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EXPLOITING THE TEMPORAL COHERENCE OF REPETITIVE SATELLITE IMAGERY

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I. ABSTRACT

Imagery from ERTS or the Synchronous Meteorological Satellites, because of its precisely repetitive nature, is ideally suited both for subjective enhancement via time-lapse display and for objective measurements of changes with time. The SRI ESIAC, a hybrid system providing both viewing and image processing functions, is described. A representative application involves the measurement of changes in aerial extent of snow cover within specified mountain watersheds.

Subjective viewing of time-lapse sequences of the snow scenes provides valuable insight into the nature of numerous extraneous signals, permitting the interim implementation of operationally useful snow measuring systems while hopefully leading toward the design of fully objective classifiers.

A short movie of selected ERTS time sequences will be shown to illustrate the concepts discussed.

II. INTRODUCTION

One of the most attractive attributes of all satellite imagery is its dependable, repetitive coverage--a highly desirable feature for numerous applications involving change detection or measurement. Imagery from the geosynchronous satellite or from ERTS is particularly useful for temporal studies because sequential views, which have been taken from essentially the same point in space, can be registered with little or no geometric correction. With such a data bank at hand, it is perhaps curious that relatively few earth resources investigators have yet reported on theme enhancement through temporal processing.

Undoubtedly this void is partially explained by an understandable desire to squeeze the maximum information from the best available individual frames before devoting time to what might be considered more marginal cases.

Additionally, temporal analysis often is neglected because the facilities and techniques required to create well-registered multidate sequences are somewhat specialized and not generally available. Preparation of even a simple movie loop is annoyingly time consuming, and then one is still left with the problem of extracting quantitative data. When operating from the digital tapes, spatially related trends are difficult to follow unless some provision also is made for time-lapse viewing.

At SRI, research meteorologists became impressed with the power of time-lapse sequences early in the life of ATS-1 (Serebreny et al., 1967, 1970), and the Institute has maintained an active program of temporal analysis of meteorological and earth-resources imagery ever since. In this presentation, we will describe some of the facility and procedures that have evolved from that work. One function of the equipment is its use as a viewer, a rather elaborate device to permit the rapid assembly, storage, and playback of registered image sequences, either in monochrome or in color and with input from either digital tape or analog transparencies. This provides a mechanism for presenting a tremendous amount of data to a scientific investigator in a familiar and easily assimilated format. Of more interest, perhaps, to an audience primarily concerned with machine processing, the equipment provides a variety of well-controlled analog image processing functions, with the results obtained in real time. These functions include the creation of binary thematic maps based on multispectral radiance ratios. The fact that the thematic extractions, along with numerous diagnostic displays, can be viewed in time-lapse fashion simultaneously with, or even in superposition with, the main image display provides an extremely useful link between subjective human photo-interpretation and objective image processing. A highly interactive editing feature permits the operator to apply localized corrections to the machine-derived extraction to partially compensate for cloud effects and other anomalies. While the precision of the analog processing seldom is the limiting factor affecting the validity of the numerical results, if necessary, critical individual cases can be rerun with digital processing using classification criteria determined from the viewing session.

III. ANIMATION FOR ENHANCEMENT OF BOTH FIXED AND MOVING THEMES

During our work we have become convinced that just as still photos are virtually indispensable when working with individual images whether the actual analysis be done manually or by machine, so there is a basic need for some form of animated imagery as the workhouse tool for guidance in temporal studies. Nothing else seems to communicate the message to a human quite so quickly or clearly as time-lapse sequences, flicker comparisons, and the like. And even while striving to achieve machine processing, humans seem destined to remain in the loop for the foreseeable future--if only to formulate the problems and check the results.

To illustrate this point, let us take time to view a short movie sequence showing imagery from one of the synchronous meteorological satellites (ATS-2). The area shown is the Southeastern United States and the pictures were taken about 18 minutes apart. First, the sequence is shown in slow motion and some organized cloud motion is evident. Next, when the presentation is speeded up, note how much more information is conveyed. It does not take a professional meteorologist to see that the wind motions are clearly different at different elevations or to infer that there are probably mountains present to cause the uplifting and condensation over the Ozarks. Note also how well the eye can map the shape of the Florida peninsula even though we are viewing it through a considerable amount of cloud cover.

