straight-forward. Another reason is that not every subject domain is amenable to the current state of expert system technology.

Some good "rules of thumb" concerning the applicability of expert system technology to a domain are:

* A typical problem can be solved by an expert in a few minutes to a few hours, ie. the domain is reasonably bounded.

* The expertise is decomposable into modules of expertise.

* The expertise can be taught to a novice, ie. it is succinctly describable.

We believe that the problem of finding good control information satisfies these criteria. However, satisfying such "rules of thumb" does not constitute a demonstration of feasibility. Clearly, what is required for every separate case is a more detailed analysis of the structure of the appropriate working knowledge.

Another issue concerns whether the implementation of the domain-specific knowledge should procedural, ie. they do not separate the logical from the control content of the program. The control structure determines the order of execution in a program. In procedural programs, this order of execution is intimately connected with the order of its statements. However, programs also have a logical content which is determined by the logical relationships among its logical clauses.

In non-procedural programming, these logical relationships do not depend on physical relationships among a program's statements, such as their order. The control and logical contents are separated, and so what is to be done can be separated from how something is to be done. This separation of functions is very convenient for implementing domain-specific knowledge. Individual statements representing such knowledge can be added or removed from the knowledge base without regard to their order. Thus modification of the knowledge base can proceed entirely on the basis of its logical content. PROLOG is an example of a language supporting such logic programming. In PROLOG a knowledge base is implemented using "rules". These rules take the familiar form of an "If (hypothesis)...then (conclusion)" paradigm. This type of rule-based programming will be the choice for implementing the expertise for selecting control information.

The knowledge base will take the form of rules used by experts to choose control information. These rules are generally based on heuristics, and "rules of thumb" commonly employed by practicing experts. The value of a rule should be its applicability in a wide variety of typical cases.

Rules with negative conclusions are important also. For example, a rule which cautions against picking mountain peaks as control points in direct map-to-image matching is as useful as one which positively chooses the intersection of two roads on flat terrain. Such reasoning allows the system to eliminate possibilities.

There will likely be a type of "gray area" between positive and negative rules wherein it is not clear that a feature is suitable or not. This means that rules which eliminate a candidate feature are not necessarily converses of rules that choose a candidate. Therefore, most rules will not give both necessary and sufficient conditions for choosing a particular feature as candidate control information. Such a situation creates the possibility of inconsistent rules being added to the knowledge base. However, it is hoped that usually rules will be related by being partial converses of each other. Therefore, inconsistencies should be relatively rare.

4.3.2 Preliminary Investigation of Control Information Expertise

Expertise for the problem domain of image-to-map mode of matching proceeds by registering the real image directly to the map or indirectly using a synthetic image. However, regardless of the sensor type employed and desired mode of registration, the expertise must answer the questions:

- Which map features to choose?
  - man made
  - natural

- How many features should be chosen and what should be their distribution?

The answers to the question of how many features are required involve what type of matching transformation is to be estimated. The question of the distribution of the features involves avoidance of singularities and sensitivity of the transformation equations to the relative positions of the features.

The answers to the question of which features to choose depend on the type of imaging sensor type and the mode of registration. However, for each such combination of sensor type and mode of registration, there are a number of characteristics of map features that determine the suitability of a feature for achieving good control information. We identify some of these characteristics below:

- strength of return
  - sensor wavelength
  - sensor spatial resolution
  - feature geometry
    - size
    - shape
  - feature material properties
  - weather-induced moisture
  - illumination power onto scene
  - illumination direction

- magnitude of local contrast
  - expected signal strength difference between feature and local background
  - sensor spatial resolution
  - sensor radiometric resolution

- geometrically distinctive components
  - points
  - contours
    - open
    - closed

- potential for confusion
  - local similarity
  - geometrically induced artifacts and distortions

As an example, consider the case of direct map-to-image matching for SAR. The scale of most man-made features, other than entire cities, is such that they are important to registration only if higher resolutions are employed. Often, such objects give rise to point or lineal features which are suitable for registration. Cities often provide strong lineal returns if some of their streets run perpendicular to the direction of illumination. Road and seismic line crossings may provide good point returns.

However, many such man-made objects involve height discontinuities with their surroundings, such as buildings or towers. Therefore, care must be taken to account for height-related imaging anomalies that are peculiar to radar imagery, such as lay-over, radar shadows, and edge-migration. Imaging of extended regular areas such as cities may involve confusion as to which streets are actually being imaged.

An example of a type of natural feature providing good point returns is a small river mouth in a flat area. An extended crossing that is wider can still be used, but now some point-like derived feature such its centroid is often used. River windings may also be useful as contour-like features. However, the surrounding terrain must be relatively flat or else geometric distortion will be present, resulting in improper location of the feature in the image. This concern with topography makes it difficult to use mountainous terrain, drainage, or peaks for control points. On the other hand, if synthetic images are used then such terrain relief can be used for registration. This is because the geometric distortions inherent in SAR imagery of such scenes will be faithfully reproduced in the corresponding synthetic images.

An initial task for the query generator will be to determine whether topographic shadowing is significant to the current registration goal. This will involve consideration of the sensor geometry and type, as well as the general degree of ground relief in the region of interest. If needed, the query generator must then calculate those areas of the region actually visible to the sensor. Only those areas will be subject to subsequent investigation.

Clearly, the type of sensor used to create the image to be registered is the most basic parameter into the query generator. The sensor type will influence the sizes, types, and attributes of the features to be searched for in the database. In formulating the initial query, the generator must also account for some other aspects of the particular task in work. Environmental factors such as temperature and precipitation will affect both the sensor performance and the feature characteristics. The degree of registration precision, and the speed with which that registration is performed will also influence the choice of ground control features.

Typically, choices of control features will be made as a result of a number of tests concerning the specific registration task, the image matching and registration techniques available, and the feature content of the region in question. Several qualitative examples will serve to illustrate the formulation of queries to the database.

```
1)  If     ((image-type = aerial-SAR) and
             (topographic-relief = 'low'))
    then   (find  (search-area = defined by initial sensor geometry) and
                       (feature-type = road) and
                       (orientation = 'near-parallel-to-flight-path'))
```

In this case, a feature of a specific type is being extracted; the knowledge that roads have surface material compositions and shapes/geometries (e.g. long and thin, relatively flat) that are good for aerial SAR control is not explicitly expressed. The possibility that roads may be mis-located in SAR imagery of areas with significant relief is accounted for in the second test. The geographical limits of the search area may be determined by any of the dead-reckoning techniques that provide preliminary sensor location and orientation information. In this particular case, the search area determination would not require consideration of DEM information, because the topographic relief has already been found to be low. Finally, the orientation of the road with respect to the flight path must be appropriate. An example of the importance of this requirement to radar registration can be seen in Figures 4a and 4b [Domik, 1986]. The actual evaluation of most if not all attributes such as 'orientation = near-parallel-to-flight-path' will be quantitative; the determination of appropriate metrics (and values appropriate for the control generation task) for such characteristics being a significant portion of subsequent effort in this area.

```
2)  If     ((image-type = SIRB-SAR) and
            (topographic-relief = 'high'))
    then   ((create-simulated-image
                  with(region = determined by initial sensor geometry)) and
            (extract windows from simulated image with large radiometric
              dynamic range))
```

This meta-rule finds windows suitable for the automated SAR registration technique described earlier [Guindon and Maruyama, 1986]. It would make use of the DEM data for the image simulation process. More sophisticated simulation methods which would also require knowledge of the surface character and feature content can be envisioned.

```
3)  If (image-type = aerial-photo)
    then  ((calculate-relevant-feature-size
                 with(sensor position, resolution)) and
           (find      (search-area = defined by initial sensor geometry) and
                      (feature-shape = linear-intersections) and
                      (feature-contrast = 'bright')))
```

In this example, the control information is searched for on the basis of its characteristics as an image feature. It is not identified as a particular type (as were the 'roads' in example 1). Rather, any intersection of 'bright' linear features may be useful for registering aerial photos, and so all such features are extracted. The size (width) of features useful for this task will depend on the resolution and range of the sensor; this illustrates the benefit of being able to efficiently search the spatial database for features of a given size range, as well as features located within a given region.

The query/control module must also supervise all subsequent searches to the GIS. This would be necessary if the initial search did not find enough features, or if the image matching software could not find them in the image. In these cases, a search similar to the first, but with relaxed conditions could be executed. After an initial matching/registration step, registration could be refined by using features not initially reported. For example, a feature in a cluster may not have been used in the first iteration because of the possibility of an incorrect match with similar objects nearby. The initial registration can be used to restrict the subsequent search space so that this feature then becomes usable.

4.4 Error Estimation

In addition to the features themselves, estimates of the probable limits of error between the preliminary registration and actual registration must also be passed to the image matching software. These estimates are used to define the region of the image within which the matching software will search. The query/control mechanism will calculate these error probabilities based on the accuracy of the sensor geometry, the sensor resolution, and the character of the feature and image matching processes.

A classical concept involves the computation of approximate image coordinates for a specific control feature. An error envelope is defined for the image area in which the matching image feature should be found. The matching then consists of finding an object of known properties in the search area.

The evaluation of the sources of error in registering different image types will be an important aspect of subsequent (Phase II) work. The errors inherent in the initial sensor position determination systems (e.g. the various dead-reckoning tools) and in the image matching techniques will be an important consideration for the extraction of control information.

4.5 Performance

A major concern in the design of a Smart MC&G Control Generator is the speed at which images can be registered to a common reference frame. In general, the goal is to perform such operations in 'real-time'. However, precisely what is meant by real-time varies with the image type. An infrared sensor operating at a scan rate of 30 Hz requires that each new frame by registered in something less than 0.033 sec, while the registration of photographs of an area taken days apart is under virtually no time constraint.

Fortunately, the registration of frames from a continuously operating scanner (such as an infrared sensor) can be performed rapidly. Each frame can be registered by relying on the registration of the previous frame. This is done by predicting the location of features in the new frame based on the motions of those features in past frames. Thus, the search space for the actual image matching (for refinement of the registration) is kept quite small.

FIGURE 4

This figure shows the dramatic effect that the flight orientation of an SAR sensor can have on the features visible in the image it produces. These two SIR-B images are of the same region in Argentina. The image on the left was produced as the sensor was moving from the upper-left to lower-right, while in the image on the right the sensor is moving from lower-left to upper-right.

Notice the linear features that are strongly visible in the left image. These are streets (and houses along the streets) that are aligned nearly parallel to the flight-path. The same streets are not visible in the right image, because they are nearly perpendicular to the flight path. (from Domik, 1986)

Registration of synthetic aperture radar images proceeds on a somewhat different time-scale. The intent is to register imagery as it is received at the platform. For example, assume an aircraft ground speed of 500 km/hour, and an image swath of 20 km in width. Then a 20 km by 20 km image is received every 144 seconds. Generation of ground control and image matching should occur in something less than than 144 seconds in this case.

An important aspect of future work in this area will be the identification of those aspects of the control generation and image registration processes that can be implemented in parallel and pipelined systems. The growing availability of such hardware, and the parallel nature of many image processing tasks, makes this sort of development attractive for real-time applications.

The generation of candidate ground control should clearly be done as rapidly as possible, as the actual image processing and matching processes are likely to be more time consuming than a database search. However, the generator system should take into account the time constraints of a particular registration task as well as the accuracy requirements. This will allow the proper balance between speed and precision to be achieved.

