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natural resource mapping in mountainous terrain by computer analysis of erts-l satellite data

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16. Abstract
This report describes the significant results of a two year interdisciplinary study involving the use of computer-aided analysis techniques applied to ERTS/MSS data collected over rugged mountainous terrain in southwestern and central Colorado. These results involve five specific areas of research, including: 1) Ecological Inventory, with emphasis on the utilization of ERTS data and computer-aided analysis techniques for forest cover mapping and acreage estimates; the results also include a cost analysis; 2) Hydrological Features Survey involving the capability for utilizing ERTS to monitor the change in snow cover and inventory water bodies; 3) Geomorphological Features Survey, with a discussion on the utilization of ERTS data in combination with ancillary information; 4) Interpretation Techniques, discussing the concepts of modeling topographic relief in order to be able to develop better analysis procedures; and 5) Data Collection Platform, a review of the operations of a DCP under adverse climatic conditions.

A section is devoted to a large number of specific results and conclusions of significance, and recommendations for future earth observational systems.

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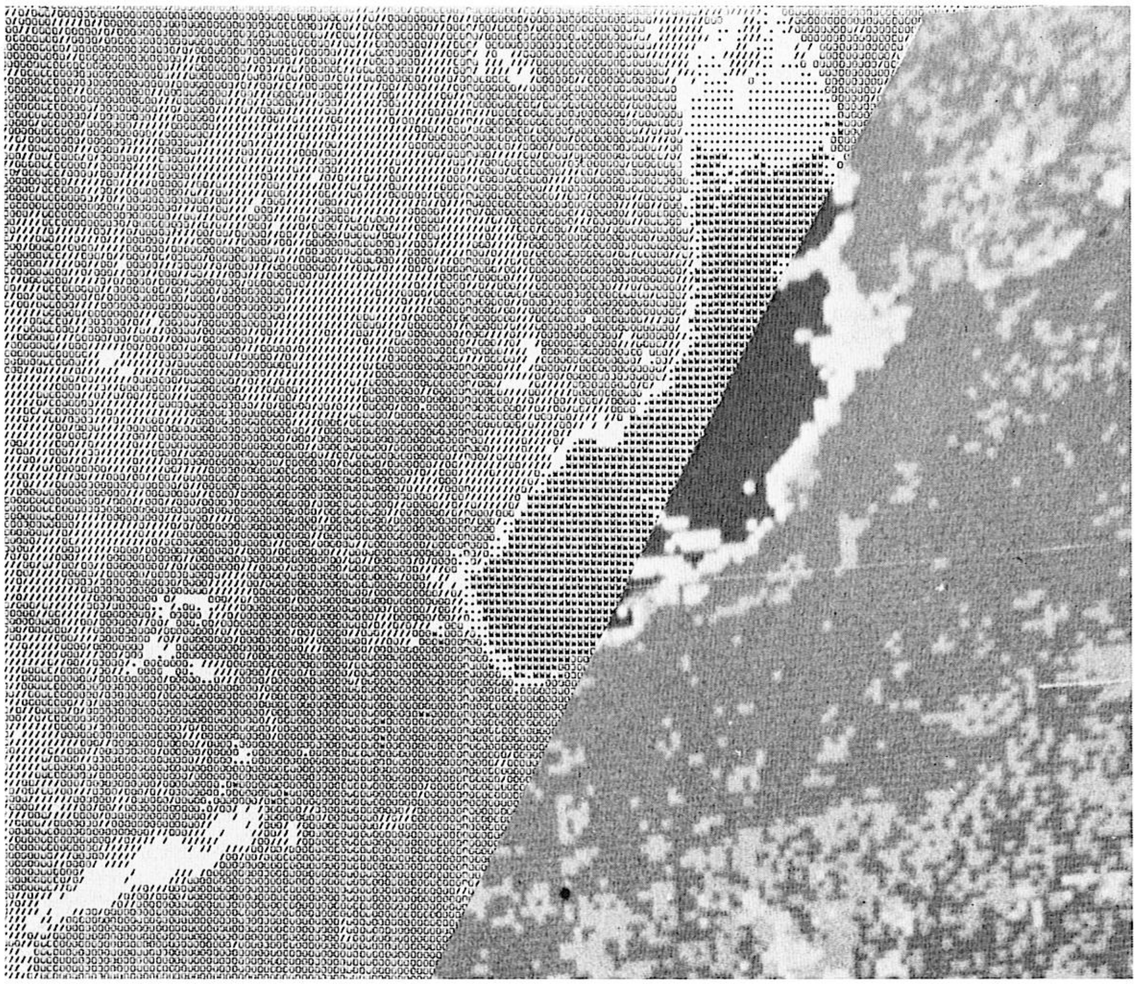

A composite image of a portion of a Level 1 classification for the Vallecito Intensive Study Area. The image is a combination of a computer printout and a picture from the LARS digital display. The information is presented in this fashion to highlight the capability of the ERTS digital data and computer-added analysis techniques.

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ACKNOWLEDGEMENTS

The principal investigator would like to thank many individuals who were involved in the successful completion of this project. Starting with the staff of the Laboratory for Applications of Remote Sensing who were directly involved in this contract, particular recognition should go to Mr. Richard Mroczynski who, as project coordinator, had a difficult task in keeping many different aspects of the research functioning in concert and as close to schedule as possible. Special recognition should also go to Mr. Michael Fleming who spent many extra hours preparing and compiling the final report, in addition to an outstanding and very effective job of research in the Ecological Inventory activity. Special acknowledgement is also given to Mrs. Tina Cary and Mrs. Barbara Davis for their work on topographic modeling, Mr. Stephen Luther for his work on the Hydrological Features Survey, Dr. Wilton Melhorn and Mr. Scott Sinnock for their work on the Geomorphological Mapping activity, Dr. Ray Frederking for his topographic analysis work, and finally, to Mrs. Donna Dasaro for her excellent secretarial support throughout the various phases of the research activity and to Mrs. Rhoda Nagle for her outstanding job of typing the final report.

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In addition to the various LARS Personnel indicated above who were involved in specific phases of this project, there were many others whose work directly impacted the effectiveness of the research conducted under this contract. The development of various data handling programs was particularly important, and had a significant impact on the outcome of this project. This work was done as part of the ERTS-Wabash Valley contract, NASA Contract Number NAS 5-21773, and involved a considerable amount of effort on the part of Mr. William Simmons in developing data handling techniques for reformatting the ERTS data tapes, Dr. Paul Anuta for his work in the geometric correction processing, and Mr. Dave Freeman for the implementation and operational aspects of the pre-processing activities. Many other personnel too numerous to mention by name were also involved in various phases of the handling and processing of the ERTS data. A big thank you is expressed to each of these individuals.

Acknowledgement should also be given to two other INSTAAR projects for assistance in collecting, recording and transferring field data to suitable base maps. Support in these activities was made available through NASA-PY Project Grant Number NGL-06-003-200 and the Bureau of Reclamation Contract Number 14-06-7-7-52 (the San Juan Ecology Project).

Special thanks is also extended to personnel of the U. S. Forest Service, Denver Federal Center, for their aid and assistance in making various forms of aerial photography and forest cover maps available for use during this research, and for their valuable suggestions concerning information needs that might be met through the use of ERTS data and the data analysis outputs.

Finally, I would like to gratefully acknowledge the support given to this ERTS-1 research project by NASA Grant Number NGL 15-005-112 (D. A. Landgrebe, Principal Investigator) which provided the computer time for analyzing this ERTS data.

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Introduction

This report discusses the results of a joint study conducted by the Laboratory for Applications of Remote Sensing (LARS), Purdue University and the Institute of Arctic and Alpine Research (INSTAAR), University of Colorado. The purpose of the study was to test the applicability of computer-aided analysis techniques (CAAT) to identify, classify, and map major cover types in the Colorado Rocky Mountains, using ERTS-1 multispectral scanner data. Emphasis was placed on developing and testing analysis techniques that would be useful for effectively processing satellite collected MSS data. The ultimate goal of such analysis techniques was to prepare maps and tabular information applicable to resource management needs.

Previous work at LARS had proven the value of using computer-aided analysis of remote sensing data for resource inventories (Anuta, 1970; Hoffer and Goodrick, 1971; MacDonald *et al.*, 1972; Coggeshall and Hoffer, 1973; Todd *et al.*, 1973), but most of this work had been restricted to areas of minimal topographic relief. LARS researchers believed that variations in slope and aspect would significantly affect the analysis of ERTS-1 data collected over mountainous terrain.

Since user agencies have emphasized the importance of defining the conditions under which such satellite data could be utilized on an operational basis this is relevant information because important forest, water, and geologic resources of the United States are found in areas of mountainous terrain. LARS/INSTAAR research was designed to focus on utilization of ERTS-1 multispectral scanner data for a test site in which topographic parameters could influence spectral response. If computer-aided analysis techniques which use satellite collected MSS data are to provide this operational capability, then the circumstances and conditions under which these techniques can be effectively utilized must be understood. We believe that the results of this study have provided a significant step toward our understanding the operational limitations and capabilities of multispectral scanner data obtained from a satellite.

BACKGROUND

This research was developed from a cooperative program between two independent research activities:

1. The development of remote sensing technology; particularly the applications of computer-aided analysis techniques to multispectral scanner data, at the Laboratory for Applications of Remote Sensing (LARS), Purdue University; and

2. the environmental field work of the Institute of Arctic and Alpine Research (INSTAAR), the University of Colorado; whose work is aimed at increasing the understanding of natural processes operating in alpine and subalpine eco-systems of western Colorado.

The combination of the remote sensing expertise at LARS, and the alpine and subalpine experience at INSTAAR made an extremely strong scientific team, especially suited for the analysis evaluation of ERTS data. Results indicate that neither group would have made significant progress if they had worked independently.

Traditionally, resource managers have been concerned with the spatial distribution of resources over large geographic areas. A major need of many managers has been for a regional resource inventory. Such an inventory necessitates the identification, description, classification, and mapping of the various component resources. Carefully compiled regional inventories are useful to land managers for making sound decisions. However, a difficulty arises in assessing the extent of the various land use classes, particularly when there are significant changes in the characteristics of the ground cover during short periods of time. We believe that computer-aided analysis techniques applied to ERTS multispectral scanner data offer particular promise in attempting to map changes in ground cover conditions over large geographic areas.

Central Colorado is typical of many western states in terms of its water, forest, range and recreational resources. Water for much of the southwestern United States is centered around runoff in the upper mountain watersheds of the Colorado Rocky Mountains. This water is necessary for industry, public consumption, and irrigation. Accurate information about changes in snowpack and snow density is necessary if runoff estimates are to be obtained in a more accurate and economical manner than is now possible. We believed that computer-aided analysis techniques, applied to ERTS-1 data, would be particularly useful in cases involving the periodic mapping of snowpack areas.

Forest resources in Colorado comprise an important part of the economy of both the State and Federal governments. In addition to being an important supplier of wood fiber they offer potential for wildlife and recreation. Forests are a prime factor in the management of watersheds and the production of water. Resource managers have a need for current accurate information in order to be able to develop management models for the region. ERTS-1 presented a basis for gathering this information.

As an aid in accurately identifying land use categories, we felt that an important part of this research should include a study of the effects of topography on spectral response. The characteristic ruggedness of the terrain (a factor which makes ground survey difficult), also affects the ability of computer-aided data processing and analysis techniques. The effect of topography on spectral response as a function of cover-type was not well understood. However, the unique quality of the ERTS-1 MSS data and the availability of ground data for the San Juan Mountains made such a study feasible.

OBJECTIVES

This interdisciplinary research activity was designed to test the applicability of digital computer-aided analysis techniques to identify and classify major cover types in selected test sites of the Colorado Rocky Mountains using ERTS-1 multispectral scanner data. The results from these procedures would allow maps and tables of acreage estimates of the various cover types to be obtained. Five major phases of the research were defined:

- An Ecological Inventory, involving forest cover and alpine cover mapping.
- A Hydrological Features Survey, including snow cover mapping, and temporal changes in the snow cover.
- A Geomorphological Features Survey, centered on land-form mapping, and including avalanche and landslide hazard delineation, and alpine soil moisture and permafrost mapping.
- Interpretation Techniques Development, involving terrain modeling and shadow effect assessment, and the impact of terrain on spectral response.
- Evaluation of Data Collection Platform (DCP) capabilities and performance in an alpine environment.

In conjunction with these applications objectives, another key objective involved the development, refinement, and evaluation of data processing and analysis techniques required to utilize ERTS-1 multispectral scanner data. This project involved several major efforts, the results of which are described in detail in the following sections. However, to provide a brief overview of the many aspects of this work, general evaluation of the major accomplishments of this ERTS-1 research effort is provided in the following paragraphs.

GENERAL PROJECT EVALUATION

Ecological Inventory

Development of a new analysis technique (involving a refinement of the existing proven analysis method) was an important facet of this portion of the experiment. Previous analysis techniques were centered around manual training field selection (referred to as *supervised*) and machine-aided training field selection (or *non-supervised*). Because of the irregular boundary characteristics of the areas involved and the highly variable spectral characteristics of the cover types, a modified analysis technique involving a combination of supervised and non-supervised procedures had to be developed. This procedure has continued to be developed and tested throughout the course of this research. We believe a reasonably effective approach has been defined that will maximize the efficiency of analysis of MSS data. The details of this approach will be discussed in a later section under the Ecological Inventory portion of this report.

The definition of type mapping criteria suitable for work with satellite scanner data developed into a more difficult task than originally anticipated. Traditional methods used in mapping forest species have been developed to meet timber management requirements and do not necessarily reflect the spectral composition of the species being mapped. In order to accurately assess the capability of computer-aided mapping of ERTS-1 data, a different approach had to be developed.

Experience showed that the development of this approach required good quality small-scale aerial photography. The high-altitude color infrared photography obtained by NASA was most beneficial in developing the vegetation mapping criteria. Many portions of the San Juan test site had no photographic data available; therefore, NASA photography was essential for successful completion of the project. However, delays in acquisition of aerial photography hampered progress in this area during the early and vitally important phases. Although a complete underflight with the NASA WB-57F aircraft had been requested for the San Juan site for the summer of 1972, delays in the contract negotiations resulted in delays of the aircraft coverage. The result was that color infrared aerial photography for the test site could not be obtained under snow-free conditions until the summer of 1973, and much of the mapping and the field work required for checking the cover type maps could not occur on schedule.

The field season in these high mountain areas is short. Therefore, timing for the sequence of obtaining aerial photography, interpreting the photography, checking cover type maps, and carrying out the classification and interpretation phases of the research became extremely critical.

Classification results indicated that a Level 1 cover type classification (involving deciduous and coniferous forest cover, agricultural land, alpine areas water, exposed soil and rock and snow) could be obtained with a reasonably high degree of accuracy (80-85%). Even in these areas of mountainous terrain we believe this result is of major significance, since this was the first time that computer-aided analysis techniques have been successfully applied to satellite MSS data from this type of test site. However, a Level 2 classification (involving individual forest cover types) resulted in a much lower classification accuracy (55-65%). We believe that analysis techniques which account for topographic variability will have to be developed before a satisfactory degree of accuracy can be obtained for Level 2 cover types. However, we do believe that such analysis techniques can be developed, and that they will allow an adequate performance to be achieved.

Detailed statistical analysis of the interaction between spectral response of different forest cover types and the density, slope, aspect, and elevation of the forest stands indicated that all of these variables significantly influence the spectral response as measured by ERTS.

Hydrological Features Survey

The ability to utilize ERTS MSS data in conjunction with computer-aided analysis techniques proved to be very effective in mapping the areal extent of snow cover providing that cloud-free data could be obtained. The digital format of the data and an appropriate conversion factor (1.12 acres per resolution element) allowed rapid summarization of the acreage of the snowpack for selected areas of interest—either individual watersheds or quadrangles, or other specified areas.

In addition to the capability for rapidly mapping the areal extent of snow cover, a computer program was developed to allow several sets of ERTS data to be digitally overlaid to create a spectral/temporal data tape. During this investigation, one analysis sequence on the Animas watershed involved the creation of a 24-channel tape, composed of four channels of ERTS data from each of six different dates, obtained during the 1972-1973 winter. Computer analysis of this data allowed rapid assessment of the temporal changes in the areal extent of the snowpack, in either percentage or acreage figures. Unfortunately, several other data sets during the major spring runoff period were unusable due to cloud cover conditions.

The detectors in all four wavelength bands tended to saturate when either cloud or snow cover were encountered in the scan sweep. Therefore, a reliable differentiation between these two cover types with the ERTS data cannot be made when only the amplitude of the signal is relied on. In many cases manual interpretation of the data can differentiate between snow and cloud cover because of the shadows associated with the clouds. (Preliminary analysis of SKYLAB data indicates that the use of middle infrared channels would resolve this problem since clouds are highly reflective in the middle infrared [1.5-1.8 or 2.0-2.6 micrometers], and snow cover has a very low reflectance in these wavelength bands.)

A very low spectral response resulted from water bodies as well as topographic and cloud shadow areas. In many cases reliable separations between areas in shadow and bodies of water cannot be made. Detailed analysis of spectral characteristics on a number of data sets did indicate that such separation would be possible in the visible wavelength, particularly the green, but that the infrared wavelengths did not allow any distinction between water and shadow areas. In many cases this indicated that several wavelength bands were tending to cause confusion in the classification results, and that emphasis needed to be placed upon the shorter wavelengths to allow adequate separation of these areas.

The areal distribution of water bodies can be mapped with a reasonable degree of accuracy with ERTS data. Lakes and ponds as small as two acres can be identified with a reasonable degree of reliability. However, the spatial resolution of ERTS caused an edge effect around the water bodies which had to be accounted for to prevent the acreage estimate for surface water from being too low. Techniques for handling this edge effect phenomena have been developed, using data from both Colorado and Indiana (in conjunction with ERTS Wabash Valley project).

Cloud cover conditions over the selected test sites during several of the ERTS passes limited the amount of data available for studying the temporal freeze and thaw sequence of mountain lakes. However, the analysis did indicate that ERTS data could be utilized effectively for monitoring the freeze and thaw sequence of mountain lakes, and that the sequence is indeed closely related to the elevation of the water bodies involved. The 18-day cycle was not frequent enough during the critical portions of the year to allow the freeze-thaw sequence to be studied effectively.

Geomorphological Features Survey

Geomorphic analysis of the data indicated that there is a strong correlation in many areas between vegetative cover and the geomorphical features of interest. Therefore the vegetative cover proved to be a good indicator of the significant features for the geologist involved in the study.

Results of the study also indicated that the synoptic view provides an invaluable source of information which could not otherwise be obtained. This result has been shown many times by other investigators working with ERTS data, and our investigations certainly support this view. Use of the computer to enhance many of the spectral characteristics of the data, followed by manual interpretation of the spatial features present in the ERTS data, proved to be an extremely effective approach to obtain geomorphic information from the ERTS data. A great deal of manual interpretation of the computer-aided results was essential to achieve satisfactory results in the geomorphic analysis of the ERTS data, and a simple classification of the spectral characteristics of the data did not provide an adequate final result. This indicates that a careful consideration of the interactions between spectral, spatial and temporal data must be made, and that appreciation of the spectral characteristics of the data will provide only a portion of the information required. For geomorphical mapping, the spatial features play a very important role in developing satisfactory final products.

Interpretation Techniques Development

A model to utilize computer programs that map shadow areas for any solar elevation and date was developed and tested. These programs have a great deal of potential in helping to alleviate some of the shadow water spectral interaction difficulties encountered. Techniques to account for the interactions between topographic relief and spectral response were developed further.

Data Collection Platform

The testing of the data collection platform in an alpine environment indicated that such procedures could be utilized effectively to produce reliable data from extremely inaccessable locations having very adverse weather conditions during some months. The DCP performed very satisfactorily. However, again the 18-day cycle of ERTS-1 proved inadequate to provide the continuous flow of information required for many aspects of studies involved in monitoring climatic conditions in alpine locations.

Data Handling and Analysis

Many different analysis capabilities were developed during the course of this and related investigation. These techniques were essential to successful completion of several phases of this research, so are summarized separately here. They are discussed in more detail only under the Ecological Inventory Section of this report. Four key developments in data handling and analysis capabilities are:

- A procedure to rotate, deskew and geometrically scale the multispectral scanner data from ERTS-1 was developed in conjunction with the ERTS Wabash Valley project. Results of this procedure allow production of a cartographically corrected 1:24,000 scale computer line printer output. A 1:24,000 scale printout (individual wavelength bands or classification results) can be overlayed directly on a 7½ minute U.S.G.S. topographic map, thereby enabling accurate location of various features on the ERTS data. Until this capability had been developed, much of the detailed evaluation of classification results of the ERTS-1 data was severely hampered.
- Several scales of computer-enhanced "false color infrared" composites of multispectral ERTS-1 scanner data can now be obtained through the LARS digital display unit, using a procedure that was developed during the course of the ERTS-1 investigations. This procedure allowed one to obtain a color rendition of the data from the ERTS tapes, but the primary advantage for this technique was the ability to enlarge individual resolution elements to a point where they could be clearly discerned by the human eye, thereby allowing the analyst to more easily interpret the data and to effectively work with the tremendous amount of detail that is actually present of the ERTS data tapes. Our feeling is that the 9" x 9" standard product imagery and even the 1:250,000 scale photographic enlargements of ERTS imagery do not fully portray the tremendous amount of detail that is defined by the ERTS-1 scanner system. It is only through the use of the computer enlargement and enhancement procedures that one can clearly resolve the full level of detail present on the ERTS data tapes.
- A technique to superimpose a grid of any selected interval on the data displayed on the digital display unit was developed. Once the initial starting point is determined the grid indicates regular intervals, such as one or ten miles, ten kilometers, or even latitude and longitude. Such a grid technique proved very useful in locating the line and column coordinates of specified areas of interest in the data, such as avalanche tracks, areas of burned timber land, or specific stands of forest cover.
- Analysis of temporal overlays of multiple data sets proved effective for evaluating changes in snow cover. This analysis is effective because of the gross changes in spectral characteristics of the scene from one date to the next (e.g. little snow cover on one date and a great deal of snow cover on a subsequent date). This technique had to be used carefully, but the results showed the approach to be highly effective for assisting the measuring and mapping of rapid changes in the area of interest. Initially, this

program could not be utilized because of the apparent saturation of the ERTS-1 detectors when either snow or clouds were present. However this problem was overcome by modifying the normal program analysis sequence, and the effectiveness of detecting changes in snow cover using temporally overlay data was clearly shown. The utilization of such an overlay capability to detect changes in land use (e.g. development of building sites, clear cutting of forest lands, and changes in water level in high mountain reservoirs) has a great deal of potential. Numerous applications could benefit considerably from such an analysis capability.

User Agency Contacts

An extremely important result of this effort involves the contacts that have been developed with user agencies; particularly the U. S. Forest Service, National Park Service and the Bureau of Reclamation. Preliminary results of cover type classification and acreage assessments in areas of particular concern to these agencies have generated considerable interest. These results have also provided a valuable initial step in developing an awareness to the potentials of obtaining inventory information useful to the agency in their on-going activities. We found that developing interest in the user agency community required a great deal of time, patience, and skill. We believe that a great deal of progress has been made in developing interest within user agencies for evaluating results of satellite data processing to determine how such techniques can be incorporated into existing systems. However, there will be a time lag before the most useful applications will be incorporated into existing systems. The continued flow of satellite data and further development of remote sensing techniques is necessary to allow the capabilities and limitations of remote sensing techniques to be fully developed and defined. Our firm belief is that ERTS-1 has provided a major milestone in the development of remote sensing technology, and that future years will show that it had a major impact on developing techniques useful in many areas of resource inventory work.

Section A
Ecological Inventory

Contributors

LARS	*INSTAAR*
M. Fleming	P. Krebs
R. Hoffer	D. Keammerer
T. Cary	D. Groeneveld
R. Mroczynski	

The spatial distribution of cover types in large geographic areas has traditionally been of concern to geographers, ecologists, foresters, hydrologists, watershed managers, rangeland managers, and others. A major need of many land managers is for regional inventories which necessitate the identification, description, classification, and mapping of the various component cover types of the region. Carefully compiled regional inventories provide a framework for land managers to make sound decisions based on factual information. In many cases such inventories are required in a map format, and in other cases, only tabular data describing the areal extent of the various cover types is of concern.

Past work with remote sensor data and computer-aided analysis techniques had indicated great promise for mapping and tabulating acreages of various cover types. Because ERTS-1 data could be obtainable on a repeatable basis, in a digital format for large, inaccessible geographic areas, the ecological inventory phase of this research involved the use of computer-aided analysis techniques applied to the ERTS-1 multispectral scanner data. The ultimate goal was to map and tabulate acreages for cover types in each of two designated test sites in the Colorado Mountains. Previous work with aircraft data had been largely limited to flatland terrain. We anticipated that variations in slope, aspect and elevation, as well as variations in forested areas due to differences in density and cover type, could cause significant variations in spectral reflectance. However, since many of the more commercially important forest resources of the United States are located in areas of mountainous terrain, we felt it important to determine the capability to reliably map cover types in these rugged areas as well as in flatland areas. If computer-aided analysis techniques are to provide an operational capability for cover type mapping, it is important to know under what circumstances and conditions they can be used, as well as to define the reliability and amount of detail that can be obtained with these techniques.

The Ecological Inventory section of this research effort was therefore designed to determine the capability to utilize ERTS-1 spectral data. The computer-aided analysis techniques were developed at LARS to identify major forest cover types, and map the areal extent of such cover types. Secondary objectives include the mapping of rangeland and alpine tundra regions, preliminary work on biomass productivity in mountainous areas, evaluation of costs of computer-aided analysis techniques, and a statistical analysis of topographic effects on spectral variability of the ERTS-1 scanner data in forested areas.

Since much of the test site had not been previously mapped into detailed cover type classes, much effort was involved in developing such cover type maps. This work was largely carried out by the personnel from INSTAAR, University of Colorado, and involved a large amount of photo-interpretation and supplemental field work.

The computer-aided analysis work was conducted by LARS personnel, and involved two major phases. The first involved developing suitable techniques to process and analyze the ERTS-1 data, while the second phase involved the classification and evaluation sequences. This second phase could be further subdivided into four sequences involving: 1) a detailed analysis of a small area in the San Juan Mountains (concentrating on forest cover mapping), 2) a detailed analysis of a small area in the Indian Peaks test site (concentrating on alpine mapping), 3) mapping of the entire San Juan Mountain test site, and 4) mapping the entire Indian Peaks test site areas.

After a discussion of the characteristics of the two test sites involved in the study, the other sections of this chapter discuss the cover type mapping effort by INSTAAR personnel, a discussion of the data analysis techniques developed at LARS, and a discussion of the classification results. A number of significant results have been achieved from this ecological inventory research, and we believe that these results represent a significant step forward in developing remote sensing technology.

TEST SITE DESCRIPTIONS

Two test site areas are involved in the Ecological Inventory section as indicated in Figure A.1. The two test sites are the San Juan Mountain Test Site in the San Juan mountains of southwestern Colorado, and the Indian Peaks Test Site in the front range, west of Boulder, Colorado. The test sites will be described separately because of the different location and vegetative characteristics of the two areas.

Test Site 1. San Juan Mountains

The San Juan Mountains Test Site is situated in southwestern Colorado, and forms an approximate square with dimensions of approximately 100 X 100 kilometers (62 X 62 statute miles); about 10,000 square kilometers (3844 square miles). The area of coverage included portions of Archuleta, Hinsdale, LaPlata, Mineral, Ouray, Saguache, San Juan, and San Miguel counties.

This test site consists primarily of Tertiary volcanics with the topographic expression of a maturely dissected plateau which has been further modified by extensive valley glaciation. The area is characterized by numerous landslides, avalanches, rock glaciers, commercial stands of spruce-fir forest, glacial lakes, and meadows. Extensive areas of mine tailings indicate its former prominence as a mineral, particularly silver, producing area.

Most western tree species have a geographical and altitudinal distribution (Figure A.2). Therefore, a summary of the vegetation zones and species are included, along with a summary of the major factors that have great influence on the distribution of the various species.

The distribution of plant life, or vegetation, over the earth's surface is dependent upon the interaction of various external factors, such as climate (temperature and rainfall), topography, soil, biotic factors including man, and fire. Forests occur where there are relatively long, warm, moist growing periods, and where the soil is moist throughout the year. Grasslands are found generally where most of the rainfall occurs during the growing season, and where low moisture or a dry season prevents tree growth.

The major vegetation zones that are found in the San Juan Mountain Test Site include:

Alpine Tundra. The alpine area occurs above timber line, about 12,000 feet in elevation. Because of the short frost-free growing season (frost may occur at anytime of the year) the vegetation is limited to short grasses and sedges, hardy forbs, alpine fir, subalpine willows, and other low shrubby plants. The principal plant species in this alpine zone include a number of species of sedges, apline timothy,

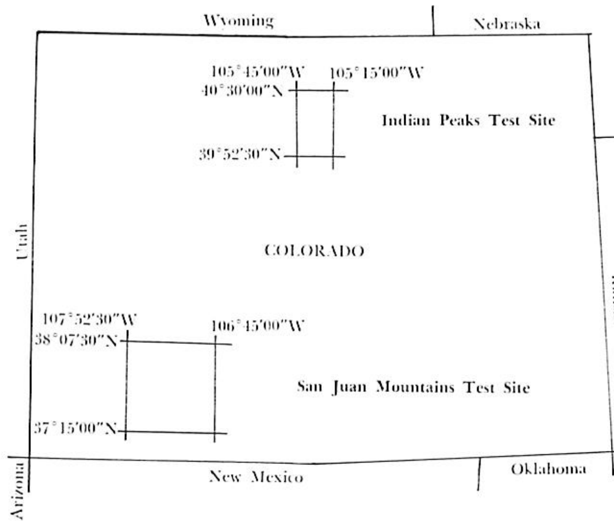

Figure A.1. Relative location of Colorado test sites for the LARS/INSTAAR study of ERTS-1 satellite data.

thurber fescue, tundra rush, arenaria, tundra bluegrass, and a few species of alpine clovers.

Spruce-Fir. The spruce-fir timber zone extends from about 9,000 feet to timber line. The dominant tree species in this type include Engelmann spruce, subalpine fir and cork bark fir. Other components of the type include aspen, limber pine, scovler willow, thin-leaf alder, water birches, currants, and snowberries. Interspersed throughout this spruce-fir type are numerous subalpine, wet mountain meadows, and grasslands. These meadows and grasslands characteristically are park-like openings between 9,000 feet and timber line. The vegetation consists of lush growth of grasses, and grasslike plants and forbs.

Ponderosa Pine-Douglas Fir. The ponderosa pine timber zone (or Montane Conifer Forest) extends from an elevation of about 6,000 feet to 9,500 feet, with Douglas fir providing an important component of the timber zone between the elevations of 8,000 and 9,500 feet, especially on north-facing slopes. Other woody components of this type include white fir, aspen, Rocky Mountain maple, alder, and Gambel oak. The grass and forb understory in the open and semi-open stands of ponderosa pine primarily on south-facing slopes and associated species include Arizona fescue, mountain muhly, pine dropseed, and blue grama. The forbs include geranium, vetches, and clovers.

The lower part of the forest below about 8,500 feet is warmer and drier, and is primarily a forest of ponderosa pines, except on north-facing slopes. At midforest elevations, douglas fir, and ponderosa pine variously intermingle on all but north-facing slopes. Douglas fir is dominant on north-facing slopes above 7,500 feet and at about 8,500 feet they become

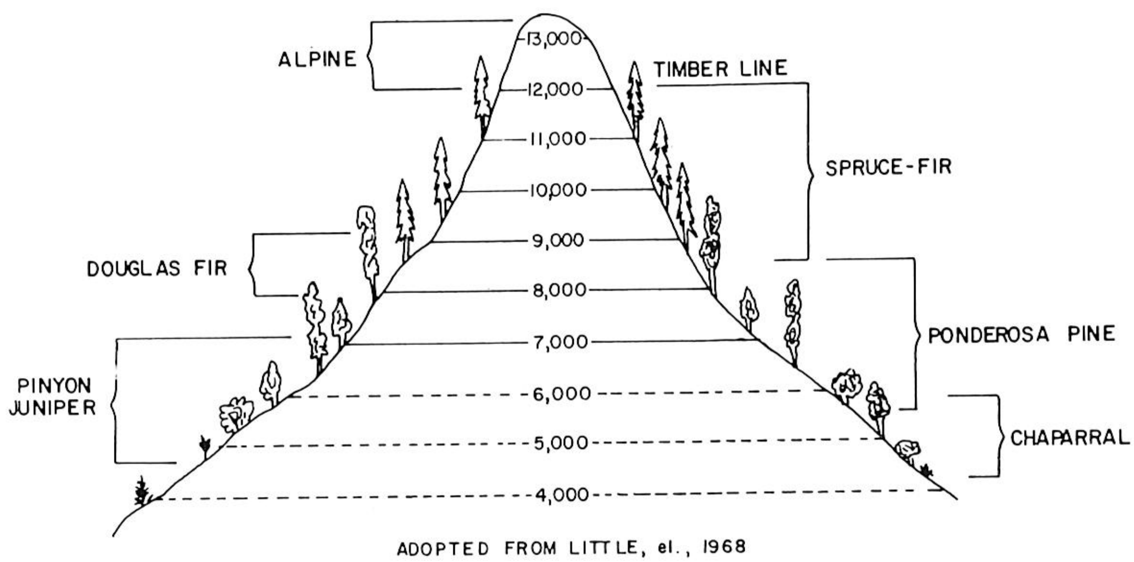

Figure A.2 General elevation ranges of the major cover types found in the San Juan Mountains test site and the Indian Peaks test site.

increasingly more prevalent in the forests on all slope exposures.

Pinyon-Juniper. The pinyon-juniper type occurs at elevations above 5,000 feet and generally occupies an area immediately below the ponderosa pine. The principal species in this type include one-seed juniper, Utah juniper, Rocky Mountain juniper, and pinyon pine; with an understory of oak, ceanothus, buckbrush, and clift rose. Blue grama, galleta, sand dropseed, and Arizona fescue make up the principal grass species.

Oak-Shrub Woodland. The oak-shrub woodland type extends from an elevation of about 4,000 feet to 5,500 feet. The principal species include Gambel oak, mountain mahogany, manzanita, ceanothus, cliff rose, Apache plume, and numerous species of cacti. Under normal conditions the oak-shrub type has a good stand of bluestem, sideoats, black and blue grama, and sand dropseed.

The basic vegetation communities found in this test site area vary greatly in their location, distribution, and species of plant life found in them. There are several factors which influence and modify each community. The two major influences are: 1) human activity, including mining, farming, grazing, and timber harvesting; and 2) climatic factors, including weather phenomena, exposure, and the aspect and angle of the slope.

The direct effects of mining are severe but quite localized. Mine tailings have a low organic content and usually have a low pH due to the mineral content. Because of these factors the tailings tend to remain sterile and non-vegetated. Erosion has washed the tailings into many stream channels, thereby affecting the riparian habitat. Farming is minimal within the San Juan study area and is limited primarily to hay crops at lower altitudes. Riparian communities are common along the irrigation ditches which supply water to the hay fields. Grazing has a considerable effect upon the ecosystem. Within the grazing range, those herbs which cattle and sheep find most palatable are gradually being eradicated. As a result, in heavily grazed areas, erosional problems are more common; especially where flock management is poor. Logging and the attendant increase in fire incidence have produced an extensive alteration of the vegetation over the years. Denuded slopes in mining areas were produced by logging operations to provide wood for fuel, building materials, and mine timbers. Today, these old logging sites and burns are largely revegetated by a mixed deciduous-coniferous forest.

In areas where human influence has not caused major changes, the vegetative cover is determined by complex interactions of edaphic, topographic, and climatic influences. For example, as elevation increases, precipitation generally increases and mean annual air temperatures decrease. A complex relationship also exists between elevation and quantity and the quality of solar radiation. There is some tendency at high altitudes toward increased cloud cover; but the radiation that penetrates the cloud cover, and the solar radiation present at other times is of great intensity due to less atmospheric attenuation. The aspect and angle of the slope significantly effects microclimatic conditions, also due to associated differences in the quantity of solar radiation. For example, during the summer an exposed site with a high sun incidence tends to dry quickly and vegetation in these sites must be adapted to water stress during much of the growing season. The integration of these many complex interactions between the topographic characteristics of the area, the climatic influences, and the soils found in various areas, produces a distribution of vegetative cover types that is particularly related to elevation and aspect (Figure A.3). As seen from this figure, many of the species in the San Juan test site are found in the same elevation ranges, but there is frequently a distinct difference in the frequency of occurrence at the same elevation. One also sees that there is a general shift toward lower elevations when the species is on a north-facing slope, as compared with a south-facing slope. The frequency of occurrence is often much lower on north-facing slopes than on south-facing slopes for many of the species.

To prevent too much detail from being included in this section of the report, but to allow interested readers to obtain a better understanding of the characteristics of the various species of concern in this ERTS-1 study on the San Juan Test Site, a more detailed discussion of the various species and the influences and reaction to changes in the environment is included in Appendix A.1. This appendix includes a discussion of some of the species not found in the San Juan Test Site, but which are found in the Indian Peaks Test Site, and vice versa.

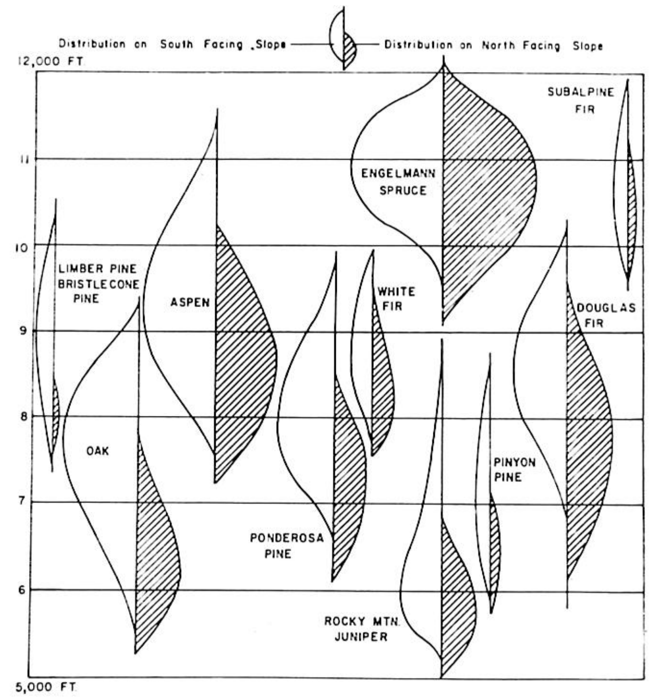

Figure A.3. Distribution of forest species relating to elevation and the slope aspect.

Test Site 2. Indian Peaks

The Indian Peaks Test Site is situated in the Colorado Front Range approximately 20 miles west of Boulder, Colorado as previously indicated in Figure A.1. The area is rectangular in shape with an area of approximately 2967 square kilometers (1144 square miles). Linear extent is approximately 69 kilometers north-south and 43 kilometers east-west. The area includes portions of Boulder, Gilpin, Grand, Jefferson, and Larimer counties.

The test site derives its name from the "Indian Peaks Intensive Alpine Tundra Study Site" of the IBP Tundra Biome, and includes a large portion of Rocky Mountain National Park. Also included within the area is Niwot Ridge, which is the location for the INSTAAR permanent alpine research field station.

The area roughly coincides with the Boulder District (Fenneman, 1931, p. 101) which is geomorphically distinctive for preserved, but glacially modified remnants of the formerly extensive Flattop Peneplain surface. Geologically the area is characterized by an exposed granite core along the western margin flanked by eastward dipping sedimentary sequences ranging from Triassic through Cretaceous age. Basic vegetative cover types which occur as mappable units include alpine tundra and meadow, Engelmann spruce and subalpine fir, aspen, interior Douglas fir, lodgepole pine, ponderosa pine, and range grassland. The location of the Indian Peaks Test Site is particularly important because it includes a complete transect from range grassland through alpine tundra and demonstrates the altitudinal zonation of different life zones.

The types and characteristics of the vegetation found in the Indian Peaks Test Site are basically the same as those of the San Juan Mountain Test Site. There are, however, two distinct differences—the Indian Peaks Test Site contains large, pure stands of lodgepole pine, and is generally lacking Gambel oak.

Lodgepole pine is a subclimax species that often behaves like a climax species. It has a broad range of temperature and moisture tolerance, and while it characteristically occurs at middle elevations in the mountains (8,000-9,000 feet), it may tend to replace ponderosa pine and usually runs well into the zone occupied by the spruce-fir type. Typically it is a dense, pure type that occurs where the climax species have been disturbed by man or by fire.

Gambel oak is an important part of the understory in the San Juan Mountain Test Site, but it is not found in the Indian Peaks Test Site. Rather than Gambel oak, a mixture of grass species occurs under the Ponderosa pine stands.

VEGETATION MAPPING BY PHOTO INTERPRETATION

A critical part of the entire investigation involved the support data set "ground truth" to be utilized in conjunction with the computer-aided analysis of the ERTS-1 scanner data. We determined that the majority of this support data would consist of cover type maps of key test area locations. Since detailed cover type maps did not exist for most of the test area, they had to be developed by personnel familiar with the area and the ecology of the region. Therefore, the task of developing the support data set constituted the primary thrust of the activities of the INSTAAR group.

Good quality, small-scale color, and color-infrared aerial photography was required as input for the cover type mapping activity. Results showed that the color-infrared photography was more effective than the color photography for much of the detailed mapping work, particularly where forest cover types involving different coniferous species were involved. The resultant cover types maps were drawn to a 1:24,000 scale so that they could be utilized directly with 7½" U.S.G.S. topographic maps, and with the 1:24,000 geometrically corrected line printer output format developed by LARS for handling ERTS-1 data. The cover type maps were initially drawn to show individual forest cover types at a Level II, (Table A.1) degree of detail and accuracy. These Level II type maps were then reduced to a simpler form showing only the Level I cover type groups.

The cover types defined as Level I and Level II in this report are basically the same as the land use types discussed in the Geological Survey Circular 671 (Anderson, 1972). Since the major emphasis of the Ecological Inventory chapter is on forest cover mapping, more detail is included here at Level I and II for the forest cover types than used in the Geological Survey Circular 671. For example, the Level I types (coniferous, mixed coniferous-deciduous, and deciduous) used in this chapter correspond to the Level II types of Circular 671. However, the definitions are basically the same for all of the cover types.

A considerable amount of effort went into the initial definition of methodology and definition of the cover type groups to be mapped. For example, many areas had ponderosa pine as the dominant species in the overstory, with a dense understory cover of oak. Although traditional techniques might involve mapping units in which the frequency of occurrence of a particular species would determine the cover type indicated on a type map, in remote sensing one has to consider the characteristic crown dominance, as would be observed from aircraft or satellite altitudes. For this reason, suitable techniques had to be defined and tested before appropriate cover type maps to use as a basis for the analysis of the ERTS-1 data were to be developed. Due to delays in initial coverage by aircraft of the test site, a final definition of the appropriate mapping units and procedures for defining different cover types was not achieved until the 1973 summer field season.

Table A.1. Cover type breakdown.

Level I	Level II	Level III
Conifer	Pinyon-juniper	Densities
	Ponderosa pine	Densities
	Douglas and white fir	Densities
	Spruce-fir	Densities
	Krummholz	Densities
	Colorado blue spruce	Densities
Deciduous-conifer	Douglas and white fir, Ponderosa pine, and aspen	Densities
Deciduous	Cottonwood-willow	Densities
	Alpine shrub	Densities
	Oak-shrub	Densities
	Oak	Densities
	Aspen	Densities
Grassland and crops	Cultivated crops	
	Cultivated pasture	
	Pasture	
	Meadow	Densities
	Tundra	Densities
	Wet meadow	Densities
Rock and soil	Exposed rock	
	Exposed soil	Wet
		Dry
Shadow	Ridge shadow	
	Cloud shadow	
Water	Clear	
	Turbid	
Snow	Snow only	
	Snow-forest mix	
Cloud		
Urban		

The sequence of vegetation mapping that was followed involved four phases:

1. Intensive area mapping in a four quadrangle region around Vallecito Reservoir in the San Juan Test Site,
2. Cover type mapping in specified areas throughout the San Juan Test Site,
3. Tundra mapping,
4. Vegetation mapping in the Front Range region of Colorado.

Intensive Area Mapping

The vegetation mapping of four quadrangles in the San Juan Mountain Test Site (Ludwig Mountain, Vallecito Reservoir, Lemon Reservoir, and Rules Hill) began with Ludwig Mountain quadrangle, and was then extended into Vallecito Reservoir and the other quadrangles. These areas were first mapped during spring 1973 using some available Mark Hurd quadrangle centered photography. The use of this black and white photography limited the detail of mapping. Acquisition of color and color infrared photography from NASA Missions 238, 239, and 248 for this area greatly increased the ability to distinguish the vegetative detail. In most cases, the color infrared film was preferred over the color positive film (see detailed comments concerning this photo-interpretative work in Appendix A.2). The reason for this was the generally greater difference between the responses of deciduous or herbaceous vegetation, and coniferous vegetation on color infrared than on color film. The distinction between the green tones on color film was not as great as between the red tones on color infrared film. There is also a greater distinction between exposed soil or rock, and vegetation on color infrared film than there is on color positive film. These exposed areas are often highly reflective and frequently influenced the computer classifications of cover types. Thus, it was important to map such areas accurately.

After selection of the film type and coverage best suited for mapping, the ground observation data were consulted. All sites for which forest densities and composition were known were marked on the topographic map to be used as base information. These areas of known composition were then used as photo-interpretation standards on the NASA underflight photography. Once confidence in identification of color, texture, crown shape, or community characteristics for each cover type and each film was achieved, the actual mapping could begin (see Appendix A.3).

Three different symbol systems were developed for use in the various aspects of vegetation mapping. The first symbol system generated early in the project (Table A.2) served mostly for mapping outside the intensively studied areas. The second system (Table A.3) resulted from the need to map in a manner more compatible with the levels of detail involved in the computer-aided analysis. The third system (Table A.4) was a symbol system created for a limited area, yet compatible with the second system discussed. The usage of the third system was always involved in the initial work on a fairly homogeneous area (i.e. tundra) which required only a few of the symbols present in the second set. Upon expansion to a larger

Table A.2. Vegetation symbol system for wide range usage with corresponding ERTS categories.

Number code	ERTS no.	Category	ERTS category
00.	B.1	Non-vegetated	Exposed rock
	B.2		Exposed soil
01.	W	Water	Water
02.	U	Urban	Urban
110	161	Grasslands	Agricultural
121	C.6	Colorado blue spruce	Colorado blue spruce
122	D.1	Cottonwood-willow	Cottonwood-willow
130	N.1	Montane/subalpine meadow	Meadow
141	N.2I	0-30% vegetative cover tundra	0-30% vegetated tundra
142	N.2II	30-70% vegetative cover tundra	30-70% vegetated tundra
143	N.2III	70-100% vegetative cover tundra	70-100% vegetated tundra
144	N.3	Graminoid wet meadow, usually tundra	Wet meadow
145	D.2	Alpine shrub	Alpine shrub-willow
151	D.6	Wet shrub	Wet shrub
152	D.3	Dry shrub	Oak-shrub
153	D.4	Oak	Oak
211	D.5	Aspen	Aspen
221	C.1	Piñon pine/Rocky Mountain juniper	Piñon pine/Rocky Mountain juniper
222	C.2	Ponderosa pine	Ponderosa pine
222.1	C.2	Ponderosa pine with shrub	Ponderosa pine
223	C.2	Ponderosa pine/Rocky Mountain juniper	Ponderosa pine
224	C.2.3	Ponderosa pine/Douglas fir	Ponderosa pine/Douglas fir
225	C.4	Engelmann spruce-subalpine fir	Spruce/fir
Zipatone	C.5	Krummholz	Krummholz
225.1	C.4	Engelmann spruce/Douglas fir	Spruce/fir
226	C.7	Lodge pole pine	Lodge pole pine
227		Limber pine/bristlecone pine	Not extensive
228	C.3	Douglas fir/white fir	Douglas fir/white fir
229		Mixed coniferous (DF/WF/ESP/PP)	Special analysis required
231	M.1	Douglas fir/Ponderosa pine/aspen	Douglas fir/white fir, Ponderosa pine, other conifers
232	M.1	Douglas fir/white fir/aspen	Douglas fir/white fir, aspen/oak
233	M.1	Lodge pole/aspen	Douglas fir/white fir
234	M.1	Mixed coniferous-deciduous	Douglas fir/white fir
161	A.3	Pasture	Pasture
162	A.1	Cultivated crop	Cultivated crop
163	A.2	Cultivated pasture	Cultivated pasture

geographical area or one which is more heterogeneous, set three was easily translated into the broader usage set two.

Two methods were used in the two stages of mapping the four quadrangle intensive area. The first two quadrangles were completed using a simple interpolation from stereo interpretation of NASA aircraft coverage to U.S.G.S. quadrangles. In the larger scale photography observations of individual tree crowns in stereo permitted faster identification of species. For

Table A.3. ERTS-1 vegetation map categories and cover type breakdown.

General		Level 1		Level 2		Level 3
Forest	C	Conifer (Con)	.1	Pinon-juniper (PJ)	I	0-30%
			.2	Ponderosa pine (P. pine)	II	30-70%
			.2.3	Ponderosa pine/Douglas fir	III	70-100%
			.4	Spruce-fir (SF)		
			.5	Krummholz (Krum)		
			.6	Col. blue spruce (CBS)		As above
			.7	Lodge Pole pine		
	M	Deciduous-coniferous (De-Con)	.1	Coniferous species and aspen		As above
	D	Deciduous (Decid)	.1	Cottonwood-willow		
			.2	Alpine shrub (AS)		
			.3	Oak shrub (OS)		
			.4	Oak (O)		
			.5	Aspen (A)		
			.6	Wet shrub (WS)		
Herbaceous	A	Agricultural (Agrl)	.1	Cultivated crops (Cul. crop)		
			.2	Cultivated pasture (Cul. past)		
			.3	Pasture (Past)		
	N	Non-agricultural (Non-Ag)	.1	Meadow (M)		
			.2	Tundra (T)	I	0-30%
					II	30-70%
					III	70-100%
			.3	Wet meadow (Wet mead)		
Non-vegetated	B	Rock-soil (Bare)	.1	Exposed rock (B. rock)		
			.2	Exposed soil (B. soil)		Wet
						Dry
		Shadow		Ridge shadow (Shadow R)		
				Cloud shadow (Shadow C)		
	W	Water		Clear		
				Turbid		
	S	Snow		Snow only		
				Snow-forest mix (Snow-for)		
	C	Cloud				
	U	Urban				

Table A.4. Example of a type 3 symbol system, created for initial mapping in a limited geographical area (i.e. tundra mapping, Indian Peaks Test Site).

Category	Code	ERTS code	Comments (related to CIR film, Mission 248, roll 69)
Moist tundra	1A	N.2 III	Bright red, most uniform moist meadow
	1B	N.2 II	Bright-pale red, some blue of bare rocks
	1C	N.2 II	Mosaic of bright red, pale red and blue of bare rock
Dry tundra	2	N.2 I	Light pink-red, much blue showing through
Willow	3A	D.2	Very bright red of bog vegetation mixed with deep red of willows
	3B	D.2	Light red of alpine meadow mixed with deep red of willows
	3C	D.2	Blue of rocks mixed with deep red of willows
Krummholz	4	C.5	Scattered dark red
Wet meadow	5	N.3	Brilliant red
Water	6	W	Black-deep blue
Snowbank	7	S	White-blue white
Bare rock	8A	B.1	Blue grey-light grey
	8B	N.2 I	Blue grey of rock with slight pinkish cast of sparce vegetation
Deciduous	9	D.5	Bright red, mounded appearance
Coniferous	10	C.4	Very deep red
Meadow	11	N.1	Light red below timberline

example, during mid-season the brilliant red signature of willow communities on color infrared was very close to the response of aspen. Stereo interpretation permitted the analyst to separate these species on the basis of height.

Working with the stereoscope and a light table, the areas were penciled in on the U.S.G.S. topographic base map and labeled according to the broader usage and vegetation mapping symbol system. Densities and comments, where necessary, were added. The areas were rechecked and then inked. A mylar overlay was then made of all information contained in the map. The broad range usage symbol system was translated into the ERTS-1 symbol system (Table A.3), Levels II and III. The entire map was checked and then machine copied (Figure A.4). After rechecking, LARS was provided with the mylar version and one copy for use in the computer-aided mapping and evaluation.

The progress on the Vallecito Reservoir quadrangle was slowed by difficulties in obtaining suitable NASA aircraft coverage to meet the long-term work schedule. Missions 238 and 239 did cover the entire area. However, both missions were flown on June 6, 1973. A very late winter season had prevented snow melt or complete vernalization by this date. Thus, the areas with elevations above 10,200 feet are either snow covered (tundra) or not leafed out (deciduous trees). This condition greatly increased the difficulty of mapping aspen stands and deciduous-coniferous forests. The tundra was completely obscured by snow on both Mission 238 and 239.

Mission 248 was flown on August 4, 1973. The frames which covered parts of Vallecito Reservoir quadrangle were excellent for distinguishing deciduous from coniferous vegetation (Appendices A.2 and A.3). Thus, we found that the most effective technique was to first use Mission 248 data (August 4, 1973) to separate the aspen from the coniferous species, and determine the coniferous-deciduous areas. Then use Mission 238 data (June 6, 1973) to identify the coniferous species present, and to aid in the separation of shrub communities from aspen or meadows where distinctions were unclear on the August data.

Type Mapping Specified Areas in the San Juan Test Site

The descriptive cover type maps of vegetation generated for this phase of the project provided a more synoptic view of land use patterns in the San Juan Test Site. This interpretive application of vegetation maps is based on the inter-relationship of vegetative cover to topography, and an understanding of predictable ecological phenomena.

The study area covered fourteen 7½ U.S.G.S. quadrangle maps along a belt near the southern border of the San Juan Mountain Range plus four additional quadrangles farther north in the San Juan Mountains (Figure A.5). By using the U.S.G.S. quadrangles as base maps, a comparison of spatial relationships of plant communities and related topographic features became apparent. The cover type categories used represented maximum content of information without sacrifice to overwhelming detail. These categories represented consistently occurring and repetitive plant associations (Table A.2).

Standards located and verified during the field season were noted on preliminary maps, and these cover type standards were used for photo-interpretation purposes to insure a high level of accuracy. The photo-interpretative results from the color infrared aerial coverage were delineated directly on Hurd quadrangle centered, 1:24,000 scale photographs, where these were available. Correct placement of boundaries was insured by keying on geographic points and topographic features visible on the two types of aircraft coverage. For portions of several quadrangles, complete NASA coverage was not available. Photo-interpretation of those areas had to be based strictly on the available black and white Hurd coverage. This analysis sequence is illustrated in Figure A.6.

The color and hue of the various cover types were distinctive on the color infrared film. However, accurate photo-interpretation in areas of shadow requires an awareness of both topographic features and elevation. By knowing the distribution of species as modified by these factors (Table A.5), the probable cover type categories in shadow areas could be inferred.

Tundra Mapping

The Howardsville area was initially selected for tundra vegetation mapping. This quadrangle contains few topographic extremes and many square miles of gently rolling tundra, so it seemed well suited for this research. However, review of the data available for this portion of the San Juan Test Site during periods when the tundra would be snow free showed that, at best, approximately 30% of the selected area was obscured by clouds. Therefore, the remainder of the tundra mapping effort was focused on the Indian Peaks Test Site, rather than the San Juan Test Site.