As many of you know, while remarkable progress ress has been made in machine tracking of well-defined cloud cells, meteorologists routinely use film-loop sequences such as these to easily follow complex multilayer situations, which thus far have eluded even the most sophisticated machine pattern recognition procedures.

Time-lapse sequences of ERTS imagery normally are superficially much more confusing than cloud sequences--principally because the surface features that change lack the large-area organization of the clouds. Again, the remarkable capability of the human eye-brain combination enables an observer to read through the clutter and integrate out basic patterns or to quickly detect small areas of anomalistic behavior. This gives hope that we may be able to teach machines to do the same thing; or at a minimum, we may be able to provide machine processing to enable a human operator to make classifications more efficiently.

During the ERTS-1 program we were fortunate to have NASA funding to investigate the applicability of temporal analysis to the needs of a number of ERTS scientific investigators. They represented a variety of disciplines, from botany to glaciology, but all were generally concerned with detecting, mapping, and measuring scene changes with time.

The hardware setup has evolved through several generations and is called ESIAC for Electronic Satellite Image Analysis Console. It uses relatively standard TV animation and display techniques and has been generally described elsewhere (Evans, 1973). While we are immensely proud of ESIAC's capability, we regard the equipment itself not so much as a prototype installation but rather as an extremely versatile design tool with which to test what form of special-purpose temporal analysis equipment appears justified for specific applications under consideration.

Briefly, ESIAC provides 600 TV frames of analog video disc storage, organized into two 300-frame sections, each independently addressable by a separate moving head. The memories can be loaded either from film or hard copy input stations or from digital tape via a fast digital-to-analog converter. The operator is provided with a display screen and simple video mixing controls that permit him to add positive or negative amounts of images from the disc memories or from a wide variety of other input sources (e.g., map viewing camera, calibration grids and gray scales, cursor, and system-generated overlays). The readout heads can then be stepped sequentially through any number of disc tracks at any desired rate to create a custom-designed animated display.

The preferred input medium for most operations is 70-mm positive film transparencies. Tape input, while providing the ultimate in precision, usually has been too expensive and time consuming to be justified for "first cut" analyses of long time sequences. Filmed images are much easier to scale and to register, particularly when image rotation is required.

After the first image is sized and stored on the disc memory, other images of a desired sequential series are placed in front of the camera, brought into register with the previously stored image, then stored. For film input, registration is achieved with the aid of a set of film micro-positioners while viewing either a composite image or a sequentially flickered image pair. If a color composite display or multispectral signal processing is desired, each of the multiband images is entered separately. These are combined as required during playback.

For tape input, a trial entry is made, then the stored trial image is shifted electrically to achieve register with previous entries, as judged by superposition or flicker comparisons. The digital image is then reentered with the required offsets, and the correction data are recorded for future use.

IV. QUANTITATIVE MEASUREMENTS

Creation of a sequential display normally is only a necessary first step for an actual project task--needed to help the operator identify some feature or theme of interest. Usually the desired end product is some quantitative measure of the specified theme. To provide area measurements, ESIAC is fitted with a set of level decision circuits (LDCs) capable of operating on the video signals. These LDCs are essentially fast one-bit analog-to-digital converters having threshold decision levels adjustable by the operator. Level decisions can be made independently and simultaneously in two or more spectral bands or on additive combinations of two signals. The binary outputs can be combined logically to create a binary video signal that can then be displayed as a two-dimensional binary thematic mask and whose white or TRUE picture elements can be totaled in a digital counter.

To aid in the quantitative interpretation of multispectral data and to provide guidance in the setup and adjustment of controls on the Level Decision Circuits, an auxiliary display is provided to present the video information in two-dimensional color space at the same time that it is being viewed as a conventional image on the main display (Image Space Display). The Color Space Display is a dynamic version of the plot shown in Figure 1.

In a typical application, vertical (y-axis) displacements are caused to be proportional to infrared radiances at the same time that horizontal (x-axis) displacements are made proportional to radiances in a visible band. For imagery such as ERTS, where reference gray scales are available on the film, a unique data entry procedure permits samples of these scales to be replicated and used to define both axes and the 45° diagonal. The two-dimensional color coordinates of any pixel or small group of pixels (as specified by the cursor intersection in the main image display) can be read directly from this graphic presentation in units linearly correctable to absolute radiance values for the scene.