Section 5

Related Work

The earliest work in the field of automated image registration concentrated on developing algorithms to perform the calculation of the transformation function by which the coordinate system of an image can be related to another. The time-consuming and error-prone calculation of an affine transformation or the Helmert transformation is a task obviously suited to even the earliest digital computer systems. However these early registration aids still required that a human operator detect and input the coordinates of distinct features visible in both images. Automation of this task was first proposed and demonstrated with optical imagery that featured little if any geometric or radiometric differences. Extensions to dissimilar imagery, or to the registration of imagery to non-image references, remains a relatively undeveloped field of study.

Many of the various aspects of the problem of automated image registration have been studied, although the integration of these subtasks into a working system remains a goal yet to be achieved. Our current efforts in developing an automated control generation system serve not only to closely examine that particular subtask, but to provide a framework to model the entire registration process. Because of the need for a control generating system to account for all aspects of image registration, an extensive review of past and current work in image-to-image matching, spatial data representation and image-to-map registration was performed prior to and during the execution of Phase I. The following will step through work done on the various component problems that contribute to the Smart Control domain.

5.1 Image-to-Image Matching

The automated detection of homologue points in a pair of images touches many of the basic areas of research in image processing. One early (but still used) approach involves the direct correlation of subsets of the two images. The normalized cross-correlation technique [Quam,1971] finds the coordinates at which one subimage best corresponds to another, producing a single ground control point. This correlation can also be done in the frequency domain through the use of Fast Fourier Transforms, for an improvement in the speed of the matching [Anuta, 1970]. Emmert and McGillem [1973] discover only those coefficients of the affine transformation needed to account for geometric distortion between images in the Fourier domain and then use simple image segment correlation to find the translation components of the transformation.

A class of algorithms termed *Sequential Similarity Detection Algorithms* (SSDAs) has been presented in an attempt to decrease the computational expense of image matching [Barnea and Silverman, 1972]. These algorithms attempt to quickly identify offset values for which the correlation coefficient is poor. They randomly sample the pixel locations in the two images rather than systematically examine each location. A potential match is discarded when enough (randomly chosen) pixels have been examined to indicate that the correlation coefficient for this offset will exceed a certain threshold. This method suffers from the lack of a statistical description of the quality of the match.

Still another way to reduce the cost of correlation is to reduce the number of possible matches to be tested with a coarse-to-fine pyramid structure [Moravec, 1977]. Correlation begins between coarse images that span a larger portion of the scene than the finer images. Discovery of a matching offset at this coarse resolution reduces the size of the search space for matches at finer resolutions. These multiple resolution techniques have been used by several researchers; reviews of some of this work have been prepared by Burt [1982; 1983]. The success of this approach depends on the 'pull-in' range of the regions being correlated [Crombie, 1983]. A correlation that peaks sharply only very near a good match is said to have a narrow pull-in range. In any case, it is advantageous to register two images by looking for matches in regions that seem likely to exhibit high correlation. Various interest operators, filters that isolate features that stand out from their surroundings, have been proposed to discover such regions [Moravec, 1977; McConnell, 1987].

Several types of imagery have been registered by discovering offsets between windows in the images through area correlation. Anuta's work with fast Fourier transforms dealt with multispectral scanner and vidicon imagery from the Earth-Resources Technology Satellite (ERTS) [Anuta, 1970]. Images from the second Shuttle Imaging Radar mission (SIR-B) have been registered by correlating windows from the images with segments of a simulated image derived from topographic information about the area [Guindon and Maruyama, 1986].

Techniques that continue to use some version of image correlation, but that operate with features detected in the images have also been explored. For example, methods that attempt correlation using detected edges in the images are numerous, and all rely on the research done in the field of edge detection itself. Classical work in this area includes the development of an variety of operators for detecting edge elements (intensity contrasts) in images. The Roberts, Sobel and Kirsch operators are all well-known examples [Roberts, 1965; Sobel, 1973; Kirsch, 1971]. Another set of operators act by matching image data to pre-defined models of ideal edges of varying shape. The Hueckel operator and later refinements by Nevatia are of this type [Hueckel, 1971; Nevatia, 1975]. The Hough transform [Hough, 1962] and its generalization by Duda and Hart [1972] and Ballard [1981a] detects linear features of arbitrary shape by use of appropriately parameterized transformations. Image matching using edges usually relies on the correlation of entire edge images. An early approach developed for Landsat image-to-image matching [Nack, 1974] has been used and expanded by other authors. The matching of images in order to produce stereo (three-dimensional) information from image pairs has also been performed with a segment-based approach [Medioni and Nevatia, 1985].

An edge operator that is currently receiving considerable interest in the image processing community is based on research into the way edges and boundaries are recognized by humans. Edge-based image matching algorithms derived from such studies utilize the zero-crossings of the Marr-Hildreth edge operator (i.e. the Laplacian of the two-dimensional gaussian function) [Marr and Poggio, 1976; Marr and Hildreth, 1980]. An algorithm of this type has been used for automating stereopsis of aerial photographs [Grimson, 1985]. Another promising application of this operator has the goal of automatic SAR image-to-image matching [McConnell, 1987]. This work, being performed at VEXCEL Corporation, is now being expanded into the realm of SAR-to-optical image matching.

Early implementations of the Marr-Hildreth operator were quite slow, the large two-dimensional masks used in convolving the gaussian function with the image requiring substantial computation time. Recently, however, a much more efficient method has been presented [Wiejak, 1985]. Wiejak shows that Marr-Hildreth masks can be separated (i.e. factorized) and performed as a sequence of one-dimensional convolutions.

One particular measure of the degree of correspondence between the Marr-Hildreth zero-crossings of two images considers the distance between those zero-crossings at a given offset. These distances can be easily computed by transforming the zero-crossings array created by the operator into an array of numbers representing the distance from each pixel to the nearest zero-crossing. Such an array is created with only two passes through the zero-crossing array by a process called 'chamfering' [Barrow, et al, 1977].

The vast majority of image matching research addresses pairs of imagery that are similar and present only geometric differences. Synthetic Aperture Radar (SAR) does not fall into this category. Minor differences in sensor position can drastically affect the appearance of this type of image. Future research is expected to become progressively involved with matching dissimilar images.

5.2 Image-to-Map Registration

A major source of map data is a variety of remote sensing imagery including aerial or space photography, electro-optical sensing, synthetic aperture radar, and infrared sensing. The integration of this data into existing databases is a complex problem, and most of the processes involved are currently labor-intensive. The first step is clearly to register the new image with the existing database. Only then can geometric and/or attribute information extracted from the image be added to or compared with the existing data. The important tasks of feature detection, change detection and automated database updating all require this initial registration.

This registration procedure is presently accomplished by a human operator who selects corresponding points from the database and the image of interest. These points can be used to determine the sensor position and attitude (exterior orientation) and the coordinate transformation needed to move from the reference frame of the image to that of the database and vice versa. In special cases the points may also serve to determine parameters of the sensor's internal imaging geometry (inner orientation). The calculation of the exterior orientation and transformation are relatively well-understood and tools for machine-support exist. The time-consuming aspect of the registration process is the manual identification and reporting of the ground control points. The creation of autonomous systems for that process is thus of great value; considerable effort needs to be spent to develop such systems.

In recent years, the amount and quality of geographical data collected by aerial and satellite sensing systems has greatly increased. The numerous commercial, environmental and military applications of such data requires that much more efficient techniques for the maintenance of digital map databases be implemented. Thus, the development of a "Smart Mapping, Charting and Geodesy (MC&G) Control Generator" is a central need.

The use of various examples of spatial data storage for the registration of images has been a major aspect of the work done with spatial databases in general. The automated generation of control information for such registration has been an important aspect of that work, and thus a significant base of previous research exists. Much of this research builds upon early work done by Barrow, et al [1977], in what they termed 'map-guided' feature analysis.

Linear features have always been attractive candidates for the registration of images to maps, and work by Tennenbaum, et al [1978], and Fischler, et al [1979], has concentrated on these types of features. One technique suggested by these workers employs a distance array created by the 'chamfering' procedure described earlier. This array then guides a line-following process to identify linear features in the image.

The MAPS system developed at Carnegie-Mellon University relates a map database to an image, but does not specifically address the automated generation of control information [McKeown, 1982; McKeown and Denlinger, 1984; McKeown, et al, 1984]. This work concentrates on scene segmentation based on general rules about objects and on geometric information from the map database. Another effort related to image segmentation is that by Havens and Mackworth [1983] in which the segmentation process is guided by a description of map information. Sties, et al [1977], and later Kestner and co-workers have developed an image-to-map matching concept to perform similar map-guided image segmentation [Kestner, 1980; Kestner and Rumpler, 1984].

Medioni and Nevatia describe a recent effort to automatically match two aerial images with each other and with an existing map. The map information used consists of object boundaries. The map database itself is not the focus of this work, nor is the imaging geometry of the sensor explicitly modeled [Medioni and Nevatia, 1984]. Both of these aspects of the problem are of significance for our proposed efforts during Phase II.

A database design developed in Europe has been used to explore the registration of aerial photographs [Leberl and Ranzinger, 1982] and satellite images [Kropatsch and Leberl, 1981; Ranzinger and Ranzinger, 1984]. Other work concerned with the exploitation of digital map databases for the purpose of map-guided feature extraction or photo-interpretation must also necessarily address the issue of map-guided image registration [Leberl and Kropatsch, 1979; Ranzinger, 1985]. These efforts differ from the work of other authors in that the database is searched for candidate control features, the sensor geometry is modeled and the search for these features in the image is tailored to the specific features of interest.

Image registration control based upon non-point features is of particular relevance where only linear and/or areal features exist. Lugnani [1982] investigated the use of non-point ground control in conventional photogrammetry; the control information in this work consisted of linear features. Some of the image matching work refered to earlier [Medioni and Nevatia, 1984] also explored the use of linear features for control, as does the work on image rectification done by Paderes, et al [1984].

The use of representations of areal features for matching (as opposed to simple correlation using image segments containing those features) is a field where the current understanding is less complete. Landsat imagery has been registered to a map in work done by Mokhtarian and Mackworth. Their method represents areal objects with a 'generalized scale space' image which is invariant under rotation, uniform scaling and translation [Mokhtarian and Mackworth, 1986].

An increasing emphasis on the use of rule-based expert systems to perform automated image registration and database exploitation is apparent [Robinson, et al, 1986]. The development of rule-based systems to perform photo-interpretation is the subject of some of the more recent work with the MAPS database system [McKeown and McDermott, 1983; McKeown, et al, 1984]. A more general system called LOBSTER is an attempt to integrate a Prolog-like language with the spatial database scheme and query language being developed by Frank and his co-workers [Frank, 1986].

5.3 Digital Representation of Spatial Data

The primary concern of the Phase I (and subsequent) effort was the registration of imagery not to other images, but to a digitally stored representation of the region or surface imaged. A number of methods for representing spatial data have been developed. These include a several variations on the theme of spatial decomposition: quadtrees, hexagonal structures, etc.. Another basic technique encodes feature information in the form of point coordinates and vectors. The suitability of these various basic data formats to the problem of automatic ground control generation was a major concern of the Phase 1 work. The creation and manipulation of such representations will be an important part of future efforts.

One major group of concepts and algorithms for the storage and manipulation of spatial data centers around the idea of recursive decomposition of the area or volume to be represented. Reviews of quadtrees and related structures have been presented by Samet [Samet. 1984]. Although quadtrees in their basic form are strictly areal structures, techniques have been developed to allow for the representation of linear features and the boundaries of areal features with them. These involve a number of conversion algorithms to place boundary (chain) code data or vector data into a quadtree representation (and vice versa) [Samet and Webber, 1984; Dyer, et al, 1980; Nelson and Samet, 1986]. The efficiency with which quadtree data can be maintained in memory may be increased with the use of 'linear quadtrees' [Gargantini, 1982]. A quadtree-like structure for representing point data amounts to a multiple-dimension generalization of a binary search tree [Finkel and Bentley, 1974]. A further refinement of this idea led to the development of the K-d tree [Bentley, 1975].