In reviewing data from the Indian Peaks Test Site, we found the scene I.D. 1352-17134 (July 10, 1973) was nearly cloud free. An area approximately the size of a U.S.G.S. quadrangle was selected for tundra mapping, which included the western three-fourths of the Ward quadrangle and the adjacent eastern one-fourth of the Monarch Lake quadrangle. The area is centered on Niwot Ridge (for which an extensive amount of data has been collected since 1952), and extends westward over the Continental

Figure A.4. Example of a vegetation cover type map prepared by INSTAAR through the use of 1:100,000 scale color infrared photos obtained by NASA. A similar level of detail was included on the maps prepared for all of the quadrangles shown in Figure A.5.

Divide. Figure A.7 illustrates the general characteristics of this area. Along the 14.5 kilometers of the Divide within the tundra mapping area, the elevation varies from 3660 to 4120 meters. Eastward and below the rock-dominated divide region are three broad, gently rolling igneous-metamorphic rock highlands which show evidence of prolonged mass wasting. Upon these structures and within the intervening valleys is found a mosaic of tundra plant communities (Table A.4). Extreme moisture gradients, exposure to the wind (which determines the snow accumulation areas), and geomorphic freeze-thaw phenomena (such as solifluction and frost creep) have contributed to the complex pattern of vegetation

Table A.5. General photo-interpretation characteristics of cover types on color infrared.

Cover type	Color IR characteristics
Aspen	Blotched, fluffy, and bright red with yellow spectral shift with fall color change. Comparable color to oak, but differentiable in overlap due to shadow length from taller crown form.
Oak	Fluffy, bright red, blotched only at periphery of stand where vegetation becomes discontinuous. Spectral shift in fall, but occurring later than in aspen. Leaves are shed much later and the shifted color appears grayer-grainier than that of aspen.
Meadow	Bright red, smooth in spring and early summer due to green plants. Pattern turns discontinuous by late summer. Blotched red due to isolated shrub or moisture patches surrounded by gray-brown, bluish, or sand color, indicating reflectance from bare soil and bloomed-out grasses and herbs.
Ponderosa pine	Red-brown and fluffy textured with round full crown form.
Douglas fir	Red-brown, fluffy textured, and with same crown form as ponderosa when mature. Differentiable from ponderosa pine only when photo-interpreter is thoroughly familiar with ecological amplitude of these two species and pays strict attention to topographic effects in the map area. Usually, douglas fir grows with a shorter conic form in areas of ponderosa pine growth. Where douglas fir grows tall and exhibits a mature, broad crown form, ponderosa pine is usually absent.
White fir	Dark red, conic, and coarsely textured. Easily distinguishable from surrounding tree crowns.
Engelmann spruce	Dark blackish red, darker and less coarse in texture than white fir. Engelmann spruce cover boundaries are easily distinguishable from surrounding forest.
Subalpine fir	Tall, dark red, less dark than Engelmann spruce, but darker than white fir. Tall, spire-like and of the same texture as spruce, usually indistinguishable from Engelmann spruce.
Limber and Bristlecone pine	Indistinguishable because of limited, scattered, and restricted occurrence. Areas of probable occurrence can be located on ridges with low percentage cover characteristic of these two species.
Pinyon pine	Dark brownish red, coarse in texture, and forming rounded bumps. Usually found by checking slope angle, aspect, and elevation, and then consulting the photo.
Rocky Mountain juniper	Purplish-brown, rounded, small, smooth texture. Distinguishable from pinyon pine due to darker color and slightly larger size.

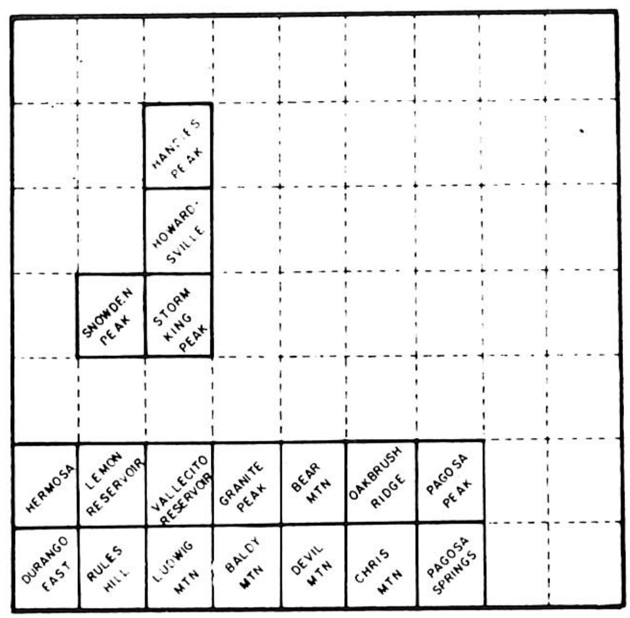

Figure A.5. Quadrangles in the San Juan Mountain test site that were cover type mapped using photo-interpretation techniques.

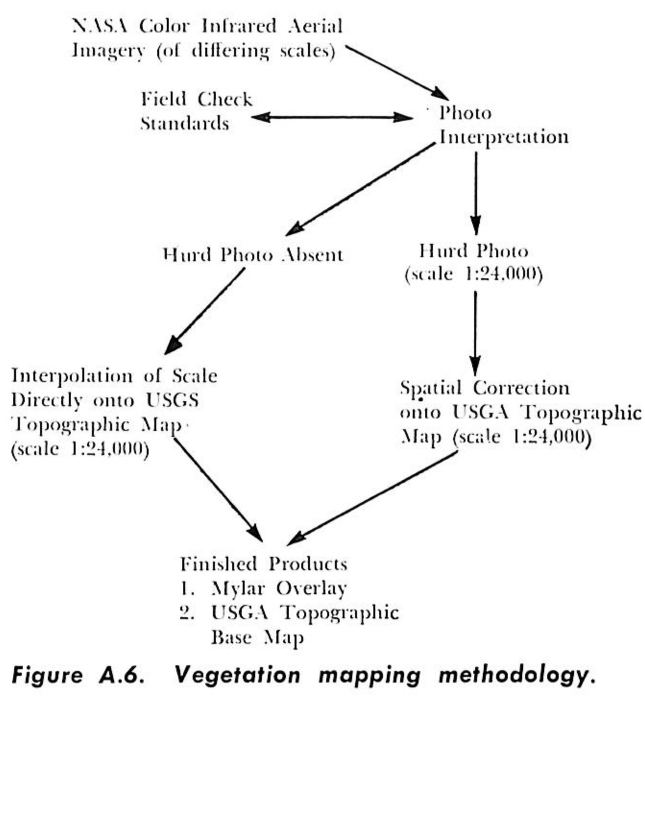

Figure A.6. Vegetation mapping methodology.

cover types present in this area (Osborn, 1958; May, 1973).

Treeline occurs at about 3350 meters where the alpine communities merge with and are replaced by a dense spruce-fir forest. A few lakes, bogs, and aspen groves are scattered throughout the otherwise uniform coniferous forest.

Due to a greater confidence in the accuracy of mapping with the Bausch and Lomb Zoom Transfer Scope, this instrument was preferred over a stereoscope. In cases where some doubt existed in the distinction of cover types of similar color but different vegetation heights, the stereoscope was used to help discriminate. Cover type boundaries were first drawn directly on a plastic cover sheet over the NASA photography (Mission 248, roll 60, frames 0088-0080). These boundaries were then rechecked before being transferred to the 1:24,000 scale U.S.G.S. base map. Figure A.8 illustrates the complexity of the cover types in this area. Eleven recognizable cover types could be mapped from interpretation of the NASA film. Appendix A.4 gives the detailed description of the photo-interpretation criteria used.

Test fields to use in evaluation of the computer-aided analysis of the data were selected from a rescaled, geometrically-corrected printout of channel four from scene ID 1352-17134. This was done by placing the gray scale over the vegetation map on a light table. A number of snow fields, topographic shadows, and a cloud-cloud shadow area occurred on the ERTS scene. During selection of the test fields, these areas were avoided where they interfered with vegetation cover types.

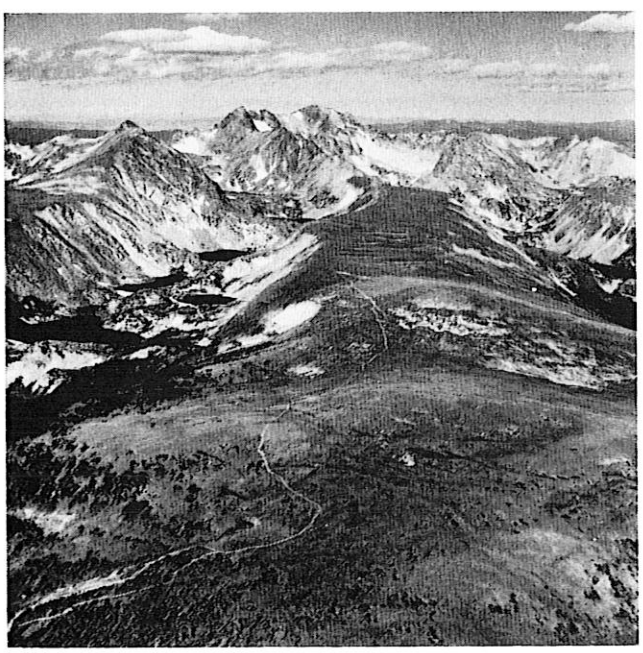

Figure A.7. Oblique aerial view of Niwot Ridge.

Vegetation Mapping in the Colorado Front Range

Vegetation mapping was conducted for forest-cover types from 8,800 feet to 11,100 feet at timberline. Douglas fir/ponderosa pine associations were encountered at lower elevations (to 9,200 feet) with Douglas fir commonly dominant on north-facing slopes. Encroachment by aspen in disturbed areas and mixing with lodge-pole pine, limber pine, and blue spruce contributed to cover-type diversity in the test area. Dry grass meadows appear at lower elevations in areas cleared for grazing, and commonly above stream courses and drainage basins where willow and birch are dominant shrub types. Interpretation of the subalpine region extended from 9,200 feet to the forest-tundra ecotone at about 11,100 feet. At lower elevations heterogeneous stands include assemblages of limber pine, lodgepole pine, and Engelmann spruce/subalpine fir associations. At higher elevations, lodgepole pine and aspen give way to denser stands of Engelmann spruce/subalpine fir (9,800 feet). Limber pine commonly appear on ridgetops as discrete assemblages and scatter krummholz "islands" of Engelmann spruce delimit the upper reaches of the forest-tundra ecotone. Wet meadows and shrub stands were encountered in depressions with high water tables and at the effluents of reservoirs (i.e. Left Hand Reservoir). Poor tonal quality of CIR imagery prevented accurate discrimination between cover-types along stream courses and drainage basins.

A cross-evaluation chart (Figure A.9) was developed to show the degree of differentiation between vegetation associations mapped in the test area using NASA CIR imagery (scale = 1:46,000). Overall, greatest confusion was experienced between vegetation categories with similar tonal quality. For example, lodgepole pine was not easily distinguished from Engelmann spruce/subalpine fir associations. Cover types eliciting red tonal responses such as aspen, riparian vegetation, and dry and wet meadows were also confused prompting greater reliance on textural and topographic characteristics.

The results of field and forest-cover mapping activities on this area showed that 1) heterogeneous coniferous cover-types appear as undifferentiable mapping units requiring inclusion into broader vegetation categories with loss of ground information, 2) discrimination between coniferous/deciduous forest cover and forest/meadow is excellent while discrimination and information content drops off markedly between cover-types of similar tonal aspect, and 3) additional aircraft coverage of this test area will be required for generation of detailed vegetation maps suitable for computer-aided analysis beyond the Level I classification.

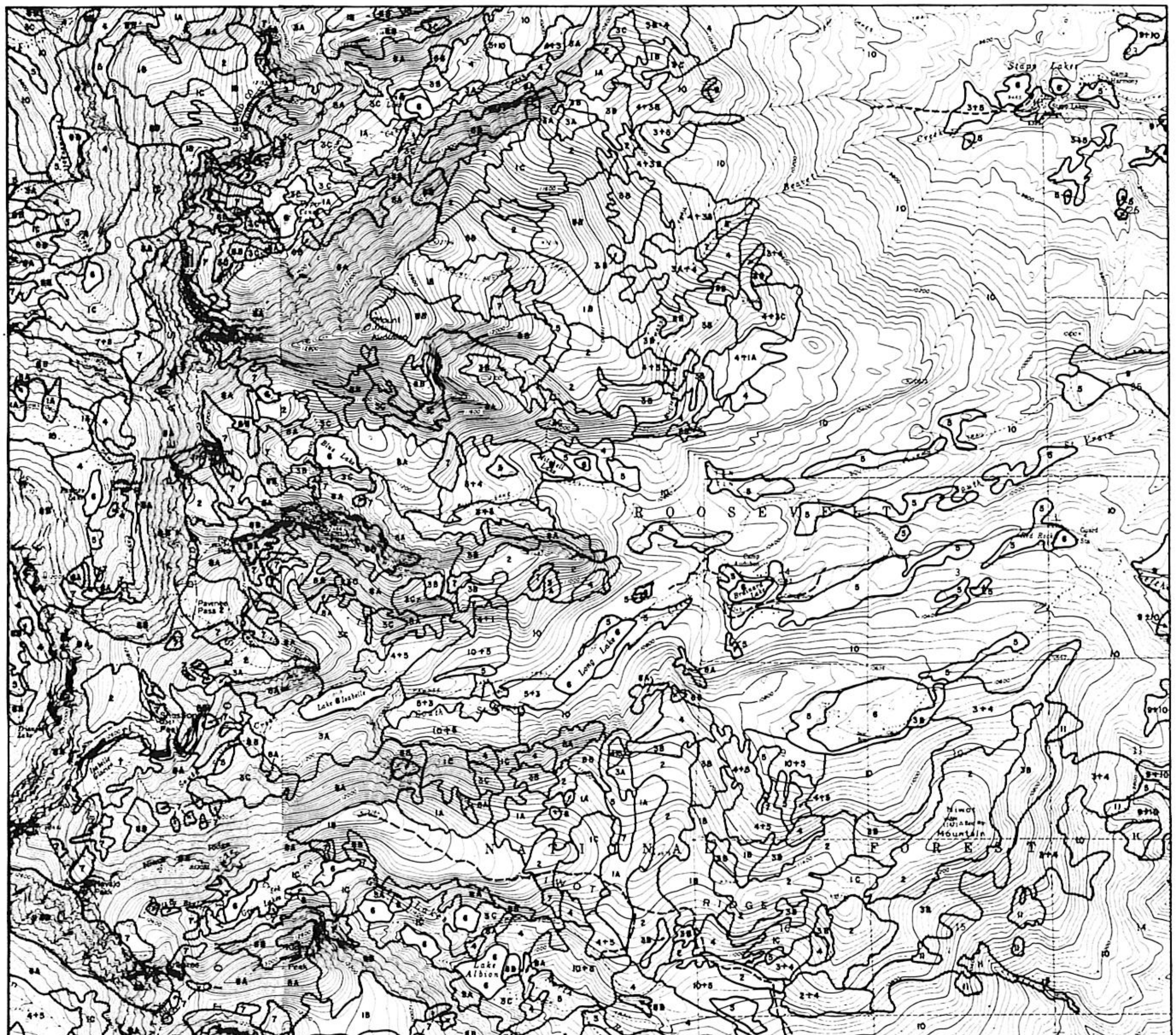

Figure A.8. Cover type map of the Ward-Monarch area at level II, illustrating the complexity of the cover types in this area. (Vegetation map prepared by INSTAAR.)

Item	Association 1	2	3	4	5	6	7	8	9	10	11	12	Overall association evaluation
1. Ponderosa pine		−	+	++	−	−	−	++	++	++	++	++	+
2. Ponderosa pine/ Douglas fir	−		+	++	−	−	+	++	++	++	++	++	++
3. Spruce-fir	+	+		+	−	−	+	++	++	++	++	++	+
4. Krummholz	++	++	+		++	+	++	++	++	++	++	++	++
5. Lodgepole pine	−	−	−	++		+	+	++	++	++	++	++	++
6. Limber pine	−	−	−	+	+		++	++	++	++	++	++	+
7. Conifers/aspen	−	+	+	++	+	+		+	++	+	++	+	+
8. Cottonwood/willow	++	++	++	++	++	++	+		−	−	+	−	++
9. Aspen	++	++	++	++	++	++	++	−		+	+	+	++
10. Wet shrub	++	++	++	++	++	+	+	−	+		−	−	+
11. Dry meadow	++	++	++	++	++	++	++	+	+	−		−	++
12. Wet meadow	++	++	++	++	++	++	+	−	+	−	−		++

++ Excellent differentiation (approximately 100%)
+ Good differentiation (limited confusion)
− Limited differentiation (often confused)
−− Poor differentiation (undifferentiable in most cases)

Figure A.9. Cross-evaluation chart showing degree of differentiation between vegetation associations based on interpretations performed using NASA CIR photography (scale = 1:46,000).

VEGETATION MAPPING BY COMPUTER-AIDED ANALYSIS TECHNIQUES

The thrust of this phase of the ecological inventory research involved the utilization of ERTS-1 multispectral scanner data and digital computer-aided analysis techniques (CAAT) developed at LARS to: 1) identify major forest cover types and map the areal extent of such cover types, and 2) to differentiate and map alpine tundra and rangeland areas.

As pointed out previously, we anticipated that a great deal of spectral variability would be encountered within each forest cover type due to differences in slope, aspect, elevation, and density variations within each species group. During the early phases of the research, it became clear that these factors were having a strong influence on the spectral response, thereby creating a very complex analysis task. Much of the preliminary research efforts were necessarily involved with modifying the analysis techniques and procedures previously utilized at LARS, so that an appropriate procedure could be developed for the type of data involved in this study. The first section of this part of the report describes the details of the techniques development work. These efforts finally resulted in a technique believed to allow the most satisfactory approach to classification and evaluation of such complex data sets. The second section describes the results of four analysis sequences involved in mapping and tabulating acreages of forest, alpine, and rangeland cover types. Various levels of detail are described. The first two analysis sequences involve relatively small intensive study areas, while the second two analysis involve much larger test site areas (the entire San Juan Mountain and Indian Peaks Test Site).

The first two analysis sequences involved study areas having quite different characteristics. The Vallecito Intensive Study Area involved a detailed forest cover type mapping problem in the San Juan Mountain Test Site, while the Ward-Monarch Intensive Study Area concentrated on alpine mapping problems in the Indian Peaks Test Site. Following the detailed analysis of these two intensive study areas, the entire San Juan Mountain and the Indian Peaks Test Site areas were mapped and evaluated.

Evaluation of Alternative Computer-aided Analysis Techniques

Possible Approaches

The ERTS-1 satellite is an entirely unique type of data collection system. The data differs in several ways from any other data source, in that one resolution element is approximately 1.1 acres in size, each frame covers a very large area (approximately 8.5 million acres), and data is gathered in four distinct wavelength bands. These differences, combined with very complex vegetation types and complex topography in the two test sites, indicated some question as to the suitability of the "standard" supervised classification approach previously developed at LARS. Preliminary work with the ERTS-1 data showed that the usual data analysis procedures would not be satisfactory. For example, selecting homogeneous training samples which would represent all possible variations in spectral response for each of the cover types of significance proved to be an extremely difficult task. This is due to spectral differences caused by variations in slope and aspect, as well as to many spectral differences in the cover types themselves, involving both species and density variations. Therefore, we realized that an essential phase of the Ecological Inventory effort would involve development of a more effective procedure for analyzing forest and alpine areas in the Colorado mountains when using ERTS-1 MSS data and the LARSYS computer software system.

In utilizing the LARSYS software for analyzing multispectral scanner data, one normally follows a procedure that involves:

(1) defining a group of spectral classes (training classes); (2) specifying these to a statistical algorithm which calculates a set of defined statistical parameters; (3) utilizing the calculated statistics to "train" a pattern recognition algorithm; (4) classifying each data point within the data set of interest (such as an entire ERTS frame) into one of the training classes; and finally, (5) displaying the classification results in either map or tabular format (or both), according to the specifications of the analyst.

During the past few years, experience at LARS has shown that there are many possible refinements in the methodology utilized by the analyst for obtaining training classes, while the rest of the procedure does not vary much from one analysis task to another. The most common techniques for defining training classes involve the so-called "supervised" approach, and the "non-supervised" or "clustering" approach.

In the "supervised" approach, the analyst selects areas or "fields" of known cover types and specifies these to the computer as training fields, using a system of X-Y coordinates. The statistics are obtained for each area and category of cover type. The data is then classified and the results evaluated. Because the analyst has defined specific areas of known cover types to the computer, such classifications are referred to as "supervised".

The second method uses a clustering algorithm which divides the entire area of interest into a number of spectrally different classes. The number of spectral classes into which the data will be divided must be specified by the analyst. The spectral classes defined by the clustering algorithm are then used to classify the data, but at this point the analyst does not know what cover type is defined by each of the spectral classes. Normally, after the classification is completed, the analyst will identify the cover type represented by each spectral class using available reference data or cover type maps. Because the analyst does not need to define particular portions of the data for use as training fields, but must only specify to the computer the number of spectral classes into which the data is to be divided, a classification using this procedure is referred to as "non-supervised". Because of the difficulty of knowing how many spectral classes might be represented by any one species or cover types, previous work had indicated that the non-supervised approach was usually more satisfactory when analyzing data from wildland areas.

Additionally, two variations of these basic methods for defining training classes are possible. One is to select training areas of known cover type (a supervised approach up to this point), but then utilize the clustering algorithm to refine the data into unimodal spectral classes for each cover type. This is called a "modified supervised" approach. The second variation involves designating small blocks of data (30-60 lines by 40-60 columns) to the clustering algorithm, then identify each spectral class within these small "cluster training areas". The statistics for a single spectral class are then combined, using data from several of the small cluster training areas. This last method is called the "modified non-supervised" or "modified clustering" approach, and will be described in greater detail later.

As discussed later, three of the four methods described above were used to obtain training classes for the Ludwig Mountain quadrangle using ERTS data from September 8, 1972 (scene ID 1047-17200). The method not used to obtain spectral classes was the first one described, which simply involves manually selecting training fields (the "supervised" approach). That method was not used because of the extreme spectral variation within cover types in the Ludwig Mountain quadrangle, as indicated by multimodal classes of the various cover types (i.e. deciduous, agricultural, etc.). Such spectral complexity causes spectral overlap between cover types, and previous work had indicated that the manual approach would not allow satisfactory results to be obtained for this type of area.

The Ludwig Mountain quadrangle was specifically selected to develop an analysis procedure because it is complex and contains a wide variety of cover types. Therefore, if a good analysis technique could be defined for this area, the same technique should also be suitable for other less difficult analysis areas.

To evaluate the performance of each of the methods being tested, but to prevent possible bias in the evaluation prior to any of the analysis, a total of 34 test areas were defined. These represented approximately 2 percent of the area within the quadrangle.

Comparison of Analysis Techniques

Using a non-supervised approach, training classes were obtained using the clustering algorithm on the Ludwig Mountain quadrangle to generate 10 spectral classes based entirely on the spectral characteristics of the data. Utilization of the clustering algorithm to generate training classes leaves the analyst with the task of relating the spectral classes to the cover types. To do this, each spectral class was identified through the use of the vegetation map supplied by INSTAAR

(Figure A.4). The classification was then evaluated using the previously defined test fields. For the non-supervised approach, the results indicated an overall test field accuracy of 76.6% (Table A.6). A comparison between the computer printout of the area and the type map indicated that 10 spectral classes were not sufficient. Some spectral classes represented more than one cover type, and some cover types were represented by more than one spectral class. Most of the error in the classification was caused by several spectral classes that represented more than one cover type. In particular, there were two spectral classes that represented coniferous forest in one location and deciduous forest in another. The cover types that represented a small percentage of the area (less than 5%) included water, cloud, cloud shadow, and barren. These were not separated by the clustering algorithm. Thus, water and cloud shadow were included in one of the agricultural land spectral classes. If one hopes to obtain reasonably accurate classification results, one spectral class should not represent more than one cover type. Therefore, to try to alleviate this problem, the number of spectral classes was increased from 10 to 20.

The results of the classification using the 20 spectral classes indicated a test field performance of 78.5% (Table A.7). These results also showed that there were still several spectral classes that represented more than one cover type. Most of the error was caused by confusion between coniferous forest and deciduous forest, and between coniferous forest and agricultural land. A comparison between the classification and the type map showed that the confusion was primarily due to different crown closure densities in the coniferous forest. Because of the relatively large variance in all the spectral classes, the low density coniferous forest was being identified as the understory, either grass (agricultural land) or oak (deciduous forest). This indicated to the analyst that even more spectral classes were needed, but it was already difficult to identify the actual cover type associated with each of the classes when 20 spectral classes were used. Therefore, a further increase in the number of spectral classes, which would be needed to reduce the variance, would make identification of all spectral classes difficult. Thus, another approach was required.

The next technique to be evaluated was the modified supervised approach for obtaining training statistics. The coordinates for training fields were determined by overlaying a geometrically corrected grayscale printout on a type map. To statistically describe each cover type, training fields for each cover type were selected throughout the area. The histograms generated for each cover type showed multimodal distributions. Since such distributions violate the basic assumption of the Gausian classifier, modification of the training fields was necessary before a classification could be performed. To do this the clustering algorithm was used.

All of the training fields for each cover type were clustered as a group. The exact number of spectral classes that each cover type was separated into de-

Table A.6. Ludwig Mountain quadrangle, non-supervised, 10 cluster classes, level I test class performance.

Group	No. of samples	Percent correct	Conifer	Deciduous	Agricultural	Water
1. Conifer	415	76.4	317	61	2	35
2. Deciduous	176	68.2	23	120	4	29
3. Agricultural	60	100.0	0	0	60	0
4. Water	8	100.0	0	0	0	8
Total	659		340	181	66	72

Overall performance (505/659) = 76.6
Average performance by class (344.6/4) = 86.1

Table A.7. Ludwig Mountain quadrangle, non-supervised, 20 cluster classes, level I test class performance.

Group	No. of samples	Percent correct	Conifer	Deciduous	Agricultural	Water
1. Conifer	415	90.8	377	2	33	3
2. Deciduous	176	40.9	79	72	5	20
3. Agricultural	60	100.0	0	0	60	0
4. Water	8	100.0	0	0	0	8
Total	659		456	74	98	31

Overall performance (517/659) = 78.5
Average performance by class (331.8/4) = 82.9

pended on the variability of the cover type (i.e. more variation required more classes). Most cover types had to be defined by four or five spectral classes. These spectral classes appeared to correspond to variation in slope, aspect, and crown closure. Using the modified-supervised approach, the test field results indicated a classification accuracy of 70.0% (Table A.8). The classification had considerable error between the deciduous forest, coniferous forest and agricultural land cover types. This error was primarily due to the confusion between low density coniferous forest and deciduous forest, and agricultural land. This error is the same type that occurred with the non-supervised approach. The error, however, was caused by the difficulty in selecting and appraising the spectral classes, and not caused by the large spectral variation. Selection of training fields was difficult because of the complexity of the area.

Once training fields were selected and clustered into spectral classes, we determined that some spectral classes contained only a few data points and therefore had to be deleted. Several classes were spectrally similar, but were actually different cover types. Selecting the disposition of these spectral classes was difficult. For these two reasons, another change in approach was required.

A "modified clustering" method was the next approach utilized. In this method, several small training areas are designated, each of which contain several spectral classes. Each area is then clustered and the spectral classes for all cluster areas are combined. Results using this method indicated that the classification map of the Ludwig quadrangle compared reasonably well with the cover type map prepared by INSTAAR, both qualitatively and quantitatively. The test field results indicated an accuracy of 84.7% (Table A.9). This was a substantial increase in accuracy. Perhaps of even more importance, a general qualitative comparison between the type map and the classification indicated a higher level of classification accuracy than what the test field results showed. Detailed analysis and comparison of the results obtained through the use of this and the various other methods investigated indicated that this modified clustering procedure for obtaining the training spectral classes would be most satisfactory for use in the remaining analysis work in this Colorado test site. Because of the importance of effective utilization of the LARSYS software, the following section will describe this particular analysis procedure in more detail.

Modified Clustering Method

The basic sequence for the modified clustering method is: 1) select training areas to be clustered; 2) cluster each area independently into 8 to 15 cluster classes; 3) combine the cluster classes into information spectral classes; and 4) classify the area of interest. Each of these steps will be considered individually in the following paragraphs.

Table A.8. Ludwig Mountain quadrangle, modified supervised, level I test class performance.

Group	No. of samples	Percent correct	Conifer	Deciduous	Agri-cultural	Water	Bare	Shadow	Cloud
1. Conifer	415	73.5	305	90	18	0	2	0	0
2. Deciduous	176	53.4	64	94	13	0	0	5	0
3. Agricultural	60	100.0	0	0	60	0	0	0	0
4. Water	8	25.0	0	0	0	2	0	6	0
Total	659		369	184	91	2	2	11	0

Overall performance (461/659) = 70.0
Average performance by class (251.9/4) = 63.0

Table A.9. Ludwig Mountain quadrangle, modified clustering, level I test class performance.

Group	No. of samples	Percent correct	Conifer	Deciduous	Agricultural	Water	Bare
1. Conifer	415	91.3	379	19	7	1	9
2. Deciduous	158	63.9	50	101	7	0	0
3. Agricultural	60	100.0	0	0	60	0	0
4. Water	8	37.5	5	0	0	3	0
Total	641		434	120	74	4	9

Overall performance (543/641) = 84.7
Average performance by class (292.7/4) = 73.2

Selection of Training Areas. Selection of training areas for the clustering algorithm was dependent on three factors; first, the amount and quality of reference data or "ground truth" available; second, the existence of at least four to six cover types within an area; and third, the presence of a representative sample of cover types.

The reference data are important because the accuracy of classification results is heavily dependent upon the accuracy of the training data. If twenty spectral classes are defined it is vitally important that the cover type category of interest be accurately identified and associated with each of the spectral classes present. For the Ludwig quadrangle, the reference data consisted of a cover type map produced by INSTAAR, 1:120,000 scale color infrared aerial photos obtained by NASA, a U.S.G.S. quadrangle map, and Mark Hurd ortho-projection aerial photography.

To insure that the best classification accuracy is obtained, a sample of each cover type should be included in one or more of the training areas. This provides a reasonably representative data set to the classification algorithm. Ideally, a sample of every spectral class in the test site would be included in at least one training area.

To most effectively utilize the clustering algorithm, each of the small training areas should contain a variety of spectral classes. Work with the data indicated that generally one should define an area in which four to six cover types were present. Since each cover type was usually represented by several spectral classes, such areas would provide a data set in which the clustering algorithm could effectively define the natural spectral groupings in the data. This also gave us a comparison within a single clustering area among several cover types, so that one could easily see whether the various cover types of interest could be defined on the basis of their spectral response. In other words, if a single spectral class showed up in areas containing different cover types, this immediately indicated that a straightforward relationship did not exist between the spectral classes present and the cover types of interest.

Clustering. Each training area was clustered independently into 8 to 15 cluster classes, depending on the variability of the area. The number of cluster classes that each area was clustered into depended on the number of cover types and the variability of each cover type. As a general rule of thumb, each area was first clustered into twice as many cluster classes as there were cover types. Since in some areas, there may be several cluster classes for each cover type, the cluster map and the variance table were checked to determine if the specified number of cluster classes should actually be used. If the patterns in the reference data matched the patterns in the cluster map, and if the variance in ERTS-1 data for most of the classes was between 0.8 and 3, then the particular number of clusters defined was optimum. As a general rule, if the variance of several cluster classes was lower than 0.8, the number of cluster classes for the area was reduced, and if several of the cluster classes had variances greater than 3, the number of cluster classes was increased.

Each cluster class was then identified as to actual cover type by using the support data. This was done by overlaying the cluster map with the type map supplied by INSTAAR, since both the geometrically corrected ERTS data, and the type maps were at a 1:24,000 scale.

Pooling Statistics. The statistics and separability algorithms were used to combine the cluster classes into information spectral classes. A saturating transformed divergence number, obtained from the separability algorithm, is a measure of the distance between classes in multi-dimensional space. This measure, which ranges in value from 0 to 2000, is referred to as the "divergence value". High values indicate class pairs which are more separable. Past experience indicates that class pairs with a divergence value of 1750 or greater, when grouped, will yield bimodal distribution (which violates the basic assumption of the maximum-likelihood Gaussian classifier).

The large number of cluster classes obtained for the area, 60, made comparison of all divergence values at once difficult. For this reason, the combining of cluster classes was performed in three steps.

The first step was to calculate the divergence value for each pair of cluster classes. With a small amount of experimenting, we found that combining all pairs having a divergence value of 1000 or less reduced the number of cluster classes to approximately 35, which was much easier to work with. These combined cluster classes will be referred to as "spectral classes".

The second step in combining the classes was to use the separability algorithm to calculate the divergence value for each pair of spectral classes. In this step, all spectral classes with a divergence value of 1750 or less were combined. When combining the spectral classes, the cover type was checked for each cluster class making up the spectral class. Any spectral class with more than one type present (mixed cover types) was deleted unless the mixed class was a desired information class. The combined spectral classes were then identified and named. The named spectral classes will be referred to as "information spectral classes".

The third step required running the information spectral classes through the statistics and separability algorithms. At this point, very few divergence values were below 1750 (some further combining would have been necessary if there were many below 1750). The statistics from this step were then in final form to be used in the classification.

Classification. The statistics deck obtained from the third step of the combining process would then be used to classify the test site. The basic LARSYS classification procedure involving the maximum likelihood algorithm was utilized in the classification.

This modified clustering technique was found to give the most satisfactory classification results, even in this mountainous area having a diversity of spectral characteristics. A straight forward classification procedure maximum likelihood had been previously developed. It is not difficult to apply the classification procedure, and obtain a computer classification for any area of interest. However, for the classification to be of any value, it is essential to establish the reliability of the results. The next section will describe the methods used by the personnel working on the Ecological Inventory classification results on the test sites.

Classification Evaluation Procedures

Once an adequate training set has been defined, it is not difficult to classify a large geographic area using computer analysis techniques. However, unless one can verify the accuracy of such computer classification results, little has been accomplished by simply classifying the data over various areas of interest. A combination of three techniques proved most satisfactory to achieve a true indication of the classification accuracy.

A qualitative evaluation of the classification results can be performed by visually comparing the classification to an existing cover type map or aerial photos of the region. Although the method is subjective, it does provide a quick, rough estimate of classification accuracy. A quantitative evaluation of the results, however, must accompany the qualitative evaluation.

The two basic outputs of a computer classification are acreage estimates for each cover type, and a cover type map for an area. A combination of two quantitative evaluation techniques can be used to judge the accuracy of the two types of output. One evaluation technique involves statistical sampling of individual areas of known cover types (designated as test areas). This offers an extremely effective method for evaluating the map or locational accuracy of the classification results, and examining inclusive and exclusive error rates of the various cover types. Such techniques, however, must be used with caution, and must be carefully designed to provide statistical reliability of the results. In general, areas need to be selected in such a way that the number of resolution elements in the test areas for each cover type are approximately in proportion to the amount of that cover type present in the area.

A second quantitative technique for evaluating classification accuracy is the comparison of acreage estimates from the computer classification, and the acreage estimate obtained by some conventional method. This type of evaluation indicates the accuracy of the acreage estimate obtained for the various cover types. For statistical reliability, a large area such as an entire 7½ minute U.S.G.S. quadrangle should be used. For large samples, inclusive and exclusive location errors tend to balance out.

This dual approach to quantitative evaluation of classification accuracy was utilized throughout the ecological inventory study areas—the Vallecito Intensive Study Area, Ward-Monarch Intensive Study Area, the San Juan Mountain Test Site and the Indian Peaks Test Site. The test areas were, of course, defined prior to the computer classification of the data. The test fields for the Vallecito Intensive Study Area were determined as areas within a uniform density (based on interpretation of the aerial photography), and with uniform slope and aspect (determined from U.S.G.S. quadrangle maps). Each test field was then ground checked to verify this information. These test fields were also used in the study of the relationships between spectral response and topographic influences on vegetative cover discussed in a later section of this report. The test areas for the other three test sites were selected in a similar manner except that they were checked primarily by photo-interpretation techniques, with only limited ground checking.

To estimate classification accuracy using acreage comparisons in the Colorado test sites, entire 7½ minute U.S.G.S. quadrangles were type mapped and planimetered by INSTAAR. Acreage estimates by cover type were provided for seven quadrangles in the San Juan Mountain Test Site including the Vallecito Intensive Study Area, and five quadrangles in the Indian Peaks Test Site, including the Ward Monarch Intensive Study Area (Appendix A.5).

Differences in criteria used to produce the cover type maps and computer classifications sometimes necessitated grouping types together in order to make comparison possible. For example, all the cover type maps included three types in the forest category—coniferous, deciduous, and coniferous-deciduous mix, whereas the computer classification contained only two forest types, coniferous and deciduous. Therefore, the subclasses had to be grouped into a single "forest" class for purposes of acreage comparison.

Computer Classifications: Discussion and Results

A major need of many land managers and agencies is a reliable, up-to-date inventory in a usable format. This requires the identification, description, classification, and mapping of the various components which comprise the cover types of the region. With the techniques described in the above section of this report, the computer can easily classify a large geographic area. However, unless the classification can be presented in a usable format, it is of no value to a land manager. Two formats for presentation are used in this report: a classification map and areal estimates for cover types. Another factor must be known before the classification can be used by a land manager—an estimate of the classification accuracy. Two procedures were used to evaluate classification accuracy; test fields and areal comparisons.

A classification was performed on each of four areas: the Vallecito Intensive Study Area, the Ward-Monarch Intensive Study Area, the San Juan Mountain Test Site, and the Indian Peaks Test Site. This section of the report will discuss the background, data sets involved, the classification and its evaluation, and the end products (results) for each of the four test sites.

Vallecito Intensive Study Area

Background. Discussions with personnel from the Region 2 office of the U.S. Forest Service (Denver, Colorado) indicated a great deal of interest in utilizing ERTS-1 data for mapping forest cover in the San Juan Mountain area. Of particular interest was an area near Vallecito Reservoir, which the Forest Service believed would come under heavy pressure for development. Land development companies were actively in the area (selling summer homesites), and the Forest Service was quite concerned about the impact of such developments on the ecology of the area. Although the area around Vallecito Reservoir is quite accessible, many other areas are much more inaccessible. Thus, the Forest Service felt that if ERTS-1 data could be effectively utilized for mapping cover types and providing useful information in such mountainous terrain, satellite data and the analysis techniques being developed would provide a very useful tool to the Forest Service in their ongoing planning activities.

Because of this encouragement on the part of the user agency to study the area around the Vallecito Reservoir, and because of the accessibility of this area to field crews, this area was designated the "Vallecito Intensive Study Area". This formed the primary area on which many of the analysis techniques and procedures (discussed in the previous section) were developed.

Objectives. This section of the report will discuss the analysis of the data from this area to test computer-aided analysis techniques on ERTS-1 digital data for separation, classification, and mapping of forest cover types. More specifically, the objective of this phase of the research was to determine the degree of cover type breakdown possible, and evaluate the classification accuracy obtained at each level in an area that was primarily forest, (i.e., try to classify accurately at Level II and, if possible, Level III as defined by Table A.1).

Study Area and Data Set Utilized. The study area is approximately 11 kilometers by 20 kilometers in size (one and a half, 7½′ U.S.G.S. quadrangles) and ranges in elevation from 7000 feet to 10,200 feet. Field work in the area by both INSTAAR and LARS personnel indicated the area is extremely complex, both vegetatively and topographically. The test site is dominated by ponderosa pine, but Douglas fir, Engelmann spruce, and subalpine fir are found at the higher elevations. The majority of the grassland is found along the floodplains of the Los Pinos River which flows out of Vallecito Reservoir.

The ERTS-1 data set used in the analysis of the Vallecito Intensive Study Area was, scene ID 1047-17200, collected on September 8, 1972. There were no clouds in the test site area. The support data set used in the analysis includes a type map, developed by INSTAAR personnel, color infrared aerial photography (WB-57F Mission 248), and ground observations by both LARS and INSTAAR personnel.

Procedures. The modified clustering approach was utilized to classify the Vallecito area. Six training areas were selected using the cover type map and an MSS band 6 computer grayscale of the September 8, 1972 data. Each training area contained four to six cover types and was then clustered into ten to fifteen spectral classes. All spectral classes were identified using the type map and the aerial photography. The spectral classes for all the training areas were then compared using the statistics and separability algorithms.

After combining the spectrally similar classes, 24 information spectral classes were obtained. These 24 classes were then used to classify this Vallecito Intensive Study Area.

Classification Results and Evaluation. The computer classification produced two types of results for the test site; a classification map and an areal estimate for each cover type. Figure A.10 is a grayscale image of the test site classification showing the location and distribution of the Level I cover types. A Level II display of the classification has not been included because of the difficulty in interpreting a map with eight different shades of gray depicting the eight cover types. Areal estimates, a second type of "product" for the test site, are shown in Table A.10 for both Level I and Level II.

Along with a qualitative evaluation of the classification map, the "standard" test field evaluation procedure and a procedure to compare areal estimates were used to quantitatively evaluate the classification accuracy. A total of 124 test fields were defined within the study area, all approximately 20 data points in size. The test fields were selected as areas within uniform vegetation type (based on the type map data), with a uniform stand density (based on interpretation of the aerial photography), and with a uniform slope and aspect (determined from U.S.G.S. quandrangle maps). Each test field was then ground checked to verify this information. Figure A.11 is an MSS band 5 image of the Vallecito Intensive Study Area, indicating the location of the test fields. These test fields were used as one method, to quantitatively evaluate the classification accuracy. This was done by calculating the percentage of the data points correctly classified into each cover type, thus yielding a table of "test field performance".

The overall test field performance for Level I was 94.8% (Table A.11). The performance for all classes was approximately equal and high. As seen from Table A.11, the major cover types (Level I) in the mountainous area can be classified with a reasonable degree of accuracy. One of the key elements in this research involved an attempt to classify individual forest cover types (Level II). Since the individual cover types had been defined during the field work, the same test fields as previously used for the Level I results were utilized to test the classification accuracy at Level II. A test field performance of 76.5% resulted. (Table A.12) The table indicates a moderate amount of confusion among the individual cover types produced by use of computer-aided analysis techniques in mountainous terrain.

Figure A.10. Image from the digital display of the Vallecito intensive study area computer classification at level I. Black is water, dark gray is coniferous forest, medium gray is deciduous forest, light gray is grass and cropland and white is barren.

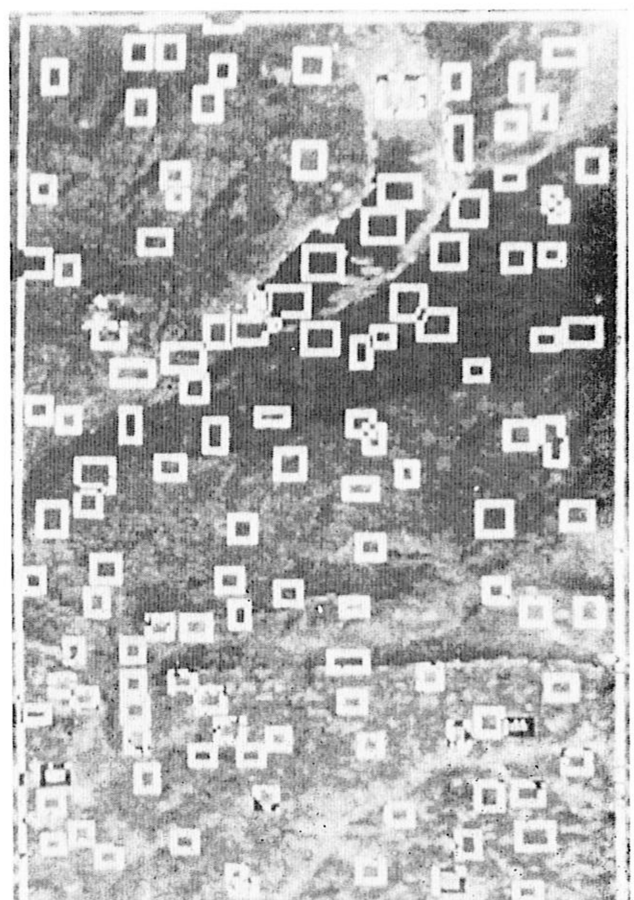

Figure A.11. ERTS-1 MSS Band 5 (0.60-0.70um) gray-scale image (frame 1047-17200) of the Vallecito intensive study area showing the location of the test fields used to evaluate the classification accuracy.

To quantitatively evaluate the classification accuracy using a second method, the cover type map for the entire test site was planimetered. It is important to note that the cover type map used as source data for this phase of the experiment had been obtained through standard photo-interpretation techniques. Therefore, the results offer a good comparison between areal estimates developed through computer classification of satellite scanner data, and areal estimates obtained through manual interpretation of aerial photos using well defined photo-interpretation procedures. A comparison between the planimetered areal figures and the computer classification figures at Level I are shown in Table A.13. An areal comparison at Level II was not possible because the planimeter figures for the type map were not broken down in the Level II cover types. Figure A.12 is a graphical representation of this comparison with the regression line and 95% confidence limits shown. All of the points lay within the 95% confidence limits. The correlation coefficient (r) value of 0.981 indicates that the areal estimates obtained from the ERTS-1 analysis using computer-aided analysis techniques are in reasonable agreement with the planimetered areal estimates.

Evaluation of the Level I and Level II classification results indicate that the various subclasses of Level II forest cover types appeared to be related to slope, aspect, and stand density as well as to the forest type itself. Therefore, a statistical investigation of these apparent relationships was conducted using the data from the Vallecito Intensive Study Area and two additional quadrangles. This work is reported in the "Supplemental Studies" section, later in this chapter. The next section of this chapter discusses the results of the classification of an intensive study site, which is basically alpine tundra.

Ward-Monarch Intensive Study Area

Objectives. One of the major objectives of the ecological inventory portion of this research involved the evaluation of computer-aided analysis techniques

Table A.10. Vallecito intensive study area, areal estimates for level I and level II.

Cover type	Acres	Hectares	Percent of area
Coniferous	31,124	12,596	54.7
Pine	(24,320)	(9,842)	(42.7)
Spruce-fir	(6,804)	(2,754)	(12.0)
Deciduous	17,044	6,898	30.0
Oak	(9,987)	(4,042)	(17.6)
Aspen	(7,057)	(2,856)	(12.4)
Agricultural	5,256	2,127	9.2
Pasture	(4,718)	(1,909)	(8.3)
Cult. crops	(538)	(218)	(0.9)
Water	1,730	700	3.0
Barren	1,772	717	3.1
Total	56,926	23,038	100.0

for mapping areas of alpine tundra. The Vallecito Intensive Study Area discussed in the last section had been selected in response to the interests and needs of the U. S. Forest Service, but since that area did not contain alpine tundra, the need still existed for testing the classification procedures on an area containing a significant amount of alpine tundra. As mentioned previously, the Indian Peaks Test Site contained considerable areas of alpine tundra, and underflight WB-57F aerial photography had been obtained on the same day as some cloud free and snow free ERTS-1 data had been gathered. This data set was superior to any available for the tundra regions in the San Juan Mountains (largely because it was cloud free and snow free). Therefore, an area identified as the Ward-Monarch Intensive Study Area was defined within the Indian Peaks Test Site. The specific objective of this phase of the research was to test the ability to utilize the LARSYS computer-aided analysis techniques and ERTS-1 data for spectrally separating, classifying and mapping tundra vegetation communities.

Study Area and Data Set Utilized. In the eastern third of the Ward-Monarch Area, a relatively homogeneous, dense coniferous forest is broken by oc-

Table A.11. Vallecito intensive study area, level I test field performance.

Group	No. of samples	Percent correct	Conifer	Deciduous	Agricultural	Water	Bare
1. Conifer	1858	97.5	1812	22	3	1	20
2. Deciduous	685	85.4	13	585	87	0	0
3. Agricultural	242	95.9	2	6	232	0	2
4. Water	240	100.0	0	0	0	240	0
5. Bare	98	93.9	0	0	6	0	92
Total	3123		1827	613	328	241	114

Overall performance (2961/3123) = 94.8
Average performance by class (472.7/5) = 94.5

Table A.12. Vallecito intensive study area, level II test field performance.

Group	No. of samples	Percent correct	Pine	Spruce-fir	Oak	Aspen	Pasture	Bare	Water	Cult. crop
1. Pine	1111	81.4	904	169	5	9	3	20	1	0
2. Spruce-fir	747	64.9	254	485	2	6	0	0	0	0
3. Oak	481	61.7	8	0	297	95	80	0	0	1
4. Aspen	204	78.4	5	0	33	160	6	0	0	0
5. Pasture	188	94.1	2	0	4	0	177	1	0	4
6. Bare	98	93.9	0	0	0	0	1	92	0	5
7. Water	240	100.0	0	0	0	0	0	0	240	0
8. Cult. crop	54	61.1	0	0	2	0	18	1	0	33
Total	3123		1173	654	343	270	285	114	241	43

Overall performance (2388/3123) = 76.5
Average performance by class (635.5/8) = 79.4

Table A.13. Vallecito intensive study area, level I acreage comparison.

Type	Classification	Type map
Coniferous	54.7	48.8
Deciduous	30.0	34.8
Agricultural	9.2	11.8
Water	3.0	4.3
Barren	3.1	0.3
Total	100.0	100.0

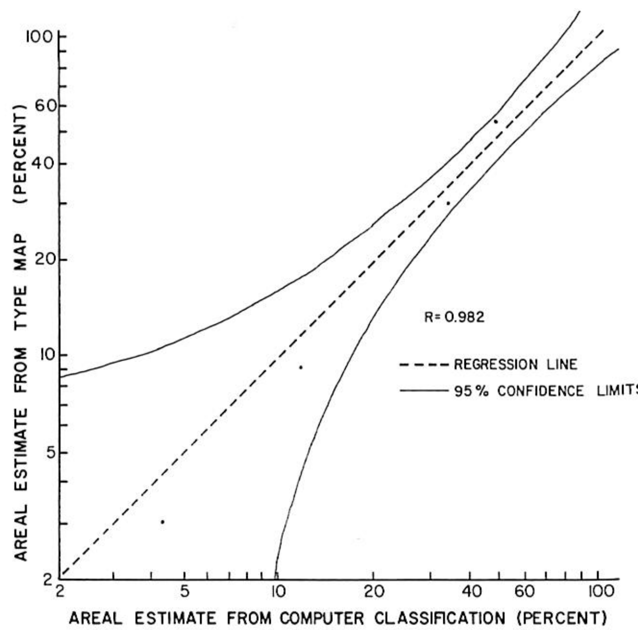

Figure A.12. Vallecito intensive study area comparison between areal estimates obtained by computer classification and those obtained by planimetering the cover type map.

casional aspen stands and moraine dammed subalpine bogs. At tree limit (3350 m), the forests grow sparse and yield to tundra communities. These treeless turfs are best developed on the deep till blanketing portions of three broad topographic highs extending eastward from the backbone of the Continental Divide, which trends nearly north to south along the western edge of the test site. Bare rock dominates the vicinity of the Divide. Unlike many alpine regions in which tundra might be found, few topographic highs cast shadows on this tundra vegetation. The major shadow in the area outlines the western flank of the Continental Divide. Thus, the area is well suited to test the capability of ERTS-1 digital data for CAAT mapping.

The ERTS-1 data set selected for the CAAT, scene ID 1388-17131, is cloud free in the Ward-Monarch area. The NASA WB-57F aerial photography, Mission 248, roll 69 used in preparing vegetation maps was flown on the same day, August 15, 1973, as the ERTS-1 MSS data was collected. Thus, the condition of vegetation and snowbeds is the same in both data sets and one variable in the comparison is eliminated. Because extensive ground observations have been made of this area for over 20 years, new observations were not made specifically for this analysis. Thus, the support data consisted of NASA Mission 248 and ground observations previously collected by the INSTAAR personnel.

There is one bad data line in the ERTS-1 data set for the Ward-Monarch area (in MSS band 5, 0.60 um to 0.70 um) and it appears as an oblique line crossing the eastern tip of Niwot Ridge.

Procedures. The procedure followed during this analysis was basically the modified clustering approach. Seven small training areas, with an average size of 1,000 data points, were selected using grayscale printouts of MSS bands 5 and 7 from the August 15, 1973 data. Each small area, containing four to nine cover types, was separated using the clustering algorithm into eight to sixteen spectral

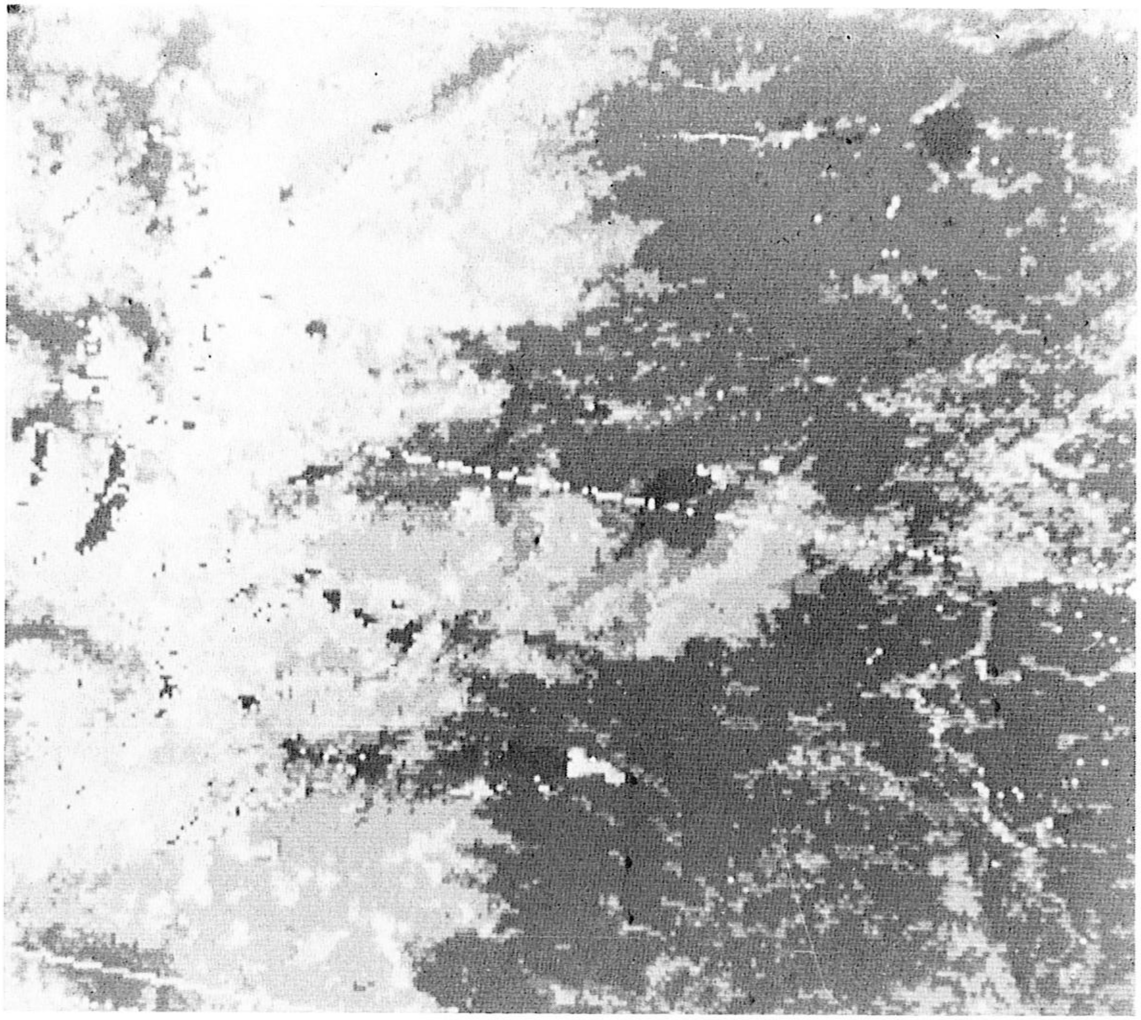

Figure A.13. Image from the digital display of the Ward-Monarch intensive study area computer classification (level I) showing water as black, coniferous forest as dark gray, tundra and grassland as 3 shades of medium gray, bare rock as light gray, and snow as white.

classes depending upon the complexity of the area. The spectral classes were then compared using the statistics and separability algorithms. The support data was examined for each class and spectrally similar classes which were within one cover type were grouped. Spectral classes containing very few data points (less than 40) or including several different vegetation types were deleted. In some cases where similar spectral classes represented more than one cover type, the class was retained as a combination of two cover types. The combining of the similar spectral classes resulted in 17 information spectral classes. These 17 classes were then used to classify the Ward-Monarch data set.