A summary impression of the spectral statistics for an entire image can be obtained very quickly by observing the brightness distribution over the diagram. Scenes containing significant areas of snow or clouds, for example, produce color maps showing most of the energy distributed along the "neutral" diagonal. A heavily vegetated scene, on the other hand, will generate a scatter diagram with most of its energy above and to the left of the diagonal. Water bodies normally map into the lower right region. Regions of the color space display can be selectively intensified by a z-axis signal derived from one of two sources; (1) a cursor intersection specifying a particular small region of the Image Space Display or (2) by the binary thematic map signal. Case (1) is used to measure the two-band color coordinates of identifiable scene features, while case (2) is useful in monitoring the spectral effect of adjustments to the Level Decision Circuits.

The Color Space Display can be time-lapsed, along with the Image Space Display. A liberal education in the realities of multispectral processing can be gained through a few hours' study of time sequences of actual image data. A seemingly endless variety of "special situations" appear to conspire to provide annoying exceptions to classification algorithms that work "most of the time." Much can be learned, moreover, by watching for any time- or space-organized patterns traced by these exceptions during an animated sequence.

V. AN APPLICATION EXAMPLE; SNOW AREA MEASUREMENT

To illustrate the use of this equipment, let us turn our attention to an earth resource monitoring application of considerable economic importance: the measurement of the areal extent of snow cover. More specifically, let us consider the problems that arise in monitoring the snowpack within well-defined drainage basins in mountainous terrain.

Figure 2 is an orientation map showing the location of the ERTS orbital tracks and nominal frame centers for the northwestern part of the United States. The coverage afforded by one particular 100 × 100 nautical mile frame in the North Cascades region of Washington state is shown shaded. The next figure (Figure 3) shows the ERTS image for that location for 2 September 1972. Alongside the image is an outline map defining a number of individual drainage basins that we have been studying. The barber-pole frame defines the coverage of the last or working stage of zoom (Figure 4), which singles out a particular 272 km^2 drainage basin--that of Thunder Creek between Lake Ross and Lake Chelan. Snowmelt from this basin drains into Thunder Creek and helps drive hydroelectric power plants located at Diablo and Ross dams--just outside the upper left corner of the enlarged view. The basin boundary overlay is derived from a template stored in the video memory and defines the precise region within which the snow area measurements must be confined by a procedure to be described later.

Our objective is to measure the acretion and ablation for this snowpack with particular emphasis on the critical spring melt period. As a first step, the operator views monochrome and/or color time sequences of scenes similar to the one shown in the upper left panel of Figure 4 and studies the general behavior of the snowpack in space and time. For quantitative measurements on individual dates, he stops the animation and attempts to create a binary thematic map which represents the best visual match to the observed snowpack for that date.

Since the snow appears to be visually well defined in the MSS-5 image, our first attempts were to operate on video signals from band 5 images and to count all those pixels within the basin where the radiance exceeded some threshold level. As in all such thresholding schemes, the all-important question is, "Where does one set the threshold level?"

The binary thematic masks obtained by "slicing" the single date image at five different threshold levels are shown in the last five panels of Figure 4, along with measures of their areas. We found the area-above-threshold to be a very sensitive function of the threshold setting (see Figure 5 for typical curves made for Mt. Rainier). The functional slope is so steep that it appears completely impractical to use preassigned threshold levels. Our initial hope was that by electronically overlaying masks such as those of Figure 4 over the full tone scale image--sometimes even displayed in color--and giving an operator the opportunity to study the match dynamically while adjusting the threshold level, we would be able to arrive at a setting that would be representative of the snow-covered area within the basin. Results with this method, while encouraging at first, showed discouragingly high variances between operators and even for repetitive trails by the same operator. For certain times of the year--particularly in early winter when the cover was light and the sun angle was low--variances of ±30 percent of the snow-covered area were common and variance well in excess of 100 percent were not rare. Through careful study of multidate time-lapse sequences and topo map overlays we verified what has been suspected from the beginning--that a major source of difficulty is the effect of sun angle. Snow on south-facing slopes is illuminated nearly perpendicularly and exhibits high radiance to the satellite, while the radiance of snow on the north-facing slopes may be much lower due to illumination at near grazing angle or it may be completely shadowed.