The decomposition of area into hexagonal regions rather than the rectangular regions used in quadtrees leads to an addressing scheme known as the Generalized Balanced Ternary, and the representation of areas as hexagons and groups of hexagons [Gibson, et al, 1984]. The decomposition of linear features into ever smaller segments, each one represented by the elongated rectangle that contains it, leads to a structure known as a strip-tree [Ballard, 1981b].

Much work has been done in the creation and use of databases for spatial data. Workers at Carnegie-Mellon University have developed a system called MAPS (Map Assisted Photo-interpretation System), which is an attempt to integrate image, terrain and map data into a single database [McKeown, 1983; McKeown,1984]. This database contains image segments as well as point coordinates of landmarks and representations of objects, which include attributes and shape descriptions as well as location.

A database structure that is based on a regular three-by-three areal decomposition has been described by Raetzsch [1985]. This 'nine-tree' concept (termed an areal identification tree) is similar to the quadtree techniques that have been so extensively explored, although it offers some computational simplifications.

An extensive set of software has been developed at the Jet Propulsion Laboratory under the name Image Based Information System (IBIS). It allows for the merging of image data and data in the form of maps (vectors) and tables. Although the different data types are maintained separately, the non-image data is converted into a raster format when comparisons or combinations are needed. This supports such applications as merging thematically classified Landsat data with georeferenced data to report land cover distributions [Angelici and Bryant, 1976] and the digital analysis of thematic imagery for land use planning and geological study [Farrell and Wherry, 1978; Logan, 1981]. Recently, efforts to develop a database query system for IBIS that will allow direct Boolean queries have been made [Friedman, 1982; Friedman 1986].

Database systems based on point and vector coordinate lists have been examined by a number of workers in Europe (e.g. Kropatsch and Leberl [1981]). Point coordinates are maintained in lists ordered so that the vectors and polygons defined by those points are represented by the location of those coordinates in the list. Further, pointers are used to link related vectors represented in differing places in the coordinate list.

An advanced geographical information system being developed at Kork Systems, Inc also uses a point and vector format with associated attributes to represent spatial features [Keating, et al, 1986]. This system makes use of several layers of data organization in order to group features by location and size. An important aspect of these systems is their use of internal buffering in order to speed memory intensive operations. A query language for the efficient retrieval of information from such database systems is an area of active research [Frank, 1982].

5.4 Dead-Reckoning for Image Registration

With the increasing availability of satellite ephemerides to users of remote sensing imagery, the published body of literature on the registration of satellite data via dead-reckoning is increasing. This is deals largely with Landsat and Spot imagery. An example is work by Puccinelli [1976].

Radar images have also been rectified using ephemeris data. Examples are by Curlander and Brown [1981], Curlander [1984] and most recently by Meier and Nuesch [1986]. Essentially this work, as well as related efforts with other types of digital image dead-reckoning, concentrate on the geometric transformation of pixel coordinates into a world coordinate system.

Of great interest is the source of navigation data, namely GPS/INS and satellite orbit determination. GPS is the most widely discussed source for air or spaceborne application. An excellent review paper is by Hartl and Wehr [1986]. Recent work is described in the proceedings of symposia of ISPRS Commission I [1986] and on Position, Location, and Navigation [1986], including GPS reports by Klensberg and Wells [1986]. A broader review of navigation data has been authored by Corten [1984].

GPS applications to image dead-reckoning have not come to our attention. INS uses have been reported early on (e.g. Roessel and de Godoy, [1974]) but concentrated more on navigation than on rectification. VEXCEL is currently under contract to INTERA Technologies Ltd. to develop a capability to rectify aircraft SAR images using on board INS observation. This work is in progress. The ultimate intent is to also include GPS data.

5.5 SAR Imagery Registration

We have referred in several instances to SAR-map and SAR-SAR registration in various parts of this proposal. The question has been addressed by numerous authors in the field as documented in SAR review papers [Leberl, 1983] and recent research articles [McConnell, 1987]. The major difficulty with SAR in a registration task is the geometric resolution and dependence of image contents on platform position. A recent major effort dealt with Shuttle SIR-B digital SAR data. Multiple images were co-registered to create new data sets (Domik, et al, 1986). SIR-B has become a major source of experimental SAR data.

The dissimilarity of SAR images as a result of sensor positions has been addressed in work reported by Fullerton, et al [1986]. Attempts were made to remove the dissimilarities. This was successful for large features, but could not achieve success with image micro-detail.

5.6 Infrared Imagery

Geometric work on infrared imagery is scarce in the open literature. Infrared line scanning was modeled by Konecny [1971], Leberl [1972] and others. However, application scenarios that would drive a geometric rectification or registration effort have yet to develop.

Conceptually, infrared imagery is obtained in one of two ways. The first is by optical-mechanical scanning; the method is thus geometrically identical to Landsat-MSS type sensing. Otherwise, a framed image is created where the focal plane of an optical system is scanned. In that case the geometric model is a central perspective.

The uniqueness of infrared imagery is therefore not in the geometry but in the radiometric properties. Figure 5.1 illustrates this by presenting night time and day time infrared images and compares this to a panchromatic aerial photograph (all images being of the same scene). Figure 5.2 is another example showing a day time infrared image of a lake with traces of a boat that distributed the lake surface.

Infrared imagery, through efforts to automate the recognition of military targets, has been subject to extensive pattern recognition research. This is documented in extensive technical reports, for example by Milgram, et al [1978]. However, the work does not address registration or rectification.

Figure 5.1: Night time (a) and daytime (b) infrared image of a lake, and comparison with a panchromatic photograph (c). Note the temperature reversal between lake and land from day to night.

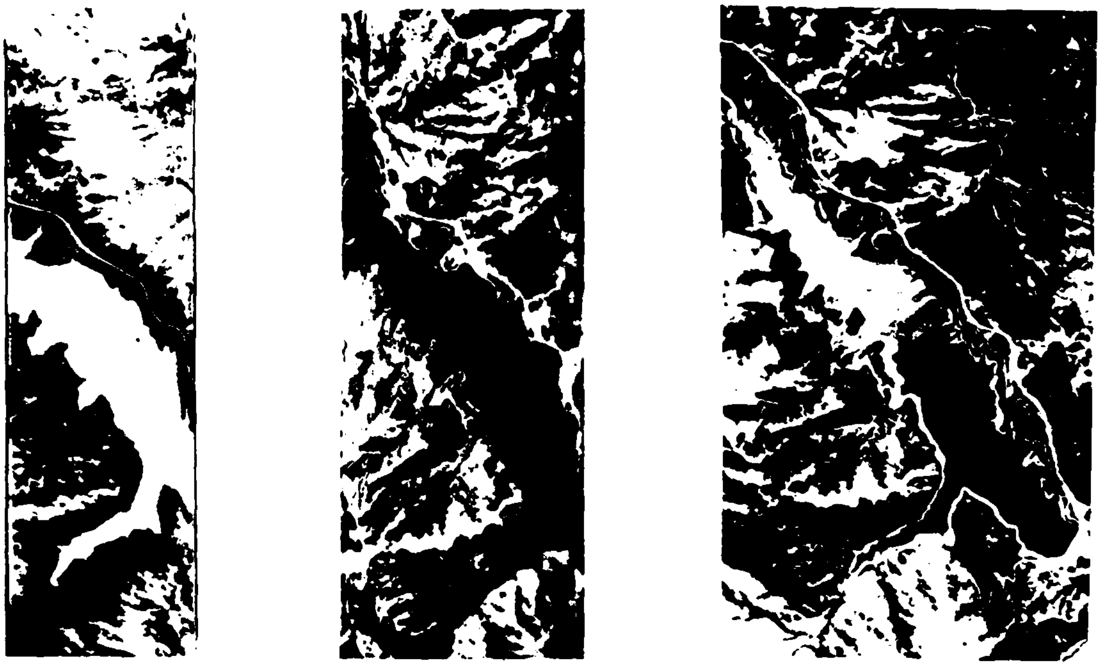
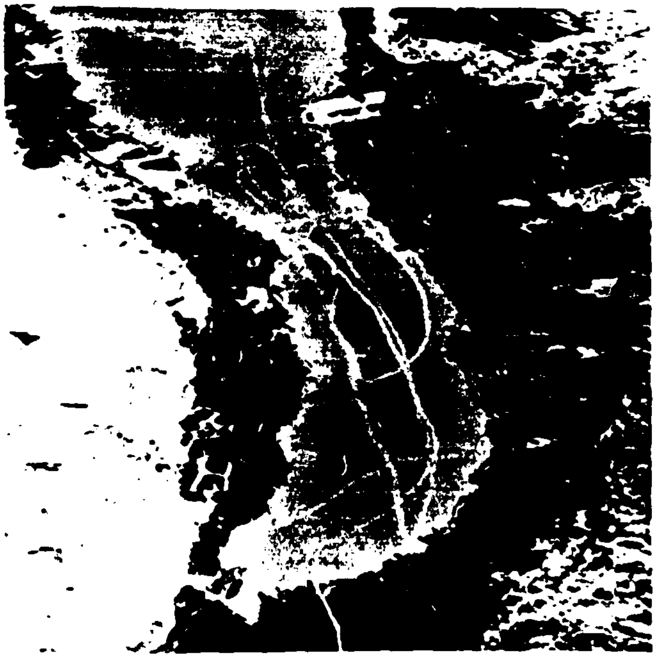


Figure 5.2: Example of an airborne infrared image of a lake showing traces of a boat. Note the brightness of the south-facing shape due to sun-heat.



5.7 Conclusion

The implementation of a database system to generate ground control data for image registration is a natural outgrowth of the recent research in spatial database design, image matching and expert system development. Clearly, the primacy of the registration task makes this an obvious realm for initial attempts to create working, productive systems (as opposed to research testbeds). Additionally, the exploitation of existing spatial database design concepts through the use of rule-based systems is a field of endeavor that is ripe for exploration and development. The relatively straight-forward nature of the knowledge involved in choosing candidate ground control features from a spatial database makes this particular function an appealing place to begin this development.

Section 6

Prototype Specifications

While a detailed analysis of the process by which a prototype of the Smart MC&G Control Generator will be created during Phase II, the basics of a viable approach seem clear. The emphasis in this approach is on developing the general spatial data-handling capabilities needed in such a system without restricting it to a specific set of current sensor attributes, image matching techniques, or applications. Thus, this prototype could serve not only to develop the capability of using current technology to register imagery, but also to explore the utility of new sensor and image matching methods.

The heart of the system, the spatial database itself, should be built from an existing, highly-structured point/vector format database system. Further, this system should allow for the maintenance and manipulation of features as objects, comprising the geometric and attribute data of interest as single, coherent units. It should employ feature clustering techniques to minimize memory space and disk access. This clustering should be according to feature size as well as location and type. At least one such system is currently being developed in a form that appears to suit the basic requirements; it is likely that others could also be found.

The most important aspect of the prototype development will be the construction of the rule-based query generator. This will be both the mechanism by which the database is exploited, and the primary source of interaction between the control generator and a human operator or other software modules. This portion of the control generator will also calculate the propagation of error estimates to be reported along with the candidate ground control. Because these estimates will be dependent on knowledge of the sensor and matching techniques encoded in the rule system, the query generator is the appropriate module in which to house this functionality.