Classification Results and Evaluation. Two basic types of "products" resulted from the computer classification—a point by point classification map, and areal estimates for each cover type in the test area. Figure A.13 is a grayscale map of the classification showing the location and distribution of the Level I cover types in the test site. A Level II cover type map was generated, but is not shown because of the difficulty in interpreting a map with eight different cover types shown as different shades of gray.

A second type of computer output "product", areal estimates for the test area, are given in Table A.14 for both Level I and Level II. These areal estimates were used to provide a second method of evaluating the accuracy of the classification results, using the planimetered acreage estimates from the cover type map as a basis for comparison. The areal estimates developed from the computer classification results were later used to estimate the biomass productivity for the test site. The Supplemental Studies section of this chapter discusses some preliminary work on biomass productivity in the Ward-Monarch Intensive Study Area.

Again, three different methods were used to evaluate the classification accuracy: qualitative evaluation, quantitative test field evaluation, and areal compari-

Table A.14. Ward-Monarch intensive study area, areal estimates for level I and level II.

Type	Acres	Hectares	Percent
Deciduous	1,206	488	3.4
Coniferous	12,570	5,087	35.4
Barren	4,755	2,329	16.2
Snow	1,319	534	3.7
Tundra	13,773	5,574	38.7
Dry	(4,092)	(1,656)	(11.5)
Wet	(5,883)	(2,381)	(16.5)
Willow-krum	(3,798)	(1,537)	(10.7)
Water	905	366	2.6
Total	35,527	14,378	100.0

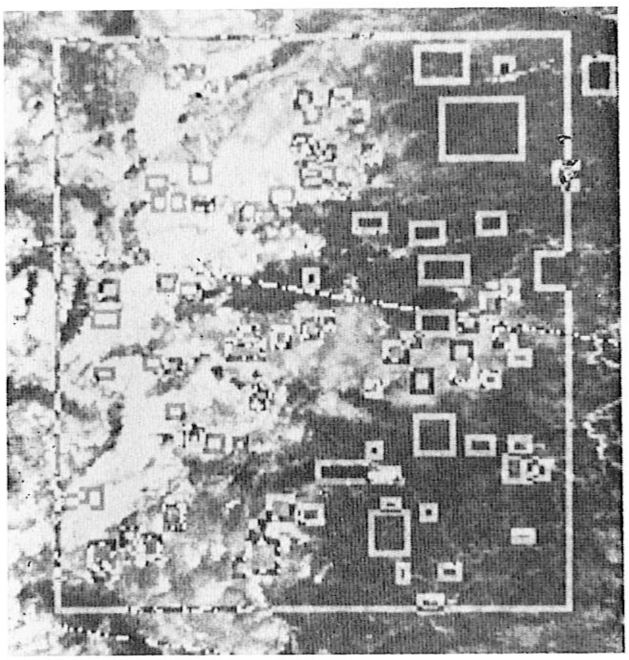

Figure A.14. ERTS-1 Band 5 (0.60-0.7um) grayscale image (frame 1388-17131) of the Ward-Monarch intensive study area showing the location of the test fields used to evaluate the classification accuracy.

son procedures. In the qualitative evaluation, the computer classification map compared favorably with the cover type map prepared from the aerial photos, although some variations within the tundra groupings were noted. Next, LARS and INSTAAR personnel, working together, selected 90 test fields using the WB-57F photography, the Ward-Monarch cover type map and an MSS band 6 computer grayscale. Figure A.14 shows an MSS band 5 digital display image of the Ward-Monarch area with the test fields delineated.

The overall test field performance for Level I is 93.3% (Table A.15). The poor performance for the deciduous forest class (57.8%) is due to confusion between subalpine bogs (deciduous) and wet tundra (tundra). Subalpine bogs are spectrally similar to

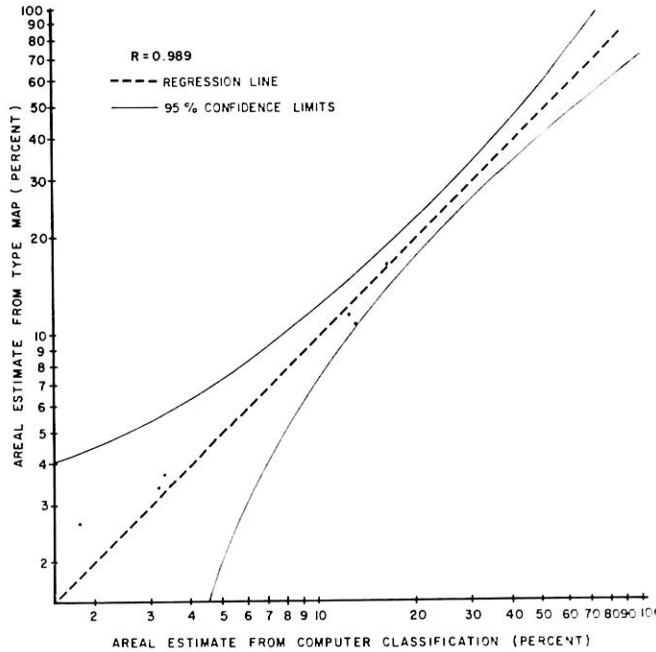

Figure A.15. Ward-Monarch intensive study area comparison between areal estimates obtained by computer classification and those obtained by planimetering the cover type map.

aspen and are primarily willow, which is a deciduous species, but do contain some wet tundra. Therefore, it is a reasonable and explainable type of confusion.

A Level II test field performance (Table A.16) shows the same classes as the Level I classification, except that the tundra has been broken into three subclasses including dry tundra, wet tundra, and willow-krummholz. The subclasses of tundra were not particularly well-differentiated using this procedure on this data. The major cause for this difficulty in differentiation is the large variation in spectral response within these tundra sub-classes. This variation has two causes: wide variation in characteristics of these tundra cover types and spatial characteristics of the ERTS-1 data in relation to the finely dissected spatial characteristics of the tundra cover.

As a second quantitative technique to evaluate classification accuracy, the cover type map was planimetered over the entire test site by INSTAAR personnel. The acreage for each cover type was then totaled. The cover type map acreage estimates were compared at Level II to the areal estimate obtained from the computer classification (Table A.17). To obtain the computer estimates, the number of data points classified into each cover type was totaled and the percentages calculated. A visual comparison between the two shows that the computer classification estimates are close to those obtained from the type map. As a more quantitative comparison, the percentages were plotted (Figure A.15), and 95% confi-

Table A.15. Ward-Monarch intensive study area, level I test field performance.

Group	No. of samples	Percent correct	Conifer	Deciduous	Bare	Snow	Tundra	Water	Badline
1. Deciduous	147	57.8	85	7	0	0	55	0	0
2. Conifer	1019	98.3	0	1002	0	0	8	9	0
3. Bare	90	86.7	0	0	78	9	3	0	0
4. Snow	103	82.5	0	0	17	85	1	0	0
5. Tundra	673	94.8	15	4	13	2	638	0	1
6. Water	163	97.5	0	4	0	0	0	159	0
Total	2195		100	1017	108	96	705	168	1

Overall performance (2047/2195) = 93.3
Average performance by Class (517.7/6) = 86.3

Table A.16. Ward-Monarch intensive study area, level II test field performance.

Group	No. of samples	Percent correct	Deciduous	Conifer	Bare	Snow	Dry tundra	Wet tundra	Willow-Krum.	Water	Badline
1. Deciduous	147	57.8	85	7	0	0	0	43	12	0	0
2. Conifer	1,019	98.3	0	1,002	0	0	0	0	8	9	0
3. Bare	90	86.7	0	0	78	9	1	2	0	0	0
4. Snow	103	82.5	0	0	17	85	1	0	0	0	0
5. Dry tundra	183	66.2	0	0	12	0	121	35	15	0	0
6. Wet tundra	395	89.9	10	0	1	2	25	355	2	0	0
7. Willow-Krum.	95	67.4	5	4	0	0	0	21	64	0	1
8. Water	163	97.5	0	4	0	0	0	0	0	159	0
Total	2,195		100	1,017	108	96	148	456	101	168	1

Overall performance (1,949/2,195) = 88.8
Average performance by class (646.3/8) = 80.8

dence limits and the correlation coefficient (r) were calculated. Figure A.15 shows that all of the points are close to, or within the 95% confidence limits. This, combined with the 0.989 correlation coefficient, indicates a high degree of correlation between the computer acreage estimates and the cover type map acreages. The results from this second intensive study area increased confidence in the capability of such computer-aided analysis to achieve accurate cover type maps and areal estimates of the various cover types in areas of mountainous terrain.

San Juan Mountain Test Site

Objectives. To test the results obtained in the analysis of the intensive study areas over a much larger geographic area, the next step was to classify the entire San Juan Mountain Test Site. The analysis results from the intensive study areas showed that it was possible to accurately classify an area at the Level I (basic cover type) degree of detail. Thus, the objective of this phase of study was to test the ability of computer-aided analysis technique (CAAT) to classify basic cover types over a large geographical area using ERTS-1 MSS data.

Study Area and Data Set Utilized. The San Juan Mountain area in southwestern Colorado is extremely rugged, ranging in elevation from 5,000 feet to 14,000 feet, with several peaks in the "over 14,000-foot" category. The area has been the subject of an intense ecological research for the last several years. Since 1970, Colorado State University (CSU), the Institute of Arctic and Alpine Research at the University of Colorado, and Fort Lewis College have been using the area to study the ecological impact of winter cloud seeding. Other ongoing research in the San Juan Mountain area includes avalanche research, energy budget studies, and a feasibility study for using microwave reflectometry to measure snow pack parameters.

The San Juan Mountain Test Site encompasses 993,800 hectares (2,456,000 acres) in southwestern Colorado. The test site contains sixty-three 7½ minute U.S.G.S. quadrangles. The location and names of all quadrangles involved are shown in Figure A.16.

The ERTS-1 data set selected for the CAAT was scene ID 1425-17190, September 21, 1973. This ERTS-1 data set is cloud free over the entire test site, and has a minimum of snow present. The support data consisted of vegetation maps for portions of 16 quadrangles scattered throughout the test site, WB-57F color infrared aerial photography from Missions 239 and 248, and ground observations by LARS and INSTAAR personnel.

Procedures. The modified clustering approach was used to classify the San Juan Mountain data set. Sixteen training areas were used to obtain the spectral classes. The training areas were selected on an MSS band 6 computer grayscale within quadrangles for which cover type maps were available. The number of cluster classes obtained for the training areas ranged from 12 to 18. The number of spectral classes was reduced to the minimum number that would still allow separation of the Level I classes. This resulted in a total of 14 information spectral classes that were used to classify the San Juan Mountain data set.

Table A.17. Ward-Monarch intensive study area, level II areal comparison (%).

Type	Classification	Type map
Deciduous	3.4	3.2
Coniferous	35.4	36.0
Bare rock	16.2	13.2
Snow	3.7	3.3
Dry tundra	11.5	12.5
Wet tundra	16.5	16.7
Willow-Krum	10.7	13.3
Water	2.6	1.8
Total	100.0	100.0

The amount of computer time required to do a classification depends on three factors: (1) number of classes, (2) number of data points (area), and (3) number of channels. In this study, the area was fixed, and the number of classes was minimized. To further minimize computer time (and therefore analysis cost), consideration was also given to using a subset of the four available MSS bands (4, 5, 6, and 7). The average transformed divergence value (Swain, 1971) for the 14 information spectral classes was computed for several channel combinations. The average transformed divergence value for MSS bands 4, 5, and 7 was essentially the same as for all four bands, indicating classi-

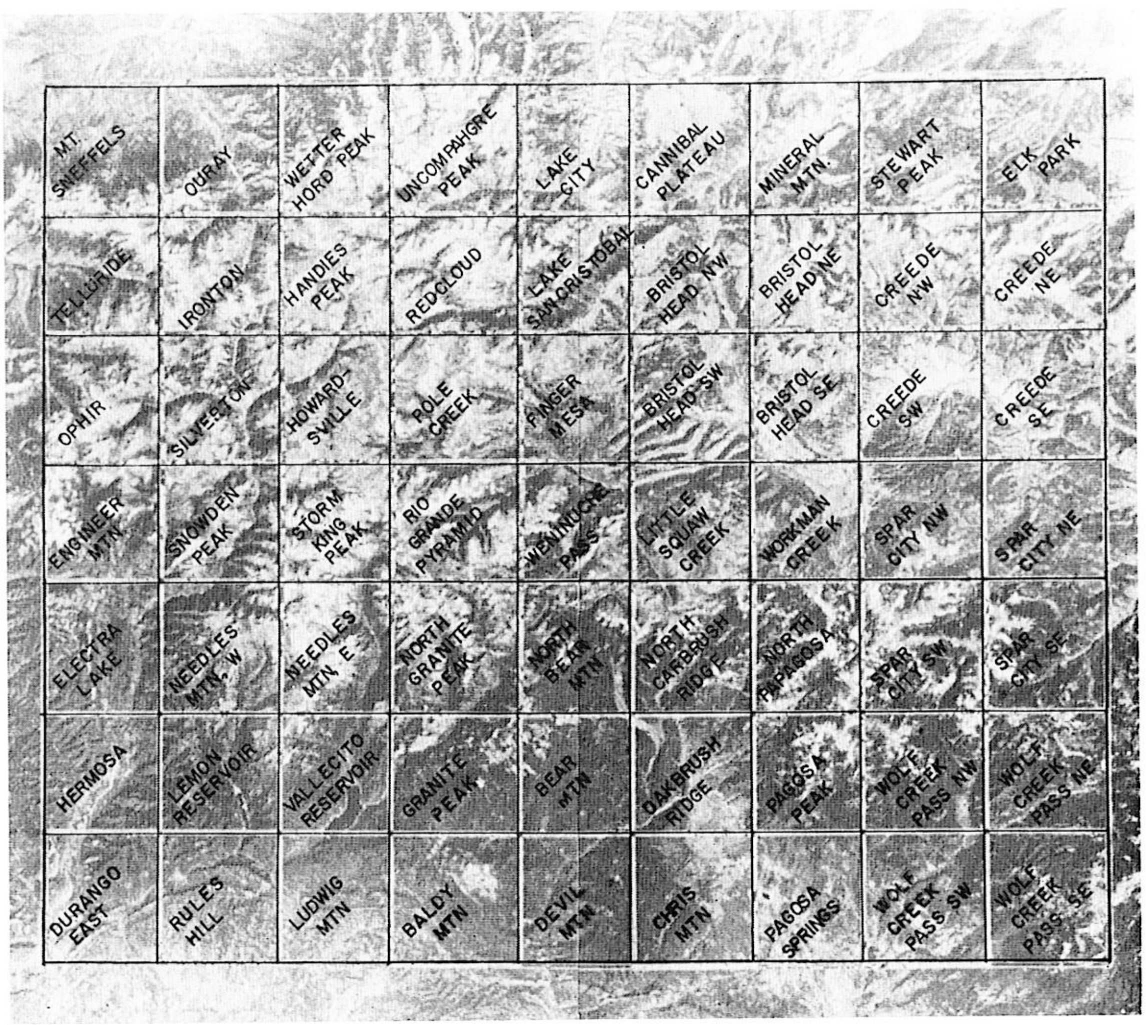

Figure A.16. ERTS-1 MSS Band 5 (0.60-0.70um) grayscale image (frame 1425-17190) of the San Juan Mountain test site showing the location and names of the 63 quadrangles in the test site.

fication accuracy (at Level I) would not be significantly reduced by using three bands instead of four. Therefore, only MSS bands 4 (0.5-0.6 um), 5 (0.6-0.7 um), and 7 (0.8-1.1 um) were utilized in the actual computer classification.

Classification Results and Evaluation. The classification of the 2.5 million-acre San Juan Mountain Test Site involved the utilization of three wavelength bands of ERTS-1 data (MSS bands 4, 5, and 7) and 14 information spectral classes. As in previous classifications, the results obtained were basically in two formats—a classification map of the area and areal estimates of each cover type. Figure A.17 is a digital display of the classification showing the five Level I cover types as different tones of gray. Areal estimates (in acres) for each Level I cover type in all 63 quadrangles were compiled from the computer classification. These areal estimates are shown in Table A.18. This table clearly shows one of the major advantages for utilizing computer-aided analysis techniques—developing areal estimates over large geographic areas in an extremely rapid and cost effective manner. However, the accuracy of such areal estimates is dependent upon the accuracy of the classification results from which the areal estimates were developed.

To evaluate the classification accuracy for the entire test site, a qualitative evaluation was first carried out, utilizing the available support data. This evaluation indicated that the Level I computer classification map for the entire test site appeared to be reasonably accurate. However, to provide a quantitative evaluation of the classification results, test fields and areal estimate comparisons were conducted.

Utilizing the cover type maps prepared by INSTAAR, 100 test areas totaling 16,170 data points of known cover type were defined. The location of these test areas are shown in Figure A.18. The size of the individual test areas ranged from less than 50 data points to over 1,000 data points, but most areas contained between 150 and 250 data points. An effort was made to select test areas in a quadrangle in which no training areas were located, and most test areas were so defined. However, in the west and northern portions of the test site, since only a couple

Figure A.17. Image from the digital display of the San Juan Mountain test site computer classification of level I. Black is water and terrain shadow, dark gray is coniferous forest, medium gray is deciduous forest, light gray is grass and cropland and white is barren.

Table A.18. Acreage estimates for the San Juan test site.

Quadrangle	Conifer	Deciduous	Grassland	Barren	Water
Mount Sneffels	16,766	4,289	11,824	4,246	994
Ouray	19,669	3,483	9,794	4,361	813
Wetterhorn Peak	14,253	927	14,467	7,183	1,080
Uncompahgre Peak	8,314	297	20,210	8,745	552
Lake City	16,294	665	15,097	3,127	51
Cannibal Plateau	14,631	420	16,774	5,884	200
Mineral Mountain	18,790	274	13,378	5,653	24
Stewart Peak	22,897	298	9,509	5,007	198
Elk Park	19,626	143	12,341	6,185	35
Telluride	13,639	2,864	12,244	7,982	1,185
Ironton	10,757	811	16,718	8,648	980
Handies Peak	5,212	187	22,170	9,182	954
Redcloud	9,166	278	15,338	11,827	1,305
Lake San Cristobal	18,502	400	12,858	5,871	491
Bristol Head NW	17,448	98	15,847	4,265	47
Bristol Head NE	11,009	118	21,104	5,567	115
Creede NW	11,527	173	17,399	8,161	445
Creede NE	10,852	105	18,817	7,943	406
Ophir	10,038	1,633	14,992	9,677	1,573
Silverton	15,406	1,117	15,657	5,015	719
Howardsville	6,922	591	21,942	7,433	817
Pole Creek	8,225	594	22,524	6,274	296
Finger Mesa	14,818	946	18,440	3,655	261
Bristol Head SW	18,387	473	15,392	2,924	529
Bristol Head SE	12,238	464	19,744	5,015	452
Creede SW	16,784	288	13,983	6,588	61
Creede SE	17,218	203	13,304	7,338	61
Engineer Mountain	18,610	4,892	11,799	2,511	63
Snowden Peak	16,889	1,834	14,394	4,030	767
Storm King Peak	7,976	1,205	17,163	9,515	1,845
Rio Grande Pyramid	14,850	1,470	16,627	4,684	281
Weminuche Pass	20,496	1,409	12,159	3,191	866
Little Squaw Creek	22,533	1,859	11,345	1,877	90
Workman Creek	22,424	757	11,923	2,710	100
Spar City NW	27,863	842	6,796	2,176	27
Spar City NE	27,401	1,795	6,899	1,966	62
Electra Lake	23,645	6,959	6,120	397	792
Needle Mountains W	22,541	2,321	11,637	1,105	310
Needle Mountains E	15,162	1,769	14,916	5,216	642
North Granite Peak	16,313	2,931	12,950	4,479	1,241
North Bear Mountain	27,519	2,940	6,356	1,217	89
North Oakbrush Ridge	23,059	4,048	7,846	1,272	481
North Papagosa Peak	25,055	1,250	8,168	3,278	163
Spar City SW	22,256	1,145	10,134	3,958	211
Spar City SE	29,167	1,519	5,673	1,582	183
Hermosa	21,304	8,432	7,317	787	74
Lemon Reservoir	24,179	7,979	5,126	180	450
Vallecito Reservoir	25,326	4,623	5,006	503	2,247
Granite Peak	29,845	3,341	4,051	512	165
Bear Mountain	32,214	2,933	2,850	120	3
Oakbrush Ridge	21,791	5,690	9,875	346	3
Papagosa Peak	24,293	5,656	5,520	2,259	186
Wolf Creek Pass NW	24,927	5,691	5,664	1,354	69
Wolf Creek Pass NE	28,352	3,823	5,062	821	65
Durango East	15,961	5,641	14,683	1,583	46
Rules Hill	20,288	7,183	10,260	184	0
Ludwig Mountain	20,255	7,493	9,662	270	23
Baldy Mountain	20,992	11,331	5,563	28	0
Devil Mountain	30,289	6,228	1,528	72	4
Chris Mountain	27,226	2,745	7,209	520	4
Papagosa Springs	14,821	6,933	14,753	1,120	287
Wolf Creek Pass SW	21,943	6,987	8,240	530	4
Wolf Creek Pass SE	28,127	4,229	4,436	1,266	65

of the quadrangles had been type mapped, test areas had to be chosen from quadrangles which also contained training areas. Even in these quadrangles, there were no data points that were used both for training and testing.

Table A.19 shows the test area performance at Level I for all of the test areas defined, and indicates that the overall performance was approximately 91% correct. The confusion between the grassland and barren grass is caused by lightly vegetated rock which is a combination of bare rock (barren) and tundra (grassland). Determining whether a test field should be identified as bare rock or tundra was difficult, thus causing the lower performance in the grassland class.

To evaluate the classification performance on an areal basis, seven quadrangles within the test site were utilized. The locations of the seven areas is shown in Figure A.19. These quadrangles were selected to represent a variety of cover types and geographical locations in the San Juan Mountain Test Site. INSTAAR personnel developed a set of Level I cover type maps and then planimetered each of the different cover types for each of the seven quadrangles. By evaluating the classification results on a basis of both test field performance and the areal extent for each of the cover types, a reasonable indication of the overall classification accuracy for the entire 2.5 million-acre test site could be obtained.

The comparison of the areal estimates obtained by the computer classification with those obtained from the type map developed through aerial photointerpretation techniques is shown in Table A.20. In this table, the acreage estimates for the selected quadrangles have been converted to percentages to reduce the range of magnitude of the values in order to facilitate further statistical analysis. Table A.20 shows that there are sometimes differences of 10% in the areal estimates for a particular cover type within an individual quadrangle, but in general, the areal estimates based upon the computer classification seems

Figure A.18. ERTS-1 MSS Band 5 (0.60-0.70um) grayscale image (frame 1425-17190) of the San Juan Mountain test site showing the location of the test fields used to evaluate the classification accuracy.

to be reasonably close to the estimates based upon planimetering the cover type maps. It is significant to note that although the estimates for the two approaches may vary from one quadrangle to the next, the differences are not always in the same direction. For example, forest cover type is not consistently over-estimated while grassland is always under-estimated. Rather, the forest cover type may be over-estimated in one quadrangle and under-estimated in another. This would indicate that as one goes to larger and larger areas, over-estimations of a particular cover type in one area would tend to be balanced out by under-estimations of that same cover type in a different geographical area, and therefore, the total acreage estimate would become more accurate as the size of the area involved becomes larger.

Table A.19. San Juan Mountain test site, level I test field performance.

Group	No. of samples	Percent correct	Conifer	Deciduous	Grassland	Barren	Shadow	Water
1. Conifer	9,634	94.6	9,110	22	53	21	332	96
2. Deciduous	1,475	87.2	113	1,286	76	0	0	0
3. Grassland	3,677	81.3	49	129	2,988	510	1	0
4. Barren	35	97.1	0	0	1	34	0	0
5. Water	1,349	98.9	6	0	0	0	9	1,334
Total	16,170		9,278	1,437	3,118	565	342	1,430

Overall performance (14,752/16,170) = 91.2
Average performance by class (459.0/5) = 91.8

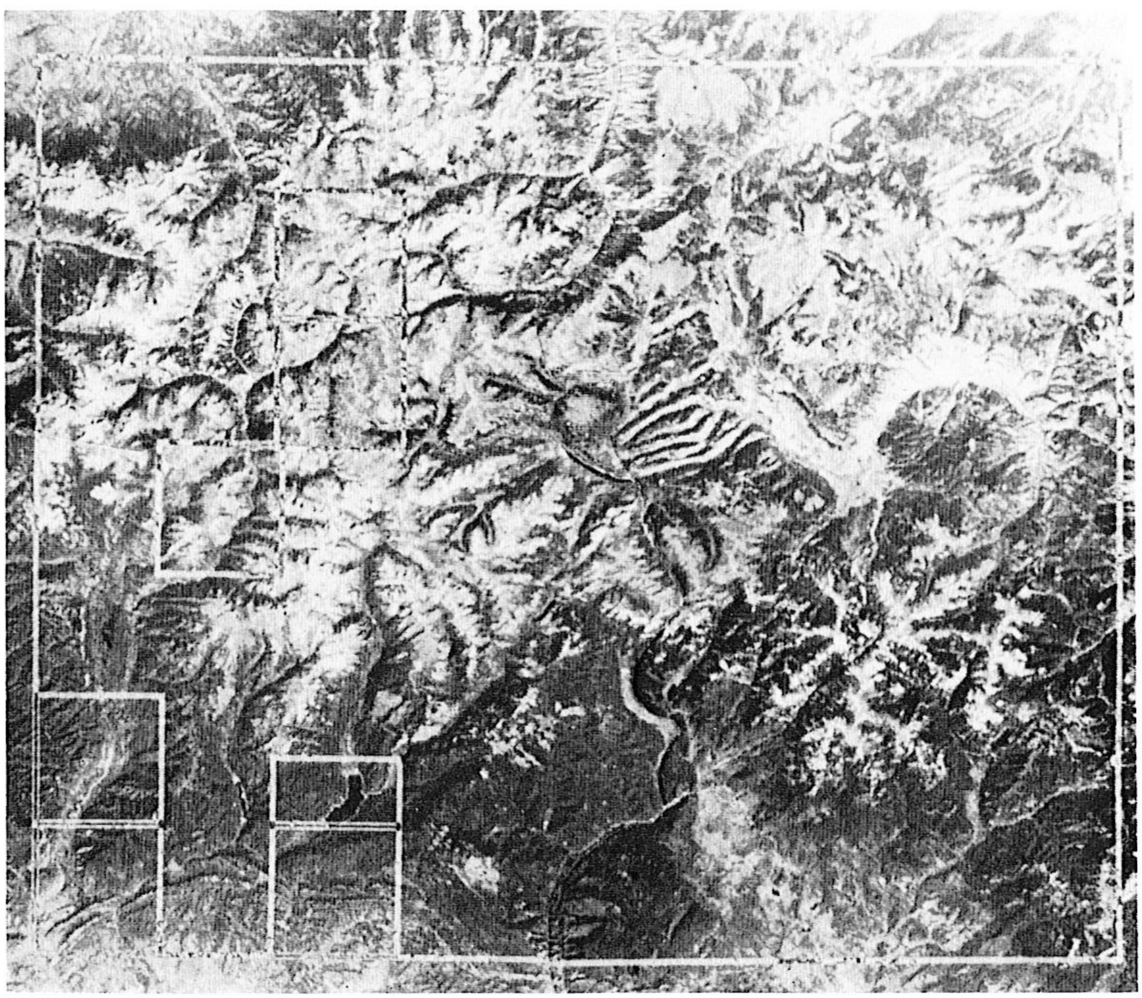

Figure A.19. ERTS-1 MSS Band 5 (0.60-0.70um) grayscale image (frame 1425-17190) of the San Juan Mountain test site showing the location of the quadrangles used in the areal comparison evaluation.

A graphical representation of the data presented in Table A.20 is shown in Figure A.20. This figure shows that the areal estimates based upon the computer classification are reasonably close to those obtained from the type map estimates. To provide a more statistical evaluation of the areal estimates based upon the computer classification results, a linear regression was performed. The correlation coefficient (r) was found to be 0.973. Figure A.20 shows the regression line and the 95% confidence limits for this data. Most of the data points on the graph are close, if not within, the 95% confidence limits. This observation and the very high correlation coefficient shown for this particular analysis indicates that the areal estimates are in reasonable agreement with the planimetered estimates, thereby providing additional confidence in the classification accuracy.

At this point it should be emphasized that obtaining accurate information is not the only goal in computer-aided analysis of remote sensing data. If these techniques are to become operationally useful, the information obtained must not only be accurate, but it must be obtainable in a cost effective manner. The "Supplemental Studies" portion of this chapter discusses an evaluation of the costs involved in obtaining the computer classification for the Vallecito Intensive Study Area and San Juan Mountain Test Site.

Indian Peaks Test Site

Objectives. The classification of this test site was undertaken to determine the degree of accuracy and level of detail possible in mapping a large, basically tundra area, using ERTS-1 MSS data and computer-aided analysis techniques.

Study Area and Data Set Utilized. The Indian Peaks Test Site, shown in Figure A.21 contains twelve 7½′ U.S.G.S. quadrangles, totaling 297,000 hectares (734,000 acres). Figure A.21 shows the location and names for all 12 of the quadrangles. The test site has basically an eastward slope that ranges in elevation from 5,000 feet to over 13,000. A transect running westward, up the slope, crosses a wide range of vegetation zones, from the range grassland near Boulder, to the alpine tundra communities at the Continental Divide.

The August 15, 1973 frame, scene ID 1388-17131, was cloud and snow free except for the permanent snow and ice fields. Since this time of the year was believed to be nearly ideal for studying tundra areas, this data set was selected for use in the analysis of the Indian Peaks Test Site. Support data consisted of WB-57F color infrared aerial photography (Mission 248, collected on the 15th of August, 1973), and the type map of the Ward-Monarch Intensive Study Area.

Procedures. As with all of the other test sites, the modified clustering approach was used to classify this test site. Six training areas were selected using an MSS band 6 computer gray-scale and the WB-57F photography. The statistics already developed for the alpine cover types in the Ward-Monarch study using ERTS data obtained on August 15, 1973, were utilized. In addition, training areas were selected to include the non-alpine cover types. Each training area

Table A.20. San Juan Mountain test site, areal comparison between type map (INSTAAR) and computer classification (LARS) (%).

Area	Forest	Grassland	Barren	Water
Ludwig				
LARS	73.6	25.6	0.7	0.1
INSTAAR	84.0	15.8	0.1	0.1
Durango				
LARS	57.0	38.7	4.2	0.1
INSTAAR	61.8	34.0	4.0	0.2
Handies				
LARS	14.3	58.8	24.3	2.5
INSTAAR	23.6	41.6	34.8	0.0
Hermosa				
LARS	78.4	19.3	2.1	0.2
INSTAAR	87.6	9.8	2.4	0.2
Snowden				
LARS	49.4	38.0	10.6	2.0
INSTAAR	43.9	38.4	17.0	0.7
Howardsville				
LARS	20.0	58.2	19.7	2.1
INSTAAR	29.4	58.0	12.3	0.3
Vallecito				
LARS	81.6	5.1	1.3	12.0
INSTAAR	82.7	4.7	0.7	11.9

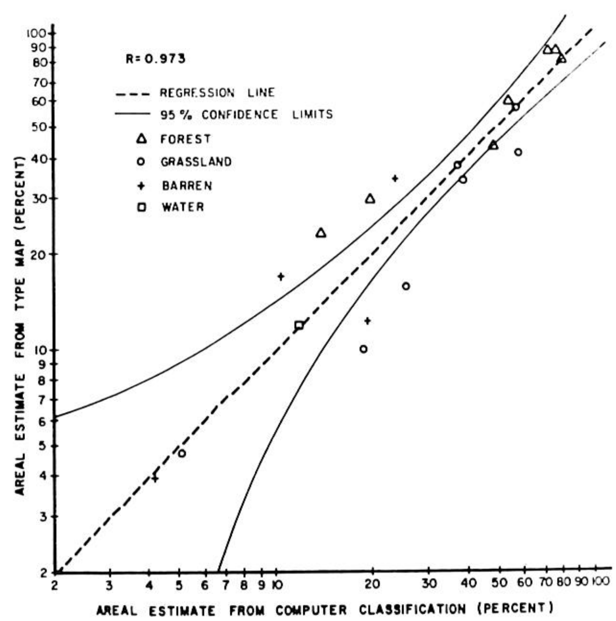

Figure A.20. San Juan Mountain test site comparison between areal estimates obtained by computer classification and those obtained by planimetering the cover type map.

was clustered independently into 12 to 15 spectral classes. The statistics from the Ward-Monarch area and the "new" training areas were compared using the separability algorithm. The spectrally similar classes were combined and a total of 22 information spectral classes resulted. These 22 classes were then used to classify the entire Indian Peaks Test Site.

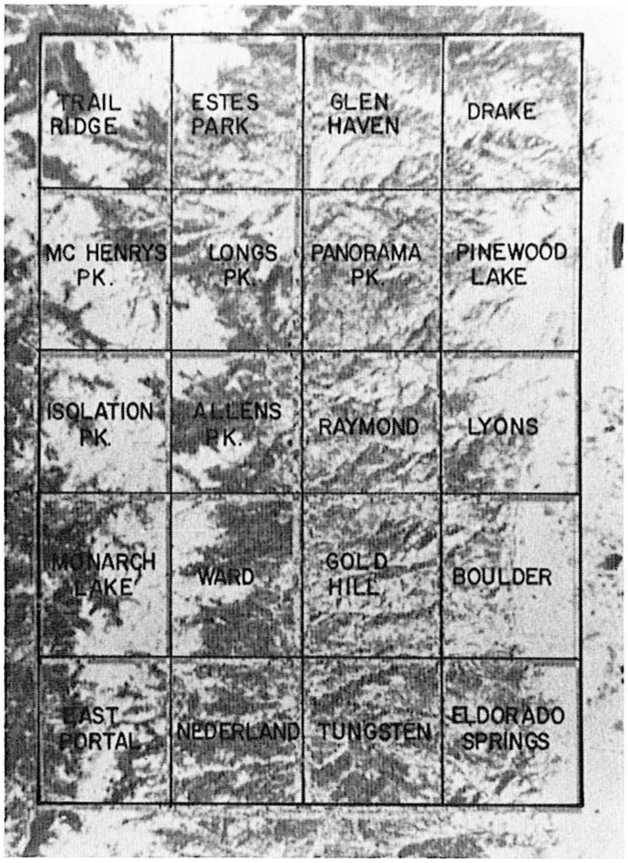

Figure A.21. ERTS-1 MSS Band 5 (0.60-0.70um) gray-scale image (frame 1388-17131) of the Indian Peaks test site showing the location and names of the 12 quadrangles in the test site.

The Indian Peaks Test Site is approximately one-fifth the size of the San Juan Mountain Test Site. Since the area was so much smaller, the number of channels utilized was not reduced.

Classification Results and Evaluation. The computer classification map for the Level I classification of the Indian Peaks Test Site is shown in Figure A.22. The five Level I classes are shown as different shades of gray. Acreage estimates of each Level I cover type for each of the 20 quadrangles in the Indian Peaks Test Site are given in Table A.21. Qualitative comparison with the cover type maps developed by INSTAAR indicated the classification was reasonably accurate.

A quantitative evaluation of this classification was accomplished using test fields and areal estimate comparisons. Thirty test fields, ranging in size from 200 data points to over 4,000 data points, were selected. The exact location of these test fields is shown in Figure A.23. The test fields were selected throughout the entire test site, and the WB-57F photography was used as support data to correctly identify each test field. The test field performance is shown in Table A.22. The same confusion between barren and grassland occurred in this test site as in the San Juan Mountain Test Site, and for the same reason. The overall accuracy of greater than 90% again indicates that large geographical areas can be accurately classified.

Table A.21. Acreage estimates for the Indian Peaks test site.

Quadrangle	Conifer	Deciduous	Grassland	Barren	Water
Trial Ridge	16,129	3,758	10,172	5,196	437
Estes Park	23,605	1,888	7,801	2,262	137
Glen Haven	27,473	1,242	5,770	486	511
Drake	27,852	1,117	5,882	269	363
McHenrys Peak	13,618	2,762	10,785	7,778	751
Longs Peak	21,376	2,469	9,386	2,078	384
Panorama Peak	28,910	2,218	3,635	286	434
Pinewood Lake	17,448	511	16,893	337	293
Isolation Peak	9,136	2,761	11,846	11,190	761
Allens Park	23,845	3,415	6,087	2,114	232
Raymond	28,061	1,250	5,269	414	489
Lyons	17,090	528	16,462	917	484
Monarch Lake	14,974	2,821	8,224	8,689	984
Ward	20,605	3,690	7,997	2,780	621
Gold Hill	26,934	2,465	5,681	254	148
Boulder	14,687	841	16,537	3,129	287
East Portal	16,474	5,732	9,195	3,850	442
Nederland	24,646	4,708	5,666	446	230
Tungsten	29,109	2,114	3,512	321	427
Eldorado Springs	20,776	1,095	11,140	1,910	560

Table A.22. Indian Peaks test site, level I test class performance.

Group	No. of samples	Percent correct	Grassland	Forest	Water	Barren	Baddata
1. Grassland	6,763	87.6	5,923	31	7	802	0
2. Forest	18,306	97.5	240	17,853	162	51	0
3. Water	2,380	100.0	0	0	2,380	0	0
4. Barren	1,333	81.8	241	1	0	1,091	0
Total	28,782		6,404	17,885	2,549	1,944	0

Overall performance (27,247/28,782) = 94.7
Average performance by class (367.0/4) = 91.7

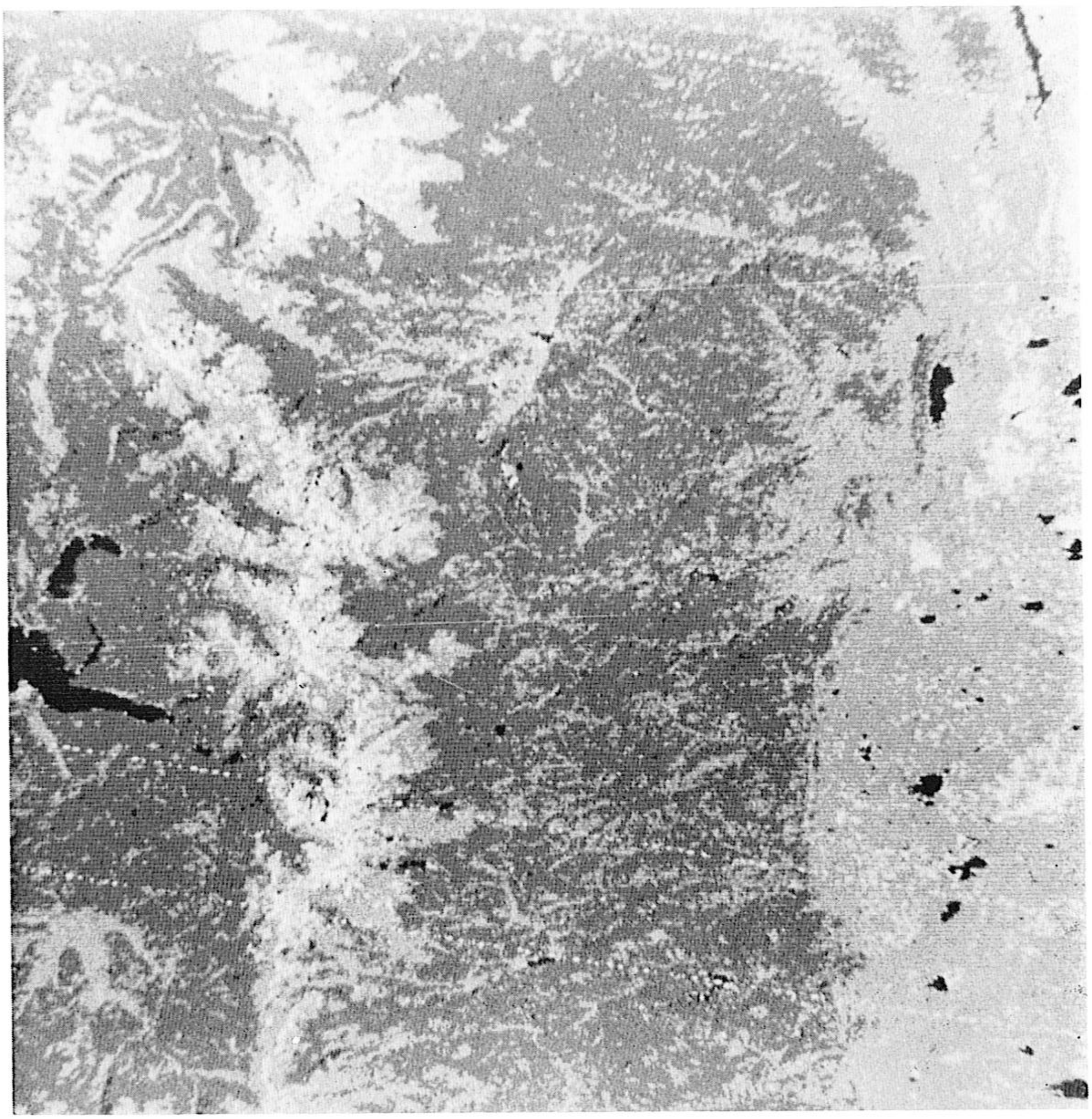

Figure A.22. Image from the digital display of the Indian Peaks test site computer classification of level I. Black is water and terrain shadow, dark gray is coniferous forest, medium gray is deciduous forest, light gray is grass and cropland, and white is barren.

An evaluation of the areal extent of each cover type was made by comparing the area estimates obtained from the computer classification and those obtained from planimetering the cover type maps. This comparison was made for the five U.S.G.S. quadrangles shown in Figure A.24. The areal comparisons for each cover type and for each quadrangle are shown in Table A.23 on a percentage basis. Figure A.25 is a graphical representation of this comparison showing the regression line, 95% confidence limits and correlation coefficient (r). Most of the points on the graph are close to, if not within, the 95% confidence limits. This, plus the high correlation coefficient again indicates a significant level of agreement between the areal estimates obtained from the type map and those obtained from the computer classification.

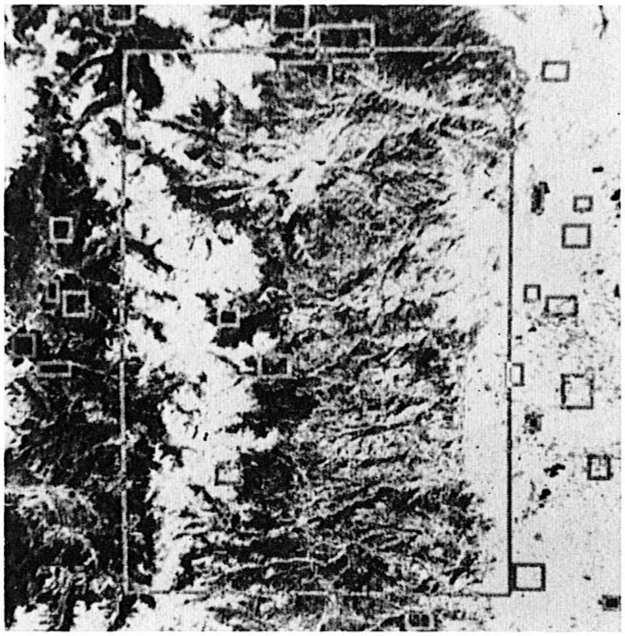

Figure A.23. ERTS-1 MSS Band 5 (0.60-0.70um) gray-scale image (frame 1388-17131) of the Indian Peaks test fields used to evaluate the classification accuracy.

Table A.23. Indian Peaks test site, areal comparison between type map (INSTAAR) and computer classification (LARS) (%).

Area	Forest	Grassland	Barren	Water
Tungsten				
LARS	87.1	10.7	0.8	1.4
INSTAAR	84.7	11.9	1.6	1.8
Ward-Monarch				
LARS	48.2	28.0	21.6	2.2
INSTAAR	52.0	21.6	24.6	1.8
Nederland				
LARS	75.6	21.7	2.1	0.6
INSTAAR	66.8	29.3	3.7	0.2
Gold Hill				
LARS	83.0	15.9	0.7	0.4
INSTAAR	87.0	12.2	0.6	0.2
Lyons				
LARS	50.2	45.8	2.6	1.4
INSTAAR	65.7	32.8	1.0	0.5

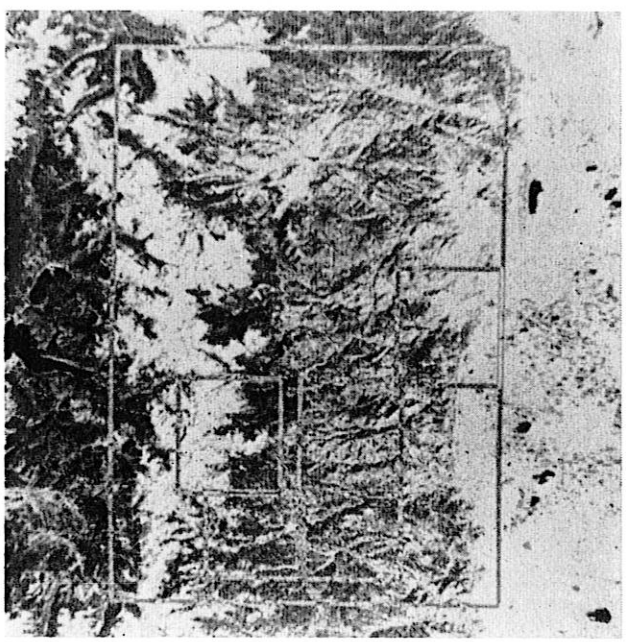

Figure A.24. ERTS-1 MSS Band 5 (0.60-0.70um) gray-scale image (frame 1388-17131) of the Indian Peaks test site showing the location of the quadrangles used in the areal comparison evaluation.

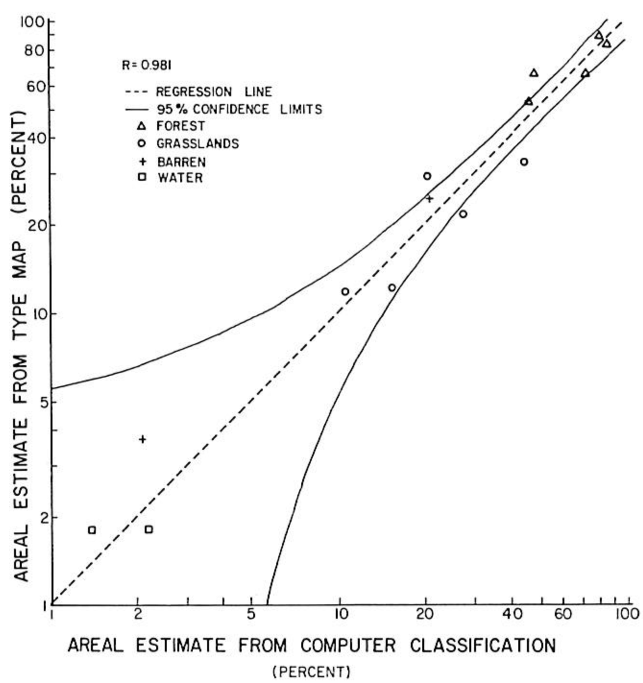

Figure A.25. Indian Peaks test site comparison between areal estimates obtained by computer classification and those obtained by planimetering the cover type map.

SUPPLEMENTAL STUDIES

In the last section, the classification results from both of the intensive study areas and the two major test sites clearly indicated that the potential exists for accurately mapping basic cover types (Level I) using computer analysis techniques and ERTS-1 MSS data, even in mountainous areas where the topography causes variations in spectral response. Results from the Vallecito Intensive Study Area indicated that accurate mapping of the individual forest types is difficult without first accounting for the spectral variability within each of the various cover types. It was believed that this variation in spectral response was caused by topographic variables such as slope, aspect, elevation, and stand density. In an attempt to determine the impact of such topographic effects on spectral response of the various forest types of interest, a statistical analysis was conducted, using the data from previously defined test areas of four forest types in the Vallecito Intensive Study Area. This study of topographic effects on forest cover types is the first of three separate studies reported in this section on supplemental research activities.

The second supplemental study involves some preliminary work on estimating vegetative biomass in the Ward-Monarch Intensive Study Area. The input data used for this study consisted of the primary productivity estimates obtained from an IBP study, and classification results obtained from the computer-aided analysis of the ERTS-1 data from the Ward-Monarch Intensive Study Area.

The third portion of the supplemental study section of this chapter discusses an evaluation of the costs involved in obtaining the computer classification for the Vallecito Intensive Study Area and the San Juan Mountain Test Site areas. The costs involved in the computer classifications are compared to the costs for obtaining similar results using aerial photo-interpretation techniques. In both the computer analysis and the aerial photo-interpretation, the final products obtained consisted of a Level I cover type map of the study site, and a table indicating the areal extent of the various cover types.

Topographic Influences on Spectral Response from Four Forest Types

This study was a statistical analysis of the influence of topographic variables and vegetative variables on spectral response.

The study was provoked by findings in the Ecological Inventory investigations. The analyst working on cover type mapping found that spectrally distinct subclasses of the various cover types appeared to be related to variations in topography and density.

Objectives

This study had three objectives: 1) to determine the impact of density, slope, aspect, and elevation on the spectral response of ponderosa pine, Douglas fir, spruce-fir, and aspen; 2) to develop statistical models for the four cover types, relating spectral response in the four ERTS-1 wavelength bands to density, slope, aspect, and elevation; and 3) to generalize the results, where possible.

Data

The data came from a 14- by 17-mile area in southwestern Colorado. The area corresponds to four U.S.G.S. 7½ minute topographic quadrangles: Vallecito Reservoir, Lemon Reservoir, Rules Hill, and Ludwig Mountain. As part of the ecological inventory research, 168 test areas were defined. Each area was homogeneous in terms of species, stand density, and had a uniform slope and aspect. All test sites were field checked. Of the 168 test areas thus defined, 101 were from one of the forest types defined for use in this study. The individual test areas (samples) ranged from 5 to 20 hectares (10 to 40 acres) in size. Table A.24 indicates the number of samples, the total number of ERTS-1 data points, and the total land area for each forest type.

The spectral data was from ERTS-1 scene 1047-17200, collected September 8, 1972. The spectral response (for each wavelength band) of a sample was defined to be the average of the responses of all ERTS-1 data points within the sample.

The density of each forest cover type was obtained through photo-interpretation of Mark Hurd quad-centered ortho-projected photography in conjunction with ground observations. Density was estimated as percentage of area covered by the tree crowns to the nearest 10% using a Photo Interpreter's Scale.

The slope of each site was calculated from U.S.G.S. topographic maps. The percent slope is equal to the change in vertical distance per 100 units of horizontal distance. A flat site has a slope of 0%, and a 45° slope has a 100% slope. Slopes were calculated to the nearest 5%.

The aspect, or direction of slope, of each sample was originally coded as one of 16 compass points; for example, WSW or SSE. These had to be changed

Table A.24. Areal extent of sample data.

Species	No. of samples	No. of ERTS data points	Acres	Hectares
Ponderosa pine	41	869	955.9	387.1
Douglas fir	26	380	418.0	169.3
Spruce-fir	12	269	295.9	119.8
Aspen	22	341	375.1	151.9

to a numeric code to be used in the regression analysis. The traditional coding—N as 0°, NNE as 22.5°, . . . , NNW as 337.5°—had some inherent difficulties. NNW and N are physically close, but numerically farthest apart when the traditional numerical coding scheme is used. Therefore, a procedure was developed so that aspects which are close together physically are also numerically close, and where each aspect has a unique representation. The choice used in this study was not the only choice which could have been made, but it offered some advantages in the later interpretation of the models containing this representation of aspect. In this study, aspect was represented by two variables which were defined by dividing the circle representing the compass into two semicircles as shown in Figure A.26. One variable takes on the value of 0 or 1, depending on which semicircle the aspect of the sample is in; the second variable represents the angle from the dividing line. The line was set between SSE and SW because the sun azimuth at the time this data set was taken was 136°. By defining the aspect dividing line in this way, the second variable (representing the angle from the dividing line) has a physical meaning in that it is related to the angle from sun azimuth. The value of the second variable at any compass point was defined as the angle between the compass point heading, and the arbitrary sun azimuth line divided by 11.25° (1/32 of a circle). Since the angle between adjacent compass headings is 2/32 of a circle and the dividing line is offset 1/32 of a circle (11.25°) from a compass heading, only odd numbers appear as values of the second variable.

The first variable thus represented only whether a sample faced generally southwest (0) or generally northeast (1). This variable was not expected to have a significant influence on the spectral response,

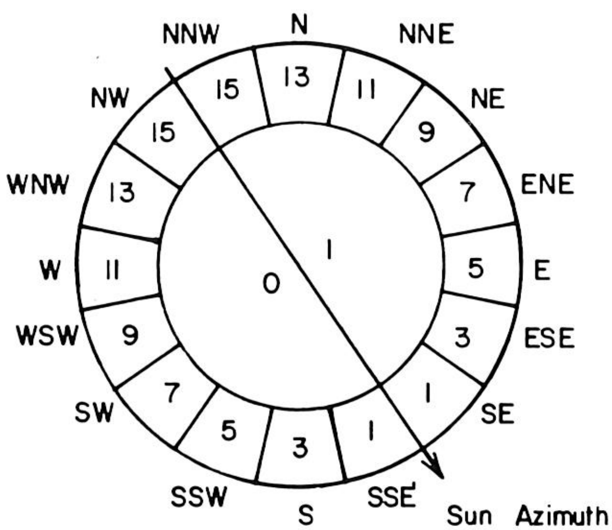

Figure A.26. Representation of aspect.

because if two samples had the same slope, density, elevation and cover type, and also were equally distant from the sun azimuth, they should receive the same amount of illumination, whether facing southwest or northeast. The second variable (angle from sun azimuth) was expected to be much more influential. If a sample had a 0% slope, both of the aspect variables were set equal to 0.

The elevation of each site was calculated from U.S.G.S. topographic maps. The elevation of a site was defined to be the average of the maximum and minimum elevations within the test site area.

The range of values that density, slope, angle from sun azimuth, and elevation had in the 101-sample data set is shown in Table A.25.

Procedures

Polynomial regression analysis (Draper and Smith, 1966) of the spectral response in each of the four wavelength bands, considering density and slope separately, suggested that the second-order terms could add significantly to the regression. An analysis of variance was not run due to the unequal number of observations and null observations at several levels of the independent variables. Instead, a program which investigates all possible regressions, DRRSQU (PUCC, 1974), was used to continue the analysis. The variables listed in Table A.26 were input to DRRSQU as independent variables. For each species, DRRSQU was run four times, once for each channel, with spectral response the dependent variable.

The variation explained by the regression was evaluated by using the R^2 value (the square of the multiple correlation coefficient) obtained from the DRRSQU output. R^2 values for single variables are given in Table A.27. The variable listed for each channel and each species is the variable which, by itself, gave the highest R^2 value of any of the nineteen variables. Notice that, for individual species, the visible wavelength bands (channels 4 and 5) have the same variables, except in one case, and the infrared wavelength bands (channels 6 and 7) have the same variables in all cases. The single exception is not serious in view of the fact that in Channel 4, Douglas fir, A^2 was the variable with the second highest R^2 value, $R^2 = .281$.