An operator who is well acquainted with the terrain can learn to watch for this effect and concentrate on the south-facing slopes. The measured value should then always be less than the true value. Perhaps in time a set of "shadow factors" for the major basins of interest could be developed and applied to improve the accuracy of the readings.

Problems with sun angle and shadows can be greatly alleviated by employing more than one spectral band and making the classification decision on the basis of radiance ratios; i.e., color rather than on brightness alone.

Figure 6 is a two-band color space plot of selected portions of a mountain snow scene. By properly manipulating the Level Decision Circuits, the binary thematic mask can be made to correspond only to those scene constituents having bispectral radiance responses within the diagonal shaded region. This procedure largely eliminates problems with variable illumination and shadowing, but uncovers another problem--partial tree cover. Classification of snow-covered area made by human photointerpreters from aircraft imagery frequently extends to significantly lower altitudes than those made from ERTS imagery. This is because the humans count the snow under the trees and infer the presence of tree-hidden snow by watching small clearings and streambeds. One might expect that all possible combinations of conifer trees like those at A and snow like that at B mixed together within individual pixels would plot along the line AB. Indeed, with the LDCs adjusted to respond only to a small spectral region centered around the approximate midpoint of line AB, the resulting mask does a respectable job of mapping and tree line. A complication arises when one considers the large size of the triangular region of the color diagram required to include all possible snow-tree mixtures when all possible illumination levels are allowed for each of the constituents. We have not yet found a satisfactory completely objective solution for the snow-tree mixture problem, but image analyses using both the image space and color space displays in the manner just described help the operator to interpret each scene and permit him to more intelligently direct his subjective "bias" when making threshold settings.

VI. BOUNDING THE DATA

Confining the measurements within precisely specified drainage basins is a relatively straightforward procedure that makes good use of the timesequenced display. A hand-drawn, silhouette-type basin outline is prepared, including several stream forks or other landmarks known to be visible on the satellite imagery for a cloud-free summer scene. This drawing is then viewed by the camera, scaled, registered to the summer scene and converted to a binary mask by one of the LDCs. Since scene data for all other dates in the sequence also will have been registered to the summer scene, the basin-derived mask can be logically ANDed with the scene-derived mask before being measured and photographed. (Unless a scene is completely cloud covered, we find that subtle ground-feature information will nearly always provide enough date-to-date correlation to permit keeping registration errors below one TV element or one ERTS pixel, depending upon which is limiting. This is true even when the scene is largely snow-covered or largely featureless, such as the Arizona Desert.)

VII. CONCLUSIONS

Animated sequences of coregistered images provide a powerful form of enhancement for numerous themes, both moving and fixed, that are of interest in repetitive imagery from satellite-borne sensors. Through electronically produced animated displays and associated interactive controls, the remarkable pattern recognition capability of the human eye-brain combination can be effectively teamed with the quantitative precision of machine storage and processing.

VIII. ACKNOWLEDGMENTS

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Serebreny, S. M., W. E. Evans, R. G. Hadfield, and E. J. Wiegman, "Electronic System for Utilization of Satellite Cloud Pictures," Amer. Met. Soc., 51, 9, pp. 848-855, (1970).