The digital elevation modeling capability needed for the control generator will be incorporated into the spatial database system described above. This work need not be done prior to the development of the rule-based query generator. Proper implementation of the knowledge base will allow for efficient updating of the rule system, so that the additional capabilities supported by the DEM functionality can be incorporated after the initial rule and meta-rule development. However, the most efficient development of the Smart MC&G Control Generator would involve the integration of the DEM capability into the database system prior to (or at least, concurrent with) the construction of the knowledge base and query generator interfaces.

These basic steps of acquisition and modification of an existing advanced spatial database, integration of digital elevation modeling functionality, and construction of rule-based query generator and interface modules would result in the rapid development of a prototype control generator. Further, this approach retains a generality and flexibility of function that will make the system useful beyond the currently envisioned purpose of generating control data from existing sensor and image technology.

Section 7

Conclusion

The basic purpose of this work was to evaluate the feasibility and utility of constructing a Smart MC&G Control Generator, and to define the basic characteristics it should exhibit. The utility of such a system is self-apparent; a working control generator would greatly increase the speed with with which imagery of differing kinds could be registered to a common coordinate system. This would allow not only the updating of an existing map data base, but the exploitation of this imagery for a multitude of operations, including feature detection/extraction, target acquisition and tracking, etc.. Additionally, this control generator would enhance the comparison and evaluation of new techniques of image matching and the integration of new sensor technology into existing applications.

The development of such a system seems more than simply feasible; in many respects, it appears to be the logical next step in both automated image registration and in the exploitation of spatial databases using some of the recently developed tools of artificial intelligence. The primary nature of the task of automated ground control generation, with its inherent dependence on both the imagery collected and the digital representation of the information in that imagery, places it central to many applications of remote sensing. Further, recently developed spatial databases appear to have many of the attributes necessary for the task.

The restricted and relatively well-defined character of the knowledge base involved in choosing candidate ground control makes this function suited to the use of rule-based systems and to the currently problematical task of developing such systems. The use of expert system techniques in constructing the prototype system will have the additional benefit of affording background and experience in the use of knowledge-based systems in image and database exploitation, an area which will surely be important to the future development of remote sensing applications.

In conclusion, we find that the development of a Smart Mapping, Charting and Geodesy Control Generator is a job that both could and should be done.

Appendix

DTED/DFAD Data for Automated Ground Control

An experiment was performed to gain a basic understanding of the utility of existing Defense Mapping Agency data in generating ground control for different image types. Specifically, Digital Terrain Elevation Data (DTED) and Digital Feature Analysis Data (DFAD) was examined with respect to its usefulness in registering high altitude photography and satellite-borne synthetic aperture radar (SAR) images.

For the area examined, we find that the terrain model represented by DTED data is quite poor, and of limited utility for control generation. This is in comparison to the terrain model produced by the analysis of photographic stereo-pairs. The density of data points and the accuracy of interpolation routines used in developing the DTED data set for a given area is apparently inadequate for modeling the high spatial frequency features (e.g. small ridges, valleys, hilltops, etc.) needed for image registration control. The DFAD data is even more sparse, containing few if any features that are both suitable for control and visible in the images.

The Data Set

The basis for choosing the particular data set used in this experiment was the ready availability of the differing data-types used. A region of approximately 12 kilometers by 13 kilometers in north-central Georgia was chosen. A swath of Georgia covered by the second Shuttle Imaging Radar experiment (SIR-B, orbited by the shuttle Challenger in October 1984) was examined in order to identify a region containing buildings, roads and other features that could be expected to be represented in the DFAD data. Upon identification of a suitable region (33° 53'05" through 34° 00'42" north latitude, 83° 37'58" through 83° 46'04" west longitude), the following data was collected:

- DTED data covering the region
- DFAD data covering the region
- National High Altitude Photographs (NHAP) of the region
- SIR-B data covering the region
- USGS topographic maps of the region

The DTED data consists of a grid of elevation values, separated from one another by three arc seconds in both latitude and longitude. At this latitude, this amounts to a nearly square grid of points 92.5 meters apart. The features represented in the DFAD data set covering this region include several lakes, a dam, an airport, an urban area, and a number of isolated buildings. The NHAP photographs are 1:80,000 scale photos with overlapping coverage so that stereo analysis is possible. The SIR-B data is SAR imagery with a pixel resolution of 12.5 meters. Finally, the topographic maps used were 1:24,000 scale, updated from aerial photographs taken in 1981.

Processing

The first step in examining the DTED terrain model was to create a second model with which it could be compared. This was done by collecting a grid of elevation points from stereo-pairs of the NHAP photos with an analytic stereo plotter. Each set of elevation data was used to interpolate a grid of three-dimensional coordinate data from which the terrain surface could be modeled. The spacing of this grid was the same in each case (96 meters square), and the interpolation routine used was the same. Thus, any differences in the models derived from the two data sets can be ascribed to the input data itself, and not to subsequent differences in processing.

A contour map was derived from this grid in order to check the quality of the data collection and elevation interpolation routines (Figure A-1). This contour map shows very good correlation with the USGS topographic maps, indicating that the terrain model derived from the photographs is quite accurate. Portions of the USGS map and of the contour map produced from the photograph-derived terrain model are shown in Figures A-2 and A-3. These portions are at the same scale, so a direct comparison can be made. The coordinate system used in all of these models is the Universal Transverse Mercator (UTM) system. The photo-derived model was initially created with this coordinate system, while the DTED-derived model was converted to it from its initial latitude-longitude system.

Perspective views of the photo-derived elevation model, the DTED-derived model, and a difference model were then constructed. These perspective views can be seen in Figures A-4, A-5 and A-6. The terrain models constructed cover a region 13.7 kilometers by 12.8 kilometers in area. The perspective views presented here show these models as seen from above and to the southeast of the region. Due to the low relief in the region (105 meters elevation difference between the lowest and highest points), the vertical scale in these views is substantially exaggerated.

Figures A-7 and A-8 show orthographic views of the photo-derived and DTED-derived DEM, respectively. These views are oriented such that north is toward the top of the image, and the illumination source from the northwest, at 45° from the zenith. The vertical scale of these images is exaggerated by the same factor as in the perspective views.

Next, both the photo image and the radar image were registered to the coordinate system of the DEMs. This involved finding points in each image that were identifiable on the USGS topographic map. This task was easily accomplished in the case of the aerial photograph. Prospective points were chosen from the original film image, and then the digitized image was examined to discover the pixel coordinates of these points corresponding to the known map (UTM) coordinates. Additionally, those portions of the original photo that extend beyond the edges of the DEM were removed. An affine transformation was then calculated to warp the digital photo image of the DEM region to the DEM coordinate system. Figure A-9 shows the original, unregistered, digitized photo image, while Figure A-11 is of the cropped and registered photo image.

A similar process was used to register the digital radar image. However, the identification of control points in the radar image was a problem of considerable difficulty. Indeed, only a single point could identified in both the radar image and the map. All other ground control was found by areal correlation with the human eye. This was done by constructing hard copy (on film) images of the radar images at the same scale as the map. These images can then be placed over the map and manipulated until an experienced observer determines that obscure features and patterns in the radar image are positioned directly over corresponding features in the map. This areal correlation is transformed into control point information by simply marking the map (pinpricks through image and map were actually used) in locations where individual pixels in the radar image are identifiable. Figure A-10 is of the original, unregistered radar image, and Figure A-12 shows the portion of the radar image (registered) covered by the DEMs.

Figures A-13 and A-14 indicate the warping which was done to the photo image in order to rectify it to the DEMs. Figure A-13 is simply a regular grid, while A-14 shows the result of applying to that grid the same affine transformation used to rectify the photo. Notice that the transformation was basically composed of a scale change and slight rotation. Slight irregularities in the grid structure of Figure A-14 indicate local distortions (with respect to the DEMs) in some regions of the photograph.

Once the photo and radar images are registered, various combined views of the images and DEMs are possible. In Figure A-15, the rectified photo image is overlain atop the photo-derived DEM - in perspective view. Similarly, the rectified radar image is overlain on that same perspective view of the DEM in Figure A-16. In Figures A-17 through A-20, the elevation information is represented by the color in the image (an intensity/hue/saturation transformation). Low elevations are blue and increasing elevations progress through the color spectrum to red. This display technique preserves more of the information in the image itself than does the perspective view overlay. In Figure A-17, the photo image is transformed with respect to the photo-derived DEM, while in Figure A-18 the DTED-derived DEM is used. Similarly, Figures A-19 and A-20 show the radar image combined with the two elevation models.

Discussion

The difference between the photo-derived and DTED-derived elevation models is quite striking. The DTED model (Figures A-5 and A-8) represents only the broad, general aspects of the region's topography. The valley in which the southeast-trending Marbury Creek is apparent, as is the eastward trending Apalachee River valley in the southern portion of the region. However, the smaller gullies and ridges formed by numerous tributary creeks are largely missing in the DTED model. In contrast, the photo-derived model (Figures A-4 and A-7) preserves these smaller features quite well. These numerous small features obscure (to the human eye) the general topographic character of the region when compared to the DTED DEM, but close inspection of the image shows that this information is retained.

The appearance of the perspective view of the difference DEM (Figure A-6), also indicates this lack of high frequency information in the DTED model. The difference DEM appears quite like the photo-derived DEM, indicating that the DTED model contains relatively few elevation changes, and large areas of nearly constant elevation. It is these smaller features that would be most useful in generating features (radar shadows, intensity contrasts, etc.) in simulated radar images that would be likely to be visible in actual radar data. Thus, it seems that the DTED-generated DEM would be of minimal utility for registering radar imagery through the use of areal or edge correlation with simulated images.

The elevations present in the elevation model derived from aerial photography range from a low of 207 meters to a high of 312 (a range of 105 meters). The DTED-derived model exhibits elevation values from 214 meters to 305 meters (a range of 91 meters), indicating that the highest and lowest features of the photo-derived model are not represented in the DTED model. The values of the difference DEM (DTED model subtracted from the photo-derived model) range from -34 meters to 48 meters. Notice that the average elevation of both the DTED and photo models is the same (259.5 meters), while the average of the difference model is 7.0 meters. This is probably due to the difficulty the DTED model has in representing small regions of high elevation (peaks and ridges), as discussd above.

Close inspection of the orthographic views of the two DEMs (Figures A-7 and A-8) reveals additional problems with the DTED model. Distinct steps can be seen in regions of changing elevation (i.e. slopes). This artifact of the data results in representing sloping areas with a staircase-like shape, rather than the more continuous elevation change seen in the photo-derived model. Again, this feature of the DTED model would present problems to a radar image simulation technique that accounted for the angle of incidence between the radar energy and the reflecting surface.

The difficulty experienced in identifying ground control in the radar image served to emphasize the problematic nature of automating such a task. The specific image we worked with was not an example of the best quality SIR-B data; however, it was not atypically poor either. The inability of experienced radar image specialists to identify specific points or even linear features in this image indicates that such information will not always be useful for automated registration. Our eventual reliance on areal correlation via the human eye suggests that approaches involving the correlation of image segments with synthetic segments generated from ground (map) information should be thoroughly explored for their utility to automated control generation. Such approaches would require that feature and attribute data relevant to radar backscattter levels be maintained in a Smart Control Generator's geographical database.