These results show that elevation and its interaction with density are the most influential variables in half the cases. The results are not the same for all species, but within a species results can be generalized over classes of wavelength bands (visible and infrared). DRRSQU also printed out R^2 values for regression models using all nineteen variables. The R^2 values obtained are shown in Table A.28. An R^2 value of .8 would indicate that 80% of the variation present in the data could be explained. Since there were only 12 simples of spruce-fir data and 19 variables, the R^2 values for spruce-fir were forced to 1.0. Therefore, further interpretation of the R^2 values for the spruce-fir data in this 19-variable regression will not be attempted. Using .8 as the criterion for adequate explanation, the output from DRRSQU indicated that the variables being considered would adequately explain the variation in the data available in ten of the twelve cases remaining (excluding the four spruce-fir cases). However, as Table A.28 shows, it would not be possible in any case to construct a model which could be expected to adequately explain the variation in an entirely new data set.

The next step was to examine the models suggested by DRRSQU to see if the regressions were significant, and if the coefficients were of the same order of magnitude.

The simplest models are those consisting of two variables. The two-variable models were inspected to determine which ones had an R^2 value greater than 0.65. Table A.29 shows the models which met this criterion. Since the models for ponderosa pine in the infrared channels, Douglas fir in the visible channels, and aspen in all four channels did not have an R^2 value greater than 0.65, they were not considered in the remaining steps of the analysis.

The models shown in Table A.29 were put through a general-purpose regression program, SPSS-15 (Nie, Bent, and Hull, 1970), to obtain the coefficients, R^2 values, and computed F-values. The results, in Table A.30 show that the regressions for these models are statistically significant at the $\alpha = .01$ level. Also, the regression equations in both visible wavelength bands and in both infrared bands have coefficients of the same order of magnitude, indicating that the models can be generalized over wavelength region.

Conclusions

The conclusions of this phase of the investigation are: 1) When considering density, slope, aspect, and elevation in order of number of occurrences as the most influential variable, density occurred in the most cases, then elevation, and aspect third. Slope did not appear as the single most influential variable in any case; 2) two-variable statistical models with an $R^2 \geqslant 0.65$ can be constructed for ponderosa pine in channels

Table A.25. Range of values for variables.

Species	Density	Slope	Angle from sun azimuth	Elevation
	percent	percent		ft.
Ponderosa pine	20-100	0-60	0-15	7260- 9300
Douglas fir	20-100	15-70	1-15	7440- 9420
Spruce-fir	50-100	10-60	1-15	9440-11200
Aspen	80-100	15-50	1-15	8000-10940

Table A.26. Variables input to DRRSQU.

Variable number	Variable	Description
1	D	Percent density of cover type
2	S	Percent slope of site
3	U	(0, 1) variable representing SW or NE semicircle
4	A	Angle from sun azimuth
5	E	Elevation of site in feet above sea level
6	D^2	Density squared
7	S^2	Slope squared
8	A^2	Angle from sun azimuth squared
9	E^2	Elevation squared
10	DS	Density-slope interaction
11	DA	Density-angle from sun azimuth interaction
12	SA	Slope-angle from sun azimuth interaction
13	ED	Elevation-density interaction
14	ES	Elevation-slope interaction
15	EA	Elevation-angle from sun azimuth interaction
16	UD	Semicircle-density interaction
17	US	Semicircle-slope interaction
18	UA	Semicircle-angle from sun azimuth interaction
19	UE	Semicircle-elevation interaction

Table A.28. R^2 values for 19-variable regression.

Species	Channel 4	Channel 5	Channel 6	Channel 7
Ponderosa pine	.847	.860	.859	.868
Douglas fir	.644	.675	.906	.941
Spruce-fir	1.000*	1.000*	1.000*	1.000*
Aspen	.889	.839	.892	.930

* There are only 12 spruce-fir samples and 19 variables in the regression. This forces R^2 to equal 1.

Table A.27. Single variable with highest R^2 value.

Channel no.	Ponderosa pine		Spruce-fir		Douglas fir		Aspen	
	Variable	R^2	Variable	R^2	Variable	R^2	Variable	R^2
Channel 4	D	.497	ED	.346	EA	.289	ED	.134
Channel 5	D	.568	ED	.259	A^2	.281	ED	.200
Channel 6	E	.291	ED	.377	DA	.647	A	.371
Channel 7	E	.395	ED	.406	DA	.700	A	.390

4 and 5, for Douglas fir in channels 6 and 7, and for spruce-fir in all four channels; and 3) the results can be generalized over classes of wavelength bands (visible and infrared).

In this study, nineteen variables were considered. Since the number of variables approaches the number of samples, the first recommendation for future work is to obtain a larger data set.

Succeeding investigations could test the models suggested here on another data set, and could model density as the dependent variable with spectral response as well as slope, aspect, and elevation used as independent variables.

Biomass Productivity

Primary productivity estimates for the major cover types in the Ward-Monarch Test Site were obtained from the International Biological Program (IBP) study results (Lieth, 1972; Webber, 1972, 1974). In some cases a single mapped cover type represented more than one plant community for which productivity data were available. The net primary productivity estimates for true composite cover types were determined using planimetric data from the manually produced vegetation map of the area (based on NASA Mission 248, Roll 69, Frames 0088-0090). The net primary productivity estimates (gm/m²/yr) were then applied to the areal estimates of the various cover types obtained from the computer classification (Table A.14, shown previously) to obtain net primary production (Table A.31).

The average net productivity over the Ward-Monarch Intensive Study Area was 753 gm/m²/yr. This figure is generally in line with estimates for

Table A.29. Two-variable regression models of spectral response ($R^2 \geqslant 0.65$).

Species	Visible	Infrared
Ponderosa pine	$Y=\beta_0+\beta_1D+\beta_3D^2+\epsilon$	
Douglas fir		$Y=\beta_0+\beta_{11}DA+\beta_{13}ED+\epsilon$
Spruce-fir	$Y=\beta_0+\beta_7S^2+\beta_{14}ES+\epsilon$	$Y=\beta_0+\beta_{16}UD+\beta_{17}US+\epsilon$

Note: The subscripts refer to the variables listed in Table A.26.

Table A.30. Coefficients, R^2 values and computed F-values for each forest type and wavelength band having $R^2 \geqslant 0.65$.

Forest type	Wavelength band	Values
Ponderosa pine	Channel 4 (0.5-0.6 micrometers)	$Y_4 = 30.53263 - 0.26099D + 0.00171D^2$
		$R^2 = 0.660$
		$F_{2,38} = 37.04280^{**}$
		$F_{2,30,0.99} = 5.39$
	Channel 5 (0.6-0.7 micrometers)	$Y_5 = 30.97367 - 0.40580D + 0.00260D^2$
		$R^2 = 0.72512$
		$F_{2,38} = 50.12079^{**}$
		$F_{2,23,0.99} = 5.66$
Douglas fir	Channel 6 (0.7-0.8 micrometers)	$Y_6 = 30.57973 - 0.01244DA + 0.00001ED$
		$R^2 = .67761$
		$F_{2,23} = 24.17103^{**}$
	Channel 7 (0.8-1.1 micrometers)	$Y_7 = 17.92902 - 0.00858\ DA + 0.00001ED$
		$R^2 = 0.72888$
		$F_{2,23} = 30.91707^{**}$
Spruce-fir	Channel 4 (0.5-0.6 micrometers)	$Y_4 = 23.22330 + 0.00436\ S^2 - 0.0003\ ES$
		$R^2 = 0.74820$
		$F_{2,9} = 9.69808^{**}$
		$F_{2,9,0.99} = 8.02$
	Channel 5 (0.6-0.7 micrometers)	$Y_5 = 18.89736 + 0.00476\ S^2 - 0.00004\ ES$
		$R^2 = 0.68306$
		$F_{2,9} = 9.69808^{**}$
	Channel 6 (0.7-0.8 micrometers)	$Y_6 = 23.87903 - 0.36237UD + 0.59708\ US$
		$R^2 = 0.65089$
		$F_{2,9}\ 8.38988^{**}$
	Channel 7 (0.8-1.1 micrometers)	$Y_7 = 13.31213 - 0.23927\ UD + 0.39489\ US$
		$R^2 = 0.65888$
		$F_{2,9} = 8.69168^{**}$

** Significant at $\alpha = 0.01$.

a selection of data referring to other ecosystems (Table A.32), although perhaps a little high. The low productivity of the bare rock and dry tundra areas (about 13% and 23% of the test site, respectively) was balanced by the highly productive and extensive forest vegetation (about 45% of the test site) (Table A.31).

Although global estimates of primary productivity have been prepared (Lieth, 1972), there is a dearth of such data on a regional level. Computer-aided analysis of ERTS imagery provides the first opportunity to obtain regional estimates through the mapping of cover type extent and the application of productivity values being made available for different plant communities by the work of the International Biological Program (IBP).

Colorado is facing a period of intensive development. Land use planners in agencies such as the Forest Service, Bureau of Land Management and many state and county organizations are in need of numerical estimates of the "worth" of natural communities. Estimates of net primary production provide one such numerical value for natural systems, which can also be compared with agricultural productivity data. Moreover, comparisons of the productivity of an existing planned community with that of a (proposed) modified community could facilitate accurate assessment of the impact of such a change upon the existing animal populations, according to their energy needs, or upon other more general measures of "carrying capacity" for the community. ERTS products are especially valuable in this context since the spatial relationships of various communities (at several levels of scale) can be considered during such analysis.

Table A.31. Ward-Monarch plant productivity, level II.

Type	gm/m²/yr.	Percent area
Deciduous	1228	3.4
Coniferous	1540	35.4
Bare rock	0	16.2
Snow	0	3.7
Dry tundra	116	11.5
Wet tundra	264	16.5
Willow-Krummholz	1000	10.7
Water	0	2.6

Table A.32. Estimated net primary productivity.

Type	gm/m²/yr.
Ward-Monarch area	753
Agricultural land	650*
Tropical forest	2000*
Boreal forest	800*
Tundra and alpine	140*

* from Whittaker, 1970.

Evaluation of Costs

In the computer classification analysis for the Vallecito Intensive Study Area and the San Juan Mountain Test Site, the amount of time involved in handling of the data prior to classification, developing training statistics, classifying the data, and evaluating the results was carefully recorded. For comparison, INSTAAR kept track of the amount of time necessary to obtain cover types maps and areal estimates on a quadrangle by quadrangle basis, using manual interpretation techniques. The type map was obtained by photo-interpretation (PI) of WB-57F color infrared photography. Areal estimates were obtained by planimetering the cover type map that resulted from the airphoto interpretation effort.

There are many ways in which one could approach this type of cost evaluation, and a variety of costs which might have been included. To prevent too many assumptions and ramifications from entering into the cost comparison in this study, the decision was made to limit the cost evaluation to a situation where only the actual costs involved in the analysis of the data is included. The objective of the data analysis for which these costs were evaluated, was to obtain a Level I cover type map and a table of areal estimates of the Level I cover types, and to provide some indication of the reliability of such cover type maps and areal estimates.

This study was not intended to evaluate the cost of computer and manual interpretation techniques under an operational type of environment, but there are a number of aspects in the cost evaluation study which should be understood in order to properly evaluate the results obtained. First, costs were not included for the data acquisition, either by aircraft or satellite. A second assumption was that the data analysis was started with personnel who were trained in the proper analysis techniques. Thirdly, the personnel were familiar with the characteristics of the cover types in the study site before beginning the analysis and that adequate background information concerning the characteristics of the area was available to the analyst at the outset of the data analysis. Finally, overhead costs were not included. There are many additional factors which could be considered in the evaluation portion of such an investigation. If one has complete confidence in the results of the computer classification that could be obtained under an operational situation, many of the evaluation costs that were included in this study could have been reduced or eliminated. The amount of field time that could be spent in checking the results of either the photo-interpretation or the computer classification could vary considerably. Therefore, since this study was not intended to evaluate the cost of computer and manual interpretation techniques under an operational type of environment, we limited the cost evaluation and comparison to those costs actually involved in the analysis of the data.

Two changes were made between the actual costs incurred in the study and those shown in the tables. The first of these involves the salary of either the computer analyst or the photo-interpreter. In the actual study, qualified and well trained graduate students were utilized in the computer analysis and photo-interpretation activities, but since a graduate student wage is much lower than normally encountered for a trained professional, we felt that it would be more realistic to develop a comparison in which the personnel costs were based upon a somewhat more realistic salary, so used a figure of $10,400 per year for both data analysts.

A second point at which the actual costs differed from those shown on the tables involved the photo-interpretation effort for the San Juan Mountain Test Site. We did not perform the photo-interpretation and develop a cover type map for all of the 63 quadrangles within the San Juan Mountain Test Site. However, cover type maps were developed by photo-interpretation techniques for all or portions of 19 quadrangles within the test site. From this information, the average cost for photo-interpretation and areal estimation for a single quadrangle was calculated and these "per quadrangle" costs were used to determine what the cost would have been if we had finished the photo-interpretation effort for the entire San Juan Mountain Test Site. It should be emphasized that since more than a third of the entire test site was actually analyzed with the photo-interpretation approach, we feel confident that these cost figures would be realistic for the entire test site.

The costs involved in the computer-aided analysis of the Vallecito Intensive Study Area and the San Juan Mountain Test Site are shown in Table A.33. This table shows that the costs involved do not increase at the same rate as the increase in the size of the area (the cost per unit area does not remain constant). The size of the area classified increased by a factor of 42 when going from the Vallecito Intensive Study Area to the San Juan Mountain Test Site, whereas the total cost increased only by a factor 5 ($250 + $288 vs. $300 + $2207 = $2507). This is because approximately the same amount of time had to be spent in developing the training statistics for the Vallecito Intensive Study Areas as for the San Juan Mountain Test Site, so the personnel costs did not increase substantially in spite of the considerable increase in size of the area involved. Most of the increase in cost, when going to a larger area, is due to the increase in computer time required. In this case, that total computer time required increased by a factor of 8. Additional computer time is required to do the preprocessing (geometric correction) and the actual computer classification.

Table A.33. Computer classification time and costs for the Vallecito intensive study area and the San Juan Mountain test site.

	Vallecito intensive study area (23,070 hectares)				San Juan Mountain test site[a] (1,011,740 hectares)			
Item	Man hours	Personnel cost ($)[b]	Computer time (hr.)	Computer cost ($)[c]	Man hours	Personnel cost ($)[b]	Computer time (hr.)	Computer cost ($)[c]
Preprocessing[d]	20	100.00	0.012	3.00	20	100.00	3.824	956.00
Classification	21	105.00	0.890	222.50	30	150.00	4.556	1139.00
Develop training stats	(20)	(100.00)	(0.800)	(200.00)	(28)	(140.00)	(1.000)	(250.00)
Classification	(1)	(5.00)	(0.090)	(22.50)	(2)	(10.00)	(3.556)	(889.00)
Tabulation and evaluation of classification results	9	45.00	0.250	62.50	10	50.00	0.450	112.50
Test area evaluation	(6)	(30.00)	(0.150)	(37.50)	(7)	(35.00)	(0.250)	(62.50)
Areal estimate evaluation	(3)	(15.00)	(0.100)	(25.00)	(3)	(15.00)	(0.200)	(50.00)
Total	50	$250.00	1.152	$288.00	60	$300.00	8.830	$2207.50
Cost/hectare		$0.010		$0.012		$0.0003		$0.0022
(Cost/acre)		($0.004)		($0.005)		($0.0001)		($0.0009)

[a] San Juan Mountain test site (2,456,000 acres) is approximately 42 times as large as the Vallecito intensive study area (57,000 acres).
[b] Based on a salary of $10,400 per year and no overhead costs.
[c] Based on the Purdue University-approved rate of $250.00/hr. for the IBM 360/67.
[d] Includes reformatting and geometric correction of ERTS-1 data, and preparation of support data for analysis.

In evaluating these results, it is also important to note that this particular classification was done on a general purpose, medium-speed digital computer (IBM 360/67). The same type of process could be done much more economically on a special-purpose high-speed digital computer. It appears that more cost-effective digital computer systems will allow the same type of classification to be performed for about 10% of the computer costs involved in this study, so future, operation data analysis activities will be much more economical. (Landgrebe, 1973.)

The time and costs involved in obtaining type maps and areal estimates by photo-interpretation, and planimetering the type maps for the Vallecito Intensive Study area and the San Juan Mountain Test Site are shown in Table A.34. The procedures and techniques used for this photo-interpretation effort were described earlier in this chapter. The cost for obtaining the results is directly proportional to the size of the area, therefore the cost per unit area is the same ($0.0046 per acre).

Table A.35 is a summary of Table A.33 and Table A.34, comparing the total cost figures for the Vallecito Intensive Study Area and the San Juan Mountain Test Site, using both analysis techniques. On a relatively small test site, like the 23,070-hectar (57,000-acre) Vallecito Intensive Study Area, the photo-interpretation approach is more cost-effective—about half of the cost for computer-aided analysis. However, when considering a relatively large area, like the 1,011,740-hectare (2,456,000-acre) San Juan Mountain Test Site, the photo-interpretation approach cost over four times more than the computer-aided analysis of the same area.

These results show that for relatively small areas, more time must be spent on developing and evaluating a computer classification and carrying out the necessary preprocessing activities. This quickly pushes

Table A.34. Time and costs involved in obtaining type maps and areal estimates by photo-interpretation and planimetering for the Vallecito intensive study area and the San Juan Mountain test site.

Item	Vallecito intensive study area		Per quad		Entire San Juan Mountain test site	
	Man hours	Personnel cost*	Man hours	Personnel costs	Man hours	Personnel costs
Preparation	3	$ 15.00	2	$ 10.00	126	$ 630.00
Type mapping	40	200.00	27	135.00	1701	8,505.00
Planimeter and areal estimates	9	45.00	6	30.00	378	1,890.00
Total	52	$260.00	35	$175.00	2205	$11,025.00
Cost/hectare		0.011		0.011		0.011
(Cost/acre)		(0.0046)		(0.0046)		(0.0046)

* Based on a salary of $10,400 per year and no overhead costs.

Table A.35. Summary of total costs for computer aided-analysis and photo-interpretation*

Item	Vallecito intensive study area (57,000 acres)		San Juan Mountain test site (2,456,000 acres)	
	Computer classification	P-I	Computer classification	P-I
Preprocessing or preparation	103.00 ($1.15)	15.00 ($0.17)	1056.00 ($0.27)	630.00 ($0.16)
Classification or type mapping	327.50 ($3.68)	200.00 ($2.24)	1289.00 ($0.34)	8505.00 ($2.18)
Evaluation or planimetering	107.50 ($1.21)	45.00 ($0.51)	162.50 ($0.04)	1890.00 ($0.48)
Total	$538.00 ($6.04)	$260.00 ($2.90)	$2507.50 ($0.65)	$11,025.00 ($2.90)
Cost/hectare	$0.022	$0.011	$0.0025	$0.011
Cost/acre	$0.0094	$0.0046	$0.0010	$0.0046

* Cost figures in parentheses are cost/square mile.

the total cost and the cost per unit area above that required to carry out development of a similar set of results using photo-interpretation techniques. However, when relatively large areas are involved in the analysis, personnel costs for a computer-aided analysis become relatively small and the computer cost itself becomes relatively small on a per area basis, whereas the photo-interpretation costs increase in direct proportion to the size of the area involved. Thus, for an area as large as the San Juan Mountain Test Site, encompassing nearly 2.5 million acres, the total cost for computer processing is approximately 0.1¢ per acre whereas the photo-interpretation is above 0.4½¢ per acre to obtain comparable products involving cover type maps and areal estimate tables. The results obtained in this comparison indicate the potential for operationally utilizing computer-aided analysis techniques to map and tabulate areal estimates over large geographic areas in an accurate, cost-effective, and timely manner.

Section B
Hydrological Features Survey

Contributors

LARS	*INSTAAR*
S. G. Luther	R. G. Barry
R. M. Hoffer	C. E. Thorne
M. D. Fleming	S. E. McVey
	D. G. Koutsopolous

The Hydrological Features Survey was initiated to study the potential that an earth resources technology satellite would have on assessing the water resources for selected areas in Colorado. This section of the report addresses that specific goal. Results of the following four objectives will be reported:

1. To map the extent and condition of snow and ice cover in a mountainous terrain using ERTS-1 data, and to map change in the snow state.
2. To determine if snow can be spectrally differentiated from clouds on ERTS-1 data.
3. To map the distribution and extent of water.
4. To study the freeze and thaw sequence of mountain lakes.

The first objective is the most applications-oriented as it deals with the supply of water in a region where the quantity and regimen of water is critical to the economic well-being of the area. Consequently, this objective has received the most intense investigation.

Spectral separation of snow from clouds is an important factor which determined the ability of computer-aided analysis techniques to perform inventories of snow cover extent and condition.

Maps indicating the distribution and areal extent of water in critical areas of the test site are included within this report. Generally, the results of the ERTS maps coincided with information from U.S.G.S. topographic maps. Most discrepancies were caused by lakes which approximated the size of a resolution element (1.12 acres), or by fluctuations of lake levels which a dynamic system such as ERTS is capable of measuring.

The study of the freeze-thaw sequence of mountain lakes was accomplished by image-interpretation. Application of ERTS data to studying this phenomena proved to be one of the more difficult aspects of this Hydrological Features Survey, due to frequency of data collection, cloud cover, and terrain shadows.

The two test sites (see Figure B.1) for this contract are in critical areas of water supply for the southwestern United States. Both test sites supply water to the Lower Colorado district which, according to a 1972 National Water Commission Report, has a mean annual runoff of 3.19 BGD, fresh water consumption of 5.0 BDG and withdrawals of 7.2 BGD. Obviously this district cannot supply its own water needs. Water from the Upper Colorado district, which has a mean annual runoff of 13.5 BGD, satisfies the deficiency in the Lower Colorado. In addition, the Rio Grande Reservoir, which is in the San Juan Mountains Test Site, is the headwater of the Rio Grande River, another water deficient district. Thus the importance of studying all of the hydrological features of this area is clearly demonstrated.

SNOW COVER MAPPING

Climate and subsurface geology combine to make water a scarce and valuable commodity in the western United States. Most of the water supply comes from the spring and summer runoff of winter snow accumulations in the Rocky Mountains. A network of reservoirs has been constructed to conserve this resource to satisfy the water needs of urban communities and to provide water for irrigation. In addition, this water is used for generating hydroelectric power and for providing recreational facilities. The network is operated by various state and federal government agencies and private corporations.

In order to regulate these reservoirs properly, these agencies must have an estimate of both the discharge required downstream and the concommitant recharge needed from the reservoir's source, which in most cases is a mountain stream. The objective of this research is to investigate methods by which ERTS-1 MSS data can be applied to the process of mapping snow cover, thereby enabling more accurate predictions of runoff from mountain watersheds.

Since the methods to be studied may vary in time, cost and practicality of application, parameters must be established to insure that the techniques involved are economically advantageous, i.e., that similar information is provided at less cost than conventional methods or that increased cost is accompanied by addi-

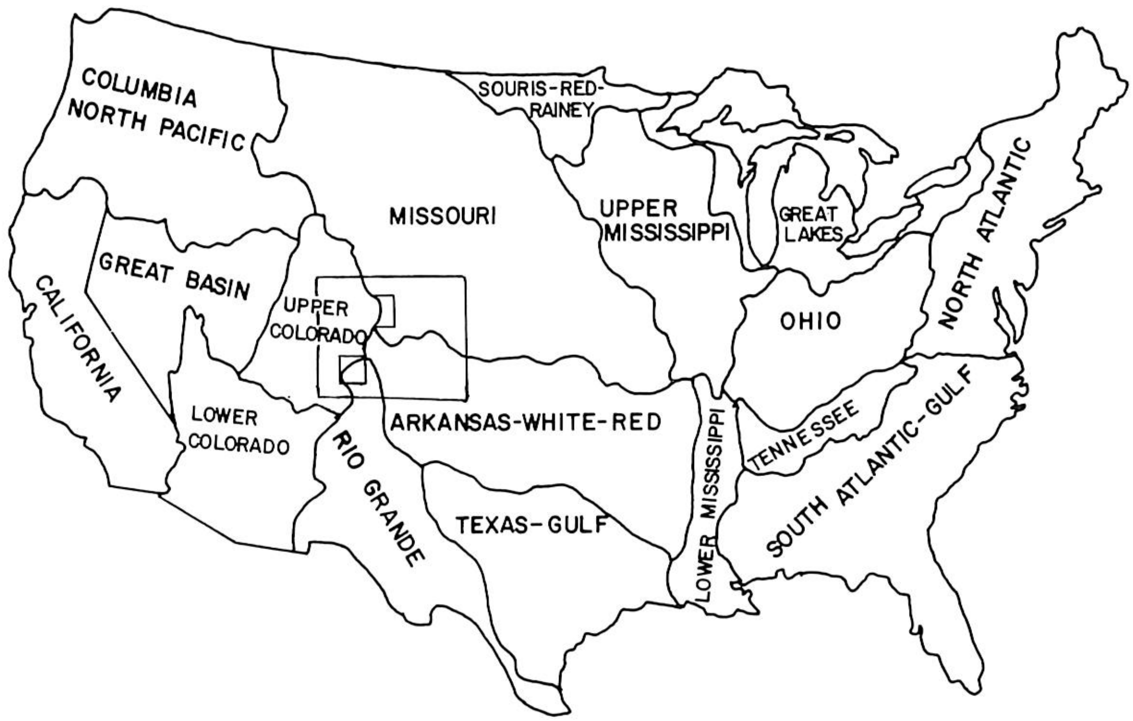

Figure B.1. ERTS-Colorado test sites.

tional information. To meet these objectives this analysis has purposely been kept simple in an effort to implement an operational system at a cost that would be acceptable to a user agency. Other, more complicated methods should be investigated at a basic research level.

Computer Aided Analysis Techniques

The Animas River watershed above Howardsville, Colorado was selected as the test site for this phase of the study because; 1) it is located in the headwaters of the Colorado River, 2) it is wholly contained in the San Juan Mountain Test Site, and 3) good records exist for the gaging station at Howardsville. The watershed boundary was physically located on four USGS 7½′ topographic maps. (see Figure B.2) The boundary was defined by elevations, the stream network and the location of the gaging station in relation to the stream.

Once determined and delineated, the boundary was manually transferred from the map to a gray scale printout at the same scale (1/24,000), by aligning the stream networks. The watershed was then defined on the ERTS imagery, using a series of line and column coordinates as individual "test areas," thus providing an accurate estimation of the total area of the watershed (Figure B.3). The data for frames 1101-17203 (1 November, 1972), 1119-17204 (19 November, 1972), 1173-17202 (12 January, 1973), 1191-17204 (30 January, 1973), 1299-17205 (18 May, 1973), and 1317-17204 (5 June, 1973) were all overlayed, rotated, and rescaled thereby eliminating the need for repetition of the outlining process. These frames are cloud free over the Animas River watershed.

In order to ascertain the accuracy of this type of areal calculation, the relative size of a printer element must be known. Previous investigations at LARS have indicated that each ERTS element contains 1.12 acres. Furthermore, a total of 32,405 elements was contained within the watershed, so the area was calculated to be 56.7 square miles. Since that U. S. Geological Survey had estimated the area to be 55.9 square miles (see WSP 1925), and this coincided with an estimate obtained by planimetering the area, the error introduced by the computer tabulation, and human errors in outlining the boundary was 1.5% Channel five digital display imagery for one of the frames (1119-17204) which contains the watershed is shown in Figure B.4. This image consists of sixteen gray levels defined by the computer program, based on relative reflectance histograms of the area.

To determine the areal extent of the snow cover, two channels, [one in the visible (.6-.7μm) and one in the IR (.8-1.1μm)], were used in conjunction with LARSYS. ERTS MSS channels four and five were generally saturated by the snow cover and the information provided by each resulted in a singular correlation matrix. This required the elimination of one of these channels in order to implement the LARSYS processor.

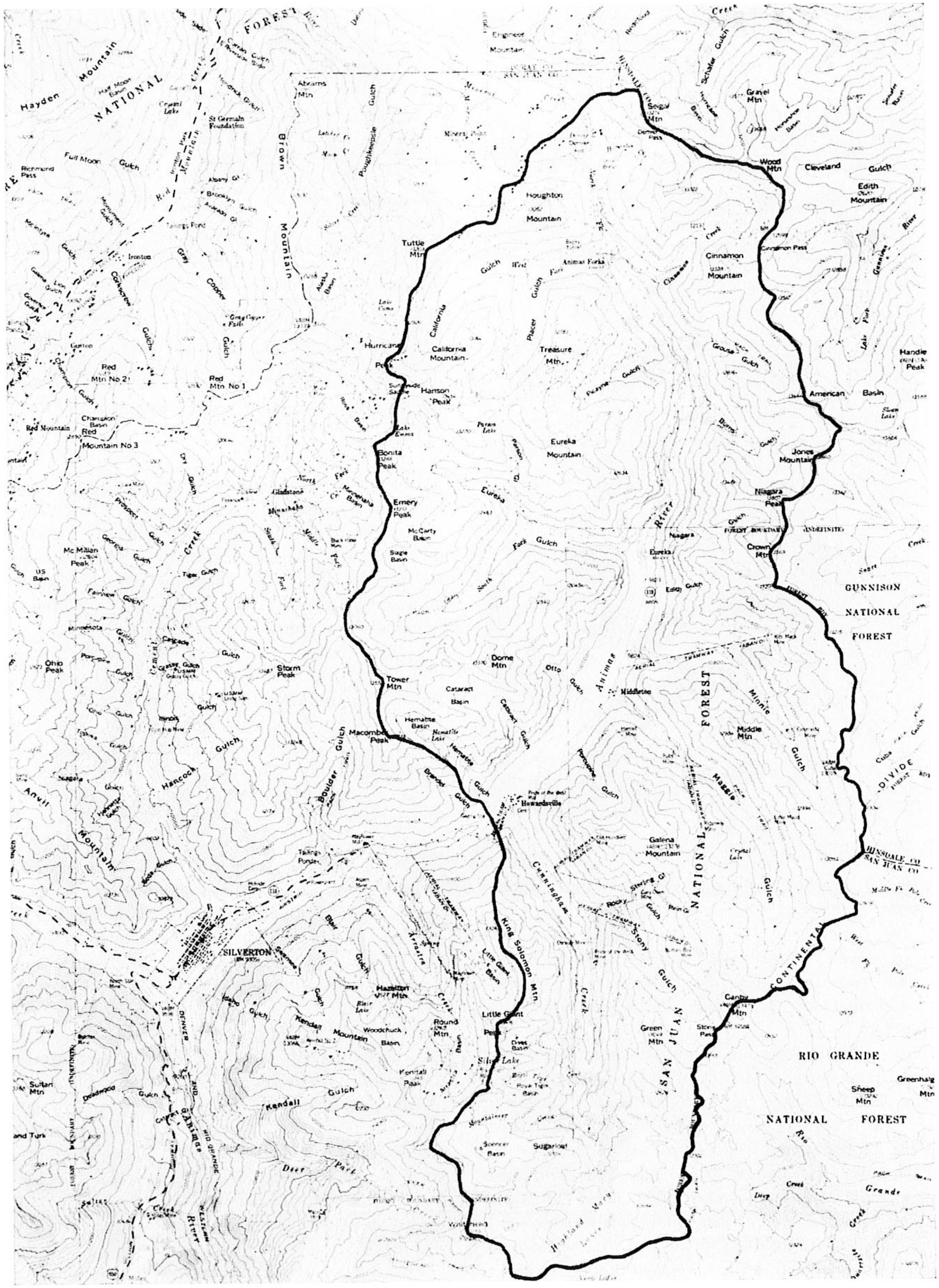

Figure B.2. Outline of Animas watershed 1:24,000 topographic map.

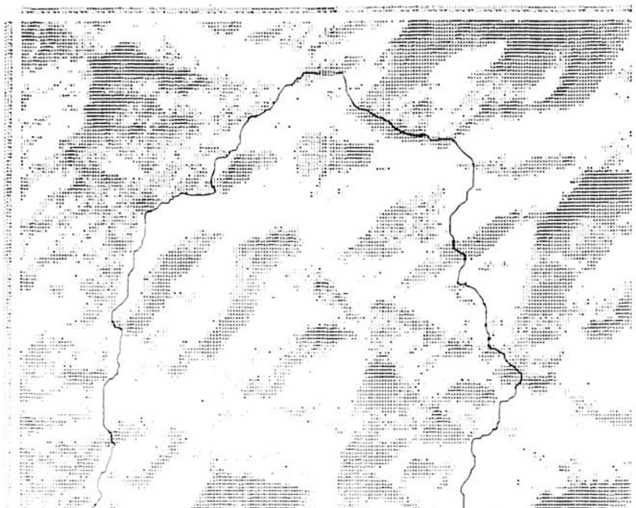

Figure B.3. Outline of Animas watershed on 1:24,000 computer-printout.

Two classes, "snow" and "other," were then requested from the clustering processor, to generate the statistics for these classes which are shown in Table B.1.

These numbers are dimensionless and indicate the relative reflectance of each class. Note that the mean of the class snow does not vary significantly between dates, and it approaches the saturation level, which is 128 for band five and 64 for band seven.

Each frame was then classified separately into two classes, snow and other, according to these statistics. Display maps of the classification results were obtained, along with a table showing the number of resolution elements within the watershed that were classified as snow and the percentage of snow cover (an example of this type of output is shown in Figure B.5.).

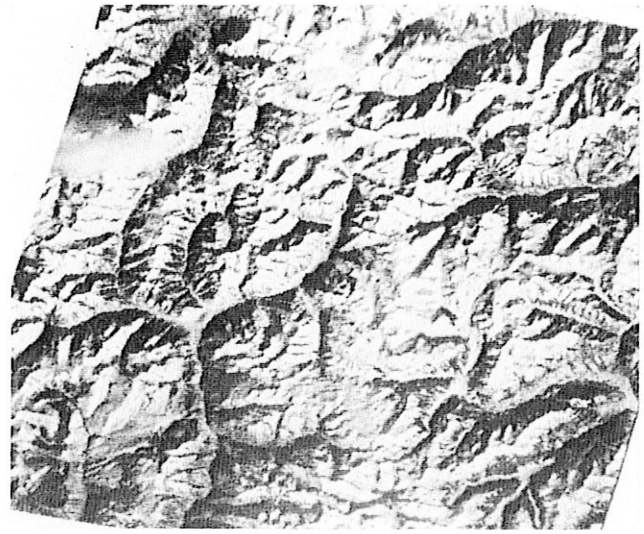

Figure B.4. Grayscale photograph of scene ID 1119-17204, November 19, 1973.

By multiplying the number of resolution elements classified as snow by the 1.12 acres represented by each resolution element or by multiplying the percentage of snow cover, the areal extent of the snowpack can be quickly and easily calculated by this computer analysis procedure. Table B.2 gives a summary of the areal fluctuations of the snowpack.

Figure B.6 shows the classification results taken from the digital display. These include that portion of the area surrounding the Howardsville watershed.

The relationship between area, snowpack density and total water content of the snowpack requires much additional study. However, ERTS can provide accurate, rapid measurements of the areal extent of the snowpack.

Several intervening dates between January 30, 1973 and May 18, 1973 have not been included in this investigation due to cloud conditions. Thus, this study clearly indicated that ERTS-1 frequency of coverage can rapidly decrease from once to every 18 days to once every 36 or 54 days, a totally unacceptable condition for studying hydrological and other dynamic phenomena.

One possible solution of the periodicity problem is an approximation which requires determining the relationship between area and elevation, and is referred to as a hipsometric analysis. Areas of known elevation, i.e., areas within contour intervals, are planimetered and summed by increasing elevations. The areas are then plotted according to increasing elevations. The resulting curve allows an investigator to readily determine the area at particular elevations or vice versa.

This analysis was conducted on the Animas watershed, and the resulting graph is indicated on Figure B.7. If the approximate snow elevation can be deter-

Table B.1. Spectral response of snow.

Date	ERTS band	Snow: Mean relative reflectance	Snow: Standard deviation	Other: Mean relative reflectance	Other: Standard deviation
1 Nov. 1972	5	124.73	7.01	37.29	18.21
	7	56.75	9.23	13.15	7.11
19 Nov. 1972	5	123.43	9.21	32.21	10.35
	7	54.54	10.66	18.22	6.96
12 Jan. 1973	5	121.73	11.17	31.36	10.31
	7	52.32	11.13	18.59	7.03
30 Jan. 1973	5	122.45	10.32	30.04	17.21
	7	52.70	10.78	10.34	6.72
18 May 1973	5	125.33	11.02	50.44	18.83
	7	53.50	17.42	21.12	5.50
5 June 1973	5	125.98	10.30	45.89	18.66
	7	51.72	15.26	22.30	5.90

mined from ground observation or inferred by photo-interpretation of the satellite imagery, the areal extent of the snow pack can be approximated from the hipsometric curve. This method, however, does have one serious drawback. The snow cover is assumed to be evenly distributed above the particular snow line elevation for that time interval. Areas which have been blown free of snow, which have melted on south-facing slopes or which contain snow obscured by clouds are not taken into account. This method therefore should be used only when direct areal measurements cannot be made.

Temporal Analysis

The general technique for determining ground cover changes between two passes is known as change detection. Several methods of analysis exist to do this. The data can be manipulated before any classification is done and classified later, or the change detection can be done after the classification is completed.

For this study classifications were made for the area on the various dates, and then these classifications were compared. Before the classifications were attempted an overlay was made which aligned the data so a ground point could be located by the same line and column coordinates. Channels 1-4 are the first date, and channels 5-8 are the second date so that two classifications exist for the same run number, the same area, but different sets of channels.

This program was used to analyze the snow classification results as an aid to analyzing re-distribution patterns of snow within watersheds and to display the results as a third 4-class classification. The diagram B.1. illustrates this process.

This program, CLASSCO, was run on the six classification results from the Animas River watershed. An example of this temporal analysis is shown in Figure B.8.

Table B.2. Snow acreage fluctuations.

Date	Percent snow cover	Total area (acres)	Variation
1 Nov. 1972	76.1	27636	
19 Nov. 1972	68.3	24791	10.2% decrease since Nov. 1
12 Jan. 1973	62.6	22731	8.3% decrease since Nov. 19
30 Jan. 1973	65.1	24757	8.9% decrease since Jan. 12
18 May 1973	81.0	30803	19.7% increase since Jan. 30
5 June 1973	87.5	33275	7.4% increase since May 18

The results of this comparison produce a third classification consisting of four classes: class one is snow on both dates; class two is snow on date 1 and non-snow on date 2; class three is non-snow on date 1 and snow on date 2; class four is non-snow on both dates. Classes one and four indicate no change while classes two and three do show change.

The number of possible classes in the result is multiplicative, i.e., the number of classes in the result is the serial multiplication of the total number of classes for each date. In equation form this is:

$$F = \prod_{i=1}^{N} C_i$$

where F is the total number of resultant classes, C_i is the number of classes in the classification of date 'i', and N is the total number of dates (or classifications) to be compared.

Snow Monitoring Cost Study

A preliminary cost study of this procedure was made to determine the feasibility of measuring snow cover fluctuations with satellite data by computer aided analysis techniques.

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                     LABORATORY FOR APPLICATIONS OF REMOTE SENSING
                                  PURDUE UNIVERSITY

       CLASSIFICATION STUDY  325548065              CLASSIFIED           SEPT 12,1973
                       CLASSIFICATION TAPE/FILE NUMBER ...    59/  6

                                    CHANNELS USED
                                  -----------------

CHANNEL  2     SPECTRAL BAND  0.60 TO  0.70 MICROMETERS    CALIBRATION CODE = 1     CC = 0.0
CHANNEL  4     SPECTRAL BAND  0.80 TO  1.10 MICROMETERS    CALIBRATION CODE = 1     CC = 0.0

                                       CLASSES
                                     -----------

          CLASS     WEIGHT                                          CLASS    WEIGHT
    1     NS-  1/   0.000                                  2     NS-  2/   0.000

                                TEST CLASS PERFORMANCE
                              --------------------------

                                             NUMBER OF SAMPLES CLASSIFIED INTO
        GROUP         NO OF   PCT.
                      SAMPS   CORCT     NS-  1/    NS-  2/

    1 NS-  1/         32367   76.2      24654      7713
                      -----             ----       ----
        TOTAL         32367             24654      7713

 OVERALL PERFORMANCE(      24654/      32367) = 76.2
 AVERAGE PERFORMANCE BY CLASS(   76.2/  1) = 76.2
```

Figure B.5. Snow cover calculation.

The classifications with two channels and two classes cost \$0.06/square mile/pass. The costs incurred by increasing the number of channels to increase the accuracy of the classification causes the CPU time to increase exponentially (Coggeshall and Hoffer, 1973). This was one reason for specifying only two channels for the classification procedure.

The CPU time required for the preprocessing techniques was substantially higher than the classification, and may or may not be considered necessary to obtain sufficient information. An 80 square mile area surrounding the Animas watershed was used for calculating the preprocessing CPU costs.

The cost of the geometric correction for the 80 square mile area was \$2.02/square mile which included \$1.75 in fixed costs and \$0.27 in variable costs. Thus the cost/area could be substantially reduced by correcting much larger portions of the ERTS frames.

The cost of one ERTS (4 channel) overlay for two dates on the 80 square mile area was \$8.90/square mile which included \$8.00 in fixed costs and \$.90 in variable costs. Again the cost/area could be reduced by overlaying larger areas.

All of the time and cost estimates are based on the use of the LARS IBM 360/67 general purpose computing system. This system demonstrates how remotely sensed data and computer aided analysis techniques can provide timely, quantitative determinations of snow cover in an inaccessable, but highly important region. ILLIAC or other high speed, special purpose computing systems can make this snow monitoring analysis much more cost effective.

Field Survey

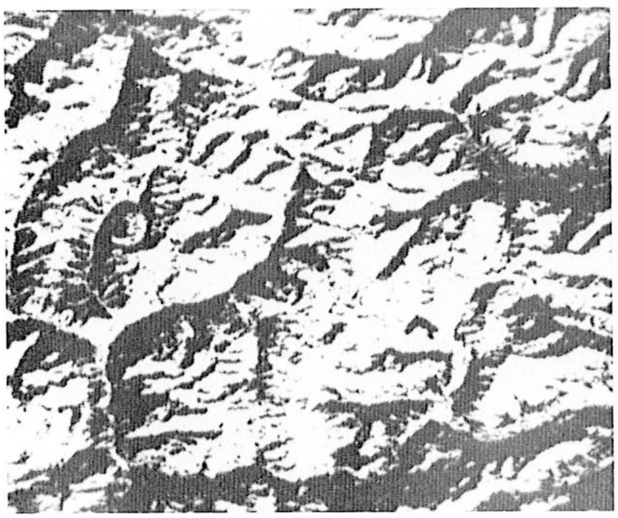
The purpose of this field study was to monitor diminution of the winter snow pack. The area studied was along the Eastern Slope of the Front Range between Rollins Pass and Estes Park. Altitudinally the site lay between 2,700 m and the Continental Divide (4,000 m).

The area observed was approximately 900 km^2 and exhibited an elevational range of 1,300 m. A variety of topographic and vegetational conditions were represented including glacial bowls, stream drainages, tundra and coniferous forest. All observations were made on the eastern side of the mountains.

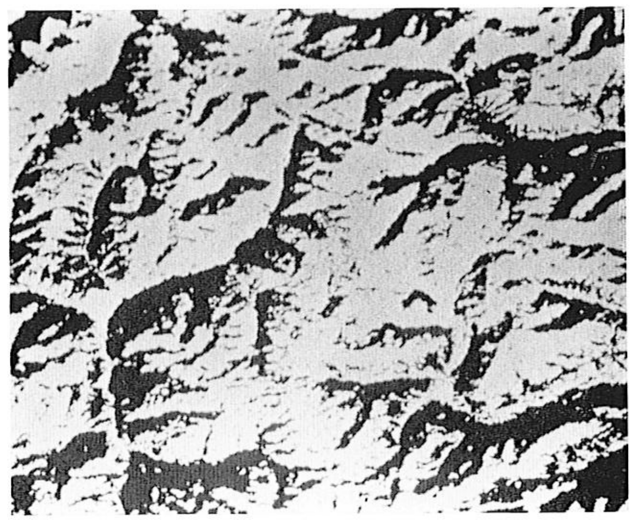
Once every 7-10 days, observations were made at 14 points along a north-south transect from Estes Park to Rollinsville and, from a panoramic viewpoint on Fairview Peak (2,515 m northwest of Jamestown). On days coinciding with ERTS-1 overpasses, ground photographs of individual snow collection areas as well as the entire study area were taken. Quantitative information from observation of the 14 points is in the

A. 1 November 1972, 1101-17203

B. 19 November 1972, 1119-17204



C. 12 January 1973, 1173-17202



D. 30 January 1973, 1191-17204

E. 18 May 1973, 1299-17205

F. 5 June 1973, 1317-17204

Figure B.6. Classification results.

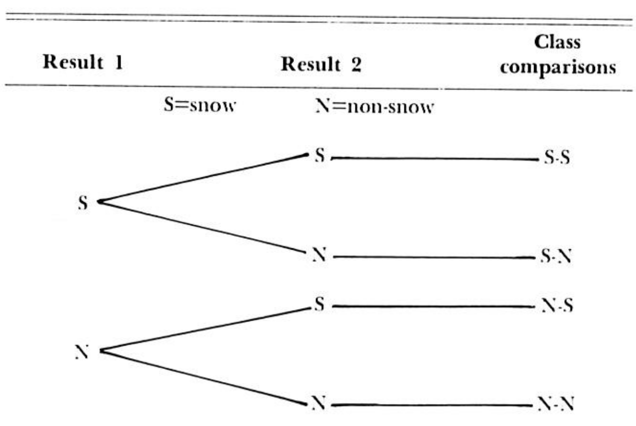
form of percent snow cover of a given slope, percent snow cover of a particular collection area, and elevation of the lower snow line (an appendix of the field notes taken from June through August, 1973, is also included in this report). The study area can be divided into four general areas: Rollins Pass/Tolland, Indian Peaks/Sawtooth Mountain, Longs Peak, and Estes Park. As the winter snow pack broke up, necessitating observation of more specific sites, each of the four areas was further divided into a number of specific bowls and areas. Preliminary study of the geometry of snow bowls and subsequent use of elementary surveying methods of measurement would be necessary. Field reports through June 27, 1973, consist of observations of each of the four general areas. After 27 June each bowl or patch is described and discussed separately. Determination was made of a profile of the skyline peaks of the study area from Fairview Peak, with major peaks verified by alidade and plane table methods.

One conclusion drawn from observations made during this field study is that the snow melt was characterized by three phases. The first lasted from the time of the last snow on June 4 until the end of June. During this period the melt proceeded uniformly along the entire transect as was shown by the recession of a continuous snow line which extended the length of the transect. There was differential elevation of this line depending on aspect of the slope. On N-facing slopes, the lower snow line was approximately 30-60 m lower than on S-facing slopes, but even this difference was consistent within the entire study area. Presumably the melt rate during this period was governed primarily by factors capable of having general inflence over an area of 900 km^2, such as climate, or by factors such as elevation whose influence would be consistent regardless of other local conditions. During this period quantitative observations were made in terms of elevation of lower snow line.

The advent of the second phase of the snow melt pattern was characterized by the disappearance of the continuous lower snow line in late June. By June 27, this line was no longer visible from the ground, and snow cover appeared to be limited to discontinuous areas on a given slope or collection of slopes. During this period it seemed that the melt rate was controlled less by such general factors as weather and elevation than by factors causing differential melt within a particular local area, such as slope exposure, percent grade of slope, topography, substrate and vegetation cover type. Quantitative observations during this period were made relative to percent snow cover on a particular slope. Effect of sight angle viewing from downslope will tend to underestimate size of snow patches which linger on the upwind side of surface irregularities.

As the summer progressed the melt pattern changed again, although at a point in time which was different for each area. During this third phase the snow was

Diagram B.1.



S-S Snow cover on both dates
S-N Snow cover changing to non snow cover
N-S Non-snow cover changing to snow cover
N-N Non snow cover on both dates

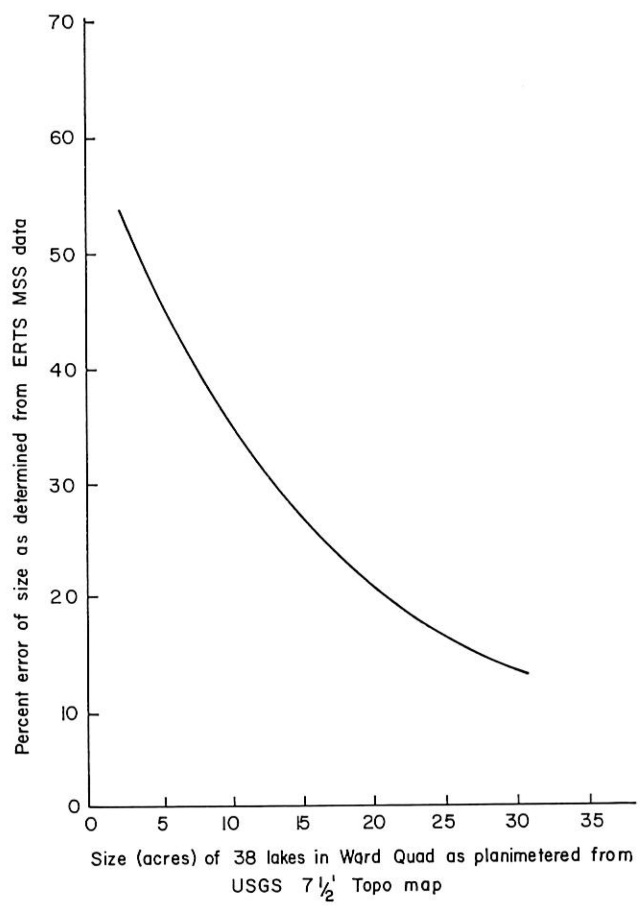


Figure B.7. Hyposometric analysis.

entirely restricted to isolated collection areas which retained the snow long after nearby areas having the same aspect, elevation and exposure to weather were snow free. Presumably substrate, local relief, and microclimate were now primary among the factors limiting diminution of snow cover. During this phase quantitative information was recorded in terms of percent cover of the original collection area.

Results

1. The lower limits of snow cover were routinely demarcated on topographic maps. The high peaks had total winter snow cover during early-mid June. The visible slopes above 3,000 m had 80-90% cover on 6 June diminishing to 25-30% cover on 15 August and 5% on 23 August, except above 3,500 m where approximately 20% cover remained on 23 August. The lower limit of snow cover rose by approximately 60 m/week until the cover became discontinuous on 27 June.

2. Observations were made in July-August on 12 selected snow bowls (depressions) and 10 snow patches (flatter sites) representing a variety of topographic, elevational, and directional situations. By 23 August, 3 bowl sites and 5 snow patch sites were clear of snow. Field measurements on 3 patches gave approximate extent of snowcovered areas in the range of 22,500-76,000 m^2 on 23 August, representing generally 25-40% of the topographic depressions filled with snow in June.

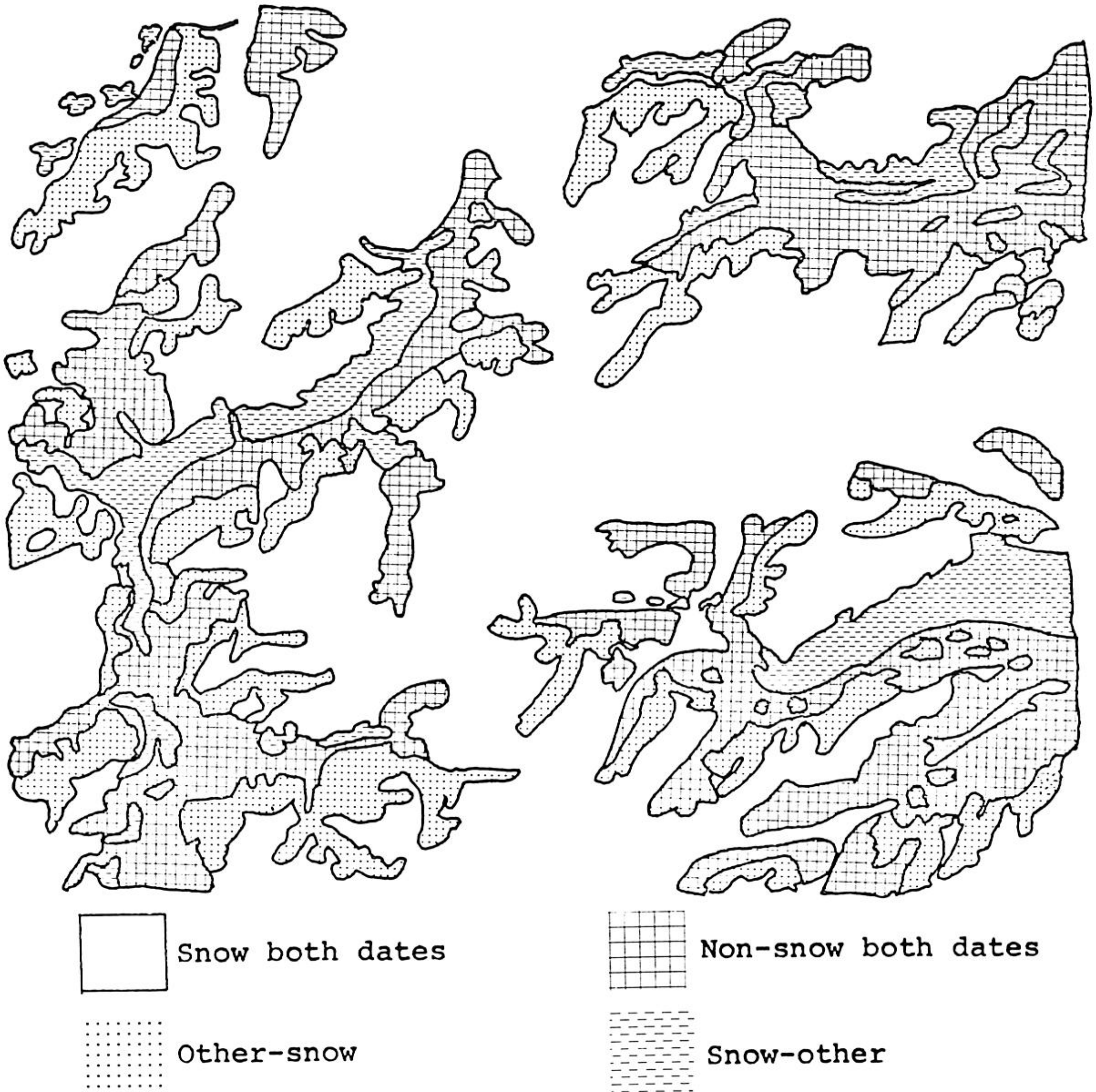


Figure B.8. Temporal analysis of ERTS scenes 1299-17205 and 1317-17204—comparison of 18 May, 1973 and 5 June, 1973.

3. Comparison of the snow cover extent observed in the field at selected sites on southeast-facing slopes of Niwot Ridge (Front Range) above approximately 3,400 m, with nearby measurements of net (all-wavelength) radiation, is shown in Figure B.9. The net radiation data were obtained by E. LeDrew in connection with an I.B.P. Tundra Biome Program (Project 6741 Energy Budget of the Alpine Tundra, Colorado). This project refers to averages for daylight hours when the net radiation is positive (averaged over 5-day periods). The shape of the snow cover depletion curve is closely similar to those presented by Leaf (1971) for the second half of the melt season on the watershed in the Fraser Experimental Forest. The periods of rapid melt in early July and again from 8-20 August appear to coincide with spells of high net radiation (i.e., energy available for melt).

Discussion

The field data has shown that there is a temporal factor in the diminution of snow cover which should be considered in making areal and volumetric estimates of the winter snow pack. Furthermore, there may be a pattern to the temporal diminution in which the value of a particular factor influencing melt varies in time with its degree of local influence.

Another implication deriving from the methods employed in the study is that the diminution of winter snow pack in the Front Range of the Colorado Rockies is characterized by its occurrence over a very large physical area as well as by its transient internal conditions. This problem does not lend itself easily to quantitative observations. The size of the area made it difficult to become familiar with the entire study site in a short time as well as to cover the entire area comprehensively.

The skyline profile of the major peaks in the study area was invaluable in enabling the observer to locate himself in reference to observation sites often removed by a distance of several miles. Another problem caused by the large study area was that of the impracticability of making on-site observation and measurement, and thus, only estimates could be made.

For comparison with the data on diminution of snow cover, we have taken runoff and precipitation records from the basin of the North Boulder Creek watershed (27.8 km^2). The gaging station for the watershed is located at 2,885 m (40°00′51″N, 105°33′20″W), and the precipitation station is in the Green Lakes Valley at 3,570 m. Sixty-five percent of the basin is tundra and thirty percent forest. Runoff totals were provided on a daily basis by T. Platt (City of Boulder), and precipitation records and evaporation estimates (based on 0.4 x potential evaporation, determined from energy budget measurements) were provided by T. Carroll (INSTAAR). The reduction of snow covered area (in the Front Range section) and the snowmelt runoff estimated from these data for the basin are shown in Figure B.10 which can be compared with the results of Meier (1973). These results, while not definitive, are at least suggestive of the potential application of data on snow cover reduction to water yield in alpine and subalpine areas of the Rocky Mountains where conventional hydrological data are scarce and costly to obtain. Given more frequent satellite coverage, in order to guarantee obtaining clear frames at about 7-day intervals, and selected point observations on snow pack depth and water equivalent, it is probable that useful estimates of water yield could be readily provided on a routine basis for a fraction of the present monitoring costs. Other difficulties arose from the transient nature of snow conditions. The purpose of the study was that of monitoring snow changes and presumably the rate of change is not constant. Consequently, more frequent observations might be required at one time than another.

A further problem developed from the unquantifiable nature of observations of snow changes. This difficulty is due in part to lack of on-site observations, and the consequent use of estimates and subjective judgments. However, the greater part of the problem is due to the fact that the nature of the process

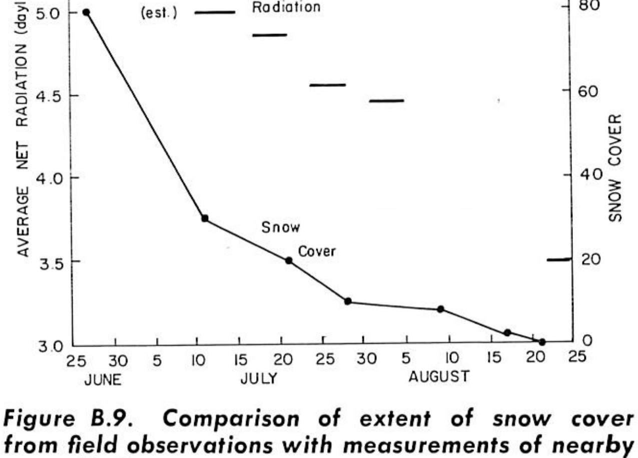


Figure B.9. Comparison of extent of snow cover from field observations with measurements of nearby net radiation.

being observed changed completely over the period of observation such that the parameters described at the beginning of the field season were not those described at the end. For example, initial observations were descriptions of the elevation of the lower snow line and some general observations regrading the rate of ascent of this line. When the winter pack broke up into patches during the last week in June, this type of observation was no longer useful. The descriptive method became the percent of snow cover of various characteristic slopes. However, a "slope" is in most cases an arbitrarily defined entity. Except for aspect and elevation there was rarely an objective standard by which one slope could be differentiated from the next. Also, at some point which differed for each site, the winter snow pack was reduced entirely to separate and distinct collection areas, all other surfaces being bare. This change of conditions once again rendered previous types of description inapplicable. Where the snow cover was described in terms of percent cover of an entire slope, the descriptions were then in terms of percent cover of the particular collection area.

Lack of data from previous years was a limitation. With the exception of some obvious glacial bowls, the collection areas which were to hold snow all summer could not, in July, be distinguished in any way from those which were to melt off in several weeks time. The consequence was that observations were being made on several scales simultaneously: elevation of lower snow line, percent cover of total slope, and percent cover of each particular collection area.

Suggested Methodology for Snow Cover Observations

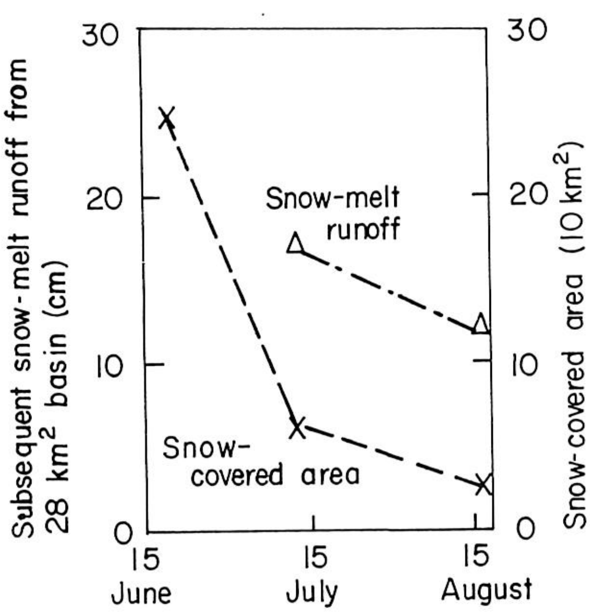
I. Preseason observer preparation

A. In the lab

1. The observer should gain familiarity with the objectives of his field work through discussion with his supervisor, perusal of the grant proposal, and reading of similar work done elsewhere.
2. The observer should gain familiarity with the particular area to be studied through perusal of previous years data, U.S.G.S. and U.S.F.S. aerial photography, and any available satellite and underflight frames.

B. In the field

1. A preliminary field run should be made by the observer with a view to being able to spot with accuracy the areas under observation on U.S.G.S. topographic sheets.
2. A field itinerary should be prepared, taking into account the facts that the utility of various points for observations varies as the season progresses, that some sites are best approached from one direction and other sites are best approached from another direction, and that some observations are best made from a distance of many miles.
3. Observation sites should be shot with a Haga altimeter to provide an accurate standard for future elevational estimates.



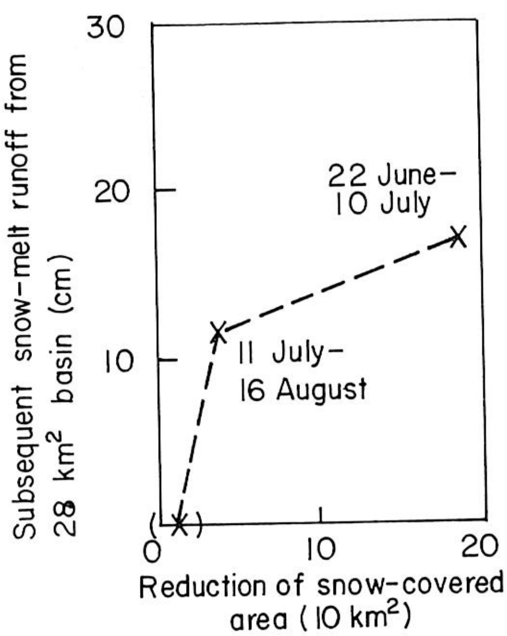


Figure B.10. Reduction of snow-covered area and snowmelt runoff estimates.

4. The observer should attempt to locate each persistent collection area in the field with the aid of previous years' maps and ground photography in order to make consistent observations on subsequent field runs.
5. A preliminary observation from the panoramic viewpoint should be made to provide a sense of scale for later observations as well as a general view of the area as a whole.
6. Field materials should be gathered. These include: 7.5 minute U.S.G.S. topo sheets of the entire study area, U.S.G.S. 1:250,000 sheets of the study area, camera and film, data sheets, xeroxed copies of portions of the 7.5 minute topo sheets showing each observation site for mapping purposes (one for each field run), binoculars, Haga Altimeter.

II. Field observaton from automobile and panoramic view point

A. Each field observation should be recorded on a standard data sheet (Figure B.11).

B. Each field report should be accompanied by ground photographs if possible.

C. Ground reconnaissance and measurement of area and depth of accessible collection areas should be scheduled and completed as early as weather and melt conditions permit.

Evaluation of INSTAAR Interpretation of ERTS-1 Imagery for Snow Cover Mapping

The potential utility of ERTS-1 for monitoring snow cover diminution was evaluated on the basis of photo-interpretation of ERTS-1 imagery for the Front Range and San Juan study sites. Image interpretation was limited to a 15 km strip (750km^2) of the Front Range Ground Study Area which extends for 50 km from Rollins Pass northward to Estes Park. This subsection was the largest unit for which coverage was available and at least 80% cloud-free on all frames for the spring-summer period under consideration. Ground study covered the period from 6 June to 16 August, 1973. Frames for 1334-17135, 1352-17134, 1370-17133, and 1588-17131 were used in the manual interpretation evaluation (Figure B.12.).

The San Juan study site was restricted to the Cunningham Gulch watershed on the Animas River