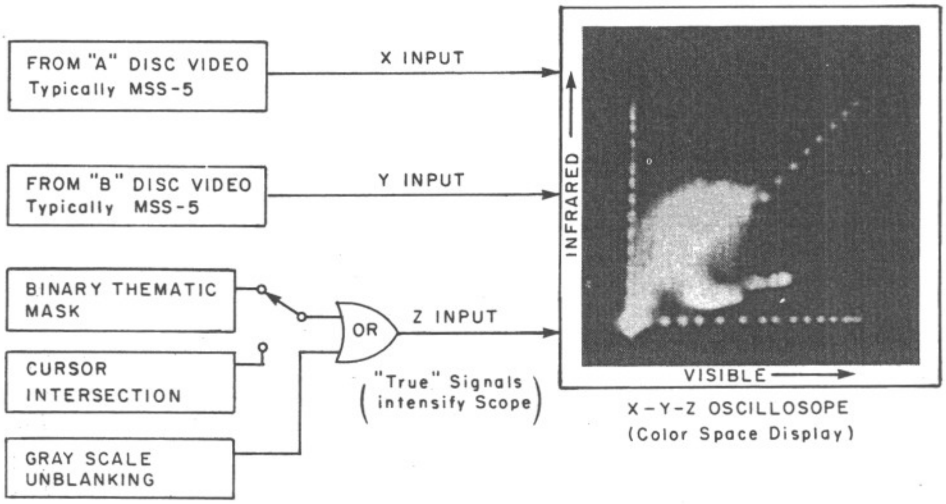


Figure 1. ESIAC Color Space Display. Energy concentrations resulting from dense vegetation, clear water and turbid water regions in an ERTS scene of South Carolina. Dots along axes are gray steps from the film record.

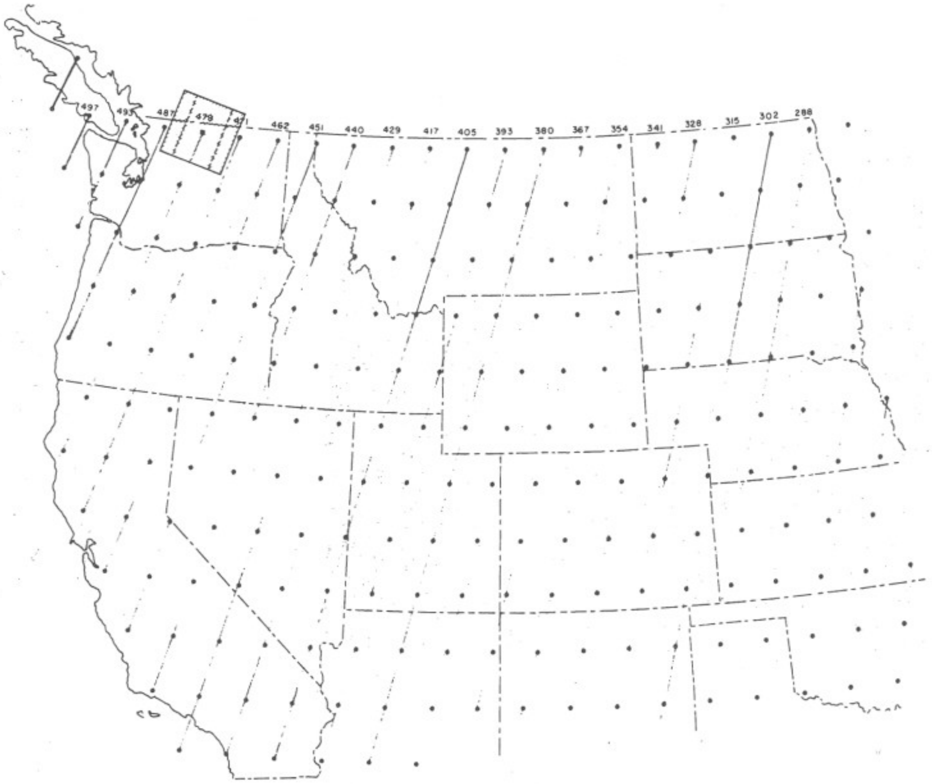


Figure 2. Map of Northwestern United States with Overlay Showing ERTS Orbital Tracks and Nominal Centers of Data Frames. Location and coverage of the frame containing the Thunder Creek drainage basin is shown shaded.