The discovery of ground control points proved a much simpler task in registering the NHAP photograph to the DEMs. Numerous features were found on the map (and thus, would exist in a Smart Control Generator's database) that were expressed as distinct intensity differences (i.e. edges or points) in the digitized photo. Areal correlation was unnecessary, suggesting that a process of image simulation from map data would be unimportant for most if not all photographic image registration tasks.

Inspection of the DFAD data from this region revealed few features that were identifiable in the photograph. An urban area (Winder, GA) is outlined in the DFAD database, but those outlines bear little resemblance to city edges visible in the image. The large lake (Marbury Lake?) is present in the DFAD data. Correlation of this shape with that region of the image would produce usable control information; either a single point related to the area itself (e.g. centroid), or several points found as inflections in the lake's boundary. An airport is represented in the DFAD data as single lines running parallel to the runway axes. This information is inadequate for choosing single pixel points in the photo image, unless other information about the relationship between the lines in the DFAD and the actual runway edges is known. The other features found in the DFAD data consist of isolated buildings. These are difficult to identify in the image without a preliminary knowledge of their approximate location. Thus, such features may be useful for refinement of an image registration given a preliminary image to map correspondence. The map features most useful for control generation - road and highway intersections and inflections, power line, pipeline and creek intersections, etc. - were not represented in the DFAD data.

The use of these DFAD features for registration of the radar image is even less promising than in the case of the NHAP photo. Even the large lake, the only really useful feature for photo registration, appears quite different in shape in the radar image. This results from a lowered water level in the reservoir, caused by increased water demand in the region due to drought during the period of SIR-B data collection. Thus, we found no features in the DFAD data that could be used to aid in registration of this SIR-B image.

Conclusion

In conclusion, we find that the Digital Terrain Elevation Data only generally describes the topography of the region examined. The details important to the task of radar image simulation and registration are largely lacking. Further, even this general (low frequency) model possesses artifacts that would coomplicate the image simulation process. It appears that DTED data will be useful only for crude, preliminary registration tasks.

The utility of Digital Feature Analysis Data for automated registration also appears severely limited. The absence from the DFAD database of the cultural features most useful for control information is its greatest drawback. However, the possibility exists that this data may be useful for certain registration tasks. Some permanent areal features may be used to generate control points. (Note that we were fortunate in this experiment that the NHAP photograph and the DFAD data were prepared at times when the lake possessed similar water levels and boundaries.) Single buildings may be useful for registration refinement.

In general it seems that a Smart MC&G Control Generator will require geographical information that is more current, more detailed, and more specifically oriented toward control generation than the DTED and DFAD data examined here.

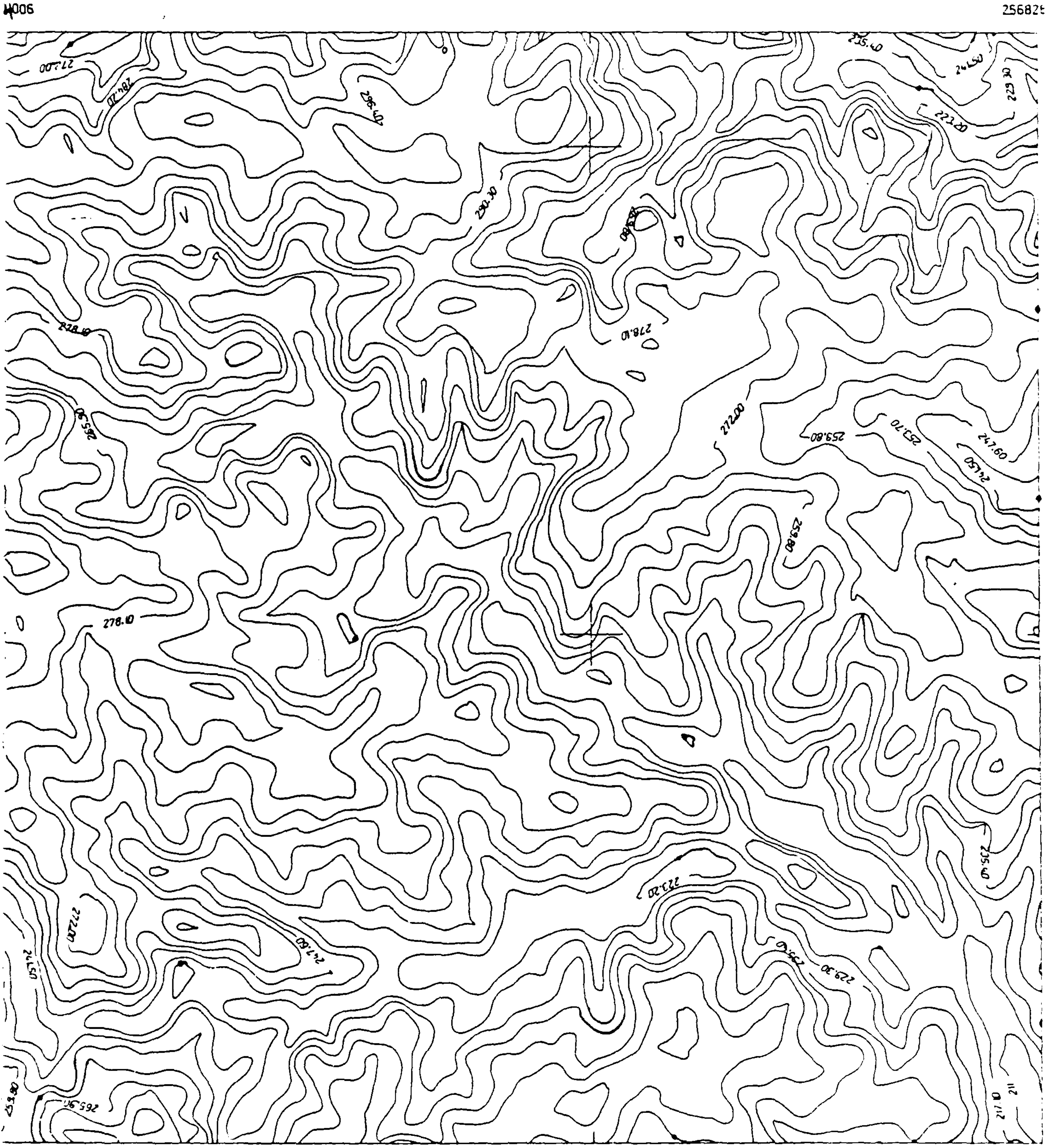


Figure A-1 Contour Map of the Digital Elevation Model (DEM) derived from NHAP photographs of the region of this study. This map is drawn at a scale of 1:60,000 and with a contour interval of 20 feet (6.1 meters). All data were treated simply as terrain points; that is, special point types (such as those on breaklines, formlines or those delineating lakes) were not treated differently than ordinary latitude-longitude-elevation measurements. The corner coordinates seen are in the Universal Transverse Mercator System.

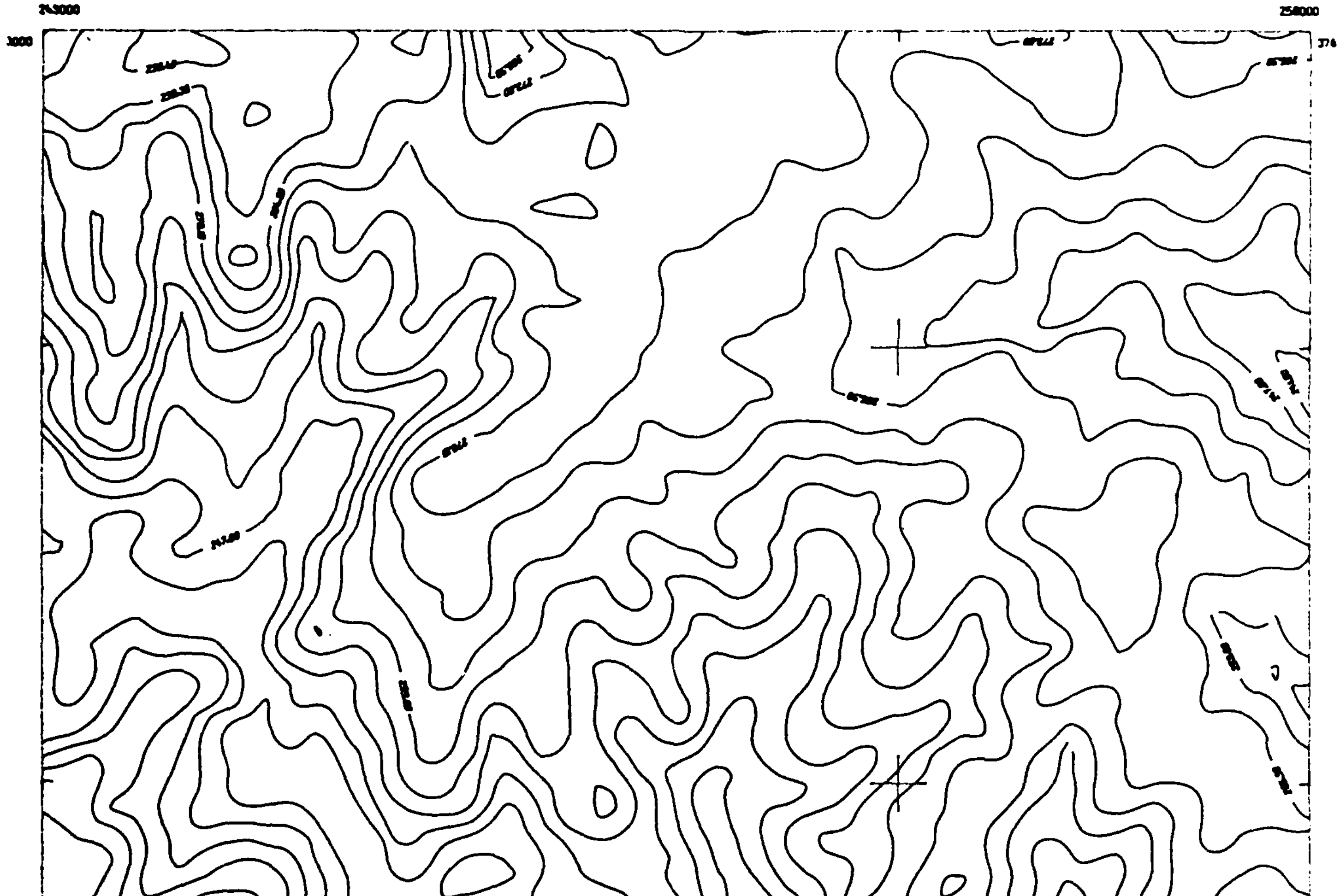


Figure A-2 Contour map of the photo-derived DEM of a portion of the region of this study. This map was originally drawn at a scale of 1:24,000 so that it can be directly compared with the USGS Topographic Map of the same area (see Figure A-3). However, both this map and the following USGS map have been reduced in scale by the same (arbitrary) amount to allow a greater portion of the area to be compared.