```
Date:                                  Field Measurement__Panorama__Auto Run__

Weather description:


Observation Point

Area observed:                                        Patch or Bowl #___

Boundaries of area observed:
  Elevation range_________ft.
  Horizontal range________ft.

Other descriptive features:
  Aspect:
  Vegetation cover type:
  Substrate:

Percent snow cover of area:
  Total slope________%
  Collection area_________%

Melt pattern:

Ground photo Identification:
  Roll #___
  Photo #___

Field measurements:
  Depth___  Area___

Other observations:
```

Figure B.11. Sample data sheet.

drainage. This area is located northeast of Silverton, Colorado. The site was at least 80% cloud-free on frames for 5 June and 29 June but was 80% cloud-covered on frames for 29 July and 16 August. The site was altogether excluded on the 11 July frame (Figure B.13.). No ground observations were made.

Image interpretation consisted of mapping either the lower snowline or the boundaries of discrete snow patches from each overpass image onto base maps with the Bausch-Lomb Zoom Transfer Scope. The United States Geological Survey, Western United States 1:250,000 series were used for the base maps, the Greeley sheet for the Front Range, and the Durango sheet for the San Juans.

The snowline on the clear frames could be determined with confidence to the nearest contour (60 m)

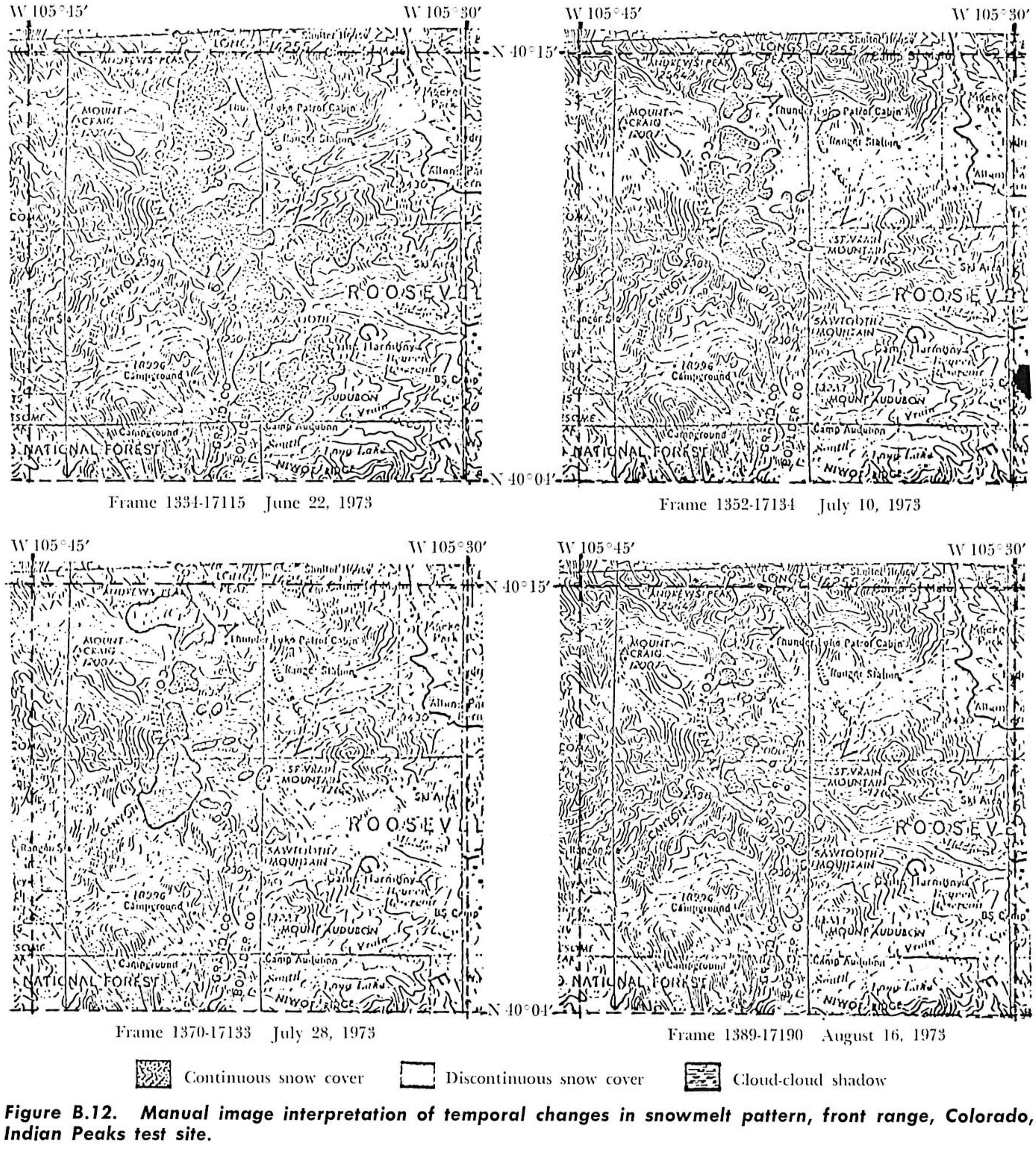


Figure B.12. Manual image interpretation of temporal changes in snowmelt pattern, front range, Colorado, Indian Peaks test site.

interval, as reported also by Meier (1973) for mapping at the 1:250,000 scale. We found that the use of the Zoom Transfer Scope helps to eliminate some of the subjectivity of snowline determination.

In evaluating the usefulness of the ERTS-1 imagery, two factors were considered: first, the effectiveness of the satellite overpass system as a means of monitoring snow cover changes; second, the suitability of the imagery as a basis for snow cover mapping.

The 18-day interval between overpasses provided six passes during the summer field season from 5 June (1317-17204) through 3 September 1972 (1407-17193). Cloud cover greater than 50% rendered two of the six images for the Indian Peaks test site usable for snow mapping at each of the two study sites. Scheduling the overpass even earlier in the morning, or scheduling two overpasses on subsequent days, could help to resolve this problem. All or part of the study area was excluded from the frame on three Front Range passes and one San Juan pass due to the particular orientation of the image.

The snow-covered area in the Front Range study site decreased over the period as follows:

	Percent of area ($750 km^2$)
22 June (1334-17134)	33.5
11 July (1353-17192)	8.3
16 August (1389-17190)	3.2

These figures exclude snow cover beneath forest canopies. Coniferous forest vegetation blocked reflectance from underlying snow. Early in the season, before the snowline has receded above the montane forest zone, this problem may introduce a substantial error. However, it is worth noting that assessment of snow cover beneath trees presents major difficulties also with respect to field observations.

Suitable imagery was available for the Cunningham Gulch site only on 5 June (1317-17204). The snow-covered area was 43.8% of the total study site with an estimated additional 32.5% for snow cover under upper montane forest, giving a total of 76.3%.

The field observations in the Front Range, discussed above, demonstrated temporal changes in the snowmelt pattern. Three stages were recognized (Figure B.12.). The first stage appeared from the ground to terminate with the break-up of the homogenous winter snow pack into patches between the observations of 20 June and 27 June. Imagery from the 28 June overpass shows the lower snowline to have broken up in many places along the transect. However, the timing of this phenomenon cannot be pin-pointed due to cloud obscuration on the preceding pass on 22 June. The second state was the melting of the snow fields until only persistent patches remained and the third stage was the gradual melting in these accumulation sites. Both stages are observable on the imagery as well as in the field. However, many of the persistent patches had a final minimum area of 0.02 km^2 or less and were not visible on the imagery.

Identification of snow patches visible on the imagery throughout the 1973 field season suggests areas for further ground observation.

The ERTS system has obvious advantages over conventional methods of monitoring snow cover changes.

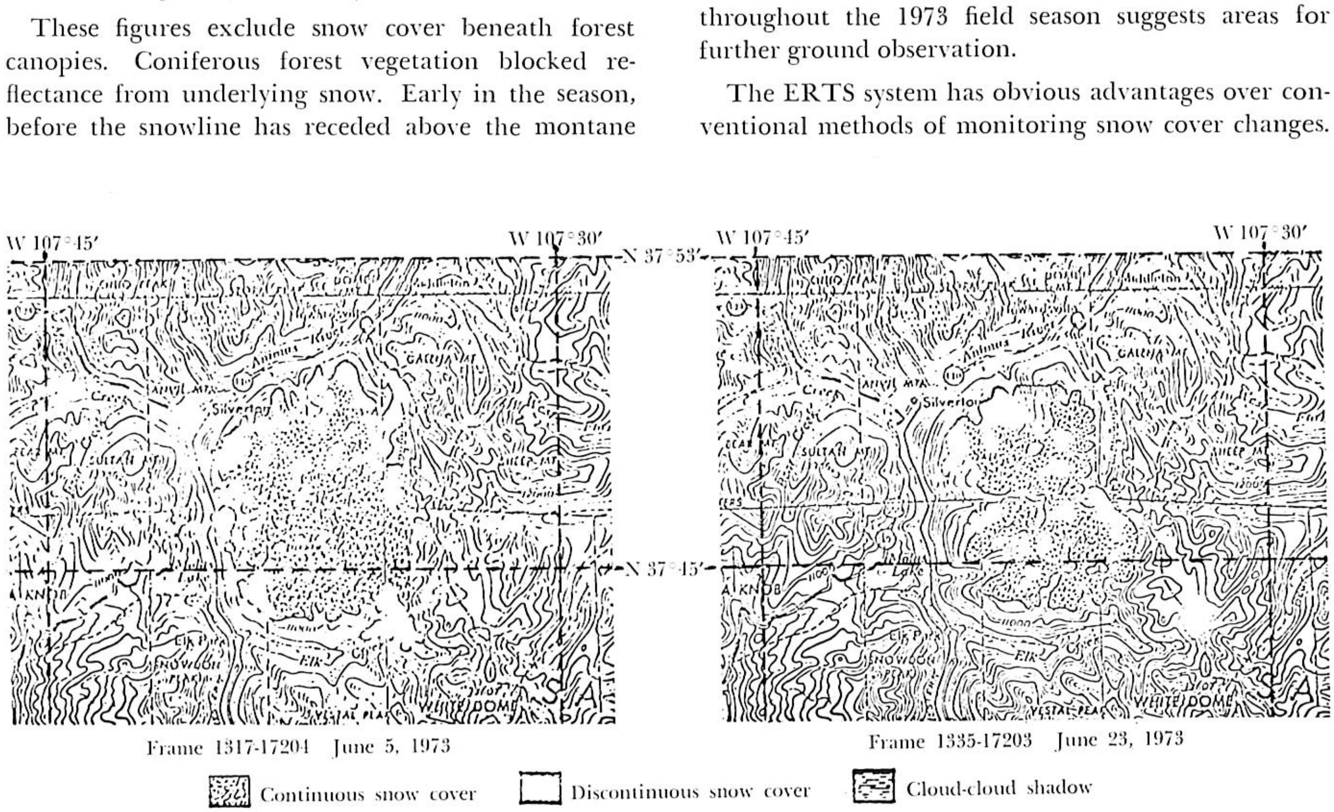


Figure B.13. Manual image interpretation of temporal changes in snowmelt pattern, Cunningham Gulch watershed near Silverton, Colorado, San Juan Mountains test site.

In particular, the satellite is able to survey a study area which is vast, difficult of access, and often invisible from the nearest roads. A further advantage lies in the satellite's potential capability of recording temporal changes with some degree of accuracy.

The chief problem in the manual mapping effort from ERTS-1 imagery resulted from resolution limitations of the imagery at a scale of 1:250,000. Patches less than 1 km on a side could not be located with accuracy. A larger scale would facilitate the mapping procedure as well as increase the accuracy of planimetric calculations.

Image interpretation techniques alone allowed separation of three cover classes: 100% snow cover, 100% snow free, and intermediate degree of cover. Although the intermediate class was observable on the imagery, it could not be separated visually from the other classes when the cover became discontinuous. Field observations in the Front Range confirmed the presence of various intermediate stages ranging from 10% to 50% snow cover. Automatic data processing techniques would be useful in making finer distinctions among classes, but extensive field checking with ADP produced maps would be necessary to establish quantitative descriptions of such classes.

The field work done in conjunction with the ERTS-1 overpasses was of value in providing direct knowledge of the areas being mapped manually. Depth measurements made in the field would extend the utility of the imagery by one dimension since volumetric calculations could then be made. The field observations were also useful in attaching an approximate value to coverage classes, and would be even more useful in subsequent years as specific selected areas could be closely monitored.

SPECTRAL DIFFERENTIATION OF SNOW AND CLOUDS

Determining the capability to use ERTS-1 data for spectral differentiation of snow and clouds has been another important objective of the Hydrological Features Survey. Such a capability is mandatory if accurate classification and areal estimates of snow cover (discussed in the previous sections) are to become operational by using computerized analysis techniques.

A detailed statistical analysis has been completed on frames 11-01-17203 (Nov. 1, 1972), 1136-17141 (Dec. 6, 1972), and 1299-17205 (May 18, 1973). These frames contain portions of the State of Colorado in which the ground elevation exceeds 5,000 feet. All areas include snow cover and clouds.

These areas of cloud and snow were outlined on the digital display to obtain the line and column coordinates. A photograph of frame 1299-17205 with the area boundaries is shown in Figure B.14. The areas were defined as snow and cloud by photointerpretation, and attention should be paid to shadow patterns usually associated with such cumulus clouds. The interpreters could see no difference in spectral response in any wavelength band available on ERTS-1.

Statistics of the spectral response of these were then obtained from LARSYS and compared. Figure B.15 contains the coincident spectral plots, means and standard deviations for clouds and snow respectively for the data obtained on November 1, 1972 (1101-17203), December 6, 1972 (1136-17141), and May 18, 1973 (1299-17205). These results indicate saturation by clouds and snow of all four channels of the ERTS-1 multispectral scanner system and therefore, the spectral separation of these clouds and the surrounding snow is not generally possible with the present system, even for dates ranging from November to May, which presumably would include a reasonable variation in snow conditions.

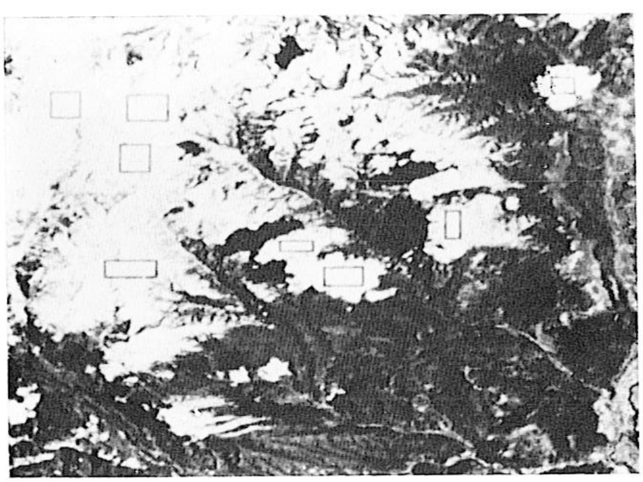


Figure B.14. Training fields of snow and clouds.

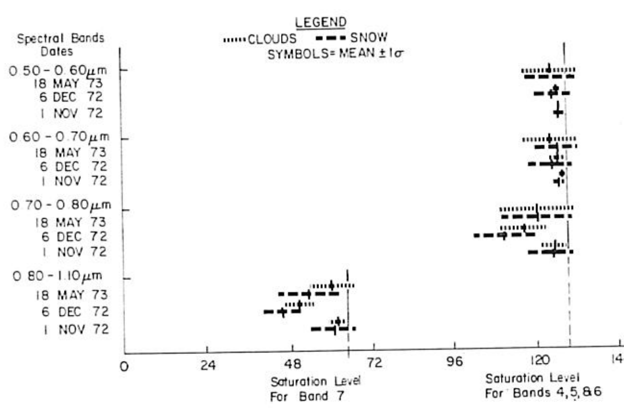


Figure B.15. Statistical analysis of the spectral response of snow and clouds.

FREEZE-THAW SEQUENCE OF MOUNTAIN LAKES

Previous photo-interpretation has demonstrated the feasibility of using ERTS imagery to study the freeze of mountain lakes. Therefore, four water bodies at various elevations were observed with this objective in mind. As expected, the water bodies at the highest elevations froze first. Table B.3 indicates the freeze sequence of the lakes according to the 18 day period of the satellite.

More frequent coverage of the test site by future satellites would yield sufficient data to make possible a study concerning the freeze-thaw sequence as a function of lake size and elevation. However, with the present 18-day period of ERTS-1 this is not possible.

SPECTRAL SEPARATION OF WATER AND SHADOWS

The objective of this investigation was to map the distribution in the areal extent of surface water in a mountainous environment. One of the difficulties foreseen was that of spectrally differentiating cloud shadows and water bodies. This difficulty also concerns the fifth objective (study the temporal aspects of the freeze and thaw of mountain lakes) in that clouds and consequently cloud shadows were expected to be in the vicinity of the specified test sites during the critical freeze and thaw periods.

The first step in accomplishing the spectral differentiation was to define areas of water and cloud shadow. This was accomplished on the LARS Digital Display. An example of this phase of the analysis sequence is shown in Figure B.16. The statistics for the areas were then requested from the LARSYS

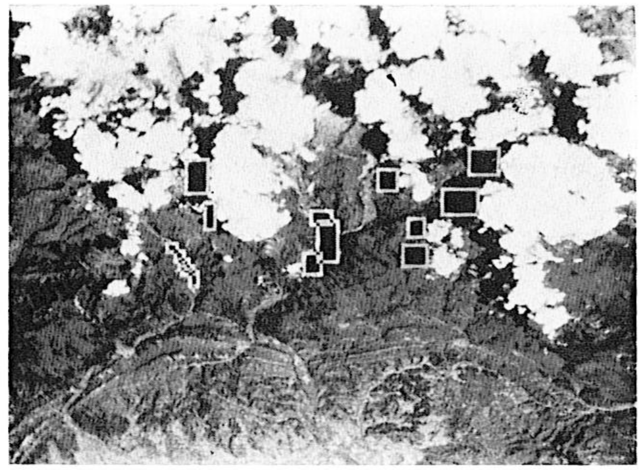


Figure B.16. Training fields of water bodies and shadows.

Table B.3. Freeze-thaw sequence of mountain lakes as determined from ERTS data.*

Elevation																														NAME
9800'																														
9600'	O	C	C	P	F	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	F	N	F	F	Rio Grande
9400'	O	C	C	P	F	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	F	N	F	F	
9200'	O	C	C	P	F	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	F	N	F	F	
9000'	O	C	C	P	F	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	F	N	F	F	
8800'	O	C	C	P	F	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	F	N	F	F	
8600'	O	C	C	P	F	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	F	N	F	F	
8400'	O	C	C	O	O	F	F	F	F	F	F	F	N	F	O	O	O	O	O	O	O	N	O	O	N	P	N	F	F	Electra
8200'	O	C	C	O	O	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	O	N	F	F	Lemon
8000'	O	C	C	O	O	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	O	N	F	F	
7800'	O	C	C	O	O	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	O	N	F	F	
7600'	O	C	C	O	O	F	F	F	F	F	F	F	N	O	O	O	O	O	O	O	O	N	O	O	N	O	N	F	F	Vallecito

9/8/72 11/19 1/30/73 4/30 7/11 9/21 12/2 2/12

Date of ERTS Overpass

* O-open, C-clouded, F-fronze, P-partially frozen, N-not available.

software package. The resulting graphical comparison of spectral response of water and shadow areas is shown in Figure B.17. Interpretation of this graph indicates that the spectral differentiation can be obtained through use of ERTS-1 data from the visible portion of the spectrum, but not in the reflective infrared wavelengths.

LAKE INVENTORY

One of the objectives defined as part of the Hydrological Features Survey in the ERTS-Colorado proposal was to map the distribution and areal extent of surface water. Early in the project, it was quite obvious that large water bodies could be accurately identified and mapped using the two infrared channels available from the ERTS data, providing topographic and cloud shadows did not cause confusion. The difficulty in spectrally separating water and shadow areas has been described above. Because of the resolution of the ERTS scanner system and the large number of small lakes, one of the key questions involved in this project involved the evaluation of the ERTS scanner system for identifying and locating these small water bodies.

The Indian Peaks Test Site (particularly Ward Quad) was used for this analysis. USGS topographic maps were used to identify and number all lakes less than 50 acres in size in the Ward Quad, and planimeter estimates of the areas were then obtained from them. The ERTS data were then analyzed by computer, and a classification map indicating all water bodies identified by the computer-aided analysis techniques was printed out. A previously defined conversation factor of 1.1487 acres per ERTS resolution element was utilized to calculate acreage for all of these water bodies identified on the computer printout. A graph was plotted to show the results of the acreage comparison for each of the lakes involved.

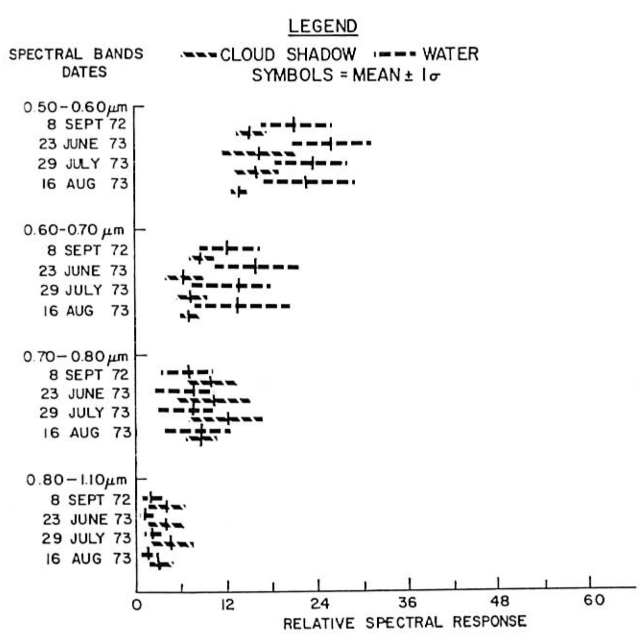


Figure B.17. Spectral response of shadows and water bodies.

The abscissa of that graph indicated the size of 38 lakes in Ward Quad, Colorado. Forty-three lakes are actually contained within the Quad; however, the remaining five were so varied in size and substantially larger than the others that a representative sampling could not be obtained and hence they were deleted.

The ordinate of the graph indicates the percent error as obtained by:

$$\text{Error} = \frac{|A_E - A_M|}{A_M} \times 100$$

Where A_E = area obtained from ERTS
A_M = area obtained from USGS map

The resulting best-fit curve was generated from a second order polynomical regression program.

The curve indicated a general trend of the error of areal estimation as determined by ERTS (as compared to a USGS topo map) exponentially decreasing as the area increases. However, this curve should not be used to interpolate or extrapolate absolute accuracies by any investigator.

Lake Inventory Classification

The initial objective of the lake inventory was to provide base data to assist in the analysis and interpretation of the temporal and spatial patterns of freeze-up and break-up of water bodies in a section of the Colorado Front Range. The limited availability of clear frames about the critical dates eliminated this project, but the lake inventory was used to evaluate the utility of ERTS data for mapping the distribution of surface water bodies and determining their areal extent. This problem is of vital interest in terms of water availability for domestic and commercial consumption in the Piedmont area, for industrial process, especially those relating to potential oil shale developments, and for recreational purposes.

Inventory

Data were taken from fourteen 1:24,000 U.S.G.S. quadrangles, covering a section from Rollins Pass to Trial Ridge, on all lakes (961) with a long axis greater than 50 feet (15m). Lake area was estimated from the area of an ellipse fitting the long axis, and one perpendicular to it at the widest point of the water body. Elevation of the lake was referred to the nearest 40 ft. contour below the lake. Table B.4 summarizes the lake areas by elevation for the eastern and western slopes.

Table B.4. Lake areas by elevation for the eastern and western slopes.

Elevation	AREA CATEGORIZATION (IN THOUSANDS OF SQUARE FEET)										Total
	< 22.5	22.5-50	50-100	100-250	250-500	500-750	750-1000	1000-2000	2000-5000	>5000	
	Square feet										
EASTERN SLOPE											
7200	35,325	35,325	0	0	0	0	0	0	0	0	70,650
7600	78,500	190,362	0	1,091,150	0	0	0	0	0	14,012,250	15,372,262
8000	182,748	200,175	761,450	192,325	0	0	0	0	2,256,875	7,899,062	11,692,635
8400	569,831	655,475	561,275	1,254,037	1,177,500	0	879,200	1,632,800	0	0	6,730,119
8800	690,800	386,612	192,325	1,159,837	1,566,075	1,083,300	942,000	0	0	0	6,020,950
9200	298,300	414,087	459,225	453,337	647,625	1,163,762	918,450	0	0	8,030,550	12,385,337
9600	190,362	492,587	113,825	955,737	757,525	518,100	800,700	0	0	0	3,828,837
10000	261,012	498,475	506,325	1,036,200	1,157,875	576,975	1,758,400	0	3,159,625	0	8,954,887
10400	261,012	209,987	445,487	993,025	1,783,912	1,738,775	2,488,450	5,226,137	3,159,625	0	16,306,412
10800	296,337	514,175	633,887	1,491,500	1,254,037	3,293,075	0	3,981,912	4,121,250	0	15,586,175
11200	425,862	410,162	877,237	1,781,950	2,653,300	3,300,925	969,475	2,892,725	0	0	13,311,637
11600	247,275	382,687	418,012	788,925	5,216,325	3,752,300	0	1,267,775	0	0	12,073,300
12000	45,137	0	149,150	808,550	0	588,750	867,425	0	0	0	2,459,012
12400	3,925	86,350	0	0	0	0	0	0	0	0	90,275
12800	0	0	0	0	0	0	0	0	0	0	0
13200	0	0	0	0	251,200	0	0	0	0	0	251,200
TOTAL	3,586,429	4,476,462	5,118,200	12,006,575	16,465,375	16,015,962	9,624,100	15,001,350	12,697,375	29,941,862	124,933,692
WESTERN SLOPE											
7200	0	0	0	0	0	0	0	0	0	0	0
7600	0	0	0	0	0	0	0	0	0	0	0
8000	0	0	0	0	0	0	0	0	0	0	0
8400	19,625	0	78,500	0	0	0	0	0	0	6,908,000	7,006,125
8800	0	0	0	0	0	0	0	0	0	0	0
9200	11,775	0	54,950	0	0	0	0	0	0	0	66,725
9600	39,250	0	0	153,075	0	0	0	0	0	0	192,325
10000	82,425	98,125	0	235,500	1,122,550	0	0	1,868,300	0	0	3,406,900
10400	51,025	58,875	149,150	0	677,062	706,500	0	1,161,800	0	0	2,804,412
10800	266,900	229,612	117,750	726,125	1,880,075	1,136,287	816,400	1,444,400	0	0	6,617,550
11200	382,687	396,425	516,137	1,256,000	1,911,475	0	816,400	0	0	0	5,279,125
11600	143,262	180,550	78,500	157,000	0	735,938	967,512	0	0	0	2,262,762
12000	7,850	0	0	0	0	0	0	0	0	0	7,850
12400	0	0	0	0	0	0	0	0	0	0	0
12800	0	0	0	0	0	0	0	0	0	0	0
13200	0	0	0	0	0	0	0	0	0	0	0
TOTAL	1,004,800	963,587	994,987	2,527,700	5,591,162	2,578,725	2,600,312	4,474,500	0	6,908,000	27,643,775

Evaluation

The first step was to evaluate how representative the U.S.G.S. quadrangles were in regard to the portrayal of water bodies. The Ward quadrangle was chosen to determine the level of accuracy of: a) lakes included, and b) size of lakes. A Bausch and Lomb Zoom Transfer Scope was used to compare aircraft coverage with the base map. For the Ward quadrangle only 5 lakes ranging in size from 20 to 100 feet (long dimension) were not represented on the map. There are more than 100 lakes of various sizes shown. The percentage of non-recorded lakes is relatively small. For natural bodies of water no significant differences in water line due to seasonal changes were detected. For artificial impoundments the water line fluctuation is due to ownership control and does not reflect seasonal changes. Therefore, the total areal extent of water bodies not represented on U.S.G.S. quadrangles is anticipated to be negligible.

Approximate locations of 14 U.S.G.S. quadrangles were delineated on the printout (unscaled, geometrically uncorrected) of part of the Indian Peaks Test Site. Only NSCLAS-6 was displayed from a 6 class breakdown in anticipation that this would depict water bodies. This preliminary classification was evaluated by comparing the printout to the U.S.G.S. quad base maps, Mission 211 and Mission 248 aircraft coverage of the area, and ERTS imagery (Frame 1352-17134 bands 4, 5, 6, and 7).

Examination of the computer classification printout depicting water bodies indicated the following:

1. Water bodies which have a long axis less than 150 feet are not represented on the printout.

2. Water bodies which have a long axis 150 to 400 feet are usually not represented (only 5-10% are represented).

3. Water bodies which have a long axis greater than 400 feet are generally depicted (90-95%).

A major problem encountered relates to shadows which are also displayed on the printout. The preliminary classification has not separated shadows from water bodies. The shadows caused by clouds and topography were indicated on the printout. The location of one cloud obscured a cluster of four moderate sized lakes (Green Lakes #1, #2, #3, and #4 in the NW sector of the Ward quadrangle). In a few instances cloud shadow or topographic shadow was partially imposed on a water body which altered the shape and size as depicted on the printout. The orographic shadows at the time of the ERTS pass (0913 hours MDT) were primarily associated with steepened north-facing slopes, west- and northwest-facing slopes, and in general they were accentuated west of the Continental Divide.

The areal extent of each impoundment within the Ward quadrangle was determined by using a dot planimeter and a Bruning mylar dot areagraph (97% degree of precision). The results of the lake inventory using U.S.G.S. topographic map (1:24,000 scale) and ERTS-1 imagery (1:1,000,000 scale) indicate: 1) 134 water bodies are present in the Ward quadrangle with a size range of approximately 15 m to 1,200 m; and 2) a total water-covered area of 3,355,577 m^2.

SUMMARY

Results of this investigation have conclusively proven that the areal extent of snow cover in mountainous terrain can be mapped rapidly and economically by using ERTS-1 MSS data and computer-aided analysis techniques (CAAT), providing cloud free data can be obtained. Temporal changes in the areal extent of the snow cover were quantitatively determined by gometrically correcting the data to a scale of 1:24,000 and overlaying six data sets ranging in date from 1 November, 1972 to 5 June, 1973. This ability should give hydrologists a new tool for predicting runoff in a mountainous terrain.

A major problem encountered in this investigation however, was a difficulty in obtaining cloud free 18-day sequential data from ERTS. If one or two overpasses were clouded the frequency of coverage could rapidly be decreased to either 36 or 54 days which is unacceptable for hydrological or other dynamic phenomena. Therefore, the frequency of coverage of future Earth Resource Satellites should be increased to 6 or 9 days to alleviate this problem.

Analysis of three data sets has indicated that snow and clouds over a mountainous terrain cannot be spectrally differentiated with either the visible or near IR detectors in the ERTS-1 MSS. Two problems were encountered here. First, both the snow and clouds were causing the detectors to saturate and therefore provide the same spectral response for both cover types. However, clouds and snow were both believed to have the same spectral response in the visible and the near infrared portions of the electromagnetic spectrum. Therefore modifying the gain settings on the MSS would eliminate the saturation problem, but would not cause a spectral differentiation to occur. To alleviate this problem in future scanner systems, detectors in the middle infrared portion of the electromagnetic spectrum (i.e., 1.55 to 1.75μm or 2.10 to 2.35μm) should be included.

The accuracy of measuring the surface area of water bodies with the MSS data increases as the size of the lakes increase. For example, lakes which were smaller than five acres could not be determined with an accuracy exceeding 55%, while lakes larger than

25 acres could be estimated with an accuracy of approximately 85%.

The best spectral separation of water and shadows is provided by ERTS Band 4 (0.5 to 0.6μm). The other three bands indicated a similar spectral response for both water and shadows.

The freeze-thaw sequence of mountain lakes can be monitored from ERTS images. This can be done rapidly and accurately by using ERTS Band 7 which includes a water absorption region of the electromagnetic spectrum. Difficulties were again encountered however, with cloud cover over the test site which decreased the frequency to 36 or 54 days. Consequentially, unacceptable gaps occur in the data used for monitoring the freeze-thaw sequence of mountain lakes.

Section C
Geomorphological Features Survey

Contributors

LARS
W. N. Melhorn
S. Sinnock

INSTAAR
J. T. Andrews
M. Bovis
P. E. Carrara

Successful geomorphic analysis by computer aided analysis techniques presumes that a recognizable ecosystem is associated with geologic material and surface form. To map geologic materials by any remote sensing technique it is necessary to assume:

1. That subsurface materials will manifest themselves as spectrally separable classes at the earth's surface.

2. That lithologic types are naturally segregated into a limited number of discrete compositional and textural categories which can be recognized and classified by pattern recognition procedures.

ERTS-1 sensors detect only the spectral characteristics of the surface material. Seldomly will a lithotype be exposed to the surface. Therefore, the identity of geologic material underlying most areas must be inferred from the identity of the surface cover. Many biologic cover types possess an affinity for soils with a particular chemical and physical composition. The chemical and physical properties of soils are in turn highly dependent on the geologic parent material from which they are derived. Consequently, cover type may reflect the character of the underlying geological lithotype. Additionally, many surface hydrologic characteristics are highly dependent upon the chemical and physical characteristics of soils and consequently upon lithologic parent material. Thus, in attempting to identify geologic materials by remote sensing techniques it is necessary to develop an understanding of the relationships among vegetation, soils, surface hydrologic features, and subsurface geologic materials.

After the geologic materials are adequately classified through analysis of their spectral signatures, then the task of landform identification begins. This task, at present, requires human interpretation of spatial relationships displayed on spectral classification maps. Automatic classification of landforms is beyond the capability of our present software system. However, existing computer-aided analysis of spectral data provides a base from which landform mapping can begin.

OBJECTIVES

As originally proposed, the objectives of the geomorphological inventory were: (a) to delineate the surface landforms of alpine regions by conventional and computer-aided analysis techniques; (b) to automatically categorize morphotypes in a statistical manner; (c) to delineate avalanche hazards through automatic recognition of avalanche trails; and (d) to detect regions of active permafrost.

The assumption underlying each of these objectives was that each earth form, such as an avalanche trail, possessed a unique and identifiable spectral signature, or that by analysis and classification of the material associated with the form, the latter could be inferred.

As experience was gained in computer applications and in the capabilities of the ERTS-1 data collection system were realized, some modification of the first two original objectives was deemed necessary. The modified objectives were: 1) determine spectral variance in the study region; 2) utilize the spectral variance shown on the computer maps to infer the botanical, pedologic, hydrologic, and cultural patterns of the study region; and 3) merge these patterns into an assemblage to define landforms by inference from their associated land use patterns.

Geomorphic research was limited to studies peripheral to the San Juan Mountain test site in southwestern Colorado. These areas were selected because they exhibited a less complex ecosystem owing to their more arid nature.

EXPERIMENTAL PROCEDURE

Automatic classification of ERTS-1 MSS data by the LARSYS system requires five general steps:

1. Selection of training sets representative of the surface types of interest.

2. Separation of the data within these sets into distinct spectral statistical classes.

3. Correlation of spectral classes with conventional surface mapping units.

4. Automatic classification of an area with spectral characteristics similar to those of the training areas.

5. Recombination of spectral classes through display techniques for generation of useful surface type maps, tables, and graphs.

The techniques used for geomorphological analysis reported in these studies are defined in detail as follows:

Step 1. Selection of a training set representative of the surface types selected for classification. The analyst must be aware of: a) conventional classification units within his field of interest; b) the general spectral characteristics of each unit; and c) the general spatial distribution of the units within the training region. If the analyst possesses this information, he is able to choose a training area representative of the classes of interest. Such sets must be chosen with careful study of ERTS-1 data, in conjunction with any available ancillary information. After selection of candidates, the training sets to be used should be selected as representative of the widest range of surface classes of interest.

If ground truth is not available, selection of representative training sets is more difficult. Decisions concerning the nature of the spectral patterns represented on non-classified data or non-supervised classification results must be made on the general distribution or planar form of these patterns. From interpretation of these patterns, an estimation of the area most representative of the classes of interest must be made. The level of uncertainty in selecting a training set in this manner is very high. Additional training set selection may be required before a final classification is possible.

Step 2. Separation of the data within the training sets into distinct spectral classes must be performed by the computer. Two methods of spectral class statistical separation are available: supervised and non-supervised. In this study both methods were used, sequentially, to obtain the final classification result. Initially, non-supervised classification was performed to define spectral separability within the training region. Supervised classification defined subclasses for more accurate results.

In one study, areas with a wide range of spectral characteristics were automatically clustered into distinct spectral classes. Training fields were then located within areas of homogeneous spectral response and spatially related geographic orientation. In another study, non-supervised classification was performed on areas of low spectral variance. Training fields defining subclasses were then selected from the non-supervised cluster maps of the individual training fields. In this case, training fields were selected before, and relocated more precisely after, automatic spectral class separation. By initially reducing the spectral variance of the clustered regions by judicious selection of fields, the clustering algorithm is able to divide each cover type into discrete subclasses. The statistics of these subclasses can be visually compared for determination of similar spectral character by use of spectral plots. Spectral plots provide a means to visualize spectral signatures. Also, spectral elements significantly different than the dominant cover type of any field can be eliminated from the training elements by spectral plot analysis, thus reducing the spectral variance within each training class.

Step 3. Once statistically significant spectral classes containing the complete range of spectral variance within the training region are defined by procedure (2), these classes must be correlated with conventional cover type mapping units, e.g. soil type, vegetation type, lithotype, etc. Essentially, this involves locating the class geographically and assigning a meaningful class name. Naming of classes is interpretive and subject to human error.

Step 4. After reasonable certainty concerning the surface nature of the spectral classes has been obtained, a decision relating to the geographic extension of those classes must be made. The statistics that represent the spectral classes are generated from relatively small geographic areas. These statistics may be extended to automatically map large regions, but how far and how accurately they may be extended is a point of decision. Once agan, judgment is a key determinant in defining the limits of such an extension. Knowledge of regional variation is essential. The spectral classes may be extended only as far as the cover type assemblage remains unchanged. If extended beyond those limits the classification may represent patterns of unknown cover type. As yet, the limits of such extension are unknown, but may be directly related to the surface material of the area being classified.

Step 5. The final step in the classification procedure is to generate maps, graphs, charts, tables, or any visual output meaningful to a user agency. Because spectral classes often represent subclasses of conventional mapping units, combination of the classes is often necessary to obtain maps useful for display. Knowledge of the spectral characteristics of surface material is essential for producing meaningful results.

The five general steps just outlined have been utilized to produce various cover type maps for areas around the San Juan test site. Each area possesses a unique assemblage of landforms, with a coincident assemblage of cover types. For each area the cover type has been classified, and inference concerning the landform assemblages in each region is based on the cover type distribution as represented on the computer maps. The following discussions reflect results obtained from four areas used for this study.

RESULTS

Four project areas were completed, each representing a different geographic location and consequently a unique cover type-landform pattern.

Durango Project

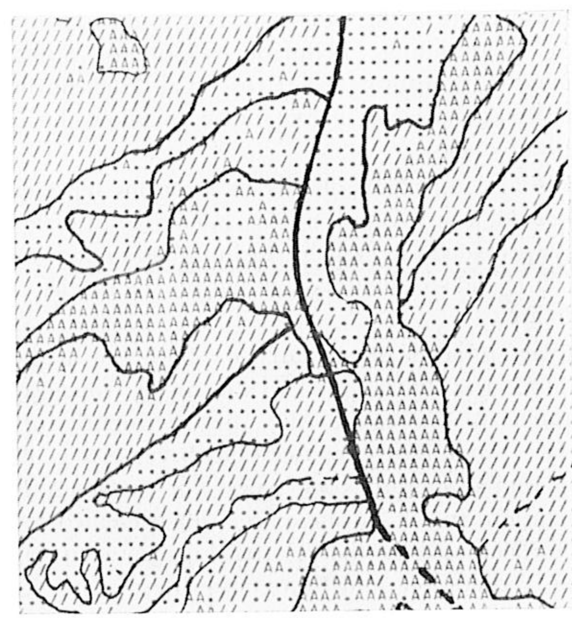
In the hogback and strike valley region east of Durango, Colorado, we chose four major display classes from the thirteen statistical spectral classes used in the classification algorithm.

Based on the information provided by Zapp (1949), we divided the lithologies of the Durango area into three discrete types for analysis—sandstone, shale, and alluvium. Sandstone is the subsurface rock type on the dip slopes of the hogback ridges; shale on the cret slopes and along the strike valleys; alluvium on the terraces and floodplains. These three material types are sufficient to describe the geologic materials of all erosional and depositional surfaces in the study area. Due to the time of ERTS-1 overpass, the west-facing cret slopes and other west-facing declivities are in shadow. Shadow areas have significantly different spectral signatures than sunlit areas and have been considered as a fourth major class.

Four areas within the study region were chosen for nonsupervised classification and display. The coordinates of these areas were procurred from gray scale imagery of the entire August 21, 1972 ERTS frame. (Scene ID 1119-17204, 21 August, 1972). The four areas contained representatives of all the rock types and topographic forms in the study area. The resultant display provided reliable visual separability of shadow patterns and alluvial areas. Interpretation of shadow patterns yielded locations for the sandstone dip slopes and shale valleys. Field coordinates were then obtained for sandstone, shale, alluvial, and shadow areas. Training fields on each sandstone dip slope and shale valley were separated into discrete training subclasses. Nine groups of training fields—four sandstone, three shale, one alluvium, and one shadow—were then processed by the supervised clustering algorithm, and the entire study area classified. The display map showed much greater visual separability of the sandstone and shale areas than the non-supervised display from which the training fields were selected. With refinement of coordinates of the training fields, addition of two alluvial subclasses, one shale subclass and two shadow subclasses, visual correlation with Zapp's geologic map improved greatly.

A geologic map of the Durango area (Figure C.1) shows four major classes which have been displayed as three classes which represent only geologic materials. Based on geomorphic knowledge of the usual relationship between bedrock types and their topographic expression we assumed that the areas in shadow are underlain by shale. The shadow areas are on cret slopes that stratigraphically fall immediately below the sandstone caprock of the ridges. In a region of hogbacks and strike valley developed on sandstones and shale, one may infer with a high degree of confidence that the surface area stratigraphically below the

A. Gray scale coded PHOTO image. (White = alluvium, gray = shale, black = sandstone.) Approximate scale of original 1:150,000.



B. Alphanumeric coded DISPLAY image. (A = sandstone, / = shale, . = sandstone.) Photographically reduced from original scale of approximately 1:24,000.

Figure C.1. Geologic map of an area around Durango, Colorado. (A) Image displayed classification result from LARS digital display. (B) Computer printout from outlined area on A. Map units from Zapp, overlayed on computer printout.

caprock is underlain by shale. With this assumption, we combined the shale and shadow classes as one displayable unit. The resultant gray scale coded map (Figure C.1A) visually compares in general with Zapp's map of the same area. In detail (Figure C.1B), the two maps are somewhat contradictory.

To test the applicability of the classification scheme over broader regional areas, an approximate 200 mi^2 area centered 35 miles northeast of Durango was classified by using the same statistics calculated on the experimental training fields located two to five miles east of Durango. This new test area was chosen because: 1) the lithologies were similar to those of the first study area, 2) the elevations and presumably the altitude dependent vegetative cover types were different, and 3) the reflective sun angle on the hogbacks was different.

Telluride Project

Much of the available ERTS-1 data had been collected during the winter months, and was characterized by an extensive snow cover. Although the available late summer and early autumn data were predominantly snow free, they were either cloud-covered or not representative of surface areas for which ground truth was available. Eventually two September 27, 1972 ERTS frames (Scene ID 1066-17251 and 1066-17254) were received at LARS. These scenes were 99% cloud-free, totally snow free, and included the western parts of the San Juan Test Site including an area surrounding Telluride, Colorado. Sufficient ground truth information (Cross, et al, 1899, Burbank, 1966) was available in map form to allow the initiation of analysis.

Visual comparison of surface locations represented on geologic maps and single channel gray scale displays provided the basis for training field selection for volcanic and sedimentary rocks in the Telluride, Colorado area.

Exact location of any area on both the map and printout was difficult due to the rugged topographic character of the region. Also, the true identity of the surface was difficult to ascertain, because a geologic map represents only rock types, not surface soils or vegetation. In the Durango area this presented less of a problem because the relationships between topography, vegetation, and lithography were more homogeneous and predictable. No such relationships between rock type, vegetation, and topography exist in the mountains around Telluride. Here, the simple, flat-lying character of the rocks betrays the complexity of the spectral expression manifest on each rock type. For example, the Mancos shale occurs beneath coniferous forest on north-facing slopes, grassland on south-facing slopes, and aspen groves on rolling benches. Each of these vegetation types defines a distinct spectral class whereas the total surface areas of the Mancos Shale defines several separable classes.

To compensate for the spectral variability developed on each rock type, a more complex classification system than used at Durango was derived for the Telluride Project. Each class has been designated by a series of symbols. This series contains factors representing each of three variables—geologic material, topography, and vegetative cover (Table C.1). Each class thus represents the spectral characteristics of surface areas characterized by a particular rock type, topography, and vegetation. For example, an area underlaid by the Tertiary San Juan Formation (Tsj), which is level (L), above timberline (1), and covered with tundra vegetation (mosses and grasses) (T), is symbolized as Tsj, L, 1, and T.

Ground truth provided by Burbank's and Purrington's geologic maps was insufficient to meet the criteria for precise training field location.

Underflight photography in the form of 1:12,000 scale color-stereo photographs (Platt, 1968) was available for a small area within the Telluride Region—the Ice Lake Basin area.

The Ice Lake Basin area is on the crest of the divide between the Animas, San Miguel and Dolores river systems. Granitic, volcanic, and sedimentary rocks are present in the area. Elevation ranges from 9,500′ to 14,000′, consequently vegetation zonation is well developed. The photos provided the necessary ground information for selection and location of the training fields for many of the desired classes. The visual correlation of locations between the photos and a gray scale display defined training field coordinates for all but a few classes of material. Interpretation of ERTS-1 color enhanced (color IR) imagery of the entire Telluride Region obtained from the LARS digital display was then visually correlated with color ground photos provided by INSTAAR to obtain the information necessary to define the locations of training fields for the remainder of the classes. Analysis of structural information (Figures C.2-C.3) provides a means to interpolate the surface location of lithotypes. A sequential process of refinement of training class designation and training field location based on visual interpretation of classification results was utilized to improve the quality of the machine-produced maps. After revisions of the classification data, the set of 28 classes presented in Table C.1 was obtained.

The results obtained in the Telluride area analysis are intermediary between the preliminary poor quality classification displays and those obtained for less rugged and varied regions. All display images described in the following section are gray scale-coded PHOTO images, photographed directly from the

Table C.1. Generalized stratigraphic section and correlative classification scheme of the Telluride, Colorado, area.

Geologic time	Stratigraphic section	Class*	Geologic material	Topography	Vegetation
		QAL, L2	River alluvium and lake beds	Level, below timberline (T.L.)	? Possibly shrub-grass
		QAL, L2, M	River alluvium and lake beds	Level, below timberline (T.L.)	Mountain mahogany-oak-grass
		QT, A2, C	Stabilized talus from Mancos (?)	Sloping away from sun, below T.L.	Coniferous forest
Recent		QT, T1, V	Active talus from volcanics	Sloping toward sun, above T.L.	None
	Qal Alluvium	QT. T1, VY	Active yellow talus from volcanics	Sloping toward sun, above T.L.	None
?	Qt Talus	QT, A1, V	Active talus from volcanics	Sloping away from sun, above T.L.	None
	Qr Rock glacier	QT, T1, G	Active talus from granite	Sloping toward sun, above T.L.	None
	Qs Landslide	QS, A2, C	Landslide deposits from Mancos	Sloping away from sun, below T.L.	Coniferous forest
Quaternary	Qd Glacial drift	QD, A2, C	Morainal drift	Sloping away from sun, below T.L.	Coniferous forest
	GG Granite-gabbro	QO, T2, M	Morainal drift	Sloping toward sun, below T.L.	Mountain mahogany-oak-grass
	Tgp Gilpin peak tuff	GG, T1, R	Intrusive igneous rock	Sloping toward sun, above T.L.	None
	Tsb Burns Fm.	GG, L1, R	Intrusive igneous rock	Level, above T.L.	None
Tertiary	Tse Eureka tuff	GG, L1, T	Intrusive igneous rock	Level, above T.L.	Tundra moss-grass-flowers
	Tsp Picayune Fm.	TGP, L1, R	Extrusive igneous rock (pyroclastic)	Level, above T.L.	None
	Tsj San Juan Fm.	TSB, L1, R	Intrusive igneous rock	Level, above T.L.	None
	Tt Telluride cgl.	TSJ, T1, T	Extrusive igneous rock (pyroclastic)	Sloping toward sun, above T.L.	Tundra moss-grass-flowers
Cretaceous	Km Mancos shale	TSJ, L1, T	Extrusive igneous rock (pyroclastic)	Level, above T.L.	Tundra moss-grass-flowers
	Kd Dakota sandstone	TSJ, T1, R	Extrusive igneous rock (pyroclastic)	Sloping toward sun, above T.L.	None
	Jm Morrison Fm.	KM, L2	Thin bedded shale	Level, below T.L.	? Possibly meadow-aspen groves
Jurassic	Jw Wahnaka Fm.	KM, L2, M	Thin bedded shale	Level, below T.L.	Mtn. mahogany-oak-grass-aspen
	Je Entrada sandstone	KM, A2, C	Thin bedded shale	Sloping away from sun, below T.L.	Coniferous forest
Triassic	Trd Dolores Fm.	KM, A2	Thin bedded shale	Sloping away from sun, below T.L.	? Possibly coniferous forest
Permian	Pc Cutler Fm.	KM, T2, C	Thin bedded shale	Sloping toward sun, below T.L.	Coniferous forest
		KM, T2, M	Thin bedded shale	Sloping toward sun, below T.L.	Mtn. mahogany-oak-grass-aspen
		K-J, T2, M	Interbedded sandstone and shale	Sloping toward sun, below T.L.	Mtn. mahogany-oak-grass-aspen
		K-J, A2, C	Interbedded sandstone and shale	Sloping away from sun, below T.L.	Coniferous forest
		WATER	Surface water	Level	Algae
		SHADOW	?	Sloping away from sun	? Mostly coniferous forest

* Legend for Class Symbols:

First set of symbols is rock type or mass movement material of the surface or in the shallow subsurface; represented by geologic symbols.

Second set of symbols is topographic characteristic: L = level, A = slope away from morning sun, T = slope toward morning sun, 1 = above timberline, and 2 = below timberline.

Third set of symbols is the vegetative cover type: R = bare rock, T = alpine tundra species, C = coniferous forest, M = mountain mahogany-shrub oak assemblage, and blank = unknown; or parent material of colluvium deposited above timberline (OT,1): V = volcanic, G = granitic, and Y = yellow.

digital display unit with 35 mm black and white negative film.

Figure C.4 is a machine-generated geologic map depicting surface distribution of the major lithologic classes of the Telluride Region. Black areas are underlaid by sedimentary rocks, predominantly Mancos shale, except on the walls of San Miguel Canyon where Permian through Cretaceous interbedded sandstones and shales are present. The gray areas on the map represent surface areas of igneous rock, both intrusive and extrusive. The authors were not able to separate granitic intrusions from the volcanic deposits. Both rock types are of very similar chemical compositions, so the surface layer may be composed of decompositional products similar spectrally as well as chemically. The white areas on the map represent colluvium in the form of talus, and rock glaciers which cover the consolidated rock materials. Figure C.5 provides geographic reference for the locations of the area classified and displayed.

Figures C.6, C.7, and C.8 represent variations of display symbols used in Figure C.4. Figure C.6 shows bare rock exposures of granitic, volcanic, and colluvial materials as the dark shades, and all other classes as light shades. This display separates areas of bare rock from areas covered with any form of vegetation. Figure C.7 is a map showing the distribution of only 2 classes of material: 1) sedimentary rock, dark; and 2) all else, light. Figure C.8 delineates only those regions covered with talus.

By changing the display combinations of the various classes, a vegetation map can be obtained using the same classification statistics utilized to produce the geologic maps seen in Figures C.6 thru C.8. Figure C.9 is such a vegetation map. The classes represented are: 1) white—bare rock; 2) light gray—tundra species;

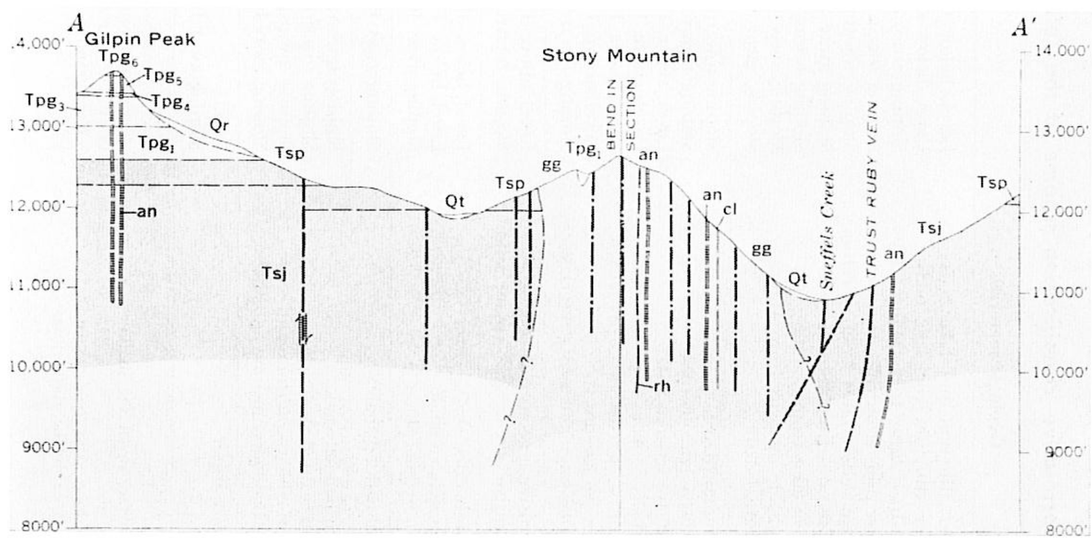


Figure C.2. Generalized geologic section of Telluride area showing relationship between an intrusive stock and bedded volcanics.

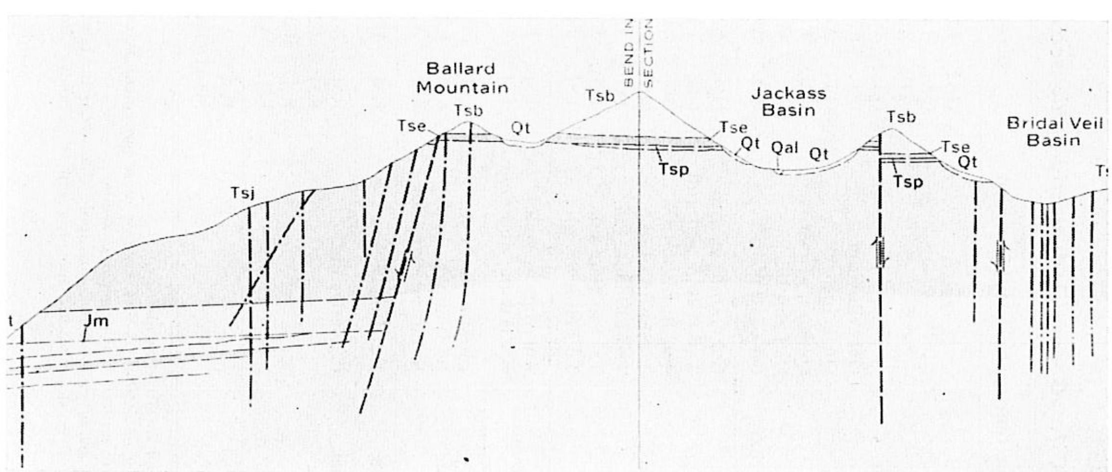


Figure C.3. Generalized geologic section of Telluride area showing relationship between sedimentary rocks and overlying volcanics.

3) dark gray—mountain grasses, mahogany, oak, and aspen; and 4) black—conferous forest. North-facing slopes are generally dominated by coniferous forests where as south-facing slopes are covered with grasses. The vegetational zonation (bare rock; tundra; coniferous forest; shrub oak, mountain mahogany) can be clearly seen on the computer-generated map. The

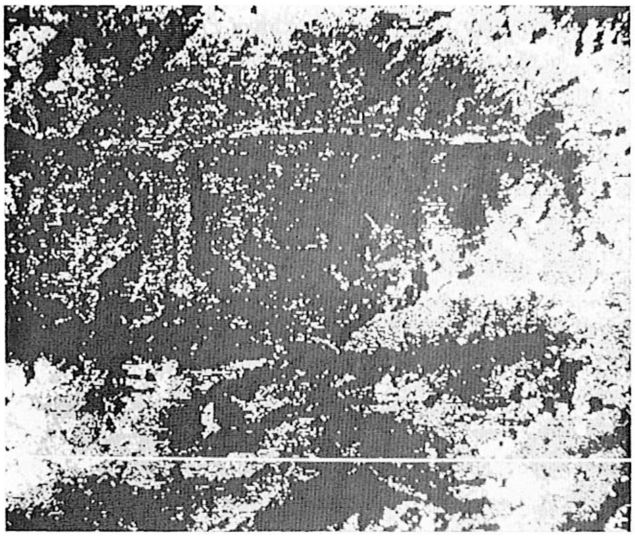


Figure C.4. Distribution of major lithologic classes, based on computer-aided analysis of ERTS MSS data. *(Black = areas primarily underlain by sedimentary rocks, gray = areas of intrusive and extrusive igneous rocks, white = areas covered by unconsolidated rock material.)*

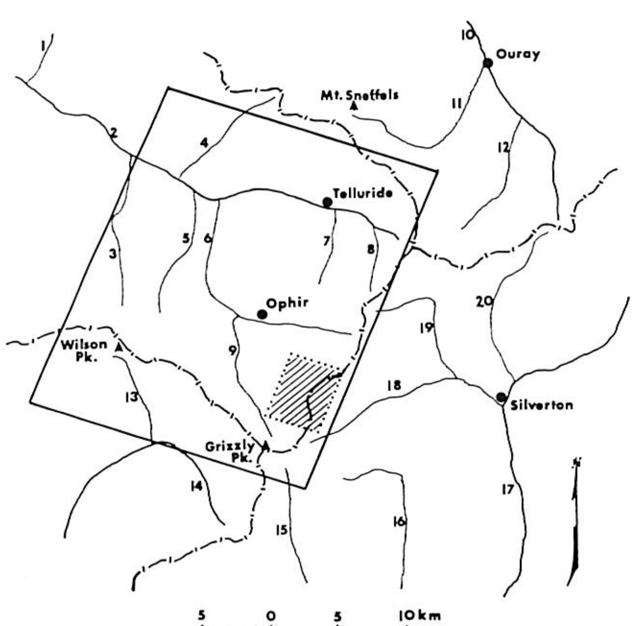


Figure C.5. Generalized geologic location of the Telluride study area. Photo images show region outlined by heavy black lines. Ice Lake Basin training areas outlined by dots. Drainage divides shown by broken lines.

Figure C.6. Intrusive and extrusive igneous rocks (dark tones).

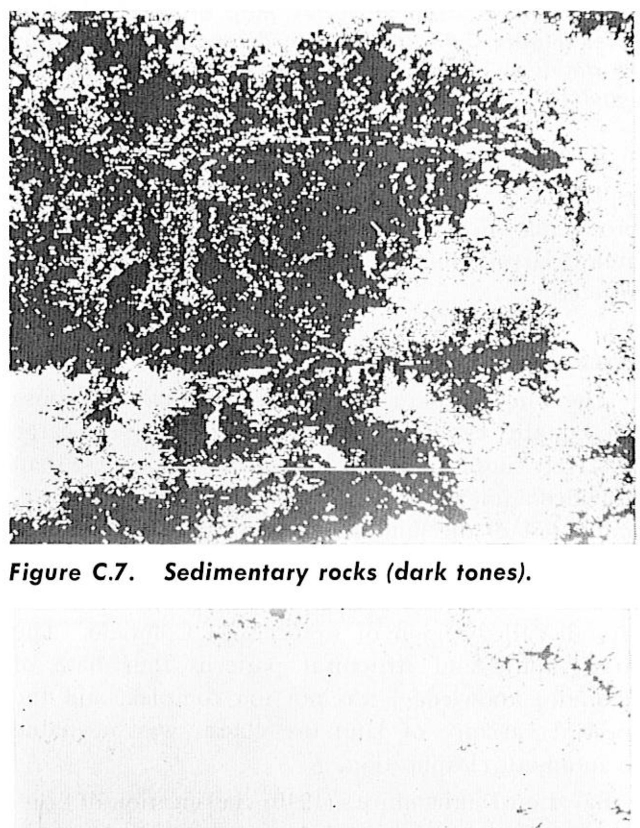


Figure C.7. Sedimentary rocks (dark tones).

Figure C.8. Unconsolidated rock material (dark tones).

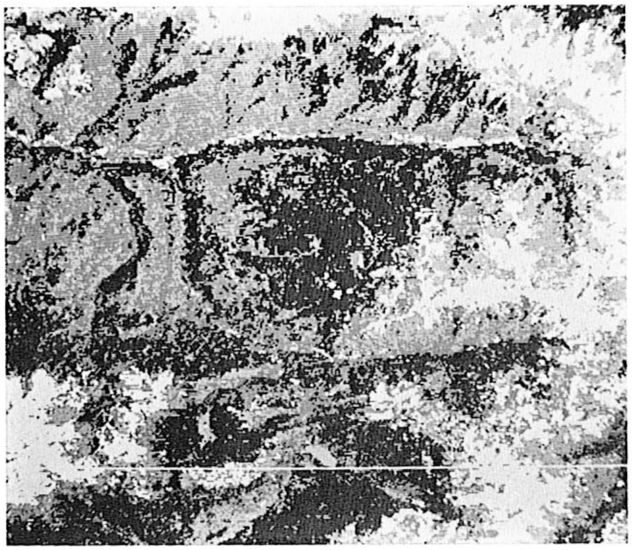


Figure C.9. Vegetation distribution map of the Telluride area, Colorado. Vegetation classes are inferred from statistics used to derive map of lithologic features (Figure C.4.) *(Black = coniferous forests, dark gray = deciduous species and grasses, light gray = tundra vegetation, white = bare rock.)*

classes representing tundra and grass-oak-mahogany-aspen are somewhat inseparable. The capability of producing such a vegetation map in the telluride area is largely due to the homogeneous nature of the vegetation.

Uncompahgre Project

The Uncompahgre Project was undertaken because good quality cloud-free data was available over a large relatively simple geologic area. Analysis of these data provided a test of the procedures previously developed, and a test of the landuse-landform hypothesis.

The area chosen for study was immediately adjacent to the test site on the west, the Uncompahgre Plateau—Grand Valley region of west-central Colorado. The stratigraphic and structural patterns (our base of reference knowledge) was not too complex, and the spectral variance of land use classes was amenable to automatic classification.

Based on Daubenmire's (1946) classification of vegetation sequences, the natural vegetation of the study area was separated into seven groups: 1) desert; 2) oak-mahogany savanna; 3) pinyon-juniper forest; 4) Ponderosa pine forest; 5) aspen-meadow complex; 6) dense, Engelmann spruce-subalpine fir forest; and 7) alpine tundra. Two cultural land use classes, agricultural and urban, were added to the seven natural vegetational classes to essentially complete the classification scheme. Although many different classes of urban and agricultural land use are spectrally separable (Todd, *et al.*, 1973; Bauer, *et al.*, 1973), the small area of man's activity in the Uncompahgre region, compared with the broad expanse of natural cover types, made further segregation of land use categories impractical for this study. Small sections on imagery of the study area were masked by clouds, cloud and topographic shadow, and water. Inclusion of these classes within the classification system brought the total number of classes separated to twelve.

Spectral classes were defined in the following manner. For each class, sample areas of approximately 100 acres were located on a color composite ERTS-1 image by photo interpretation. The basis for determining visual correlation between class name and image pattern were: 1) field reconnaissance in August, 1973, and 2) comparison of a vegetation map of the La Sal Mountains (Richmond, 1962) with the ERTS-1 imagery.

The chance that any arbitrarily selected area of 100 acres will be composed of a completely homogeneous cover is rare, particularly in near-mountain and mountain regions. Thus, each sample area was assumed to possess a dominant cover type and residual cover type.

Non-supervised machine clustering into small number of spectrally separable classes (i.e., twice the number of expected dominants) was performed individually on each sample area. The mean reflectance of each cluster was plotted as a function of the wavelength band of each ERTS-1 channel (channels 4-7) for each of the desired classes (Fig. C.10A). In this manner, the "residual" reflectance elements were statistically separated from the dominant cover type within each sample area. Commonly, each "dominant" type was composed of two or more distinct spectral classes, such as the two classes evident for agricultural areas (Fig. C.10B). In this manner, subclasses for many of the twelve major classes were extracted from the raw data. Next, each cluster for each sample area was displayed by a particular alphanumeric symbol on a printer image. Training fields were selected from the areas displayed on the printer image as the dominant class or subclasses; the training fields were chosen in areas interpreted as most representative of the dominant cover type. The pattern of dominant and residual classes as displayed on the printer image gave clues that permitted extraction of areas from within a dominant cluster that were more representative of the desired class that were elements along border lines between residual and dominant clusters. The training fields for the desired classes were then processed by a supervised classification algorithm in order to define the spectral characteristics of each training class. The 100-acre sample areas were then reclassified, based on the derived supervised classes, to test the classification system on small areas of known cover type. Patterns discernibly related to topography,

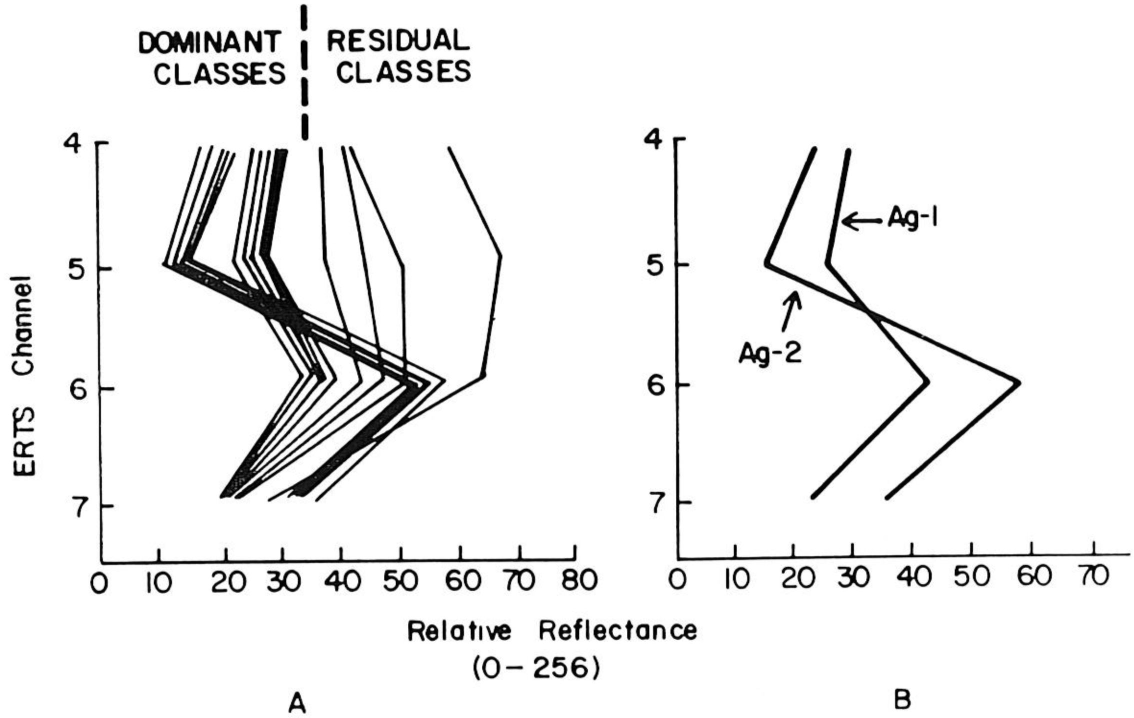


Figure C.10. *(A) Spectral plots of the non-supervised clustering algorithm performed separately on five known agricultural test areas of approximately 100 acres each. Two "dominant" classes are clearly separable from the "residual" classes. (B) Spectral plots of the supervised classes, AG-1 and AG-2.*

and consequently vegetation, as displayed on these test sites were used to further refine the location of training fields until the display patterns seemed sufficient for a regional classification. Final training class statistics thus derived from analysis of approximately 4,500 acres of sampled areas were then applied to a classification of about 4.4 million acres of the Grand Valley-Uncompahgre Plateau region. The ratio of sample areas to classified areas is about 1:1,000.

In analysis of the west-central Colorado region, we were not sure of the actual identity of the material being classified. The spectral classes were known to be statistically separable, but a genera name for each class was only tentatively assigned prior to viewing the classification results. Twenty-four separable spectral subclasses were used to obtain the separation necessary to display twelve classes of cover type and land use. Positive identification of each subclass was reserved until its geographic distribution was determined from the map displays of the entire classified area (Fig. C.11). For example, areas thought to represent surfaces covered primarily by pinyon-juniper statistically separated into three distinct spectral classes. Therefore, the tentative pinyon-juniper class was assigned to three subclasses; PJ-1, PJ-2, and PJ-3. Geographic distribution of special class, PJ-3, as represented on the digital display screen, identified it as part of a oak-savanna assemblage which dominate at elevations immediately adjacent to but lower than the pinyon-juniper assemblage. The presence of an oak-savanna class within areas dominated by pinyon-juniper indicates the normal transitional nature of boundaries between zones. Thus, the oak-savanna assemblage grows in dry valleys within the lower portion of the pinyon-juniper zone; conversely, in moist valleys the upper zone extends spatially downward into adjacent but lower oak-savanna.

The classification map of the entire area is shown in Figure C.11. Each vegetation zone and land use category is shown by a specific gray level. Agricultural areas appear dark gray. A sequence of vegetation zones is clearly visible, encircling the Uncompahgre Plateau in the center of the image, the La Sal Mountains in the southwest corner of the picture, and Grand Mesa in the northeast corner. The oak-savanna zone (very dark gray) is immediately above the desert areas (lightest gray). The pinyon-juniper zone is medium-gray tone. These three climax assemblages comprise the Foothill vegetation zone. Above the Foothill zone is a belt dominated by clumps of aspen interspersed with high, grassy meadows and scattered stands of Ponderosa pine. This, the Montane zone, is displayed as a dark gray tone. Above this, the Subalpine zone appears as black. Climax assemblages

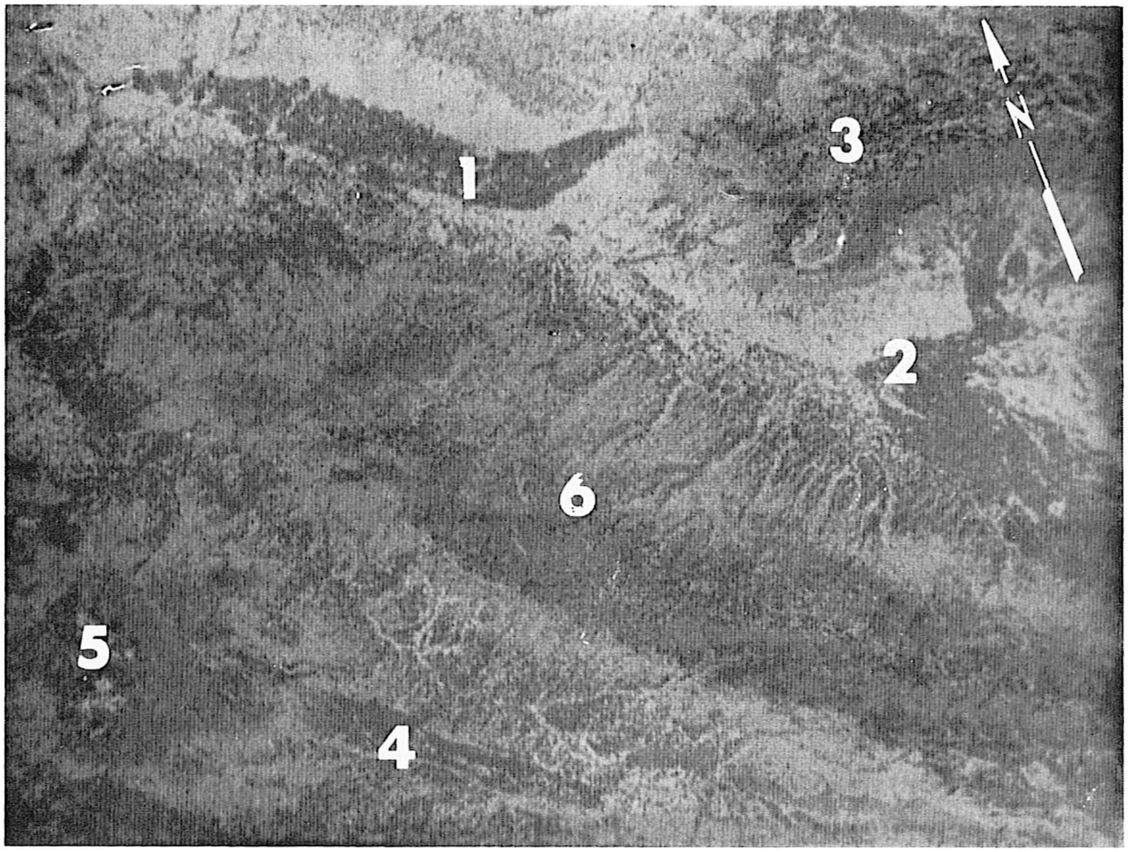


Figure C.11. Computer-aided classification map of the Uncompahgre test site. Results were displayed and photographed from the LARS digital display system. Six classes were presented as various levels on a gray scale. *Numbers refer to these features: 1 = Grand Junction, 2 = Delta, 3 = Grand Mesa, 4 = Paradox Valley, 5 = La Sal Mountains, and 6 = Uncompahgre Plateau.*

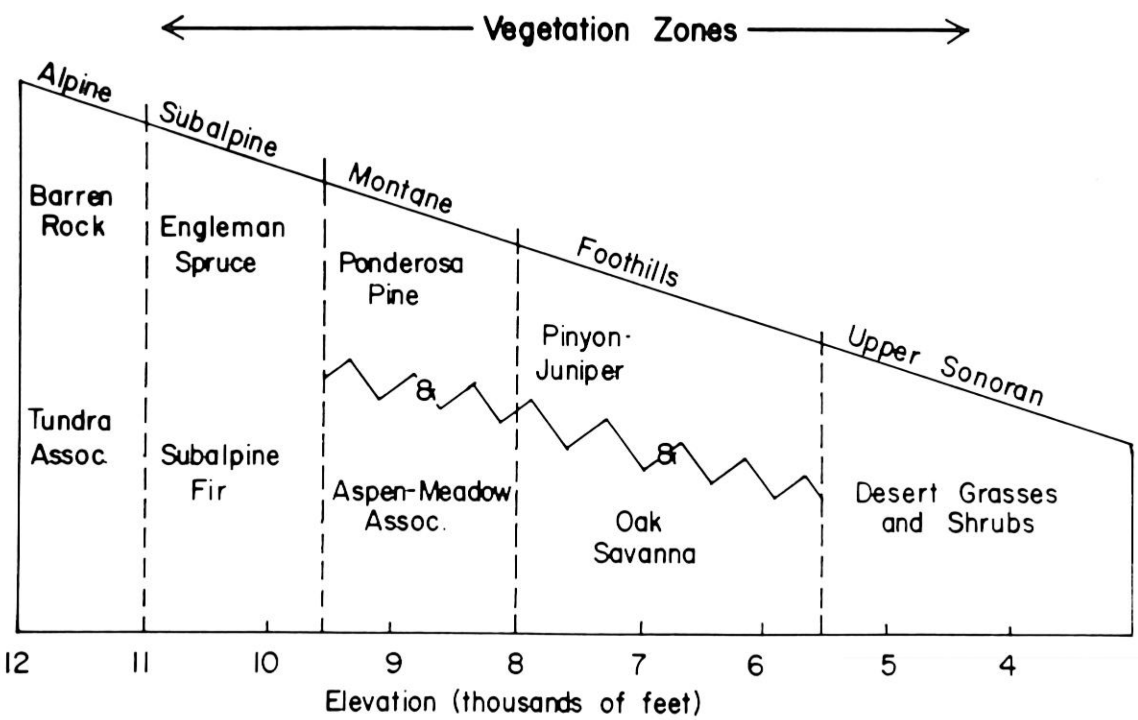


Figure C.12. Ideal model of vegetation zones in the central Rocky Mountains (modified from Daubenmire, 1943).

within this zone include Ponderosa pine, Douglas fir, subalpine fir, and Engelmann spruce. Ponderosa pine is widely spread throughout the Montain and Subalpine zones, but tends to concentrate in certain areas as a distinct band between the aspen-meadow and spruce-fir type. Spruce-fir shows as a very dark gray band along the crest of the Uncompahgre Pleateau, as slope dependent groups coincident with drainage lines radiating from the center of the La Sal Mountains, and as a "blanket" covering Grand Mesa.

The regulationships of the zones is presented graphically in Figure C.12. A transect of overlapping 400-acre fields extending from Uncompahgre Butte (9,732 feet) to the base of Grand Mesa (± 4,500 feet) was analyzed for relative percentage of each cover type. The relative proportions of cover types within each field along this transect were plotted as a function of elevation. The appropriate peaks on the resulting graph correlate very well with elevations associated with each cover type in the purely ideal model of Daubenmire (Figure C.13). Transitional areas between various zones are evident where lines on the graph intersect, the surface cover at these points being composed of equal amounts of two adjacent classes. Some secondary "peaks" which appear anomalous on the graph result from the transect crossing major topographic breaks such as valleys where, as expected, the vegetation corresponds with abrupt change in altitude and aspect. However, the graph clearly demonstrates the arbitrary nature of discrete zonal boundaries. The boundaries are actually non-existant, but their use facilitates classification.

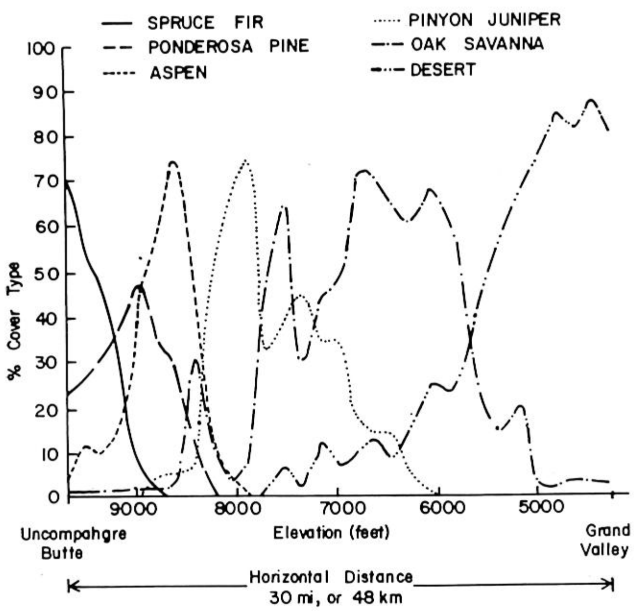


Figure C.13. Percentages of cover type assemblage as a function of elevation. *[Percentage of cover type in each of 30 overlapping 400-acre fields (20 X 20 data elements) was calculated by a LARSYS computer program. The fields defined a transect along an essentially constant topographic slope from Uncompahgre Butte to Grand Valley. Plot of the results shows the dominant assemblage at various elevations and the transitional nature of the boundaries between zones. The secondary peak on the oak-savanna curve at 8,300′ represents a misclassification of aspen-meadow-high grassland species as oak-savanna. Compare with the ideal model in Figure C.12.]*

Richmond (1962) provides a vegetation map of the La Sal Mountains which serves as a visual test of accuracy of the machine classification of the Uncompahgre Grand Valley region. Within the La Sal region the classical vegetation zones are somewhat disturbed, owing to decreasing moisture and slope exposure aspects. Areas of oak-mahogany concentrations lie above the pinyon-juniper zone; distribution of Ponderosa pine appears to be chiefly controlled by lithologic outcrop patterns and subsurface moisture retention rather than by elevation; and the aspen-meadow zone is almost absent on the west side of the La Sal Mountains. Our computer map shows vegetation patterns in the La Sal area as almost identical to those on Richmond's map (Fig. C.14). However, the machine generated map indicates a zone of savanna and desert lands which Richmond's map does not show. Lacking adequate field-based ground truth, the cause of the discrepancy has not been determined.

Colorado River Project

While performing machine analysis on ERTS-1 data obtained over a portion of the San Juan Test Site (Mroczynski *et al.,* 1973), our attention was attracted by the apparent anomalous character of certain stream channels developed on the nearby Uncompahgre Pleateau. Compared with the major high order streams (Colorado, Gunnison, San Miguel, and Dolores Rivers) within the region contained on ERTS-1 frame 1066-17251, September 27, 1973, many drainage channels occupied by low order perennial and ephemeral streams flowing on the northeastward dipping slope of the uplifted Uncompahgre Plateau exhibit three apparently anomalous characteristics:

1. Valleys occupied by some of the ephemeral streams are more extensively developed than those cut by the major rivers.

2. The dip slope valleys commonly possess high level meander scars uncharacteristic of streams with a regimen and gradient comparable to their present day occupants.

3. These valleys possess apparently correlative components on both sides of the present drainage divide at the crest of the Uncompahgre Plateau, a divide

created by uplift along a series of faults bounding the plateau's southwest side.

Analysis of ERTS-1 imagery was paramount in leading to recognition of these anomalous patterns. The synoptic view given by ERTS-1 MSS sensors provides a basis for regional pattern recognition and comparison never before possible. Texture and tone analysis enables comparison in the horizontal plane, whereas shadow pattern analysis permits comparison in the vertical plane (e.g. the depth of valleys).

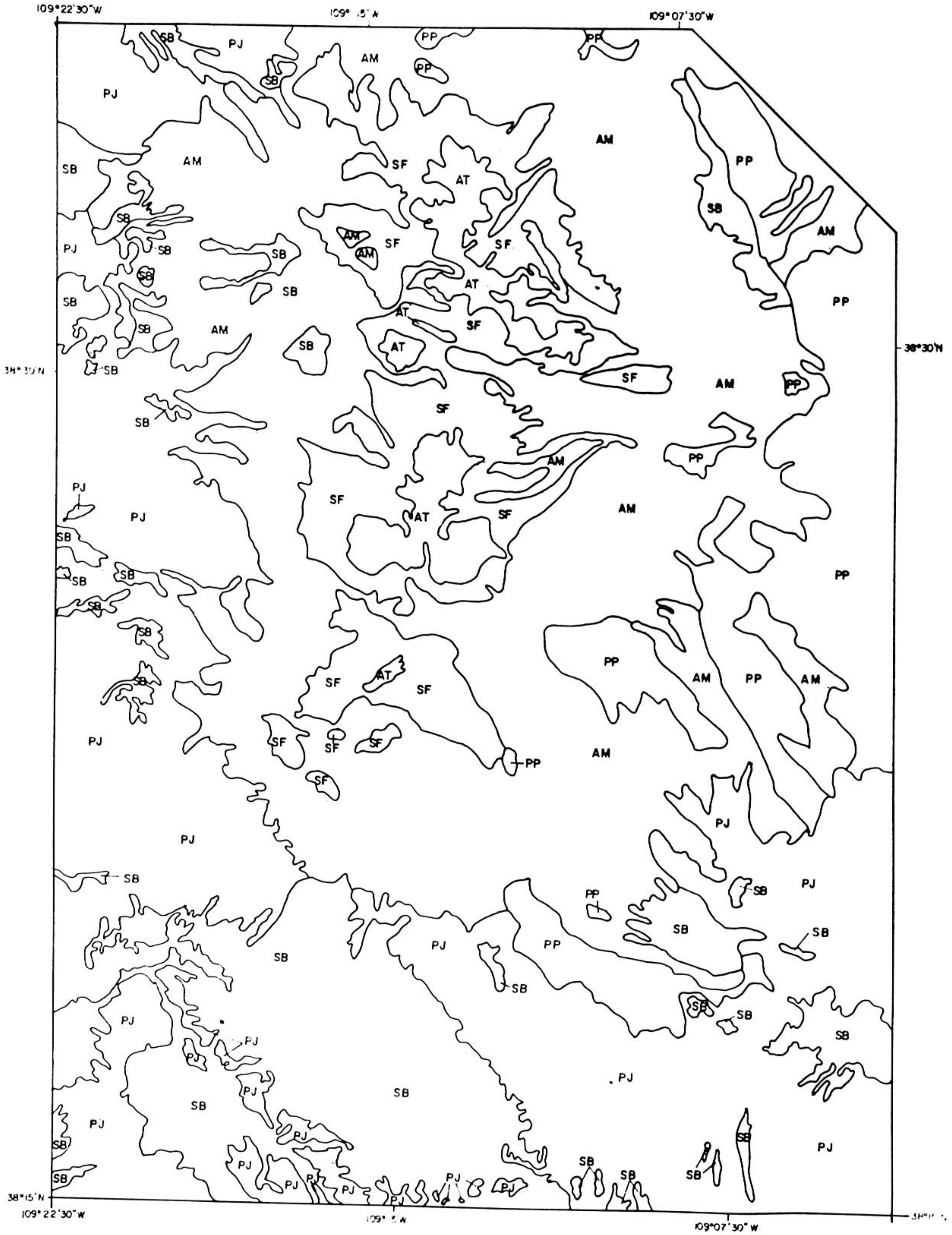


Figure C.14. Vegetation map of the La Sal mountains (simplified from Richmond, 1962). *(AT = alpine tundra, SF = spruce fir, AM = aspen meadow, PJ = pinyon juniper, SB = sage brush desert.)*

Utilization of ERTS-1 imagery in this study has provided some clues as to the possible previous location of the Colorado River. ERTS provides the synoptic view necessary to collate hitherto seemingly unrelated surface patterns.

In the original proposal, the last two objectives in the geomorphological inventory section involved the delineation of avalanche hazards and detection of regions of permafrost, based upon spectral characteristics of these features. This phase of our research efforts produced essentially negative results. We found that many of the avalanche tracks could be characterized by a deciduous vegetative cover, near Aspen or a dense oak shrub cover which could be easily distinguished from the surrounding coniferous forest cover. However, we found that many other areas had been disturbed by fire, logging or mining activities, and that these areas were also covered with a deciduous aspen or shrub cover. Therefore one could not rely on the spectral characteristics of the data to identify avalanche track areas. Through manual interpretation of the computer classification results, one could frequently delineate avalanche tracks by their spatial characteristics. In other words, a long narrow array of deciduous forest surrounded by coniferous forest could be delineated as a probable avalanche track. We found that many of the known avalanche tracks were delineated through this combination of computer classification and manual interpretation of the classification results. However, we also found that a large number of the avalanche tracks had been missed, primarily due to the spatial resolution of the ERTS-1 scanner system. The avalanche tracks were simply too narrow to be reliably identified using such a course resolution scanner system.

Work on delineation of the permafrost areas centered on interpretation of the small scale color infrared photography obtained by NASA's WB-57 aircraft. In this interpretation, areas of known permafrost were examined in relation to the surrounding terrain. The investigators could see no indication of differences between the areas of permafrost and the surrounding regions, and therefore could not extrapolate to other areas in an attempt to identify permafrost areas which were not previously known. Because of the apparent inability to manually delineate permafrost areas using the color infrared photography, we had no basis for expecting to delineate the permafrost areas on the ERTS imagery. Limited study of the ERTS data did not provide any indication that permafrost areas could be delineated from the satellite altitudes. Therefore, we have concluded that for this type of alpine area, one cannot reliably differentiate permafrost from non-permafrost areas using either the small scale color infrared photography or the ERTS scanner data.

INSTAAR ACTIVITIES

Much of the INSTAAR effort to the Geomorphological Features Survey was in field support primarily in the form of mapping. Material presented in the remainder of this section outlines those mapping efforts. Additional information concerning photo-interpretation of NASA underflight imagery is presented in Appendix C.

Field Mapping and Production of Initial Maps

Field mapping was primarily conducted during the summer of 1972. The following information was mapped on 1:24,000 USGS maps, Table C.2. Figure C.15 represents the extent of the field mapping effort in the San Juan Mountains. A typical geomorphic map is represented as Figure C.16.

Table C.2. Geomorphic cover-types of the San Juan Mountains, Colorado.

Cover types	Cover types
Lakes	Moraines
Bedrock/thin till	Forest
"Fresh" scree and talus	"Old" scree and talus
"Fresh" rock glaciers	"Old" rock glaciers
Snowbanks	Avalanche tracks
Alluvium	Alluvial fans
Cirques	Protalus ramparts
Ridge crests	Landslides

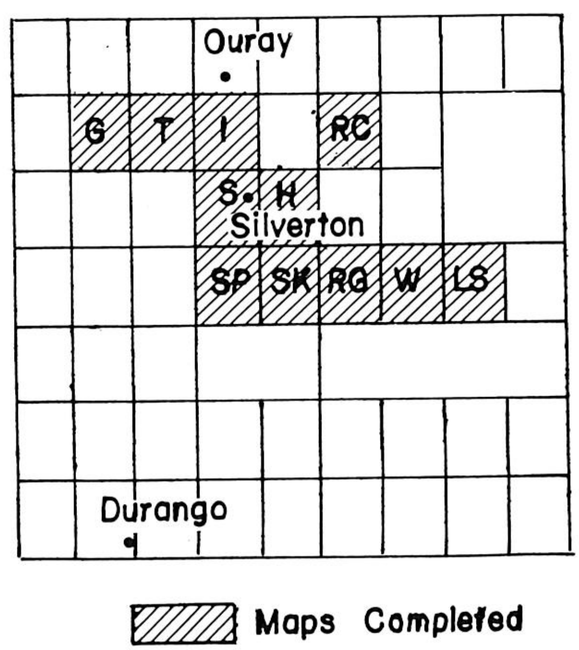


Figure C.15. Location of maps of the eleven 1:24,000 U.S.G.S. quadrangles and their location in the San Juan mountains, Colorado.

Figure C.16. Geomorphic map of the Howardsville quadrangle.

Specific information regarding the area of the quadrangles covered by each cover-type, or the numbers of a particular feature occurring within a quadrangle, are listed in Appendix C. This list can be used to provide a broad classification of the quadrangles. For example, the number of cirques provides a realistic interpretation of how dissected the terrain is and could be used to forecast the amount of significant shadowing that might be expected under a low morning or evening sun. Figure C.16 has been extensively interpreted by LARS personnel.

An important question in terms of the ERTS-1 resolution and the entire question of the interpretation of ERTS data in high mountainous terrain is that concerning the spatial variability of cover-types and geomorphic features over the 1,672 km² of terrain included within the 11 quadrangles. For the purpose of this study we can designate the 11 quadrangles as a population and thus use Principal Component Analysis (PCA), and a clustering routine developed by Caine and Clarke (unpubl. MSS 1973) to investigate this problem.

A standard PCA program (BMD CO1M) was used to analyze the data. The 11 cases were run with the 15 variables listed in Appendix C. The output indicates that 85% of the variance of the cover-types and features can be explained on the basis of the first four principal components. Table C.3 shows the significant variables associated with the first four principal components and their rank.

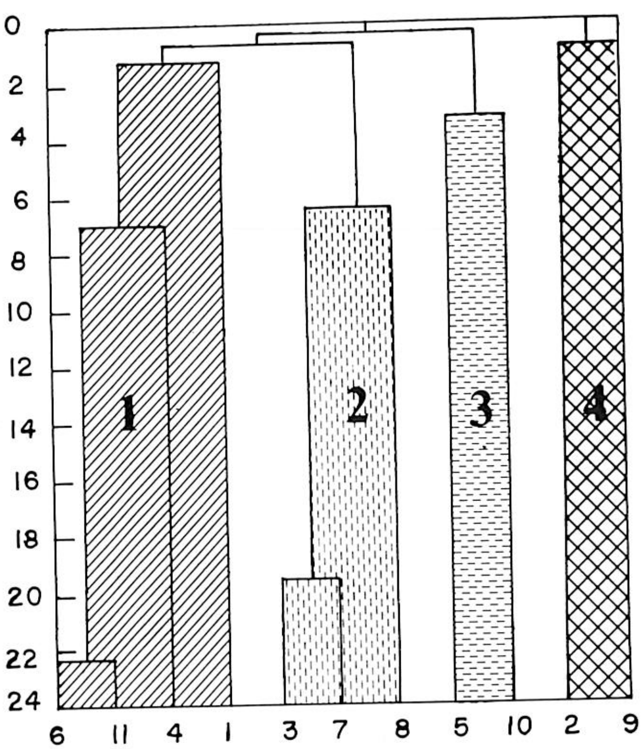


Figure C.17. Dendrogram showing the clustering of the eleven quadrangles based on the first three principal components.

Clarke and Caine have developed a clustering routine using the principal component scores as input. Dendograms can be constructed for any set of principal components. Figure C.17 is a dendogram for the 11 quadrangles based on the scores of the first three (3) principal components. Four distinct clusters emerge from the algorithm—the following quadrangles cluster together (Table C.4).

The primary question at this stage is the spatial distribution and coherence of these clusters. Figure C.18 illustrates the cluster group for each map sheet and strongly suggests that the clusters are not randomly distributed throughout the mapped region, but have considerable coherence. This indicates that there are regional variations in the geomorphic cover-types and numbers of specific features that enable broad "homogeneous" geomorphic areas to be delimited. The recognition of such areas might conceivably form an alternative approach to computer mapping techniques that generally start from the smallest level of detail, and attempt to provide the most detailed

Table C.3. Variables related to the first four principal components and their ranks (+ or −).

Principal components	Pct. explanation of variance*	Rank
First PC	42%	
1. Area of cirques		(−)
2. Number of cirques		(+)
3. Number of rock glaciers		(+)
2nd PC	66%	
1. Area of bedrock/till		(−)
2. Area of moraines		(−)
3. Area of snowfields		(−)
4. Area of rock glaciers		(+)
3rd PC	76%	
1. Area of lakes		(+)
2. Area of alluvium		(+)
4th PC	85%	
1. Area inactive scree		(−)
2. Area old rock glaciers		(+)

* Percent explanation of variance: 1st PC = 42%, 2nd PC = 66%, 3rd PC = 76%, 4th PC = 85%.

Table C.4. Quadrangle names which appear as four distinct clusters on figure C.17.

Cluster 1:	**Cluster 3:**
Gray Head	Red Cloud Peak
Weminuche Pass	Telluride
Little Squaw Creek	
Rio Grande Pyramid	
Cluster 2:	**Cluster 4:**
Ironton	Howardsville
Silverton	Storm King Peak
Snowden Peak	

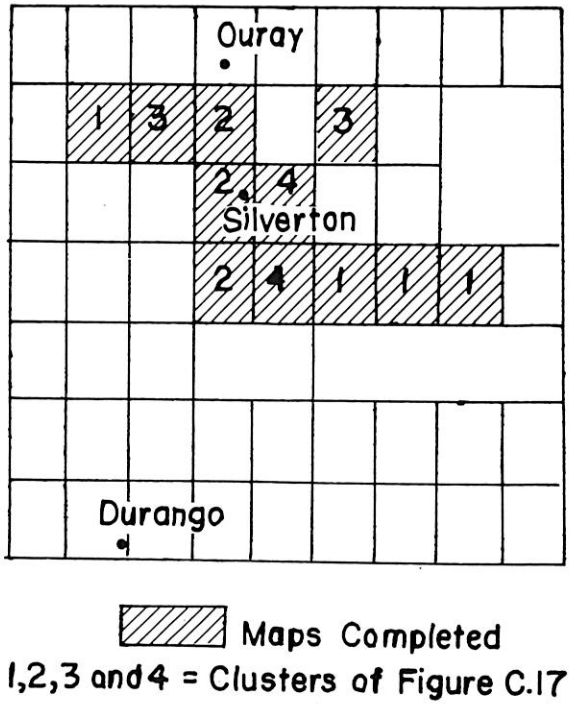


Figure C.18. The location of the cluster sets showing the spatial coherence of the major geomorphic cover-types and features.

map at the level of resolution of the system. However, for small-scale regional mapping on the scale of the 6,000 km² San Juan alpine region it is not immediately obvious that a more useful approach to geomorphic mapping is not embodied in the recognition of large terrain characteristics.

An examination of the material presented in Appendix C and the groupings of Figure C.17 indicate that the following average values for the major significant variables apply (Table C.5).

The four clusters are ranked simply in order for the first two variables and this indicates that the primary control on the classification is the degree of topographic dissection (area and number of cirques). The number of rock glaciers is partly related to the availability of select sites, that is the cirque basins, plus regional variations in bedrock type.

Discussion

Geomorphology is the study of earth surface forms (form being defined by the relative pattern of discrete elements within a set of boundaries and not by the identity of those elements).

ERTS-1 MSS sensors are capable of defining the relative spectral reflectivity of discrete surface elements in four electromagnetic bands. LARSYS provides the opportunity to statistically identify areas which are composed of similar spectral elements.

Table C.5. The first four significant variables for the PCA and the average value for each cluster.

Variable	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Area cirques	5.8	9.6	21.	25.
Number cirques	9.5	30.7	34.5	41.5
Number rock glaciers	2.3	13.3	27.5	17.
Area bedrock/thin till	53.8	30.6	23.6	75.9

Groups of elements are recognized as distinct by LARSYS when: 1) the mean relative spectral response of all elements within each of a given set of areas, and 2) the co-variance of the means within the four wavelength bands for each area are statistically separable by Gaussian maximum likelihood algorithms from the means and co-variances of elements within other surface areas (LARSYS User's Manual, 1973). This software package works well with ERTS-1 data for differentiating surface forms composed of spectrally separable surface elements. However, earth forms as perceived from a geomorphic perspective often defy automatic classification.

Based on one-acre resolution elements, two earth forms may possess similar spectral elements, but their textural and contextural patterns may be quite different. Because many geomorphological forms are defined by textural and contextual patterns, they are difficult to separate based on spectral phenomena alone. For example: a large landslide area which has developed on the Mancos shale southwest of Telluride, Colorado, is non-separable by machine analysis from an adjacent rolling Mancos shale plateau. Both areas are covered with coniferous forests, patches of aspen and meadows, and are characterized by about 500 feet of local relief. Therefore, the spectral elements of the two areas were basically identical. However, to a human interpreter able to recognize textural and contextual features, the landslide region can be distinguished from the shale plateau. The slide area is hummocky, producing random shadow patterns distinct from the more regular joint-controlled shadow patterns on the plateau. This textural characteristic is used to differentiate the slide area from the plateau. Unfortunately, algorithms have not been developed to define "hummocky" landforms, so the two landforms developed on identical lithologies with identical attendant vegetation are inseparable by present analysis techniques. The investigators concur with R. Shanmugam and R. M. Haralick (1973) that textural and contextual feature analysis is needed for more effective machine processing of MSS data.

Much has been said about classification accuracy. But let us not forget what the numbers signify. In the results section of this report you may have been struck by the absence of any quantitative estimates of accuracy for the classification statistics. This is not due to thoughtless omission nor indirect concealment of inaccuracy on our part. The reason we excluded accuracy percentages from our discussion is to be found in our concept of the meaning of such numbers.

Let us take an hypothetical example. Suppose that we were to claim that the map of vegetation assemblages in the Uncompahgre Project was 92.3% accurate. Such a statement presupposes a knowledge of the 100% accurate condition of the vegetational distribution. The question then arises, "Where did we obtain a perfect representation of vegetation distribution to which we compare our computer map, and from which we derive our accuracy statement?" To counter this question we might answer: 1) from previously published vegetation maps of the same area, 2) from airphoto "ground truth" interpretation, and 3) from in site observation on the ground. However, upon thoughtful reflection following our ascertion of perfect observation, we might see the error of our ways, and modify our statement, to say "Nowhere do we know we can obtain a perfect representation of surface cover type." At this time, if we were not too badly shaken by our realization, we would change our accuracy statements accordingly: our percentage figures are not accuracy figures, but, rather, correlation figures.

The percentages represent the degree to which one form of mapping interpretation agrees with another form of interpretation. Because the authors of this section of the report believe that we do not know the quantitative accuracy of ground truth maps, our own ground observation, or our own air photo interpretation, we have refrained from showing quantitative accuracy figures on our maps. Our mode of accuracy interpretation has therefore been qualitative, allowing the reader to estimate the accuracy; the quality of his estimation directly related to his professional knowledge concerning the classification units and his familiarity with the geographic area. This presents certain difficulties in assessing the quality of our research, but we feel our approach fairly represents our efforts. The data, i.e. maps, attest to their own accuracy; be it 20% or 99% is an unanswered question.

In considering the work with the ERTS/LARSYS system for automatic recognition and classification of the Earth's naturally occurring surface features, one important fact has been emphasized again and again—the Earth's surface is not composed of discrete classes of elements which can be easily recognized. There is no area "down there" that is only "coniferous." The surface area may be dominated by coniferous species, but also present are shadows, bare rocks, mosses, etc. No area is "composed of granite." Granite may be the rock type that underlies the surface cover, but that cover is composed of an assemblage of soils, moisture, vegetation, and man-made features. For effective classification of surface materials based on information received at the ERTS sensors, the entire biotic-non biotic assemblage must be considered. The interrelationships among the discrete classes arbitrarily defined to simplify human communication are the factors that determine the continuum of a single infinity variable class, the Earth's surface. The definition of boundaries along this continuum is a necessary and useful function toward achieving our desired ends, but for effective data analysis it must always be remembered that these arbitrarily chosen boundaries which define our classification schemes are subjective and variable. The boundaries come from our minds, not from the data. When we impose boundaries on the data, we will succeed in communicating our ideas only insofar as our boundaries are sufficiently flexible to allow for their inevitable distortion of nonseparable data.

The results presented in this section highlight the efforts of the Geomorphological Features Survey. For a more complete description of these projects refer to Appendix C.

Section D
Interpretation Techniques Studies

Contributors

LARS	*INSTAAR*
R. L. Frederking	R. G. Barry
	L. Williams

Carson and Kirby (1972, p. 1) state unequivocally, "Hillslopes have the distinction of being the commonest and, at the same time, least studied geomorphic features, . . ."

Possible slope-controlled topographic effects on remotely sensed multispectral scanner (MSS) data have also been neglected. Reasons for the lack of study of such effects may in part be attributed to youthfulness of remote sensing with multispectral scanners; concern with other more immediate technological problems; and past emphasis on development of agriculturally-oriented MSS applications. In general, areas which are dominated by large scale commercial agriculture (large fields and high level of mechanization) most nearly approximate conditions of a uniform topographic plain, and therefore, topographic effects associated with slope and relief would be insignificant.

From a geomorphic and geologic point of view, however, mountainous terrain which exhibits highly variable local relief and slope, and areas of mature dissection which display a minimum amount of relatively flat surface are most appealing for investigations. Because these areas are characterized by irregular geometric shapes and patterns which may contain heterogeneous cover types, significant difficulties in analysis and interpretation of MSS data are often encountered.

SLOPE CONSIDERATIONS

The importance of slope effects on spectral reflectance has sometimes been mentioned in the literature (Cronin, and others, 1968; Polycyn, 1967), but apparently few attempts to directly analyze these effects have been made. In general, slope can be considered a complex multifaceted element of control which complicates the analysis of MSS data. Complications arise from consideration of angular properties relating to solar incidence and reflectance values, and to induced microclimatic differences which respond to variation in slope magnitude and orientation.

With respect to the angular properties, Leonardo (1964) suggests that shortwave reflectance is generally independent of surface orientation because, owing to surface roughness, the reflectance is diffuse. Other investigators (Egbert and Ulaby, 1972; Coulson, 1966) however, have demonstrated that reflectance is substantially effected by differences in solar incidence angle. In addition, variability in the angular relationships between sun, scanner, and surface also contributes to variation in reflectance (Stohr, 1974). Based on these findings, it is suggested that reflectance from a sloping surface should vary directly as a function of surface exposure which is defined by slope magnitude and orientation.

Microclimatic adjustment as a function of slope control has long been recognized. Daubenmire (1962, p. 167) suggests that a north-facing slope inclined 5° experiences approximately the same effect as a non-sloping location 300 miles farther north. Everett (1965) has demonstrated that effectiveness of periglacial geomorphic processes are closely related to microclimatic effects of slope inclination and orientation. Marr (1961), from a vegetative study in the Colorado Front Range, implies a tendency towards vegetational zonation according to slope controlled microclimatic influences, in addition to the generally recognized altitudinal zonation (Daubenmire, 1943). These slope-induced microclimatic effects can be considered as contributing to spatially organized vegetative heterogeniety which complicates efforts to investigate slope-reflectance relationships.

The primary objectives of the current study include: 1) establishment of a methodology to achieve spatial correspondence between ERTS multispectral data and selected topographic elements, and 2) a quantitative evaluation of the degree to which reflectance from a complex topographic surface is functionally related to measurable elements of the terrain. In addition, this report will offer suggestions regarding a method for systematically controlling slope effects.

STUDY AREA

For this experiment, ERTS-1 MSS data obtained on 9/8/72, was utilized to select 39 areal units, each approximately 0.055 Km^2 (12 resolution elements). These areas are located in the Weminuche Pass and

Finger Mesa quadrangles. The areas were selected principally because of their proximity to relatively large water bodies (thereby enabling positive location on non-geometrically corrected ERTS-1 data). The data is cloud-free, and the area has consistent topographic variability, i.e., northwest and southeast facing slopes. Within the area, bare surfaces are infrequent and vegetative cover type is variable. U. S. Forest Service 15′ Planimetrics indicate open grassland and spruce-fir stands of varying size and density. Field reconnaissance in the area also indicated numerous stands of aspen.

METHODOLOGY

The methodology developed for direct comparison of spectral and topographic data consisted of visually comparing the configuration of prominent landmarks (for this study, the water bodies) on both gray scale printouts and 7½′ topographic maps, and estimating the approximate location of corresponding points. For this study, sufficient departures from regularity in the outline of lakes existed such that repeated trials indicated accuracies in establishing correspondence to ± 1 RSU (approximately 57M x 80M).

After determining correspondence of location on both gray scales and topographic maps, lines were directed through these locations parallel to Rows and Columns of gray scale data (for this study, line headings were 190° and 280° respectively). Lines parallel to Rows were then divided into 228 meter lengths, and those parallel to Columns were divided into 240 meter lengths. Although accuracies indicated line locations to be within ± 1 RSU, four columns of data rather than three were employed in order to more closely approximate square measurement areas (228m x 240m). Sample areas equivalent to 228m in the x-direction and 240m in the y-direction were then centered about each line segment on the topographic map to complete construction and transfer of sampling areas.

The data employed for this experiment consisted of mean relative reflectance values for each of the four MSS ERTS channels obtained from within the areal unit defined above. Topographic variables include mean elevation, percent slope associated with maximum relief, and effective illumination index. The topographic indices represent well-established descriptors of topographic form and, with the exception of effective illumination index, need no further elaboration.

The effective illumination index utilized is trigonometrically computed to synthesize the elements of solar elevation, direction of incident ray, magnitude of surface slope, and direction of surface slope. Modification of a preliminary effective illumination index was required because the preliminary index failed to accurately account for the area of illumination.

ANALYSIS RESULTS

Stepwise multiple regression analysis was employed to ascertain the strength of association between mean relative reflectance in each of the four channels, and topographic variability. This approach was selected because it facilitates isolation of meaningful independent variables, and establishes relative rank of variable importance.

The matrix of simple correlation (Table D.1) shows the strength of simple linear relationship between included variable pairs. It is important to note that the mean reflectance in each channel, (variables one through four), is significantly related to each of the topographic indices. In general, reflectance increases as elevation increases, and reflectance decreases as slope and effective illumination index increase.

Stepwise multiple regression analysis summarized in Tables D.2 and D.3 demonstrate that significant amounts of variability in mean reflectance is accounted for by variation in topography. The variable entry sequence at the top of each table indicates the order in which the topographic variables entered into regression.

The proceding results indicate that in mountainous areas a significant amount of spectral variability is attributable to variation in topography. It is important to note that multiple R values presented in Tables D.2 and D.3 are essentially the same, although those obtained for D.3 are based on fewer variables.

Two variables, effective illumination index and elevation, emerge as most effective and exhibit a potentially significant pattern of entry. Examination of Table D.3 indicates that elevation may be more important as a contributor to variability in the shorter wavelengths while slope effects more strongly influence reflection at the longer wavelengths. These findings are in general agreement with previously-cited literature.

Table D.1. Variable intercorrelation matrix (modified EI).

	Variables*						
	1	2	3	4	5	6	7
1	1.000	0.992	0.908	0.857	0.516	−0.529	−0.504
2		1.000	0.917	0.874	0.553	−0.538	−0.490
3			1.000	0.981	0.421	−0.448	−0.539
4				1.000	0.415	−0.443	−0.556
5					1.000	−0.617	−0.251
6						1.000	−0.669
7							1.000

for table n = 35 and .01 = .381

* Variable identification: 1 = mean reflectance in channel 1; 2 = mean reflectance in channel 2; 3 = mean reflectance in channel 3; 4 = mean reflectance in channel 4; 5 = mean surface elevation; 6 = percent slope; and 7 = effective illumination index (EI).

Table D.2. Regression sequence for original EI.

Mean reflectance in channel	Variable entry sequence				Multiple R
	1	2	3	4	
1	d*	5	6	7	0.6535
2	5	d	6	7	0.6696
3	d	5	7	6	0.6168
4	d	5	8	—	0.6494

* d indicates simple slope direction.

Table D.3. Regression sequence for modified EI.

Mean reflectance in channel	Variable* entry sequence				Multiple R
	1	2	3	4	
1	6*	5	7	6	0.6453
2	5	7	—		0.6617
3	7	5	—		0.6145
4	7	5	—		0.6246

* Variable identification: 1 = mean reflectance in channel 1; 2 = mean reflectance in channel 2; 3 = mean reflectance in channel 3; 4 = mean reflectance in channel 4; 5 = mean surface elevation; 6 = percent slope; and 7 = effective illumination index (EI).
* Variable 6 in 1 above removed from regression

The direct positive relationship between reflectance and elevation (Table D.1) may be interpreted as an indicator of altitudinal zonation of cover types, and also the atmospheric transparency associated with high mountain regions.

The importance of topographic effects in the longer wavelengths has been demonstrated by the relief shading produced by radar imaging systems (Nunnally, 1969). The pattern of entry of topographic variables described by Table D.3 indicates that variation at the longer wavelengths is more sensitive to topographic effects. In addition, Table D.3 suggests the existence of a possible wavelength threshold between ERTS channels 2 and 3 below which slope effects would be of limited significance.

The change in entry rank of effective illumination index should also be noted. The change observed between Tables D.2 and D.3 is conditioned by exclusion of downslope direction as a pertinent variable. Slope direction was excluded from this analysis because it is included as part of the effective illumination index; magnitude of slope is supposedly part of effective illumination index, but was also included as a variable.

SHADOW MAPPING STUDY

A major question relating to the use of ADP techniques in mountainous terrain concerns the effects of slope angle, orientation, and terrain shadowing on spectral signature. In order to evaluate these effects we are incorporating such information into the classification analyses.

A computer program has been written to determine the parts of any area which will be in shadow at a given time on a given date. The methods used have previously been described by Williams *et al.* (1972). Topography of the area is specified by a grid of elevations Z_{ij} over Cartesian Coordinates x and y, where grid spacing $\Delta x = \Delta y$ the gridpoint (i, j) is located at the coordinates $(i\Delta x, j\Delta y)$. From the array of elevations, slope angle and aspect at each gridpoint are approximated. Let the tangent plane of the surface at a point be expressed by $z = ax + by + c$. The horizonal distance from the origin to the tangent plane is $d = c/\sqrt{a^2 + b^2}$, so the slope angle θ of the tangent plane is given by $\tan \theta = c/d = \sqrt{a^2 + b^2}$. The y-axis intercept is at $-c/b$, so aspect A, measured from the y-axis, is given by $\tan A = \sqrt{(c/b)^2 - d^2/d} = \sqrt{(a^2 + b^2) / b^2 - 1} = a/b$, with the quadrant determined from the signs of a and b. Thus, since $\partial z/\partial x = a$ and $\partial z/\partial y = b$, the slope angle θ_{ij} and aspect A_{ij} at a grid point (i, j) may be obtained as:

$$\theta_{ij} = \arctan \sqrt{\frac{\partial z^2}{\partial x_{ij}} + \frac{\partial z^2}{\partial y_{ij}}}$$

$$A_{ij} = \arctan \quad \frac{\partial z}{\partial x_{ij}} + \frac{\partial z}{\partial y_{ij}} \quad A_o$$

where A_o is orientation of the y-axis, and the derivatives are approximated by:

$$\frac{\partial z}{\partial x_{ij}} \quad Z_{i-1,\,j} \quad - \quad Z_{i+1,\,j} \quad 2\,\Delta\,x$$

$$\frac{\partial z}{\partial y_{ij}} \quad Z_{i,\,j-1} \quad - \quad Z_{i,\,j+1} \quad 2\,\Delta\,x$$

(except that, on the boundaries, the difference over one grid space is used), A_{ij} and A_o are measured from north; positive toward the east.

With the latitude ϕ specified and declination of the sun δ determined from the date (either from tables, or computed approximately by the program), the angle of incidence β of the sun's rays at time t on a slope of angle θ and aspect A is given by (Garnier and Ohmura, 1968)

$\cos \beta = (-\sin \phi \cos H \cos A \sin \theta - \sin H \sin A \sin \theta + \cos \phi \cos H \cos \theta) \cos \delta + (\cos \phi \cos A \sin \theta + \sin \phi \cos \theta) \sin \delta$

where $H = \pi\,(t/12\text{-}1)$ with t in hours. Clearly, if $\cos \beta$ is non-positive (i.e., $|\beta| \geqslant \pi/2$) the sun's rays are not incident on the slope, and it is effectively in shadow.

A point may also be shaded by nearby topography. This occurs whenever the angle from the horizontal to the skyline in the direction of the sun exceeds the altitude of the sun T, which is given by (Robinson, 1966, p. 34).

$$\sin T + \cos \phi \cos \delta \cos H + \sin \phi \sin \delta.$$

The azimuth of the sun a (measured from south, positive west) is given by

$$\cos a = \sin \phi \cos \delta \cos H - \cos \phi \sin \delta.$$

At each gridpoint (i,j) the program searches in the direction of the suns azimuth for an elevation Z, so:

$$Z - Z_{ij} \geqslant D \tan \tau \qquad (1)$$

where D is the horizontal distance between the gridpoint (i,j) and the point at which the elevation is Z. The elevations tested for the condition; (1) are obtained by interpolation at intersections of the grid lines with the vertical plane through (i,j) and the sun.

Thus, the elevation at the intersection with the k^{th} grid line in the x-direction is:

$$Z = (c \tan a - a)\, Z_{i-b,k} + (b - c \tan a)\, Z_{j-a,k}$$

where $c = j - k$, $a = [c \tan a]$, the largest integer in $c \tan a$, and $b = a \pm 1$, the sign being that of a. The distance from this point to the gridpoint (i,j) is $D = | c \sec a |\, \Delta y$. Intersection with the k^{th} grid line in the y-direction has elevation Z and D to (i,j) given by:

$$Z = (c \cot a - a)\, Z_{k,j-b} + (b - c \cot a)\, Z_{k,j-a}$$

and $D = | c \csc a |\, \Delta x$, respectively, where $c = i - k$, $a = [c \cot a]$, the largest integer in $c \cot a$, and $b = a \pm 1$, the sign being that of a. The gridpoint (i,j) is in shadow if condition (1) is satisfied for any such values Z and D determined.

After a shadow or no-shadow condition is established for all gridpoints within the designated sub-area, the parts in the shadow are outlined on a contour map of the sub-area on microfilm. Since slope angle and aspect are determined at each grid point during the course of the computation, the option is available to plot maps of these on microfilm, as well.