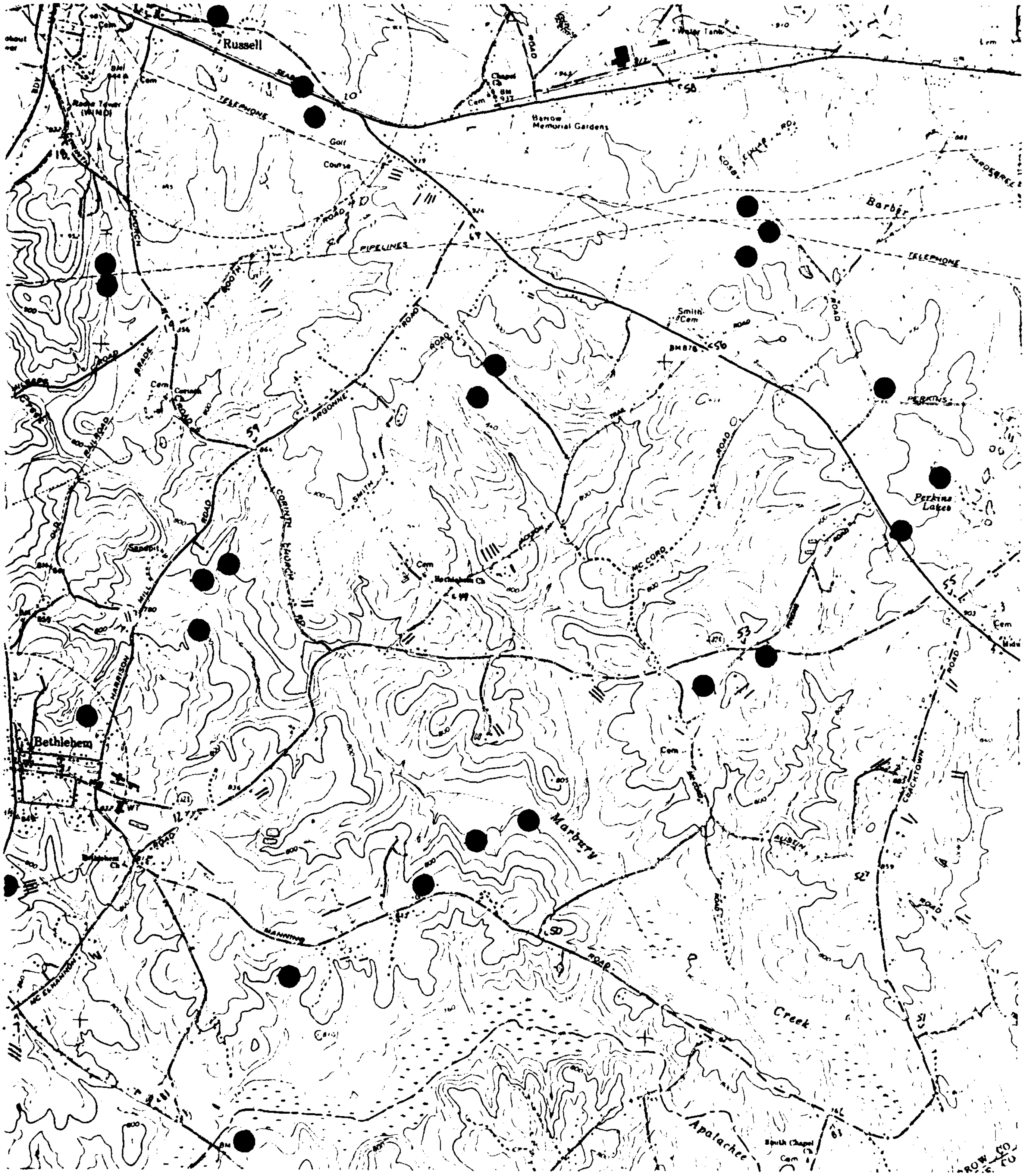


Figure A-3 The USGS Topographic Map of the same area shown in Figure A-2. Direct inspection (superimposing the two figures on a light table is helpful) shows that the photo-derived DEM accurately describes all but the smallest details of the terrain shape. The black dots visible on this map are markers used to label ground control points on the map. These control points were later used to rectify the photograph and radar images to the map coordinates (and thus, the DEM coordinates).

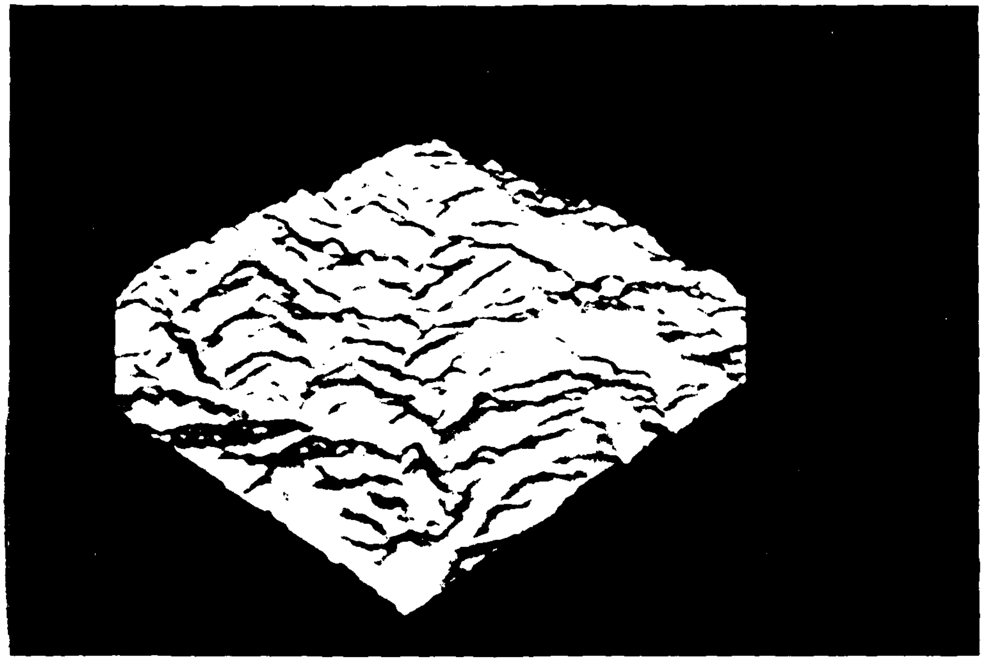


Figure A-4 A perspective view of the photo-derived DEM. This view is from above and to the southeast of the region. The following views of the DTED-derived and difference DEMs (Figures A-5 and A-6) are from the identical viewpoint. Note the relatively detailed nature of this view. Many small gullies and ridges formed by tributaries to the major streams can be clearly seen. In this and all subsequent views of the DEMs, the elevations have been exaggerated. The terrain in this area is actually quite flat, with only 105 meters elevation difference between the lowest and highest points.

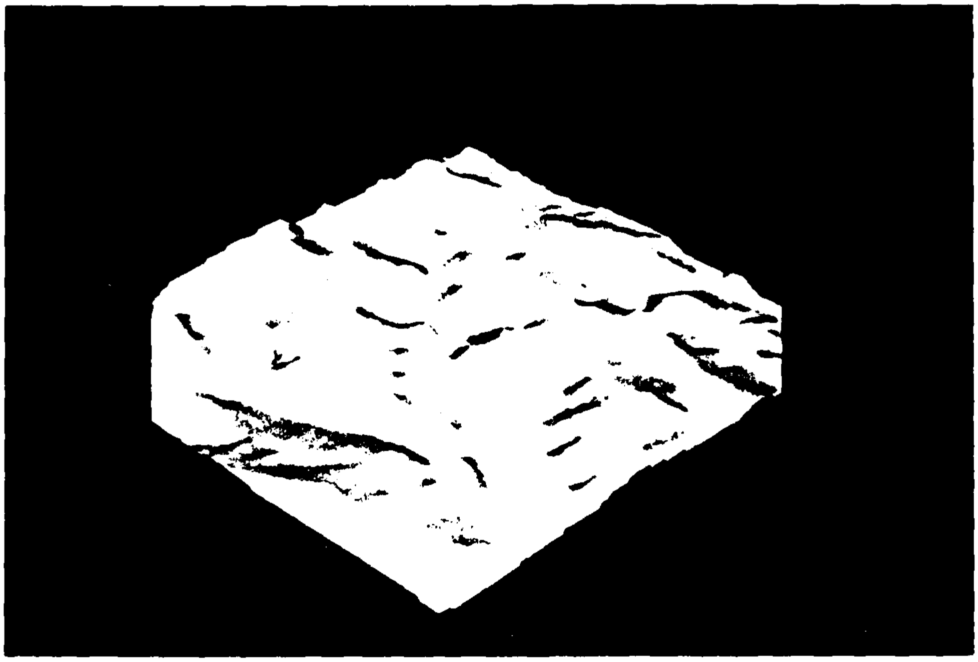


Figure A-5 A perspective view of the DTED-derived DEM. This figure shows the general nature of the topographic information contained in this DTED data. The major river valleys can be discerned, but the smaller tributary features are lost. Large areas of fine detail in the photo-derived DEM appear only as flat, featureless plateaus or valley floors in the DTED-derived model.

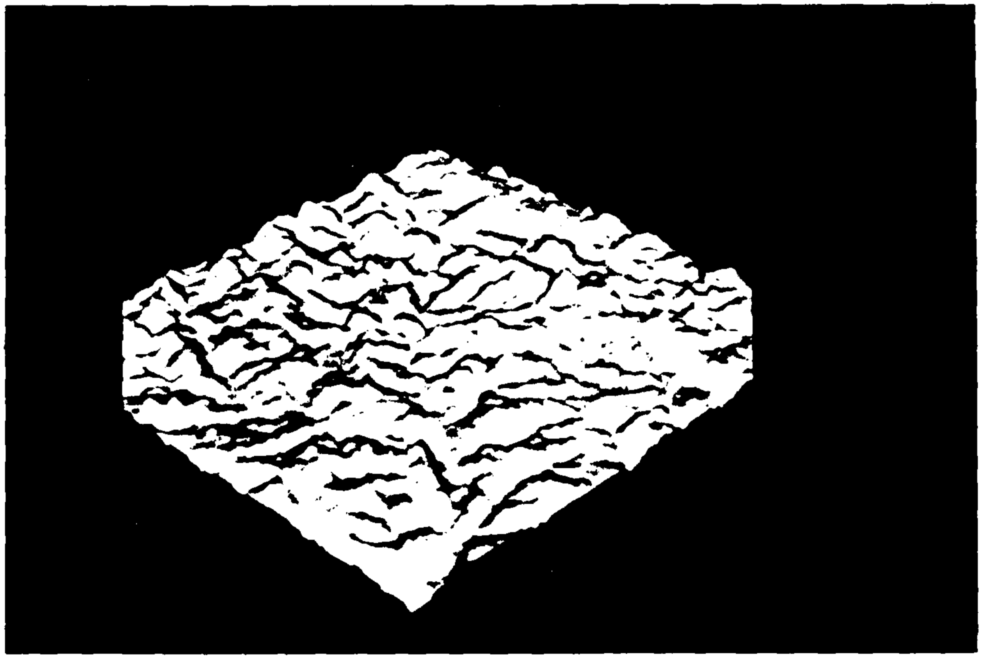


Figure A-6 A perspective view of the difference DEM. This DEM was formed by subtracting the DTED-derived DEM from that derived from the aerial photography. Again, we see that the difference between the two elevation models is the lack of high frequency content in the DTED.