The program has been tested on an area of mountainous topography of approximately 3.12 km by 1.46 km, covering the Green Lakes Valley in the Front Range west of Boulder, Colorado. The time and date for which the test was made were chosen to coincide with those at which an RC-8 air photo of the area was made on ERTS underflight coverage which was at 11:48 local time on January 24. The Green Lakes Valley appears centered about 15 cm from the left (northern) margin and 4 cm from the lower (western) margin of Frame 32, Roll 28, of Mission 228. The parts in shadow appear quite distinctly on the air photo, and agreement with the shadows predicted by the computer program is excellent. Fig. D.1 shows the microfilm output from the program for this case, with the shaded areas outlined by dark lines superimposed in lighter topographic contours (contour interval 200 ft.). Fig. D.2 illustrates how Fig. D.1 was obtained by showing which points are self-shaded (labeled "S") and which are shaded by nearby topography (arrows). Fig. D.3 and Fig. D.4 illustrate the slope and orientation maps for this topography.

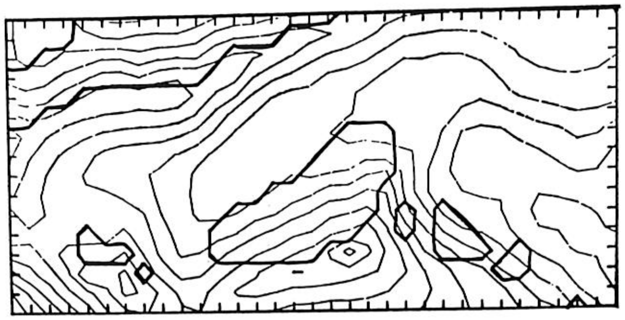


Figure D.1. Examples of output of shadow mapping program. (Shaded areas are outlined by heavier lines superimposed on lighter topographic contour lines; each contour interval represents 200 feet.)

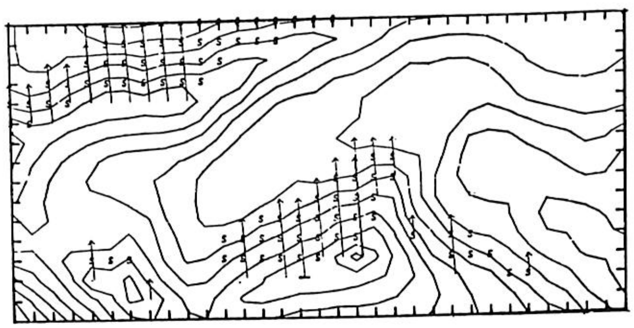


Figure D.2. Modification of output of shadow mapping program. (Arrows indicate areas shaded by nearby topography, whereas S indicates points that are self-shaded.)

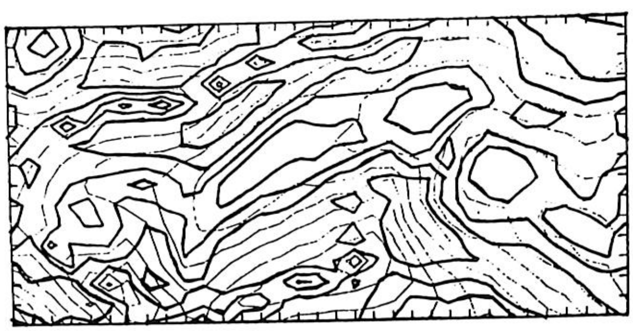


Figure D.3. Output of shadow mapping program showing areas of similar slope.

Figure D.4. Output of shadow mapping program showing areas having similar aspects.

SUMMARY AND CONCLUSIONS

This investigation should demonstrate that, in topographically-complex mountain areas, spectral reflectance is significantly related to elements of the terrain. Owing to the limited data set utilized, and the interactions between cover type and topographic variables, it is impossible to determine the net effectiveness of topographic variables. These findings should therefore be considered as indicative of general trends which require additional analysis. Specific conclusions are as follows:

1. Variation in spectral reflectance is linearly related to elements of terrain in a statistically significant manner.

2. Spectral variation in ERTS channels 1 and 2 is most strongly influenced by variation in surface elevation (which also included variation in vegetative cover type in this study).

3. Spectral variation in ERTS channels 3 and 4 is most strongly influenced by variation in effective illumination index.

4. The effective illumination index, standardized to a circle, represents a significant improvement over the originally employed value.

5. We believe that a substantial amount of spectral variability is attributable to altitudinal and slope controlled vegetation zonation.

6. Additional investigations are required to determine the net effectiveness of topographic influence and ascertain the validity of the suggested topographical relationship with different wavelength bands.

SUGGESTIONS

Development of the digital terrain model and the ability to achieve spatial per point registration of spectral and topographic data warrants the following suggestions:

1. In areas which are topographically complex and for which ground truth is limited, topographic stratification according to elevation, slope magnitude, and slope direction is recommended. This stratification can be easily accomplished if the terrain data are generated by the DTM. This approach facilitates a flexible level of control over a basic source of complexity.

2. With respect to per point assignment of topographic data, the following elements are recommended for inclusion in such a digital terrain model: (a) point elevation, (b) magnitude of orthogonal slope, (c) downslope direction of orthogonal slope, (d) effective illumination index, and (e) sun scanner look angle.

Section E
Data Collection Platform

Contributors

LARS

INSTAAR
R. G. Barry
J. M. Clark

The feasibility of collecting environmental data in extreme cold and windy environments using the ERTS Data Collection Platform was investigated at an alpine site in the Front Range, Colorado, by the Institute of Arctic and Alpine Research. The DCP was installed on a broad topographic saddle on Niwot Ridge (40°03′23″N, 105°35′06″W) at 3,536 m adjacent to alpine study plotes of the U. S. Tundra Biome, International Biological Program (Figure E-1).

An eight-channel signal-conditioning system was developed in the University of Colorado, Physics Electronics Shop to interface meteorological sensors to the DCP (Clark and Wells, 1973). The sensors in use on Niwot Ridge are as follows:

Channels 1 to 3—Thermistors for air temperature at the ground interface and at 1 and 2 m height, over a —46 to +30°C range.

Channel 4—Thermistor for ground temperature at 15 cm depth with a —15 to +10°C range.

Channel 5—Funk-type net radiometer (for radiation between approximately 0.3 and 60μm) in the range —1 to +2 cal cm^{-2} min^{-1}.

Channel 6—U. S. Weather Bureau type three-cup DC generating anemometer for measuring wind speeds up to 100 mph (45 m sec^{-1}) or 200 mph (90 m sec^{-1}) (switch selected ranges).

Channel 7—U. S. Weather Bureau weighing precipitation gauge. This channel is provided with a tare adjustment potentiometer on the interface front panel so that the collection bucket and antifreeze charge weight can be eliminated from the transmission.

Channel 8—Monteith-type pyranometer for global solar radiation measurements (between approximately 0.3 and 3.0 μm) in the range 0 to +2 cal•cm^{-2}•min^{-1}.

INTERFACE SYSTEM

The interface was designed for moderately low power consumption and to provide for testing the interface performance and the DCP function, and also to permit easy repair or any future modification. All circuits are mounted on cards so that any channel can be repaired or modified without curtailing the continuous operation of the other channels. Provision has been made to drive analog recorders from the interface outputs so that it can be utilized after ERTS becomes inactive.

The front panel of the interface unit has "five-way" binding posts for measuring battery voltages, the +5-volt regulated power supply, each of the eight sensor inputs, and each of the 0 to +5-volt outputs to the DCP. These features provide a means of confirming the proper operation of the interface, as well as providing necessary measurements for accurately trimming the signal conditioning circuits. For testing and adjustment purposes, a ten-position selector switch and two pairs of binding post terminals are also located on the front panel.

Monolithic integrated-circuit operational amplifiers of military aerospace specifications, with an operating temperature range of —55 to 125°C are used throughout the design. The very stable +5-volt power supply provides reference and bias voltages for various

Figure E.1. Nowot Ridge data collection platform station, 3536 m, lat. N. 40° 3′ 33″, long. W 105° 35′ 00″.

transducer channels and also serves as a "clamp voltage" to prevent fault level voltages reaching and damaging the DCP analog input circuitry.

An output circuit has been designed to allow switch selection of the output of 0 to +5 volts or a recorder drive of either 0 to 1mA or 0 to 5 mA. Continuous analog records provide valuable supplemental data and these will be obtained from three of the sensors. A potentiometric millivolt battery-powered recorder is coupled to the net radiator channel, a galvanometer spring-drive recorder is used on the wind-speed channel and an analog recorder is used for the precipitation channel.

To test the entire DCS, any number of channels can be locked on sending a regulated +4.00-volt test signal to the DCP through the analog output jumper card. The test signal is derived from the 5-volt supply. Switches on the jumper card allow either real data or the test signal to be transmitted while the other channels continue to transmit sensor signals.

Test data received through the DCS demonstrates a capability of ±0.2% precision and 0.75% accuracy.

EXPERIMENTAL PHASE

The DCP was installed on 25 October 1972, and it was operated initially on an experimental basis during design and construction of the interface system. From 26 October (Julian Day 299/72) to 11 November (315/72), and from 3 to 14 December (337 to 348/72), it was operated only on Channel 1 with input from a thermistor sensing air temperature. Availability of only 1.4 V DC input gave unsatisfactory resolution of the data.

Channel 1 input was grounded on 15 December 1972 (349/72), and Channel 2 input was enabled from a DC-generating wind speed transmitter. The input was passed through calibrating resistors and fuses to protect the DCP unit. Again maximum input of 1.4 V DC gave poor resolution in the data. This input was maintained from 15 to 31 December 1972 (349 to 366/72), and from 1 January to 10 February 1973 (1 to 41/73).

OPERATIONAL PHASE

"Operational" data have been obtained on eight channels from 14 February 1973 (Julian Day 45/73) beyond the end of 1973. Data are received on four to five orbits per day with one to five messages per pass at approximately 180-second intervals. An analysis of message frequency for 1973 is given in Table E-1. Non-operational periods are summarized in Table E-2.

A printout of the daily data was prepared by a data processing program. Data are often received simultaneously by Goddard and Goldstone due to the geographic location of Niwot Ridge. The program prints duplicate cards when they are present and gives the ID code for the ground station. [Monthly summaries of DCP output are available for the period from February to December, 1973.]

Slight irregularities may occur between consecutive messages due to the ±1 bit resolution of the DCP. This amounts to approximately the following units per bit: temperature, wide range — —.297°C; narrow range — 0.098°C (operated 44 to 191/73); solar radiation — .0117 ly; net radiation — .0132 ly; wind speed — .176 m sec.$^{-1}$ at 45 m sec. and .352 m sec.$^{-1}$ at 90 m sec.; and precipitation — .992 cm.

USER PRODUCT ERRORS

Three types of error were noted in the user-products. These were all relatively minor, and were as follows:

1. Mispunched data cards (5 occurrences)

Day 47	col.	13-15	=	157
Day 99	col.	13-15	=	59
Day 122	col.	13-15	=	12
Day 286	col.	13-15	=	10
Day 64	col.	35	=	alphanumeric for 0

2. Wrong cards received (1 occurrence)
   Platform no. 6075 instead of 6054

3. Only the User Product Listing was received, from which cards were punched locally (1 occurrence).

DCS PRODUCT ERRORS

Evaluation of product errors that we attribute to the DCS has been performed as follows. DCP input can be tested on any or all channels by supplying a constant 4.000 V signal switch, selected on the analog signal output circuit card. This should initiate DCS output on the user card of hexadecimal "CD", bit 205 of 256 = 4.000 v on channels (see specimen output, Table E.3).

Cards we received when tests were conducted read output, Table E.3.

Field tests on Julian Days 130 and 131/73 verified the interface output to the DCP analog inputs of 4.00 V.

It is concluded that final data from the DCS are two bits high on all channels.

This analysis demonstrates the necessity of designing a test capability into the sensors interface in order to verify data accuracy from the sensor input through signal conditioning, A/D conversion, coding, and transmission to final product. We recommend modification of the interface so that this test is performed automatically after a selectable number of transmissions, utilizing the DCP "Data gate Pulse" feature.

Table E.1. Message frequency (180 second mode).

Month	Operational days	90-minute period (MST) beginning 08:00	09:30	11:00	12:30	18:30	20:00	21:30	23:00	Daily average
February	6	8	15	15	—	3	18	15	0	12.3
March	31	57	115	76	3	29	89	95	6	15.2
April	22	44	63	39	—	28	67	64	4	14.0
May	31	57	104	57	1	31	96	95	6	14.4
June	15	30	42	32	1	22	41	36	3	13.8
July	20	45	67	40		16	55	66	1	14.5
August	9	10	28	21		20	21	18	4	13.6
September	30	64	102	62		33	96	99	2	15.3
October	31	50	113	64		42	89	91	0	14.5
November	27	48	81	52	2	37	69	76	0	13.5
December	31	63	101	67	1	32	97	96	2	14.8
Total	253	476	831	525	8	293	738	751	28	
Mean		1.9	3.3	2.1	0.03	1.2	2.9	3.0	0.1	14.4

* These tabulations exclude duplicate messages, test data, and invalid data due to sensor saturation.

Table E.2. Non-operational periods, 1973.

Dates	Julian days	Comments*
31 May-4 June	151-155	Component failures (interface) and testing
6 June-10 June	157-161	Component failures (interface) and testing
21 June-6 July	172-187	Short circuit, accidental damage to interface and retesting
20 July-27 July	201-208	Accidental shut-off of interface
1 Aug.-24 Aug.	213-236	Maintenance—relocation of mast for wind sensor and thermometer screen to shorten length of signal cable; building thermistor shields for air temperature sensors.
6 Nov.-9 Nov.	310-313	Interface power failure

* Where appropriate, these are elaborated in the section headed "Problems."

INTERFACE PROBLEMS

The only serious technical failure involved a Type 741 operational amplifier (of military/aerospace grade) used on Channel 7. This failed completely on two occasions. Voltage transients in the signal cable were suspected. The cable shield is grounded, but a separate ground to the precipitation gauge was also installed.

Operator errors occurred due to inexperience of temporary summer personnel. Measuring leads were left connected to the front panel binding posts and accidentally shorted to the interface cabinet. On future units this risk could be eliminated by the use of a non-conducting cabinet. There were also data gaps because personnel left the interface in the test mode or switched it off. Preparation of an operator instruction manual for the interface and test system will avoid such errors.

Table E.3. "CF" cards received.

Channels	Parameter value	Bit number	
1-3	14.10°C	207	These correspond to hexadecimal "CF" = 4.06 V.
4*	5.14°C	207	
5	1.42 ly	207	
6	36.11 m sec^{-1}	207	
7	20.52 cm	207	
8*	1.62 ly	207	

* Full scale was later changed but the bit error was unchanged.

DATA REPRODUCIBILITY

During periods of constant temperature, for instance, in the soil at 15 cm, we have noticed ± to 2 bit changes which could be attributed to circuit card instabilities or sensor and cable connections (see Table E.3). This is apparent on all channels.

Comparing thermistors for air temperature (Channels 1 and 2) with the U. S. Weather Bureau standard thermometers in the thermometer shelter confirms interface output agreement within 1.0°C. These comparisons are as in Table E.4.

RESULTS

The receipt of messages primarily at morning and evening hours and the 1½-hour "spread" of the message time over a 9- to 10-day cycle presents major problems of data analysis for meteorological purposes. For example, the diurnal course of temperature or solar radiation make averaging of instantaneous data from 4-5 message periods inadequate to represent mean daily values. For climatological purposes the following types of data are required: temperature — daily maximum and minimum [mean = (maximum + minimum) ÷ 2]; solar radiation, net radiation and precipitation — cumulative daily totals (preferably hourly); and wind speed — daily mean speed (based on run-of-wind total) and extreme maximum.

Analysis of wind data (m sec^{-1}) at 8 m above ground from the DCP and estimates from a corresponding analog record over the 24-hour period gives the comparison in Table E.5.

The analysis indicates that useful monthly mean wind speeds can be obtained with the present message interval with approximately 15 transmissions per day concentrated in the morning and evening hours. However, the DCP data cannot be used to estimate individual daily means unless the interface system incorporates an accumulating run-of-wind counter.

Comparison of soil temperatures at 15 cm measured by thermistors linked to the DCP, and at 10 cm by thermistors linked to a Rustrak analog recorder system for the period 12-31 May, 1973, gives the results in Table E.6.

The systematically higher reading of the DCP thermistor (at a greater depth) than the Rustrak thermistor probably reflects a difference between the sites of the installations, some 50 m apart, as well as the slight bias of 0.2°C due to the DCS product error noted previously. The time trends are in parallel during the period of comparison so that the DCP records appear to provide a good representation of this slowly changing parameter.

The tabulations of the monthly summary data are available in 1½-hour time intervals. Although the full diurnal course of radiation variations cannot be examined, some valuable results can be derived from a comparison of global solar and net radiation. It should be emphasized that in this instance the high message frequency provides a sample size much greater than that available from conventional field measurement programs including our own on Niwot Ridge. The graph (Figure E.2) suggests a family of curves which are provisionally explained as follows: Global solar radiation increases rapidly in spring. This may be related to the change from predominantly advective layer cloud in March to convective types in May-June with an absence of cloud in early morning. The May to June increase in net radiation corresponds to the increase in solar radiation and also to the reduction in snow cover which lowers the albedo. The net change in surface emission can be demonstrated to be small. Data from further seasons and other times of day are needed to check these findings, but the results, if confirmed, are of considerable interest in connection with the I.B.P. studies seeking to model the energy balance and the interrelated productivity of alpine tundra vegetation (Webber and Barry, 1973).

Table E.4. Comparing thermistors for air temperature.

Date	Parameter		Reference data (°C)	DCP data (°C)
16 Nov. 1973	Air temperature		−3.2	−2.6
16 Nov. 1973	Soil temperature	10 cm	−3.1	
		15 cm		−3.2
		20 cm	−3.3	
29 Nov. 1973	Soil temperature	10 cm	−5.6	
		15 cm		−5.3
		20 cm	−5.6	
4 Jan. 1974	Air temperature		−15.5	−15.9
Dec. 1973	Mean air temperature	08.45	−9.6	−9.1
		10.15	−9.7	−9.2
		19.15	−10.8	−10.9
		20.45	−11.8	−11.1

Table E.5. Comparison of wind data.

Month	Number of days	DCP Mean	DCP Stand. dev.	Analog record Mean	Analog record Stand. dev.	Correlation coefficient
March	14	6.5	3.8	6.9	3.9	+0.88
April	27	6.7	4.5	8.3	4.3	+0.83
May	30	7.2	4.2	8.4	4.2	+0.88
December	24	11.8	3.5	11.4	3.0	+0.87

Table E.6. Comparison of soil temperatures.

	MST (approx.)			
	10.30		20.30	
Item	Mean	n	Mean	n
Analog	−2.3	20	−2.3	20
DCP	−0.5	20	−0.5	20

EVALUATION

The DCP installed at 3,536 m on Niwot Ridge performed excellently in alpine conditions. Environmental extremes during the period of operation were as follows: *minimum air temperature* — −25.5°C (−13.9°F) (31 December 1973); *electronics interface internal temperature at circuit cards* — −18.6°C; *maximum wind speed* — 40.9 m sec^{-1} or 91 mph (12 December 1973).

The second platform delivered to us was held in reserve as a backup; shortage of funds for constructing a second interface system prevented it from being implemented operationally.

Data quality was excellent. However, the present message interval (with a concentration of passes in the morning and evening) is unsatisfactory for most meteorological/climatological applications unless more sophisticated and costly interface units are developed incorporating storage facilities. The present message frequency with the existing interface unit is acceptable only for parameters such as ground temperature which change slowly on a diurnal basis.

APPLICATIONS

Meteorological data from remote mountain locations are rare and many sections are sited for convenience in accessible valleys. For example, the climatological station at 3,750 m on Niwot Ridge, which has been serviced at weekly intervals—weather and manpower permitting—by INSTAAR personnel since 1952 represents the longest such data series at this elevation in western North America. There are few weather stations at or above 3,500 m. Data from

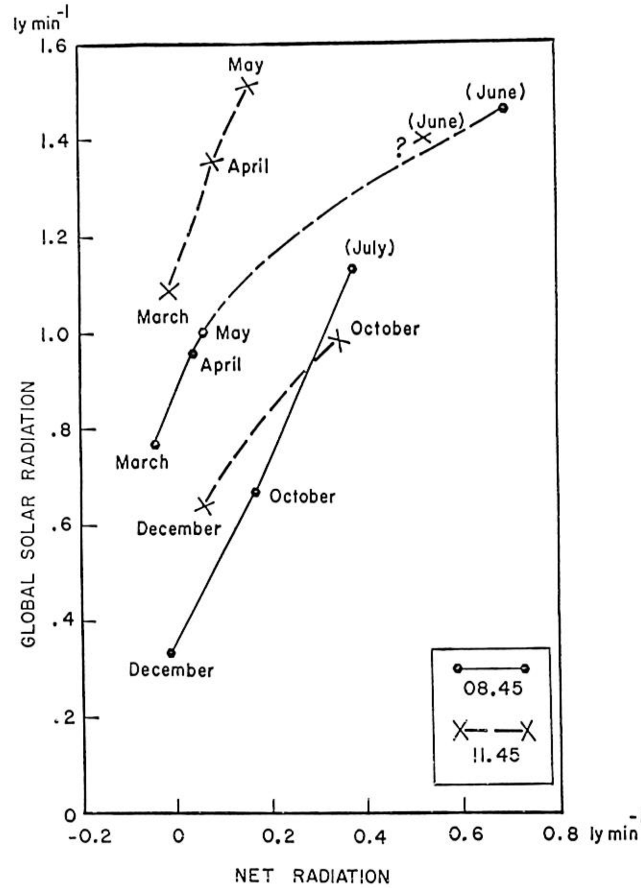


Figure E.2. Comparison of global solar radiation with net radiation.

mountain stations are of critical interest in a variety of areas.

Specific examples include: (1) monitoring current weather conditions in the high mountains to provide short-term forecasts or reports to forecasters, highway maintenance staff, tourists, and pilots of light aircraft. The potential value of such information, if available on teletype on a "real-time" basis has been confirmed by Mr. Marshall Grace, Chief Forecaster, Stapleton Airport, Denver (pers. comm., January 1974); (2) predicting snow melt and water yield; and (3) monitoring long-term climatic trends in an essentially pollution-free environment.

Section F
Results and Conclusions of Significance

Contributors
R. M. Hoffer
and all LARS and INSTAAR Staff

The first section of this report described the rationale and background of this research, defined the objectives, and provided a general evaluation of the entire project. Many different phases of our research efforts have produced results which we believe are highly significant in the overall development of remote sensing technology. New techniques for handling and analyzing multispectral scanner data were developed; various cover types were classified over larger areas than had ever before been possible; also, the results conclusively demonstrated the efficiency and applicability of computer-aided analysis techniques for mapping and tabulating acreages of Level I cover types, even in areas of mountainous terrain. The most significant results and the specific conclusions of this contract follow.

ECOLOGICAL INVENTORY

Classification Performance

• Good classification accuracy (90-95%) can be achieved in areas of rugged relief on a regional basis for Level I cover types (coniferous forest, deciduous forest, grassland and cropland, bare rock and soil, and water) using computer-aided analysis techniques (CAAT) on ERTS-1 multispectral scanner data.

• Areal estimates for Level I cover types using CAAT are highly accurate, as shown by correlation coefficients greater than 0.973 when computer derived acreages were compared to acreage estimates obtained by standard photo-interpretation techniques.

• Computer-aided analysis techniques allow accuracies of 70-80% to be achieved, without accounting for variations in spectral response due to topography, for Level II forest cover types (pinyon-juniper, ponderosa pine, douglas fir, spruce-fir, aspen, and Gambel oak), and tundra classes (dry tundra, wet tundra, and Willow-krumholtz).

• Statistical analysis showed that in mountainous areas, spectral response of Level II forest cover types is significantly (0.99 level) influenced by variations in stand density, aspect, and slope, as well as differences between species.

Cost Evaluation

• Cost comparisons showed that a Level I cover type map and a table of areal estimates could be obtained for the 443,000-hectare (2,456,000-acre) San Juan Mountain Test Site for less than 0.1¢ per acre, whereas photo-interpretation techniques (for the same area and to produce similar results) would cost more than 0.4¢ per acre. Cost comparisons on the relatively small Vallecito Intensive Study Area (24,211 hectares) indicated that using the computer-aided analysis techniques cost more per acre than the photo-interpretation technique, because some of the personnel costs involved in the computer processing did not change significantly even though the size of area involved was considerably smaller than the San Juan Mountain Test Site. Therefore, for areas of over 100,000 acres, computer-aided analysis becomes more cost-effective than photo-interpretation for obtaining maps and areal estimates of Level I cover types.

Techniques

• The "modified clustering" computer-aided analysis technique provided the most effective procedure for obtaining the training statistics, and it was therefore developed and documented as an operational approach for analysis of satellite scanner data.

• Relatively small portions of the total data set are necessary to develop adequate sets of training statistics, as was shown by the use of only 1,177 ERTS resolution elements in 16 cluster areas to train the computer for the classification of the 2,170,420 resolution elements contained in the San Juan Mountain Test Site area which covered 63 U.S.G.S. quadrangles. Thus, less than 1/10 of 1% of the total data set was utilized for training statistics and yet a Level I classification accuracy of 94% was obtained.

• To obtain a reasonable evaluation of computer classification accuracy, it is necessary to quantitatively compare the results using both a test field and an areal estimate approach.

• To effectively and accurately map forest and alpine vegetation types at a Level II degree of detail from 1:100,000 scale color infrared photography, two dates are recommended as well as stereoscopic viewing of the photography.

General

• Reasonable estimates of biomass productivity were calculated using areal estimates obtained from the computer classifications.

• Contracts with the U. S. Forest Service, National Park Service, Bureau of Reclamation, several Colorado state governmental groups, and several state and county land use planning groups have enabled the development of considerable interest, and enthusiasm for the potential applications of ERTS-1 data to meet the particular user agency needs.

HYDROLOGICAL FEATURES

Snow Cover Mapping

• Results of this investigation have conclusively proven that the areal extent of snow cover in mountainous terrain can be rapidly and economically mapped by using ERTS-1 MSS data and computer-aided analysis techniques (CAAT), providing cloud free data can be obtained.

• Temporal changes in the areal extent of snow cover could be accurately measured by digitally overlaying multiple data sets (in this study, six sets of ERTS data obtained between November 1, 1972 and June 5, 1973 were overlayed) followed by computer analysis using a specially developed change-detection analysis program.

Mountain Lake Mapping

• The freeze-thaw sequence of mountain lakes can be effectively monitored with ERTS data. A distinct relationship between elevation and time of freeze or thaw was observed.

• The freeze-thaw study of mountain lakes and the study of temporal changes in the areal extent of the snow pack both indicated that an 18-day data collection cycle was not adequate, particularly during the spring runoff. The ability to collect data only every 18 days was restricted by cloud cover problems which often decreased frequency of data collection to 36 or 54 days, a frequency which is unacceptable for many hydrological purposes.

Spectral Response Analysis

• Snow cover and clouds cannot be reliably differentiated on the basis of spectral response in ERTS-1 data, due to detector saturation and the available spectral range. This was clearly shown by analysis of several thousand data values from both snow and clouds on tapes from three different dates.

• Similar spectral response was found for many water bodies, areas of terrain shadow, and cloud shadow areas, thereby making spectral differentiation of water bodies difficult. ERTS band 4 (0.50-0.60μm) did allow spectral separation between water and cloud shadows, and water could be separated from areas of terrain shadow using ERTS band 7 (0.80-1.10μm) except where terrain shadow coincided with areas of forest cover.

GEOMORPHOLOGICAL FEATURES

• Basic lithologic units such as igneous, sedimentary and unconsolidated rock materials have been successfully identified using computer-aided analysis techniques, thus indicating that such techniques, when judiciously applied, are beneficial in studying geologic materials. However, separation of individual rock types within a lithology is more difficult than separating the basic lithologic units.

• Geomorphic form, which is exhibited through spatial and textural data, can only be inferred from computer analyzed ERTS MSS data.

• On a regional scale, there appears to be some correlation between vegetative cover and geomorphologic units. Through inference and the study of ancillary information, this relationship is useful in geologic mapping. This is significant because of the need for incorporating interpretation of geomorphologic features on land use planning activities.

• ERTS data provides geologists (and other users) with a unique previously unavailable perspective of the earth's surface. This enables previously uncorrelated earth surface features of possible significance to be identified, and delineated for further study.

DATA COLLECTION PLATFORM

• DCP systems can be utilized to produce satisfactory data from extremely inaccessible locations that encounter very adverse weather conditions, as indicated by results obtained from a DCP located at 3,536 meters elevation that encountered minimum temperatures of —25.5°C and wind speeds of up to 40.9 m sec —1 (91 mph), but which still performed very reliably.

• The present message interval is unsatisfactory for many meteorological/climatological applications, unless more sophisticated and costly interface units having storage capabilities are developed.

RECOMMENDATIONS

In addition to the significant results and conclusions defined above, it should be pointed out that this study represented one of four ERTS-1 investigations in which the Laboratory for Applications of Remote Sensing (LARS), Purdue University, was heavily involved. Many of the data handling programs utilized in this Colorado study were developed as part of the ERTS-1 Wabash Valley study. These data processing techniques have been described in the Final Report of the Wabash Valley study. It should be emphasized that without the development of these techniques in an integrated ERTS-1 research program at LARS, much of the effectiveness of the work on the Colorado test site would have been severely hampered. The geometric correction program was of particular significance in this regard.

The experiences and results of this research with the ERTS-1 data have also indicated a number of recommendations which should be considered in designing and implementing future satellite scanner data collection systems. These are as follows:

- *Frequency of data collection:* The 18-day collection sequence available with ERTS-1 proved to be inadequate for several phases of this study. Even if cloud free conditions had existed during critical times of the year, an 18-day cycle would probably not be adequate for effectively monitoring changes in the snowpack during the critical period of the spring runoff. An 8- to 10-day cycle would be much more satisfactory for hydrologic studies in the future. Because of frequent cloud cover problems, such an increase in frequency of coverage would also assure a higher probability for collection of adequate quantity and quality of data during critical periods of the vegetative growing season.

- *Wavelength bands utilized:* Work with aircraft data and recent work with SKYLAB data has clearly shown the importance of the middle infrared and thermal infrared portions of the spectrum for many applications areas. Because the ERTS-1 scanner did not obtain data in these wavelength regions, we believe that the classification accuracies achieved are not as accurate as would be possible. Addition of at least one wavelength band in the middle infrared portion of the spectrum ($1.3 - 2.6\mu m$) and at least one channel in the $8\text{-}13.5\mu m$ thermal infrared region in future satellite scanner systems will unquestionably allow significant improvements in many of the results obained, and in the utility of this type of satellite data.

- *Time of day:* In order to minimize the amount of information lost in areas of topographic shadows, a data pass near solar noon would be optimum. However, because of the normal mid-day build-up of cumulus clouds, it appears that the time of day utilized in this ERTS-1 experiment was nearly ideal, and a change in time of data collection would not be recommended for future systems.

- *Delays in receipt of data:* Lengthy delays in receipt of data in either image or tape format precluded the possibility of a rapid analysis of the data and subsequent field checking of anomalous situations. It is highly recommended that a system be developed to get an intermediate quality product into the hands of the investigators within 2-4 days after data collection. If cloud cover is minimal and overall data quality appears promising, the investigator could then request tapes and final image product outputs. A relatively short turn around would need to be possible for these final products, also.

- *Aircraft Underflight Data:* The importance of the high quality, small-scale aerial photography obtained from NASA's WB-57 should be emphasized. Without this aerial photography, the project could not have been satisfactorily completed, because many porions of the San Juan Mountain Test Site did not have any photographic data available. However, the delay in the acquisition of this base-line aerial photography from the summer of 1972 until the summer of 1973 seriously hampered progress during the early phases of the investigation. Because of nearly complete snow cover in the mountains during the winter, lack of 1972 photography meant that much of the necessary cover type mapping from the aerial photography could not be started until nearly a year after the contract was signed. This created additional problems throughout the project, and particularly during the 1973 field season. It is recommended that areas without existing aerial photography and with critical time periods for data collection should be given special consideration in defining aircraft flight schedules in conjunction with future satellite research and operational programs.

- *Data processing:* Because of the importance of geometrically correcting the ERTS-1 satellite data, and because of the growing demand by many users for geometrically corrected data, we would recommend that a system be established to geometrically correct all future data collected as early in the data processing sequence as possible. However, it is vital that the geometric correction process should not impair the radiometric quality of the data.

- *Data overlay capability:* The ability to overlay multiple data sets is becoming increasingly important, in that it allows the temporal dimension of the spectral information to be fully utilized, and will also allow satellite data to be effectively related to other map bases. Therefore, future systems should provide a data tape format that has been geometrically corrected to a standard format base.

In closing, we believe that a great deal has been accomplished as a result of this ERTS-1 experiment. Significant progress was made in learning how to process, analyze, and interpret MSS data. Contacts with user agencies indicate that they are becoming excited about the possibilities for utilizing this type of data in their day-to-day management decisions.

Looking ahead, we must strive even more diligently in future months to develop economical and effective analysis, and evaluation techniques so that maximum use can be made of data obtained from future satellite systems in various operational programs.

Appendices

APPENDIX A

Appendix A.1. Forest Cover Tree Species Description

Aspen and Oak

The deciduous tree species in the San Juan Mountains [aspen (*Populus tremuloides* Mich.) and scrub oak (*Quercus gambelii* Nutt.)] form broad seral stands following fire. Their clonal habit makes them ideal colonizers after a fire.

The intense heat produced by a fire frequently destroys conifer seed located within the volatized duff layer. The rhizomes of both oak and aspen may be located below the point of destructive heat penetration. Recolonization by deciduous species can occur via cloning from surviving rhizomes. Recolonization of burn areas is rapid and clonal stands may persist for many years. Aspen are intolerant of shade (Baker, 1949), and are gradually invaded and replaced by coniferous species which grow taller and thicker, and gradually block out the sunlight. Scattered relics of both aspen and oak persist within climax coniferous stands, and these are isolated subordinates from the nuclei for seral revegetation following another fire (Uggla, 1958).

Some aspen stands tend to resist invasion by conifers due to winter wind disbudding invading conifers in the understory. The loss of the apical bud of conifers retards height growth. This impedes both maturation and cone production, and thus postpones dominance by the invading conifers (Rowe, 1953).

Scrub oak, although unimportant as a lumber resource, contributes substantially to wildlife sustenance, and retards erosion following a fire (Reynolds, et al. 1970). Oak is frequently found associated with ponderosa pine *(Pinus ponderosa)*. The pine-oak savannah in the San Juan mountains is a product of repeated brush fires. Both species are resistant to the effects of fire, and are ideally suited to form a pyric climax.

Oak and aspen may form topoedaphic climaxes on steep slopes that have high degradation rates. Within the study area scrub oak climaxes are found on the steeper slopes of the hogbacks, particularly the southern portions of Baldy Mountain, Ludwig Mountain, and Rules Hill quadrangles. Within scattered ravines on north-facing slopes of the hogbacks there is sufficient moisture to support small populations of aspen. Aspen characteristically need a higher soil moisture than oak (Weigle, *et al.* 1911). Aspen seldom form a pyric climax due to the moisture gradient and elevational distribution.

Ponderosa Pine

Mature ponderosa pine (*Pinus ponderosa* Laws.) are ideally adapted for a pyric climax (Daubenmire, 1952) due to its thick bark, branches high on the trunk, and wide spacing. The ponderosa pine seedlings, with the terminal buds protected by long needles, are fairly resistant to the effects of brush fires (Odum, 1953).

The soils of ponderosa pine stands have a lower acidity and thinner duff layer than soils supporting Douglas fir stands [(*Pseudotsuga menziesii* Michx.) Daubenmire, 1952].

Douglas Fir

Douglas fir [(*Pseudotsuga menziesii* var. *glauca* (Brissn.)) Franco] tends to require acidic soil (pH 4.5 to 6.5) and greater moisture (Isaac, *et al.* 1958) than ponderosa pine, and is usually found on north-facing slopes in the lower elevations of its range. Ponderosa pine seedlings have low shade tolerance and cannot compete with Douglas fir seedlings under the forest canopy (Muller, 1971). Although Douglas fir is tolerant of shade, it is less tolerant than Engelmann spruce or subalpine fir (Baker, 1949).

Within the San Juan mountains, Engelmann spruce and Douglas fir may form a topoedaphic climax on rocky south-facing slopes or ridge tops. The rock nature of the sites maintain the natural spacing that permits competition with spruce at higher elevations. Several factors influence the Engelmann spruce/Douglas fir competition. Trees on these rocky sites have greater exposure to the sun which causes rapid temperature fluctuations detrimental to germination of spruce seeds (Bjor, 1970). Solarization harmful to spruce seedling development (Ranco, 1970), and the light intensity which increases the hardiness of Douglas fir (Van Den Driessthe, 1970) favor the establishment of Douglas fir.

White Fir

White fir [*Abies concolor* (G. & G. Lindl.] is prolific and reaches maturity quickly, and is an extremely efficient, seral competitor (Miekel, 1962). Within the San Juan Mountains, white fir is usually found associated with aspen in areas of disturbance. White fir and Douglas fir tend to invade Ponderosa pine stands. White fir is shorter than Douglas fir and has a much smaller crown diameter, so it is shaded out as Douglas fir canopy develops. There is evidence that the elevational limit of growth is determined by winter stress (Wright, *et al.* 1971).

Engelmann Spruce

Engelmann spruce [*Picea engelmanni* (Parry) Engelm.] forms dense climax cover, and is restricted at its upper boundary by timberline. In the timberline ecotone, which varies in elevation, Engelmann spruce forms krummholz which are horizontally flattened trees growing in the direction of the prevailing winds. The lower boundary of Engelmann spruce may be caused more by bark beetle attack than by abiotic factors. In the ecotone with Engelmann spruce and Douglas fir as codominants, a high proportion of spruce beetle infection occurs. By selectively attacking spruce, the species composition of the ecotone fluctuates. Spruce loss allows Douglas fir to assume dominance.

The association of Engelmann spruce and subalpine fir is shade tolerance (Asadetshas, 1969), and this tends to eliminate both white fir and Douglas fir in areas where these species overlap (Jones, 1971).

Pinyon Pine

Pinyon pine (*Pinus edulis* Englem.) is a species that usually forms a topoedaphic climax. It grows on south-facing gravelly slopes at lower elevations. The wide uniform spacing of the pinyon pine indicates that soil moisture determines dispersion. On moister sites, Ponderosa pine eliminates Pinyon pine shading.

Rocky Mountain Juniper

Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) is usually found on dry south-facing slopes in association with Pinyon pine or Ponderosa pine. Pinyon pine tends to replace juniper in the areas these species associate (Woodbury, 1947). Juniper and Pinyon pine tend to grow in slightly alkaline soils (pH 8.0) (Pearson, 1931). Both species are intolerant of shade (Larson, 1930). As juniper is usually found at higher elevations than Pinyon pine, it probably has greater tolerance of severe environmental conditions.

Subalpine Fir

Subalpine fir [*Abies lasiocarpa* var. *lasiocarpa* (Hoop) Nutl.] is usually found growing in association with Engelmann spruce. Subalpine fir has less exacting soil requirements and is sometimes found on soils that are too wet or too dry for spruce (Alexander, 1958). Within the San Juan Mountains, subalpine fir, or corkbark fir (A. *lasciocarpa* var. *arizonica,* Merriam Lemm.), a geographical variety, form scattered stands mixed with Engelmann spruce. Engelmann spruce forms extremely dense stands in this area, and often this reduces the number of subalpine fir due to competition.

Limber Pine

Limber pine (*Pinus flexilis* James) forms topoedaphic climaxes on ridge tops and exposed areas. In these sites, wind velocity and rocky soil eliminate competition from other species not adapted to these conditions.

Other Species

Other species of vegetation occurring in the test sites are listed below:

Sedge (*Carex* sp.)
Alpine timothy (*Phleum alpinum*)
Thurber fescue (*Festuca ovina)*
Tundra rush (*Juncus drummond)*
Avens (*Geum turbinatum)*
Tundra bluegrass (*Poa rupicola)*
Cork bark fir (*Abies lasiocarpa* var *arizonica* Merriam)
Scouler willow (*Salix scouleriana* Barratt)
Thin-leaf alder (*Alnus tenuifolia* Nutt)
Water birch (*Betula occidentalis* Hook)
Golden currant (*Ribes averum* Pursh.)
Wax currant (*Ribes cereum* Dougl.)
Snowberry (*Symphoricarpos oreophilus)*
Rocky Mountain maple (*Acer glabrum* Torr.)
Arizona fescue (*Festuca arizonica* Varsey)
Mountain muhly (*Muhlenbergia montana* (Nutt.) Hitchc.)
Pine dropseed (*Blepharoneuron tricholepis* (Nash) Torr.)
Bluegrama (*Boutelova gracilis* H.B.K.)
One-seed juniper (*Juniperus monosperma* (Engelm.) Sarg.)
Utah juniper (*Juniperus osteosperma* (Torr.) Little)
Rocky Mountain juniper (*Juniperus scopulorum* Sarg.)
Ceanothus (Ceanothus (*Ceanothus* sp.)
Buckbush (*Ceanothus fendlevi)*
Cliff rose (*Cowania mexicana)*
Galleta (*Hilaria jamesii* Torr.)
Gano dropseed (*Sporobolus cryptandrus* Torr.)
Mountain mahogany (*Cercocarpus betuloides)*
Manzanita (*Arctostaphylos pungens)*
Apache plume (*Fallugia paradora)*
Bluestem (*Andropogon scoparius)*
Side oats grama (*Bouteloua curtipenclula)*
Black grama (*Bouteloua eripoda)*
American vetch (*Vicia americana)*

Appendix A.2. Film Evaluation

Mission	Roll	Type	Date	Frames used	Description
238	48	CP	6-6-73	0017-0018	Good contrast in greens, both coniferous and deciduous types. Easily distinguished large scale is very good. One can see individual trees for crown shape and color discrimination (note CIR of same mission has poor contrast in reds. Used for northern Ludwig Mountain (Lake Simpatico and north). Wide range of green values and saturation.
	48	CP	6-6-73	0057-0058 0072-0073 0109-0110	Used in conjunction with smaller scale CIR for coniferous distinction (CIR used for deciduous due to extremely good contrast in reds was the more recently acquired 48-roll 23).
238	49	CIR	6-6-73		Generally less separability in reds between deciduous and coniferous, especially in mixed communities. Douglasfir is difficult to distinguish from aspen.
239	30	CIR	6-6-73	0111-0112 0113	Used for southern Ludwig Mountain due to lack of larger scale color (238 roll 48 does not go far enough south). Good contrast between deciduous and coniferous except in higer elevations where vernalization has been delayed by late snow. Poor contrast in coniferous among species due to smallness of scale (about ½ the size of 238 roll 48).
239	29	CPOS	6-6-73	None	Distinction between shades of green not as good as distinction between shades of red on 239-30. Thus not used for vegetation mapping. Film otherwise good.
248	23	CIR	8-4-73	0110-0111	Very good contrast between coniferous and deciduous (twice as good as 239-30 which was good). Used instead of 239-30 since it arrived in all areas where coverage occurs. It is especially much better in higher elevations than 239-30. Unfortunately 248-23 misses the tundra area on Vallecito by a very small margin. There was also some difficulty separating oak from meadow due to smoothness of texture on both and similarity of red tones.
248	22	CPOS	8-4-73	None	Distinction between shades of greens on this roll not as good as corresponding red shades on 248-23.
248	69	CIR	8-15-73	0088-0090	Very good exposure for vegetation cover type discrimination in the tundra. Some difficulty in discriminating the willows from aspen below timberline due to similar values of red. Distinction of details on eastern porton of fames 0088-90 extremely difficult within coniferous forest due to density of film. Excellent exposure for tundra, poor exposure for forest.

Appendix A.3. Photo-Interpretation Criteria for Vegetation Mapping: San Juan Mountain Test Site

Photointerpretation criteria of NASA aircraft coverage for vegetation mapping of Ludwig Mountain and Vallecito Reservoir quads, San Juan Mountains test site.

Cover type (Levels 1 & 2)	Mission /roll	ISCC-NBS color for cover type, relatively level, full sunlight conditions	Hue and value		Texture	Observed elevational limits	Community description and remarks
			CPOS	CIR			
FOREST **Coniferous** Piñon-Juniper C.1	239/30	17 v. d. Red with 19 gy. Red and 185 p. Blue		grey-red red and blue mixture	Mixed, scattered, speckled Rounded crowns visible	7,200–7,800	Found on Ludwig Mountain quad. Usually vegetation is sparse (density = I, II) and bare soil or rock is visible between the vegetation. Stands occur in xeric sites on exposed south facing slopes or hilltops on southern edge of quad.
FOREST **Coniferous** Ponderosa Pine C.2	238/48	147 v. d. G or 166 v. d. bG 151 d. gy. G*	Deep slightly greyish green		Same as above except larger scale allows analysis of crown shape which is broad and rounded	7,000-9,400	Found on Ludwig Mountain and Vallecito Reservoir quads. Densities of growth may vary abruptly from 100% crown closure to very open conditions. (I, II, III). Open to moderately dense stands (I, II) may have oak or shrub understory visible through the crowns of the Ponderosa Pine. Recent disturbance may generate very dense stands due to closely seeded young trees. Stand sites occur in all aspects of low relief in southern Ludwig Mountain quad. Further north it is replaced by other cover types on north, east and west facing slopes. Its most northern occurrence is on south facing slopes. Sites generally mesic. Occurs with Colo. Blue Spruce on flood plains in south.
	239/30	17 v. d. Red with 16 d. Red 19 gy. Red 186 gy. Blue		Dominant color deep red of Ponderosa Pine	III nearly continuous, rounded crowns visible. II mod. continuous, rounded crowns visible. I discontinuous, rounded crowns, understory visible		
	248/23	14 v. deep Red may grade to 17 v. d. Red or 16 d. Red*		Dark brownish red varies with aspect and density			
FOREST **Coniferous** Douglasfir/ Ponderosa Pine C.2.3.	238/48	147 v. d. G 166 v. d. bG 151 d. gy. G*	Slightly greyish deep green		Nearly continuous, mottled, rounded crowns visible. Ponderosa crowns resemble Douglasfir	7,200-9,400	Found on both Ludwig Mountain and Vallecito Reservoir quads. In the south it appears on the north sides of hills gradually assuming eastern and western exposures at higher elevations. Usually occurs in dense stands (III). It may grade into either Douglasfir/White Fir or Ponderosa Pine cover types. Distinguish from Ponderosa Pine mostly by aspect and density from ground observations.
	239/30	17 v. d. Red 14 v. deep Red		Deed red, slightly bluish on slopes	Mottled by crowns. Individual crowns visible but not useful for distinguishing type		

	248/23	17 v. d. Red 14 v. deep 41 deep r. Br		Deep red to reddish brown	Mottled by crowns. Individual crowns visible but not useful for distinguishing type		
FOREST **Coniferous** Douglasfir/ White Fir C.3	238/48	151 d. gy. G (white fir) 151 d. gy. G 147 v. d. G*	White fir greyish blue-green		Uneven crowns quite mottled. White fir and Douglasfir similar except for color	7,200- 9,400	Found on Ludwig Mountain and Vallecito Reservoir quad. Replaces Ponderosa Pine/Douglasfir on steep north, east and west facing slopes. Generally occurs at higher elevations than Ponderosa Pine/Douglasfir. Densities of stand usually III. Uneven crown heights and White Fir's distinctive grey-green color makes it distinguishable.
	239/30	17 v. d. Red 41 deep r. Br with a slightly bluish cast		Douglasfir and white fir similar shade—deep red, slightly brown or blue	Uneven crowns visible. Color differences more dfficult to tell		
	298/23	17 v. d. Red 14 v. deep Red 41 deep r. Br		Deep reddish brown	Uneven crowns visible. Color differences more difficult to tell		
FOREST **Coniferous** Spruce/Fir C.4	238/48	147 v. d. G 152 Blackish G. 151 d. gy. G* depending upon slope and aspect	From deep forest green to grayish green		Mottled, but crowns fairly even and pointed	9,000- 11,000	Found on Vallecito Reservoir at higher elevations. First appears on north and then east and west facing slopes, later on south facing slopes. Densities usually III. Grades into Douglasfir/White Fir. Pointed crowns on 1:40,000 scale imagery distinguishes it from other conifers.
	239/30	17 v. d. Red 14 v. deep Red 41 deep r. Br 186 gy. Blue		Grades from red-blue to red-brown with blue understory	Mottled, but crowns fairly even and pointed		
	248/23	41 deep r. Br 14 v. deep Red		Deep reddish brown	Mottled but crowns fairly even and pointed		
FOREST **Coniferous** Colorado Blue Spruce C.6	238/48	147 v. d. G 151 d. gy. G*	From deep forest green to grayish green		Mottled, crowns pointed may be discontinuous	7,000- 7,800	Found on Ludwig Mountain and Vallecito Reservoir quads along major rivers on flood plains. Densities vary from I-III. It may be mixed with Ponderosa Pine or Cottonwood. Not extensive.
	239/30	17 v. d. Red 14 v. deep Red		Deep red	Mottled, pointed crowns, may be discontinuous		
	248/23	41 deep r. Br 14 v. deep Red		Deep reddish brown	Mottled, pointed crowns may be discontinuous		

Photointerpretation criteria of NASA aircraft coverage for vegetation mapping of Ludwig Mountain and Vallecito Reservoir quads, San Juan Mountains test site.—Continued

Cover type (Levels 1 & 2)	Mission /roll	ISCC-NBS color for cover type, relatively level, full sunlight conditions	Hue and value		Texture	Observed elevational limits	Community description and remarks
			CPOS	CIR			
FOREST **Deciduous-** **Coniferous** M.1	238/48	147 v. d. G 151 d. gy. G and 146 d. G to 126 d. 01. G or 137 d. y. G	Dark green conifers mixed with more yellow green or brighter green aspen		Mottled with patches of smooth aspen mixed	7,400- 11,900	Found on Ludwig Mountain and Vallecito Reservoir quads. Occurs mostly in logged or burned areas where conifers mix with aspen. Very extensive on western Vallecito Reservoir. Densities vary from I to III. All slopes and aspects are included. Sites are mesic.
	239/30	17 v. d. Red 14 v. deep Red with 16 d. Red 13 deep Red		Darker red conifers with pinkish red to bluish pink aspen	Mottled with patches of smoother aspen mixed		
	248/23	41 deep r. Br 14 v. deep Red with 13 deep Red and 11 v. Red		Darker brown-red conifers with brilliant to deep red			
FOREST **Deciduous** Riparian Cottonwood (Willow) D.1	238/48	164 m. b. G to 147 v. d. G	Varies from lighter bluish green to deep green		Discontinuous, puffy crowned, mottled	7,000- 7,800	Found on Ludwig Mountain and Vallecito Reservoir quads along major river flood plains. Densities may vary from I to III. Mixing occurs with coniferous species and cover type grades into tall willow with increased elevation. Sites are quite moist, with high water table.
	239/30	16 d. Red		Medium pinkish red	Discontinuous, puffy crowned, mottled		
	248/23	11 v. Red		Bright red	Mottled, may be discontinuous		
FOREST **Deciduous** Oak-shrub D.3	239/30	184 v. p. B 263 White 6 d. Pink		Mottled blue-grey and light pink	Rough, discontinuous	7,000- 8,000	Occurs on Ludwig Mountain quad on dry, south facing slopes on southern half of quad. Densities usually I or II. Much bare soil or rock may be visible. Occasional Ponderosa Pine may occur.
FOREST **Deciduous** Oak D.4	238/48	150 gy. Green to a brighter grey green	Pale grey green to a brighter grey green. Varies with elevation		Mottled, slightly rough surface	7,000- 9,800	Occurs more extensively on Ludwig Mountain than on Vallecito Reservoir quad. Forest stands on north facing slopes of hog backs. To a lesser extent appears relatively frequently on all exposures and usually as understory in Ponderosa Pine stands. On south facing slopes grades into sparser and perhaps drier oak-shrub cover type. Community shape lobate or elongate, especially on hogback slopes.
	239/30	Slightly pinker than 19 gy. Red and 15 m. Red		Greyish red	Mottled, slightly rough surface		
	248/23	None apply		Bright to dark red orange	Mottled, slightly rough surface		

FOREST **Deciduous** Aspen D.5	238/48	145 m. G 146 d. G*	Fairly bright grey green		Rounded crowns visible	7,600- 11,700	Found on Ludwig Mountain and Vallecito Reservoir quads. Usually occurs on north facing slopes at lower elevations and gradually moves to all aspects with increasing elevation. May be associated with moist or disturbed areas. Occurs mixed with conifers very extensively in disturbed areas of upper elevations on Vallecito Reservoir quad. Densities are generally III. Communities have rounded or lobed form due to clonal growth habit.
	239/30	12 s. Red to 19 gy. Red and 186 gy. Blue		Varies from bright pinkish red to grey-blue at high elevations where vernalization is incomplete	Rough, rounded crowns visible		
	248/23	None apply		Bright orange red, may be darker	Rough, rounded crowns visible		
FOREST **Deciduous** Wet Shrub D.6	248/23	None apply		Bright orange red, may be mottled	Nearly smooth	7,800- 11,900	Category added to bridge a gap between Alpine shrub (above timberline) and Cottonwood Willow communities along rivers below 7,800. This cover type occurs in subalpine meadows, forest clearings, mesic hill sides and small floodplains. Can be distinguished from meadow, oak and aspen by textural differences.
HERBACEOUS **Non-Agricultural** Cultivated Crops A.1	238/30	146 d. G or bare soil from recent cultivation	Bright deep green or bare soil brown		Fairly smooth	7,000- 7,500	Occurs on Ludwig Mountain quad. Usually limited to floodplains. May show recent cultivation or row crop configuration. Usually rectangular fields.
	239/48	11 v. Red or 185 p. Blue		Either bright red or pale blue (recently cultivated)	Fairly smooth		
HERBACEOUS **Non-Agricultural** Cultivated Pasture A.2	238/30	146 d. G	Bright green		Fairly smooth	7,000- 7,500	Occurs on Ludwig Mountain quad. Usually limited to floodplains. Planted to a few species within last decade. Irrigated by system of ditches.
HERBACEOUS **Non-Agricultural** Pasture A.3	238/30	None apply	Mottled shades of yellow to grey green		Fairly smooth	7,000- 9,200	Occurs on Ludwig Mountain and Vallecito Reservoir quads. May actually occur in any meadow up to and onto the tundra. However, this cover type is reserved for use on moderate to heavily grazed areas by virtue of proximity to farm areas and ease of access for animal transport. Non-cultivated irregular areas on floodplains with mottled (pale) color.
	239/48	None apply		Mottled shades of pinkish red to blue	Fairly smooth		
	248/23	Mottled 11 v. Red to 16 d. Red or 19 gy. Red		Mottled shades of bright red to brown or grey-red	Fairly smooth		

Photointerpretation criteria of NASA aircraft coverage for vegetation mapping of Ludwig Mountain and Vallecito Reservoir quads, San Juan Mountains test site.—Continued

Cover type (Levels 1 & 2)	Mission /roll	ISCC-NBS color for cover type, relatively level, full sunlight conditions	Hue and value		Texture	Observed elevational limits	Community description and remarks
			CPOS	CIR			
HERBACEOUS **Non-Agricultural** Meadow N.1	238/30	None apply	Mottled shades of gray greens		Fairly smooth	7,000-11,900	Occurs on Ludwig Mountain and Vallecito Reservoir quads. Most meadow areas are grazed domestically to a limited extent. Where grazing is moderate the "meadow" may be classified A.3. Some clear cut areas appear classed as meadows because of the dominant vegetation. Some shrubs or rocks may interrupt the herbaceous growth of a meadow.
	239/48	None apply		Mottled shades pinkish red to blue	Fairly smooth		
	248/23	19 gy. Red 15 m. Red 12 s. Red 13 deep Red to 11 v. Red		Mottled shades of bright red	Fairly smooth		
NON-VEGETATED **Rock-Soil** Exposed Rock B.1	238/30	29 m. y. Pink to 263 White	From reddish yellow pink to white		Rough or smooth	7,000-12,300	Occurs on Ludwig Mountain and Vallecito Reservoir quads. Usually appears as cliff face or under sparse cover such as Piñon-Juniper.
	239/48	185 p. Blue to 263 White		Shades of blue to white	Rough or smooth		
	248/23	185 p. Blue to 263 White		Shades of blue to white, may appear slightly yellow			
NON-VEGETATED **Rock-Soil** Exposed Soil B.2	238/30	31 p. y. Pink to 263 White	From pale yellow pink to white		Fairly smooth	7,000-12,300	Occurs on Ludwig Mountain and Vallecito Reservoir quad. Appears on floodplains, road cuts, blowouts, reservoir margins freshly plowed fields, and between vegetation of sparsely vegetated cover types.
	239/48	184 v. p. B to 263 White		Pale blue to white	Fairly smooth		
	248/23	184 v. p. B to 263 White		Pale blue white	Fairly smooth		
NON-VEGETATED **Urban** Urban U.1	238/30	263 White	Roofs appear white, yards green		Rough with linear roads	7,000-7,600	Occurs on Ludwig Mountain and Vallecito Reservoir quads. Small clusters of building occur on several sites. No major towns are within these quads.
	239/48	263 White		Roofs appear white, yards red	Rough with linear roads		
	248/23	263 White		Roofs appear white, yards red	Rough with linear roads		

• Film colors somewhat greyer than color chips.

Appendix A.4. Photo-Interpretation Criteria for Vegetation Mapping: Indian Peaks Test Site

Photointerpretation criteria of NASA aircraft coverage for vegetation mapping of Ward quadrangle, Easternslope of the Front Range.

Cover type (Levels 1 & 2)	Mission /roll scale	ISCC-NBC color for cover type, relatively level, full sunlight conditions	Hue and value: CPOS	Hue and value: CIR	Texture	Observed elevation in feet	Community description and remarks
FOREST **Coniferous** Ponderosa Pine/ Douglasfir	248/70 0036 1:100,000	152 blackish G		Blackish green (underexposed)	Continuous to broken, smooth visible crown cover	8,800-8,900 (upper limit for association)	Upper limit in Ward quad, merging with limber and lodgepole pine in subalpine forest. Common on north-facing slopes, predominance of Douglasfir. Many disturbed sites in successional stages of development. Trees commonly less than 50 ft.
FOREST **Coniferous** Spruce-Fir (SF) C.4	248/69 0080 1:46,000	21 blackish R to 17 v. d. Red and 14 v. deep Red		Discolored red to blackish red	Continuous, smooth, visible crowns	8,800-11,000	Stable, mature stands found on Ward quad subalpine slopes. Solid, dense cover, minimal visual disturbance from roads, logging and fire (lack of Aspen intrusion). Trees to 100 feet, densely populated closed stands at higher elevations to 11,000 feet.
FOREST **Coniferous** Krummholz (Krum)	248/69 0088 1:46,000	14 v. deep Red		Reddish-brown	Clumped, discontinuous, scattered, contoured and streamlined crowns	Treeline to 11,200. Forest tundra ecotone	Associated with forest-tundra ecotone in Ward quad. Found as isolated scrub-tree islands; sites of snow accumulation. Contoured to slope aspect and prevailing wind. Common on north-facing slopes on Niwot Ridge.
FOREST **Coniferous** Lodge Pole Pine C.7	248/69 0088 1:46,000	17 v. d. Red with 21 Blackish R		Reddish-brown to dark brown and black	Solid, continuous, smooth, visible crowns	8,500-9,800	Common in subalpine forest of Ward quad, often on north-facing slopes. Some mixing with Aspen and Spruce-Fir association.
FOREST **Deciduous-Coniferous** (De-Con) Coniferous Species and Aspen M.1.	248/69 0088 1:46,000	13 deep Red and 14 v. deep Red with 17 v. d. Red		Red mixed with reddish-brown to dark brown	Aspen mottled with rounded crowns. Scattered discontinuous conifers, smooth cover, visible crowns	8,800-10,000	Lack of extensive deciduous-coniferous mixing owing to infrequency of recent disturbance (fire, cutting). Some heterogeneity at 10,000 feet. Predominance of Aspen at lower elevations among sparse, mature Lodgepole pine. Successional stand-types mixed with shrubs in moist to mesic soils.

Photointerpretation criteria of NASA aircraft coverage for vegetation mapping of Ward quadrangle, Easternslope of the Front Range.—Continued

Cover type (Levels 1 & 2)	Mission /roll scale	ISCC-NBC color for cover type, relatively level, full sunlight conditions	Hue and value CPOS	CIR	Texture	Observed elevation in feet	Community description and remarks
FOREST **Deciduous** (Decid) Cottonwood-Willow D.1	248/69 0088 1:46,000	11 v. Red		Dark red	Mottled streamers, rounded crowns	8,800-10,800	Found at reservoir runoffs, (e.g. Left Hand Reservoir), stream banks and areas with elevated water tables on Ward quad.
FOREST **Deciduous** Aspen (A) D.5	248/69 0088	13 deep Red		Dark red	Mottled, continuous to sparse rounded crowns	8,800-10,000	Successional stands found on Ward quad. Variable ecotypes, moisture, mesic and drought soil conditions, dense to open, sparse stands. Grasses and shrubs form ground cover as well as seedlings of Lodgepole pine, Ponderosa pine, and Douglasfir.
HERBACEOUS **Non-Agricultural** Meadow (M)	248/69 0090 1:46,000	16 d. Red to 13 deep Red		Light red to pink red	Smooth, continuous	8,800-9,600	Successional ecotype usually following localized disturbance to Ward quad. Prostrates, grasses, herbs form ground cover, invaded by Aspen.
HERBACEOUS **Non-Agricultural** Wet Meadow (Wet Mead) N.3	248/69 0090 1:46,000	13 deep Red and 14 v. deep Red with 21 blackish R		Deep red with dark blotches		9,000 to tundra	Solid plant cover on Ward quad, may be associated with willow-birch shrub types in the vicinity of lakes or high water table. Vigorous plant growth, year-round saturation of roots; common in depressions.

Appendix A.5. Areal Estimates by Planimetering Cover Type Maps for Selected Quadrangles

Tundra map (portions of Ward and Monarch Lake quadrangles).

Cover type	Code	Km2	mi2	Acres
Moist tundra	1A	4.45	1.91	1,223
	1B	5.59	2.16	1,385
	1C	5.27	2.04	1,302
Total		15.31	6.11	3,910
Dry tundra	2	6.26	2.42	1,548
Willow	3A	4.56	1.76	1,126
	3B	3.94	1.52	973
	3C	2.40	0.93	594
Total		10.90	4.21	2,693
Krummholz	4	8.27	3.19	2,041
Wet meadow	5	8.25	3.18	2,035
Water	6	2.54	0.98	627
Snowbank	7	4.73	1.83	1,170
Bare rock	8A	19.00	7.33	4,685
	8B	11.65	4.50	2,878
Total		30.65	11.83	7,563
Deciduous	9	3.84	1.48	948
Coniferous	10	51.70	19.97	12,780
Meadow	11	0.79	0.30	195

Gold Hill quadrangle.

Cover type	Km2	mi2	Acres
Coniferous	97.70	37.71	24,150
Deciduous	7.06	2.73	1,748
Deciduous-coniferous	21.54	8.31	5,320
Non-agricultural	17.75	6.85	4,380
Water	0.28	.11	70
Rock-soil	0.28	.11	70
Urban	0.61	.24	154

Lyons quadrangle (Boulder, Colorado).

Cover type	Km2	mi2	Acres
Coniferous	83.55	32.28	20,650
Deciduous	4.85	1.87	1,198
Deciduous-coniferous	13.09	5.03	3,221
Non-agricultural	50.65	19.58	12,520
Water	0.68	0.26	168
Rock-soil	0.78	0.30	194
Urban	0.73	0.28	180

Nederland quadrangle (only that portion in Boulder, Colorado).

Cover type	Km2	mi2	Acres
Coniferous	13.63	5.26	3,365
Deciduous	.37	0.14	90
Deciduous-coniferous	20.99	8.10	5,185
Non-agricultural	12.16	4.69	3,050
Tundra	2.97	1.15	736
Water	.13	0.05	32
Rock-soil	.15	0.06	38
Urban	1.79	0.69	442

Ludwig Mountain quadrangle.

Cover type	Square mile	Acres
Coniferous	26.37	16,777
Deciduous	7.25	4,640
Deciduous-coniferous	16.80	10,752
Non-agricultural	3.26	2,086
Agricultural	6.23	3,987
Rock and soil	0.01	6
Water	0.06	36
Urban	0.00	0

Tungsten quadrangle (only that portion in Boulder, Colorado).

Cover type	Km2	mi2	Acres
Coniferous	31.61	12.20	7,810
Deciduous	1.42	0.55	352
Deciduous-coniferous	11.07	4.27	2,730
Non-agricultural	6.19	2.39	1,529
Water	.91	0.35	224
Rock-soil	.65	0.25	159
Urban	.22	0.08	51

Vallecito Reservoir (only that portion on printout).

Cover type	Square mile	Acres
Coniferous	13.80	8,832
Deciduous	8.37	5,357
Deciduous-coniferous	5.51	3,526
Non-agricultural	0.89	570
Agricultural	0.67	429
Rock and soil	0.12	77
Water	3.97	2,541
Urban	0.13	83

Handies peak quadrangle.

Cover type	Km2	mi2	Acres
Coniferous	12.53	4.84	3,095
Deciduous	21.20	8.18	5,240
Deciduous coniferous	2.38	0.92	588
Non-agricultural	1.88	0.72	461
Tundra	61.85	23.90	15,300
Water	0.17	0.07	4
Rock-soil	53.15	20.60	13,180
Urban	0.19	0.08	5

Hermosa quadrangle.

Cover type	Km2	mi2	Acres
Coniferous	83.10	32.10	20,560
Deciduous	34.90	13.50	8,640
Deciduous-coniferous	16.31	6.30	4,030
Agricultural	0.56	0.22	141
Non-agricultural (grazed)	14.49	5.58	3,575
Water	0.36	0.14	89
Rock-soil	3.52	1.36	870
Urban	0.25	0.10	64

Durango East quadrangle.

Cover type	Km2	mi2	Acres
Coniferous	55.80	21.40	13,695
Deciduous	28.41	10.98	7,020
Deciduous-coniferous	9.86	3.81	2,440
Non-agricultural	18.05	6.97	4,460
Agricultural	1.14	0.44	281
Non-vegetated	2.29	0.88	566
Water	0.29	0.11	71
Urban	3.74	1.44	924

APPENDIX C

The following material is directly related to the Geomorphological Features Survey. This information is not presented in the main text either because of its repetitive nature or ancillary importance.

Abstracts of three papers presented by LARS staff during the course of this research project are reproduced on the following pages. Complete texts for these papers have been presented with prior reports and so are not reproduced here.

A detailed discussion of INSTAAR field efforts relating to the Geomorphological Features Survey tasks are presented to give the interested reader a feeling for the complexity of the test sites being evaluated. Because of its nature, this material is presented as an appendix rather than as part of the text.

Appendix C.1. Recognition of Surface Lithologic and Topographic Patterns in Southwest Colorado with ADP Techniques (Abstract)

Analysis of ERTS-1 multispectral data by automatic pattern recognition procedures is applicable toward grappling with current and future resource stresses by providing a means for refining existing geologic maps. The procedures used in the current analysis already yield encouraging results toward the eventual machine recognition of extensive surface lithologic and topographic patterns. Automatic mapping of a series of hogbacks, strike valleys, and alluvial surfaces along the northwest flank of the San Juan Basin in Colorado can be obtained by minimal man-machine interaction. The determination of causes for separable spectral signatures is dependent upon extensive correlation of micro- and macro-field based ground truth observations and aircraft underflight data with the satellite data.

Appendix C.2. Evolution of the Upper Colorado River as Interpreted from ERTS-1 MSS Imagery (Abstract)

Manual interpretation of ERTS-1 MSS imagery provides a synoptic basis for recognition of anomalous drainage patterns in arid regions in west-central Colorado. These patterns suggest that numerous diversions of the Colorado River System across the Uncompahgre Plateau occurred in pre-Pleistocene time. Certain topographic characteristics, common to a series of stream channels traversing the plateau, indicate that many present-day valleys were formerly occupied by a through-flowing major stream.

Geomorphic inference, based on channel characteristics, regional structure, and physiographic relationships as interpreted from ERTS-1 imagery, suggests that prior to the San Juan Mountain and West Elk Mountain volcanic episodes, the Colorado River System flowed southward along the approximate western edge of the present mountains. Orogenic uplift combined with aggradation of volcanic sediments and flows initiated a sequence of westward diversions by blockage of the former southward flowing stream. The Colorado River then migrated across the surface of the Uncompahgre region through a series of lithologically and joint controlled captures.

This process appears to have been repeated at several places until the master stream reached present Unaweep Canyon. Structural evidence suggests that uplift of the Uncompahgre Plateau commenced at this time. The subsequent history of diversion and capture of the Colorado River and its tributaries occurred as outlined in the literature.

The synoptic view provided by ERTS-1 MSS imagery demonstrates how a new perspective of the evolution of surface features may be obtained. This new perspective in a regional framework improves our understanding of geologic processes and our mapping capabilities of many important surface features.

Appendix C.3. Applications of Machine Processed ERTS-1 Data to Regional Land Use Inventories in Western Colorado (Abstract)

The Earth Resources Technology Satellite (ERTS-1) provides timely, good quality data which can be beneficial to regional land use and resource inventory assessment. Analysis of sequential data sets by nominal photointerpretive techniques is time-consuming and limited by the ability of the human interpretation system. Computer processing techniques for analyzing multispectral scanner data have been developed at Purdue University by the Laboratory for Applications of Remote Sensing (LARS) to facilitate handling of large amounts of remote sensor information.

A study area, located near Grand Junction in west-central Colorado, is well suited for testing the capabilities of computer techniques to perform resource inventories at regional scales, and to present these data in forms compatible with management requirements. The ERTS-1 data set collected 27 September 1972 is nearly cloud-free and includes a large number of distinctive natural patterns that are economically significant. Results indicate good capability for spectrally differentiating zones of various naturally occurring vegetational assemblages from the computer compatible data tapes. Cultural patterns, both urban and agricultural, can be identified on the multispectral data. The acreage of irrigated lands can be determined. Data from the near infrared channels of the scanner are useful in identifying and mapping the extent of surface water available for the area. In arid or semi-arid environments the success of this latter capability can be an important factor in influencing land use and management patterns.

After classification, information derived from the multispectral data can be displayed as computer printout comparable in scale to 7 ½′ U.S.G.S. topographic quadrangles, as a black and white image, or as a color-coded image. In addition to map output, information regarding areal extent of the various cover classifications may be obtained in tabular or graphic form, with the output then converted to acreage.

Analysis of satellite data with ADP techniques offers land managers or planners rapid access to data output. It is anticipated that as our ability to interpret these data improves, our understanding of systems required to define resource needs is also enhanced, and man will be able to better utilize this information in the development of regional land use inventory models.

Appendix C.4. Geomorphologic Features for the San Juan Mountains

Area (km²), percent of area covered and number of features for the San Juan Mountain, Colorado, based on the 11 1:24,000 quads of Figure C. 15.

	Avalanche chutes	Percent	Bedrock	Percent	Cirques	Percent	Forest	Percent	Rock glacier	Percent
1. Gray Head	.713	.0048	39.805	26%	none	—	63.531	42%	none	—
2. Howardsville	5.92	.0398	76.45	51%	22.80	15%	14.54	.0979	2.06	.0138
3. Ironton	5.29	.0356	31.58	21%	8.01	.0539	32.13	21%	3.83	.0257
4. Little Squaw Creek	2.20	.0148	51.20	34%	5.00	.0336	84.63	57%	.0793	.0005
5. Red Cloud Peak	10.82	.0728	18.60	12%	20.32	13%	35.80	24%	4.28	.0288
6. Rio Grande Pyramid	1.547	.0104	64.994	33%	11.837	.0797	46.4	31%	.637	.0042
7. Silverton	9.08	.0611	29.52	19%	14.04	.0945	50.75	34%	2.55	.0171
8. Snowden Peak	5.658	.0381	30.93	21%	7.00	.0471	51.716	35%	1.07	.0072
9. Storm King	3.277	.0220	75.42	50%	28.0481	18%	28.82	19%	2.12	.0142
10. Telluride	3.26	.0219	28.76	19%	21.68	14%	56.58	38%	7.24	.0487
11. Weminuche Pass	4.381	.0295	59.325	39%	6.513	.0438	43.028	29%	.301	.0020

Areas (km²), percent of area covered and number of features for the San Juan Mountain, Colorado, based on the 11 1:24,000 quads of Figure C. 15.

	Old rock glacier	Percent	Snowfields	Percent	Moraines	Percent	Lakes	Percent	Active scree	Percent
1. Gray Head	none	—	none	—	none	—	.124	.0007	4.467	.0300
2. Howardsville	.72	.0048	1.25	.0102	.03	.0002	.47	.0031	38.22	26%
3. Ironton	none	—	.22	.0014	none	—	.26	.0017	39.89	27%
4. Little Squaw Creek	.026	.0001	.0614	.0041	none	—	.768	.0081	19.33	13%
5. Red Squaw Creek	.93	.0062	none	—	none	—	.05	.0003	73.85	49%
6. Rio Grande Pyramid	.494	.0033	.083	.0005	none	—	.679	.0045	19.433	13%
7. Silverton	.319	.0021	1.19	.0080	none	—	.056	.0003	25.49	17%
8. Snowden Peak	0	—	.435	.0029	none	—	.648	.0043	20.66	14%
9. Storm King	.200	.0013	3.55	.0239	.169		1.34	.0090	32.95	22%
10. Telluride	.301	.0020	.6	.0040	none	—	.67	.0045	41.65	28%
11. Weminuche Pass	none	—	none	—	.011	.000074	4.192	.0282	13.230	.0890

	Inactive scree	Percent	Alluvial deposits	Percent	No. of cirques	No. of rock glaciers	No. of snow patches
1. Gray Head	30.290	20%	1.901	.0128	—	—	—
2. Howardsville	.63	.0042	3.76	.0253	35	16	21
3. Ironton	20.99	14%	1.61	.0108	26	15	5
4. Little Squaw Creek	2.25	.0151	2.476	.0166	11	2	2
5. Red Cloud Creek	none	—	5.26	.0354	34	23	—
6. Rio Grande Pyramid	5.615	.0378	.894	.0060	14	4	2
7. Silverton	24.85	16%	4.27	.0287	34	15	12
8. Snowden Peak	.9805	.0066	.986	.0066	32	10	6
9. Storm King	0	—	4.967	.0334	48	18	23
10. Telluride	14.30	.0962	3.93	.0264	35	32	7
11. Weminuche Pass	12.105	.0815	7.064	.0475	13	3	—

Appendix C.5. Re-Interpretation of the Howardsville and Telluride Quadrangles Using NASA Underflight Photography

The Howardsville and Telluride quadrangles were selected from those listed in Appendix C.4 since good, cloud-free underflight coverage was available for these areas from Mission 213 (Roll 59: frames 44-49; 60-65; 91-96) and Mission 247 (Roll 11: frames 35-38; 61-66; 127-130; 168-171). The original mapping of geomorphic features on these quadrangles (Figure C.16.) Figure C.18. was based on Forest Service air photographs on a scale of approximately 1:15,000 and served as a guide to the work described in this section. The area occupied by the Howardsville quadrangle lies mainly above timberline, and has been glaciated at least once. The geomorphic features classification (table below) consists, therefore, of spectrally distinctive features which are normally associated with mountain glaciation. Discussion in the main body of text, Section C, indicated that these features typify much of the San Juan Mountain Test Site. This implies that the Howardsville classification is applicable to adjacent quadrangles.

Geomorphic boundaries were defined first on the U.S.G.S. quadrangle at a scale of 1:24,000. Subsequently, a mylar overlay was prepared.

The nomenclature used in the table is genetic in most cases. It has been used primarily for the sake of brevity and serves to convey an impression of assemblages of features in the study area (see next page). The categories are visually separable on the basis of color and texture. For example, individual areas assigned to categories 3, 6, 9 and 10 are relatively uniform internally, whereas areas in 1, 2B, 6A, 8A and 8B have distinctive mottled or speckled textures that derive from internal diversity, the components of which are probably not resolvable by ERTS-1 sensors. A guide to surface texture is provided in the table.

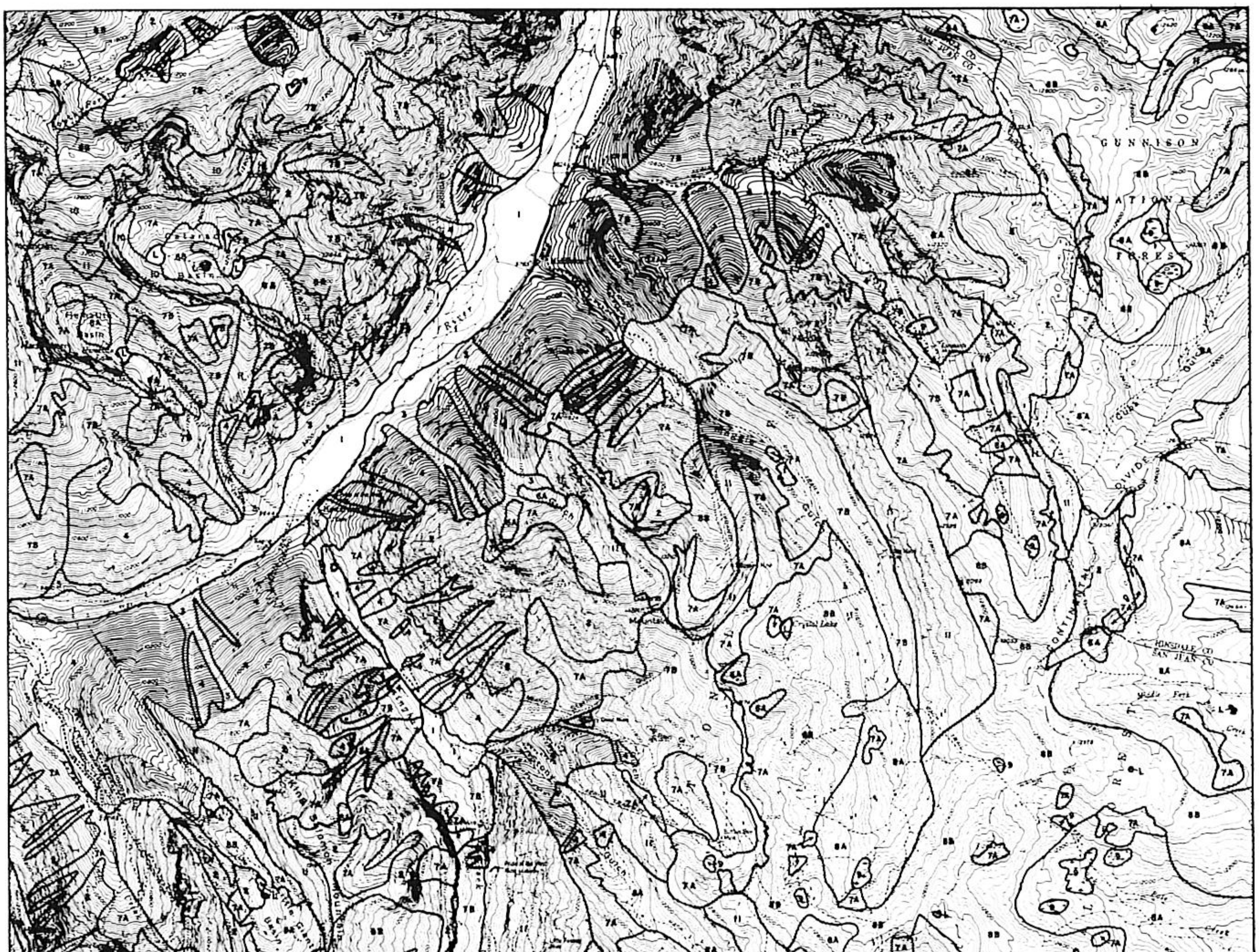
The wide variation in both slope aspect and slope declivity in the Howardsville area causes complex patterns of light and shadow which produce variations in spectral response within each category. The principal shadow areas under illumination from the southeast are indicated on the appendix figure. Spectral variation between areas in a given category is greatest for categories which are largely unvegetated, especially 1, 2A, 2B, 3, 6A, 5 and 7A.

The Telluride quadrangle (scale 1:24,000) was also remapped using NASA aircraft color infrared films. The original geomorphological map was prepared several years ago. The greater resolution of the NASA coverage, and the color and false color photography allows greater discrimination of surface features even though this photography is on a smaller scale (approximately 1:30,000) than the black and white U. S. Forest Service coverage (approximately 1:15,000). For these reasons and the fact that the NASA-PY Project (NASA Grant No. NGL-06-003-200) is currently involved in supplying environmental information to the town of Telluride, it was decided to remap this quadrangle with superior imagery.

Certain problems are apparent in using NASA imagery; however, the imagery is vastly superior to U. S. Forest Service black and white photography. One handicap is that color infrared film does not lend itself to mapping geological units as easily as true color photography, and the true color imagery of the San Juans is on a much smaller scale than the color infrared imagery. Secondly, much of the imagery was shot when the sun was at a low angle; consequently, many areas cannot be mapped as they are in shadow.

Description of geomorphic characteristics by category and textural qualities, as derived through interpretation of NASA underflight photography.

Category number	Description	Textural comments
1	Alluvial "plains," includes braided Channels	Speckled
2A	Dissected bedrock (Andesitic)	Uniform/speckled
2B	Dissected bedrock (Schistose and allied types)	Speckled/striped
3	Colluvium	Uniform
4	Coniferous forest (Undifferentiated)	Speckled/uniform
5	Lakes ponds	Uniform
6A	Rock glaciers, assumed to be currently "active"	Banded
6B	Rock glaciers, assumed to be currently "stable"	Mottled/banded
7A	Scree, currently active	Uniform/speckled
7B	Scree, currently stable	Uniform/mottled
8A	Till-mantled bedrock, till predominating	Mottled
8B	Till-mantled bedrock, bedrock predominating	Mottled/striped
9	Wet meadow and marsh	Uniform
10	Snowbanks	Uniform
11	Shadow	Uniform



Appendix C.5 Figure. Geomorphic characteristics for Howardsville quad derived through interpretation of NASA underflight photography.

Appendix C.6. Geomorphic Classification of the Indian Peaks Test Site

The test site covers the western two-thirds of the Ward quadrangle and the eastern quarter of the Monarch Lake quadrangle. The Indian Peaks Test Site was selected as an alternate site based on the extensive field research carried out in this alpine area by INSTAAR over the past few years.

NASA Mission 248 (Roll 68, CIR, Frames 88-90) served as a base for the geomorphic mapping. Boundaries were delimited first on a plastic sheet fastened over the CIR frames and were later transferred to U.S.G.S. 1:24,000 quadrangles with a Bausch & Lomb Zoom Transfer Scope. A mylar overlay was produced from this base map.

The categories shown in Appendix C.5. Figure are indexed in the table below. Only a few of the categories recognized in the Howardsville area could be defined adequately in the Indian Peaks Test Site. This may reflect differences in the extent and intensity of glaciation between the two areas.

Work was discontinued on the Howardsville and Telluride quadrangles when it became apparent that geometrically-corrected gray-scale printout would not be available for these areas. Non-geometrically corrected printout from ERTS Frame 1047-17200 (Bands 2, 3, and 4) was examined for the Howardsville area. Attempts to correlate the gray-scale printout with the geomorphic overlay map were severely hampered by scale changes across the printout and by the presence of cloud and cloud shadow areas.

The table indicates that overlap exists between the geomorphic mapping and the tundra vegetation mapping categories. The wet-, dry-, and bare-tundra boundaries on Appendix C.6 Figure were derived independently, however, and therefore provide some measure of the operator variation to be expected in this type of work (compare C.5 and C.6). The comments concerning topographic shadow are applicable to the Indiana Peaks Test Site. Categories 1 and 2 have a wide range of spectral reflectance. In most cases, this cannot be attributed to differences in rock composition and weathering. The patterned ground category is defined almost totally on the basis of texture, since the color of vegetated "stripes" in this category differs only slightly from that of dry tundra.

Index to geomorphic features in the Indian Peaks test site.

Category number	Description	Textural comments
1	Talus slopes and rock glaciers	Uniform/speckled
2	Bedrock faces (undifferentiated)	Dissected
3	Glacially-scoured valley floors (principally granite-gneiss-partially vegetated)	Banded
4	Patterned ground (extensive areas on alpine interfluves)	Striped
5	Moist tundra (includes wet meadow)	Uniform
6	Dry tundra interfluves (some patterned ground)	Mottled
7	Bare tundra interfluves (principally regolith)	Mottled
8	Forest-tundra ecotone region	Speckled
9	Forest (undifferentiated)	Mottled/uniform
10	Snowbanks	Uniform
11	Lakes and ponds	Uniform
12	Shadow	Uniform

Appendix C.6 Figure. Geomorphic features of the Ward quad.

References

Abaljan, T. S., 1972. "Analysis of Snow Cover Distribution From Aero-photography Data Over Experimental Mountain Basin of Varzob River, *In: Distribution of Precipitation in Mountainous Areas,* Vol. II, World Meteorological Organization, Geneva (W.M.O. No. 326), pp. 103-110.

Alexander, R. R., 1958. "Silvical Characteristics of Subalpine Fir." Rocky Mt. Range Expt. Sta. Pap. No. 32. U.S.D.A. Forestry Service.

Anderson, J. R., E. E. Hardy and J. T. Roach, 1973. "A Land-Use Classification System for Use With Remote-Sensor Data", *Geological Survey Circular 671,* U. S. Geological Survey, Washington, D. C.

Anuta, P., 1970. "Multispectral Classification of Crops in the Imperial Valley, California, From Digitized Apollo 9 Photography." LARS Information Note 070770, Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana.

Asadetshas, A. I., 1969. "Effect of Differing Shading Intensity on the Growth of Spruce Seedlings." *Lesodedemil,* V. 1, pp. 95-97.

Baker, F. S., 1949. "A Revised Tolerance Table," *Journal of Forestry,* pp. 179-181.

Barry, R. G. and R. S. Bradley, 1971. "Historical Climatology." *In: San Juan Ecology Project Interim Progress Report,* 1971. H. Teller (ed.), pp. 291-334.

Bauer, M. E., and J. E. Cipra, 1973. "Identification of Agricultural Crops by Computer Processing of ERTS MSS Data." LARS Information Note 030173.

Bjor, K., 1970. "Extreme Temperatures of Forest Sites," *Tidcshs Skoghuk* 78 (2): pp. 191-196.

Carson, M. A. and Kirkby, M. J., 1972. *Hillslope Form and Process:* Cambridge University Press, London.

Clark, J. and C. Wells, 1973. "An Interface System for Meteorological Data Using the ERTS Data Collection Platform," *Arctic and Alpine Research,* V. 5: pp. 151-154.

Clements, F. E., 1916. *Plant Succession: Analysis of the Development of Vegetation.* Publ. Carnegie Inst., Wash.

Coggeshall, M. E. and R. M. Hoffer, 1973. "Basic Forest Cover Mapping Using Digital Remote Sensor Data and ADP Techniques." M. S. Thesis. Purdue University, West Lafayette, Indiana.

Connaughton, C. A., 1970. "The Revolt Against Clear Cutting", *Journal of Forestry,* (68-5): pp. 264-265.

Coulson, K. L., 1966. "Effects of Reflection Properties of Natural Surfaces in Aerial Reconnaissance," *Appl. Optics,* V. 5, pp. 905-917.

Cronin, J. F., *et al.,* 1968. "Ultraviolet Radiation and the Terrestrial Surface," in Holz, R. K., 1973. *The Surveillant Science,* Houghton Mifflin Co., Boston, pp. 67-77.

Cross, Charles Whitman, and C. W. Purington, 1899. Description of the Telluride Quadrangle (Colorado), *Folios of the Geologic Atlas of the United States,* (No. 57).

Cuskelly, S. L., 1969. "Erosion Control Problems and Practices on National Forest Lands," *Trans-ASAE,* V. 12 (1); pp. 69-70.

Daubenmire, R. F., 1943. "Vegetational Zonation in the Rocky Mountains," *Botanical Review,* V. 9: pp. 325-393.

————, 1952. "Forest Vegetation of Northern Idaho", *Ecol. Mono.,* V. 22: pp. 301-330.

————, 1962. *Plants and Environment,* John Wiley and Son, New York.

————, 1968. *Plant Communities,* Harper and Row, New York.

Draper, N. R. and H. Smith, 1966. *Applied Regression Analysis,* Wiley and Sons, Inc., New York.

Egbert, D. D. and F. T. Ulaby, 1972. "Effect of Angles on Reflectivity," *Photogrammetric Engineering,* V. 38: pp. 556-564.

Everett, K. R., 1965. "Instruments for Measuring Mass-Wasting," Proc. Permafrost Int. Conf., NAS-NRC, Washington, 1956, pp. 136-139.

Fenneman, T. D., 1931. "Silvical Characteristics of White Fir", *U.S.D.A. Min. Pub. #93.*

Garnier, B. J., and A. Ohmura, 1968. "A Method of Calculating the Direct Shortwave Radiation Income of Slopes," *Journal of Applied Meteorology,* V. 7: pp. 796-800.

Hoffer, R., and F. Goodrick, 1971. "Geographic Considerations in Automatic Cover Type Identification," *Proceedings of the Indiana Academy of Science for 1970,* V. 80: pp. 230-244.

Hornbeck, J. W., 1970. "The Radiant Energy Budget of Clear-cut and Forest Sites in West Virginia," *Forest Science,* V. 16 (2): pp. 139-145.

Isaac, L. A. and E. J. Dunock, 1958. "Silvical Characteristics of Douglas-fir var. *menziesii,*" *Silvicultural Series 9,* Pacific Northwest Range Experiment Station, U.S.D.A. Forest Service.

Jones, J. R., 1971. "Mixed Conifer Seedling Growth in Eastern Arizona," U. S. Forest Service Research Paper, RM-77, pp. 1-19.

Landgrebe, D. A., 1973. "Analysis Research for Earth Resource Information Systems: Where Do We Stand?", LARS Information Note 062273, Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana.

Larsen, J. A., 1930. "Forest Types of the Northern Rocky Mountains and Their Climatic Controls," *Ecology* V. 11: pp. 631-672.

Leaf, C. F., 1967. "Areal Extent of Snow Cover in Relation to Streamflow in Central Colorado," International Hydrology Symposium (Fort Collins), Proceedings, V. 1: pp. 157-164.

————, 1971. "Areal Snow Cover and Disposition of Snowmelt Runoff in Central Colorado," U.S.D.A. Forest Service Research Paper (Fort Collins), RM-66.

Leonardo, E. S., 1964. "Capabilities and Limitations of Remote Sensors," *Photogrammetric Engineering,* V. 30: pp. 1005-1010.

Lieth, H., 1972. "The Net Primary Productivity of the Earth With Special Emphasis on Land Areas," *In: Perspectives on Primary Productivity of the Earth,* (ed., R. H. Whittaker) Symposium AIBS 2nd National Congress, Miami (in press).

MacDonald, R. E., M. E. Bauer, R. D. Allen, J. W. Clifton, and J. D. Erickson, 1972. "Results of the 1971 Corn Blight Watch Experiment," 8th International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan.

Marr, J. W., 1961. "Ecosystems of the East Slope of the Front Range in Colorado", *University of Colorado Studies,* Series in Biology, No. 8, University of Colorado Press, Boulder, Colorado.

Meier, M. F., 1973. "Evaluation of ERTS Imagery for Mapping and Detection of Changes of Snow Cover on Land and on Glaciers." Symposium on Significant Results Obtained From the Earth Resources Technology Satellite-I, NASA, Washington, D. C., V. I: pp. 863-875.

Meikel, J., 1962. "Plant Communities of the Grand Canyon," *Ecology,* V. 43: pp. 698-711.

Mroczynski, R. P., W. N. Melhorn, and S. Sinnock, 1973. "Application of Machine Procesesd ERTS-1 Data to Regional Land Use Inventories in Arid Western Colorado," 4th Annual Conference on the Application of Remote Sensing of Arid Land Resources and Environments, Tucson, Arizona, Nov. 14-16, 1973.

Muller, R. A., 1971. "Transmission Components of Solar Radiation in Pine Stands in Relation to Climatic and Stand Variables," U.S.D.A. Forest Service Research Paper, PSW:70.

Nie, Bent, and Hull, 1970. *Statistical Package for the Social Sciences,* McGraw-Hill, New York.

Nunnally, N. R., 1969. "Integrated Landscape Analysis With Radar Imagery," *Remote Sensing of the Environment,* V. 1: pp. 1-6.

Odum, E. P., 1953. *Fundamentals of Ecology,* W. B. Saunders Company, Philadelphia, PA.

Pearson, G. A., 1931. "Forest Types of the Southwest as Determined by Climate and Soil," U. S. Department of Agriculture, Technical Bulletin 247.

Phillips, T. L., ed., *LARSYS Version 3 User's Manual,* Vol. 2, 1973, Laboratory for Applications of Remote Sensing, Purdue University, Lafayette, Indiana.

Polcyn, F. C., 1967. "Investigations of Spectrum-matching Sensing in Agriculture," Final Report, V. 1: (NASA), Institute of Science and Technology, University of Michigan.

Purdue University Computing Center, 1974. "R-Squares for All Possible Regressions", Document G2 DRRSQU, Purdue University, West Lafayette, Indiana.

Purington, Chester Wells, 1899. "Economic Geology (of the Telluride Quadrangle, Colorado) U.S.G.S. G. Atlas Telluride Folio (No. 57): pp. 15-18.

Reynolds, H. G., W. P. Clay, and P. F. Folliot, 1970. "Gambel Oak for Southwestern Wildlife," *Journal of Forestry,* V. 68 (9): pp. 545-547.

Richmond, G. M., 1962. "Quaternary Stratigraphy of the La Sal Mountains, Utah." U.S.G.S. Prof. Paper, 324: 135.

Robinson, N., (Ed.) 1966. *Solar Radiation,* Elsevier Publishing Company, Amsterdam.

Ronco, F., 1970. "Influence of High Light Intensity on Survival of Planted Engelmann Spruce," *Forest Science* V. 16 (3): pp. 331-339.

Rowe, J. S., 1953. "Forest Sites—A Discussion," *Forest Chronology* V. 29: pp. 278-289.

Shanmugan, K. and R. M. Haralick, 1973. "Combined Spectral and Spatial Processing of ERTS Imagery Data," Symposium on Significant Results Obtained from Earth Resources Technology Satellite-1, Vol. 1 Section B, pp. 1219-1228.

Stohr, C. J., 1974. "Delineation of Sinkholes and the Topographic Effects on Multispectral Response," Unpublished M. S. Thesis, Purdue University, West Lafayette, Indiana.

Swain, P. H., T. V. Robertson, and A. G. Wacker, 1971. "Comparison of the Divergence and B-Distance in Feature Selection," LARS Information Note 020871, Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana.

Todd, W. J., P. W. Mausel, and M. F. Baumgardner, 1973. "Urban Land Use Monitoring From Computer-Implemented Processing of Airborne Multispectral Sensor Data," LARS Information Note 061873, Laboratory for Applications of Remote Sensing, Purdue University, West Lafayette, Indiana.

Uggla, E., 1958. "Ecological Effects of Fire on North Swedish Forests," Alinguist and Wiksells, Uppsala.

Vaartaja, O., 1962. "The Relationship of Fungi to Survival of Shaded Tree Seedlings," *Ecology,* V. 43: pp. 547-548.

Van Den Driessche, R., 1970. "Influence of Light Intensity on Frost Hardiness in Douglas Fir Seedlings," *Canadian Journal of Botany,* V. 48 (12): pp. 2129-2134.

Van Wagner, C. E., 1970. "Duff Consumption by Fire in Eastern Pine Stands," *Canadian Journal of Forest Research,* V. 2 (1): pp. 34-49.

Webber, P. J., 1972. Comparative Ordination and Productivity of Tundra Vegetation," 1st Annual Symposium of the U. S. Tundra Biome Program (Lake Wilderness Center) U. S. Tundra Biome, pp. 55-60.

———, and R. G. Barry, 1972. "Project 6111: Seasonality of the Tundra Vegetation," *In: The Structure and Function of the Tundra Ecosystem,* I.B.P., U. S. Tundra Biome, 1973 Proposal, pp. 41-43.

———, 1974. "Tundra Primary Productivity," *In: Arctic and Alpine Environments,* (ed., J. D. Ives and R. G. Barry), Methuen, London, pp. 445-473.

Weigle, W. G. and E. H. Frothingham, 1911. "The Aspens: Their Growth and Management," U.S.D.A. Forestry Service Bulletin, V. 93.

Williams, L. D., Barry, R. G., and J. T. Andrews, 1972. "Application of Computed Global Radiation for Areas of High Relief," *Journal of Applied Meteorology,* V. 11: pp. 526, 533.

Woodbury, A. M., 1947. "Distribution of Pigmy Conifers in Utah and Northeastern Arizona," *Ecology,* V. 28: pp. 113-126.

Wright, J. W., W. A. Lemmien, and J. N. Bright, 1971. "Genetic Variation in Southern Rocky Mountain White Fir," *Silvae Genet,* V. 20 (5/6): pp. 148-150.

Zapp, A. D., 1949. "Geology and Coal Resources of the Durango Geological Survey, Oil and Gas Investigations Preliminary Area, La Plata and Montezuma Counties, Colorado," U. S. Map 109, 2 sheets.

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