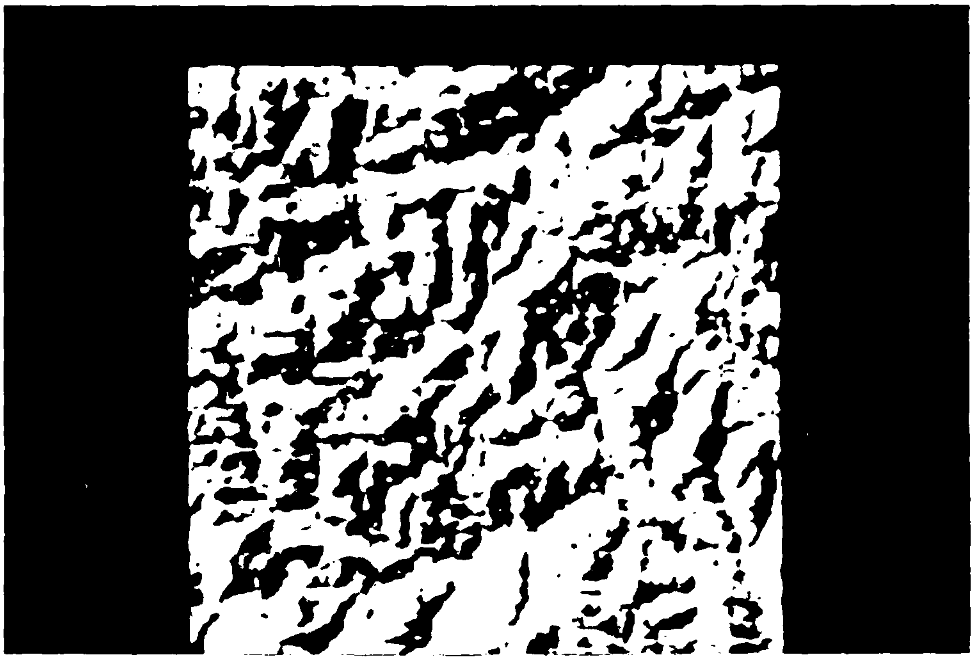


Figure A-7 This figure is of an orthogonal three-dimensional projection of the photo-derived DEM. North is toward the top in this figure. The illumination source in this figure, and in the one that follows (Figure A-8) is from above and to the northwest.

Figure A-8 The orthogonal view of the DTED-derived DEM. Comparison of Figures A-7 and A-8 illustrates some additional deficiencies in the DTED data. Note the stair-step appearance of the slopes in the DTED model (particularly visible in the southeast corner). This indicates a lack of resolution in the elevation data that would make simulation of the radar return (for the purpose of image registration) from these slopes difficult.

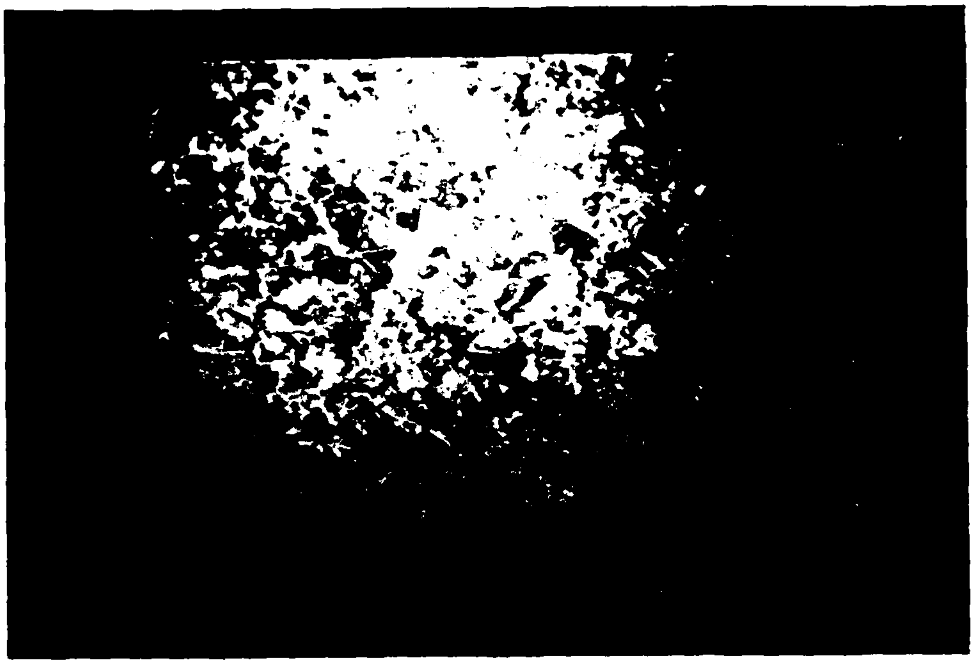


Figure A-9 The original National High Altitude Photograph (NHAP) of the region of this study. This photo extends beyond the region represented in the elevation models; nor has it been registered to the models. North is toward the top of this photograph.

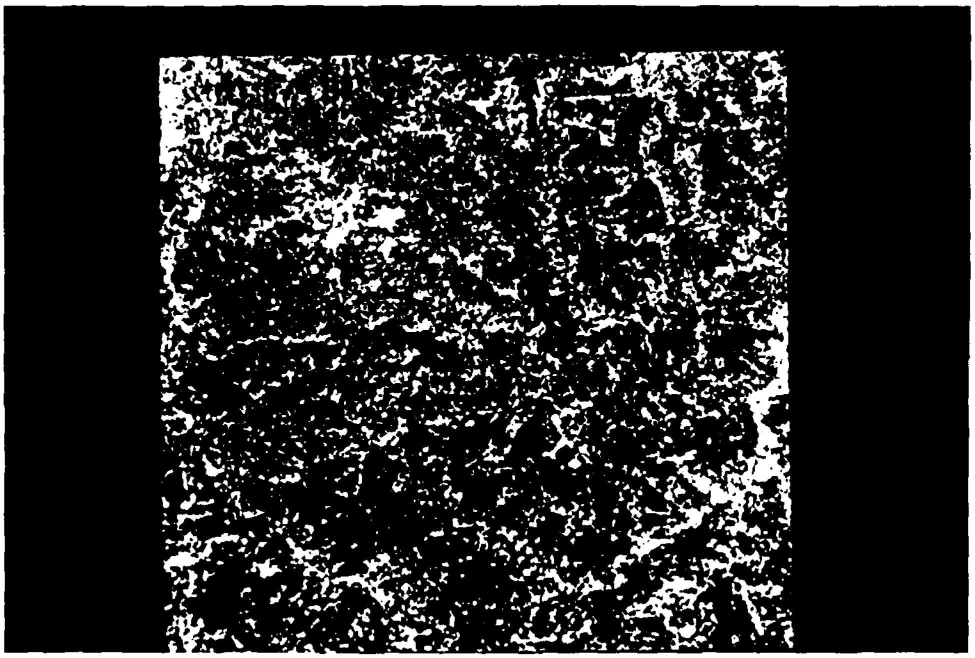


Figure A-10 An image of the digital SAR data (SIR-B) used in this study. Again, this image has not been registered or cropped to conform to the elevation models used. The top of this image is to the northeast. Notice the large lake visible in both the photograph and radar image. The shape of this lake is somewhat different in the two images, probably due to a change in the water level from one to the next. The lack of point features or intersections of linear features (identifiable on the map or image of the area) in this image required the use of the areal correlation procedure described in the text.

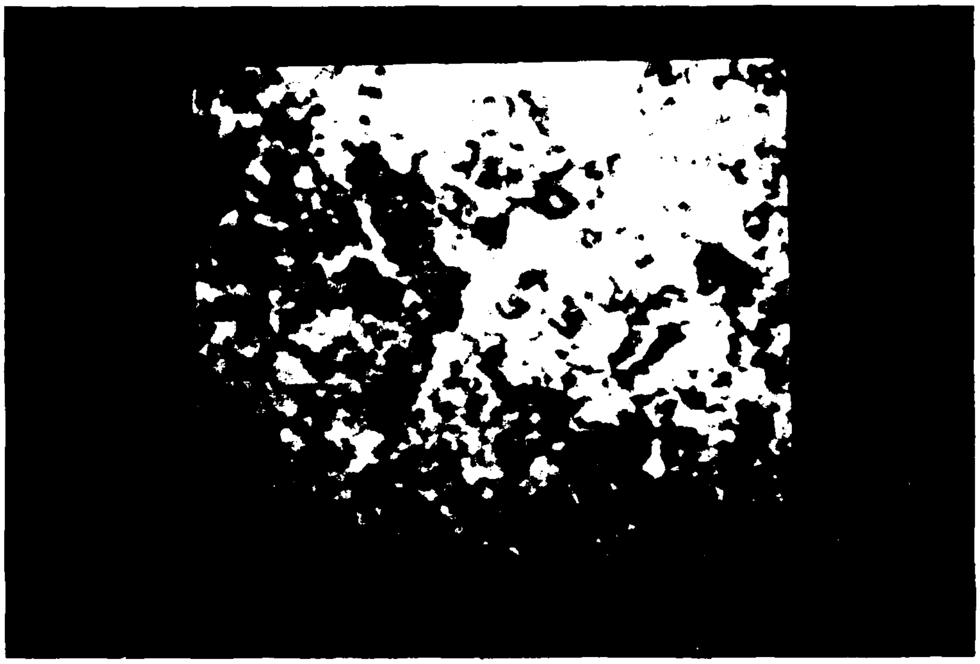
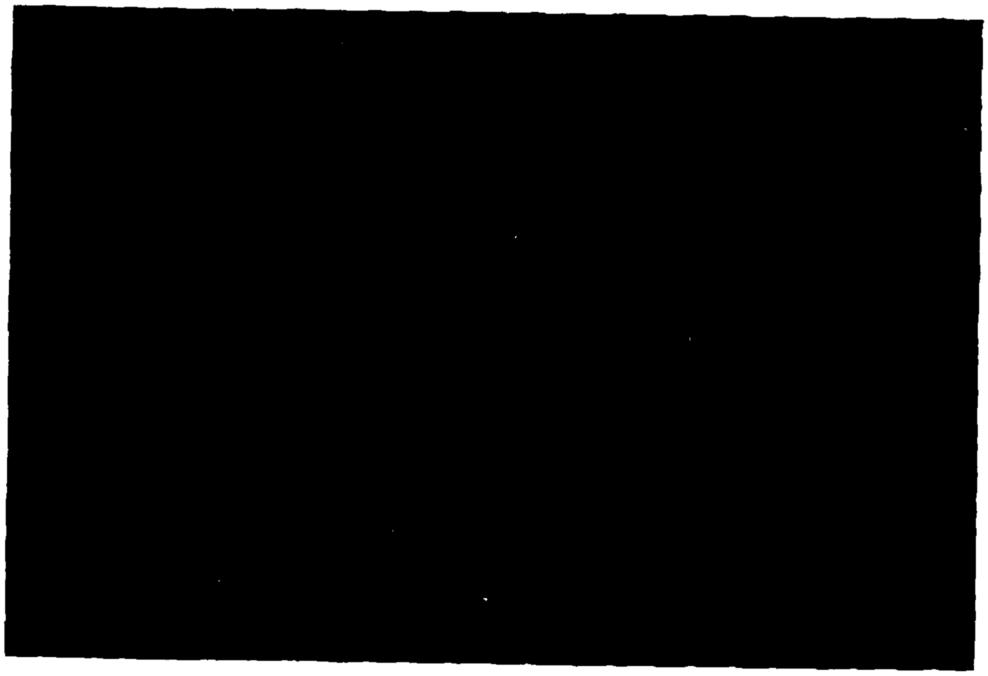
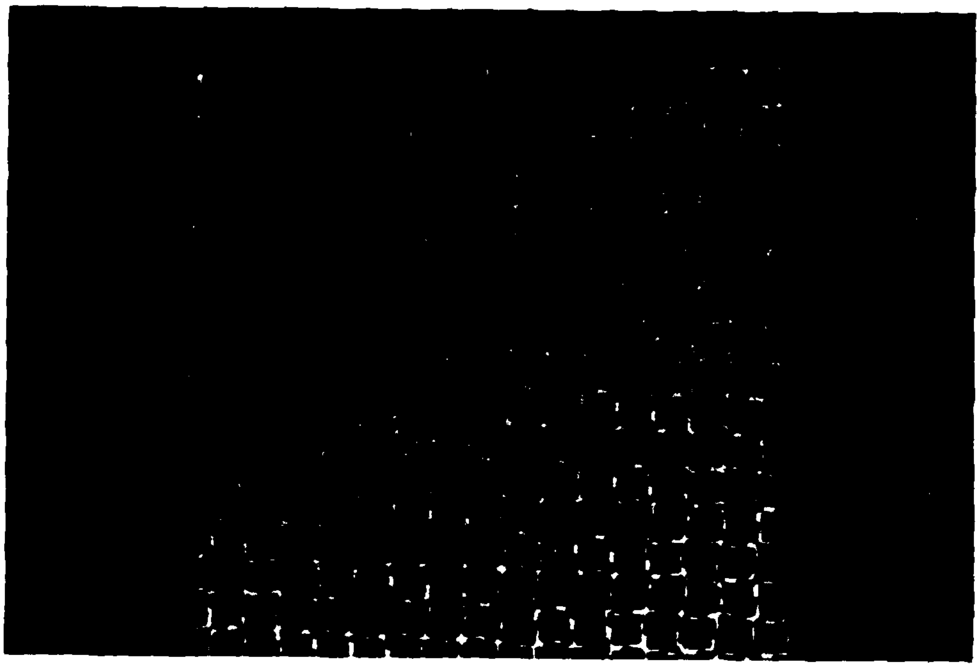


Figure A-11 The portion of the aerial photograph (NHAP) covered by the elevation models. This image has been registered to the DEMs using an affine transformation. The transformation required to register this image consisted basically (globally) of a scale change and a slight rotation (see Figures A-13 and A-14).

Figure A-12 The portion of the radar image covered by the elevation models, registered to those models. Some correspondence can be seen between this image and the photo image above; primarily the large lake and the urban area to the northeast of that lake.





Figures A-13 and A-14 These figures illustrate the transformation required to register the NHAP photograph to the elevation models. The red grid has been subjected to that same transformation to produce the green grid. Notice that the overall change involves a slight clockwise rotation and a substantial scale increase. Close inspection reveals smaller local distortions in the grid, representing local warping of the image to the elevation model.

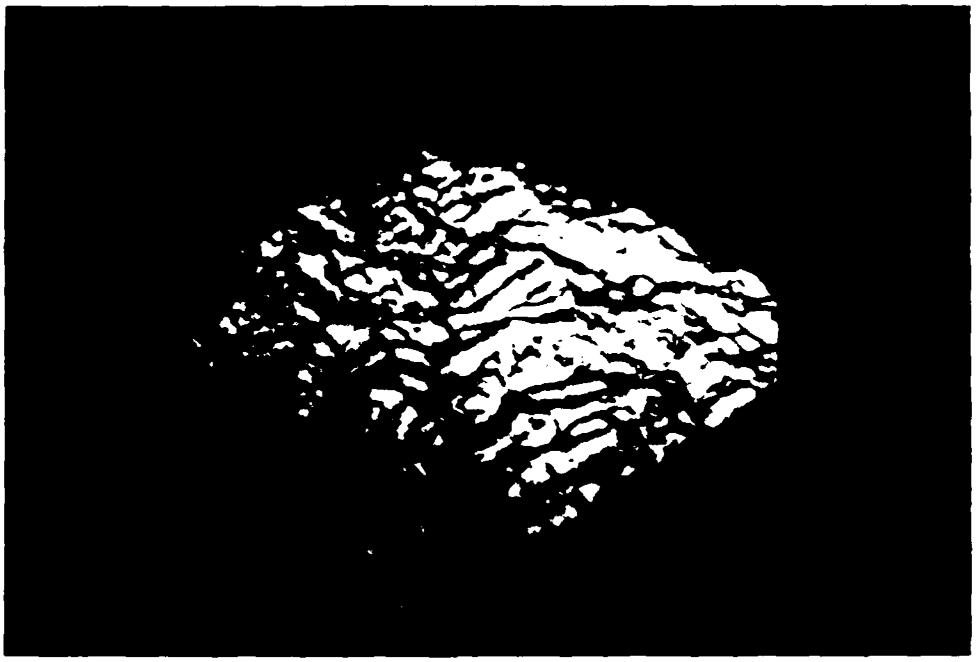


Figure A-15 Here the registered aerial photograph has been overlain onto a perspective view of the photo-derived elevation model. The top of this image is toward the northwest.

Figure A-16 The registered radar image overlain onto the photo-derived DEM. The viewpoint here is the same as in Figure A-15.

Figure A-17 The registered NHAP photograph. In this image and in the ones that follow (Figures A-18, A-19, A-20), the elevation model is represented by the color in the figure. The highest elevations are in magenta, and the lowest in dark blue, while the intermediate elevations are represented by the color spectrum between the two extremes. This figure shows the photo-derived elevation model in this way, while the next is based on the DTED-derived DEM.

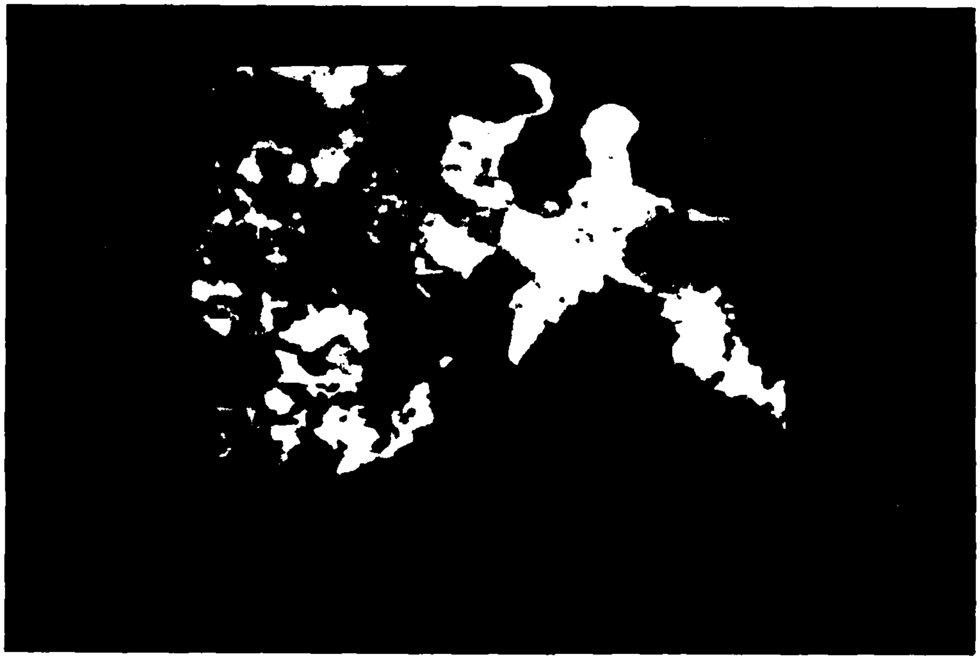


Figure A-18 The registered NHAP photo colored to reflect the DTED-derived DEM. Note the relatively slight variation in colors, indicating a lack of small (high frequency) terrain features.

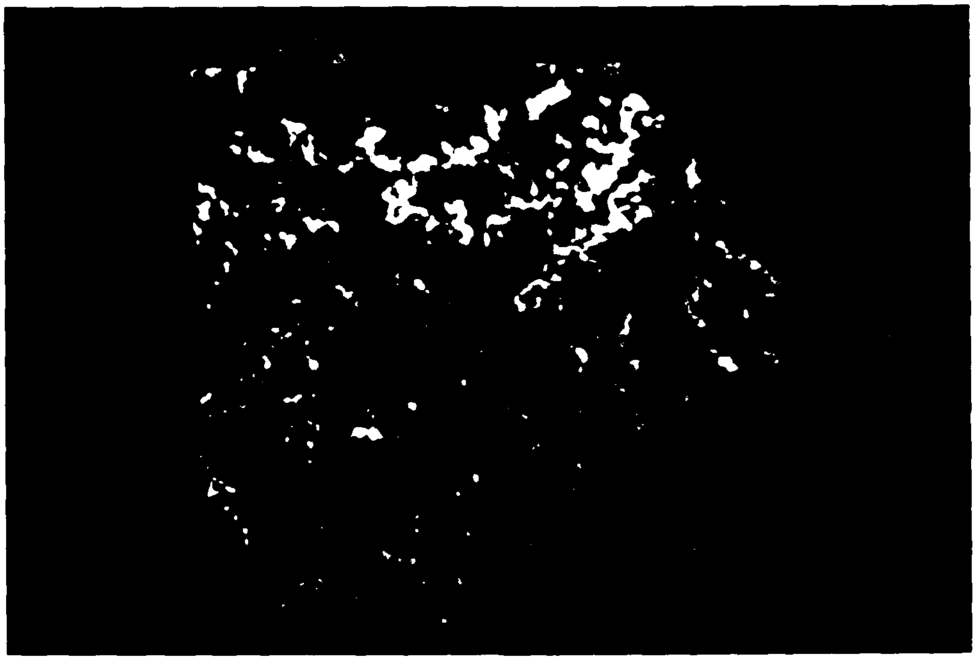


Figure A-19 The SIR-B radar image registered to the elevation models. In this figure, the coloring reflects the model derived from the NHAP photographs.

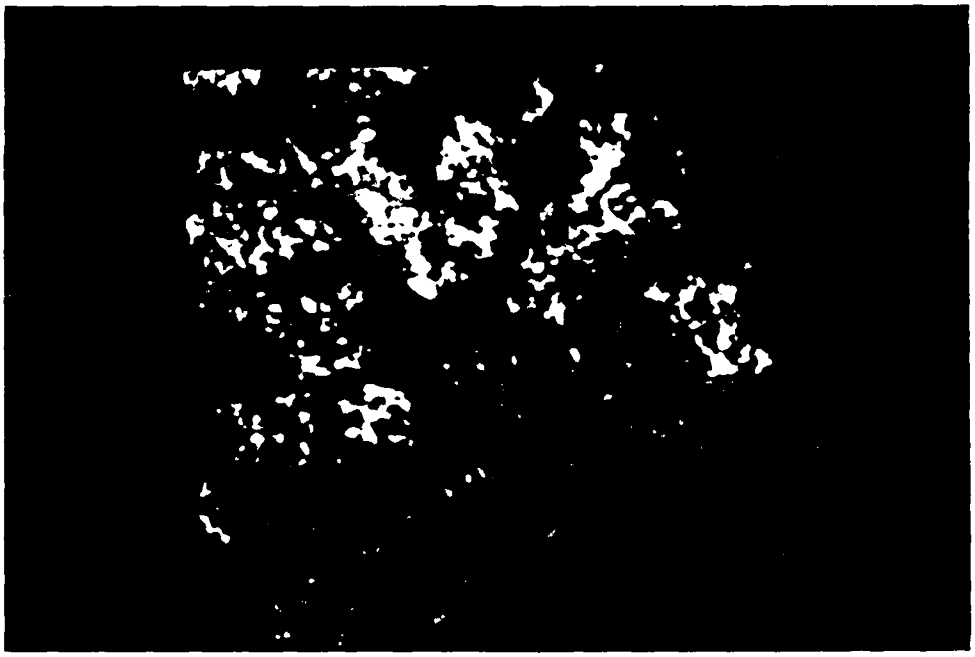


Figure A-20 The registered radar image colored to illustrate the DTED-derived elevation model.

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