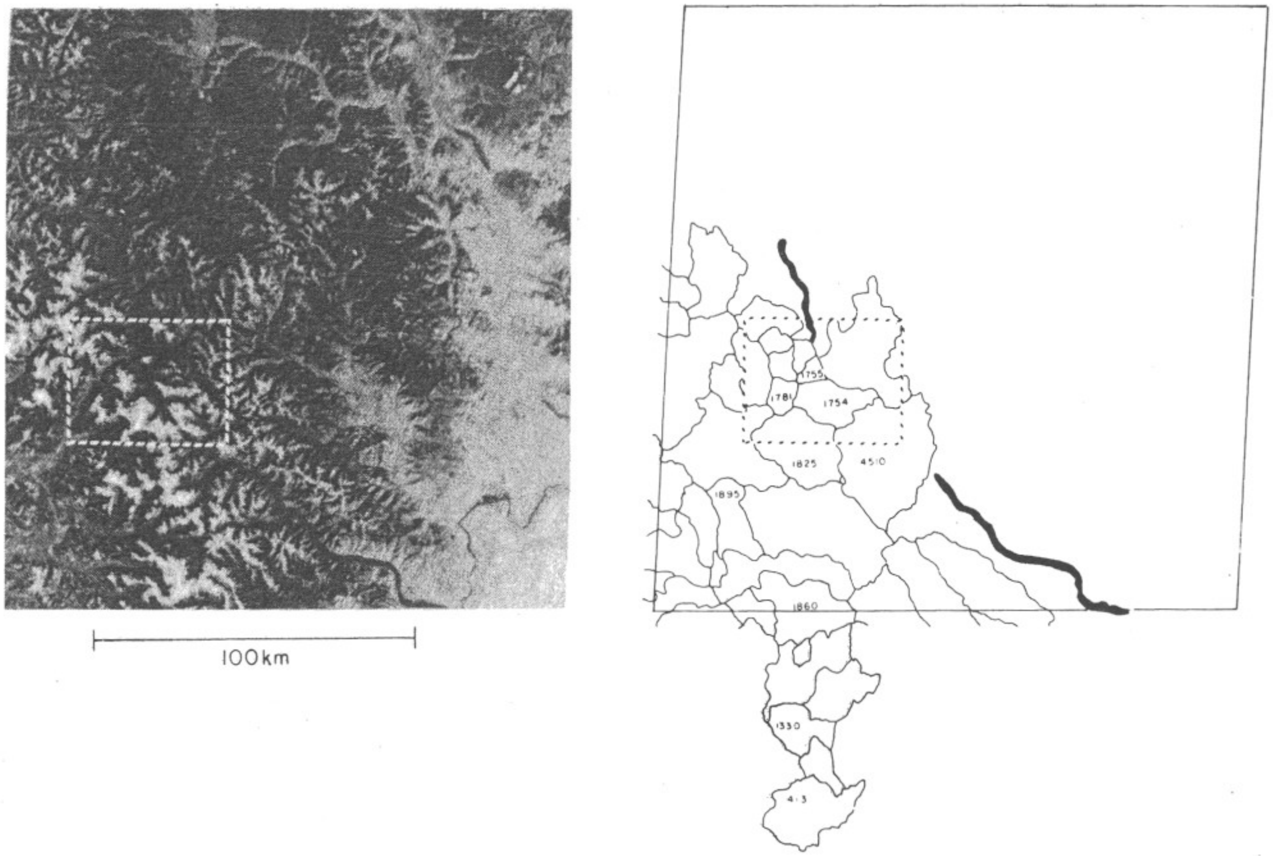
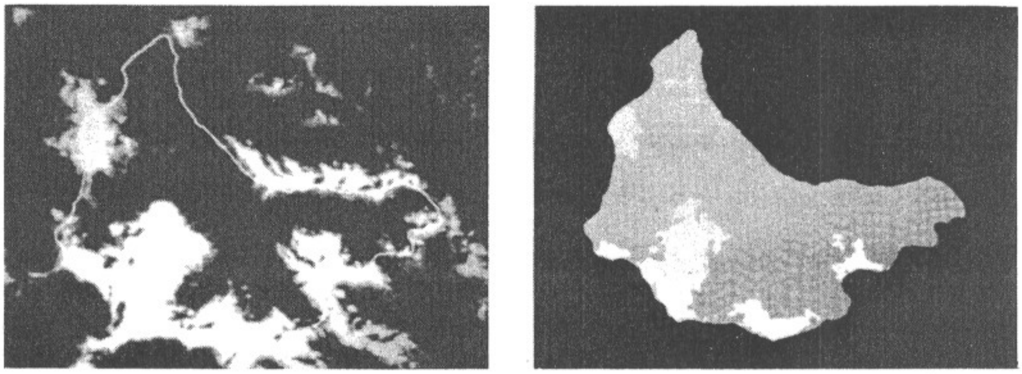
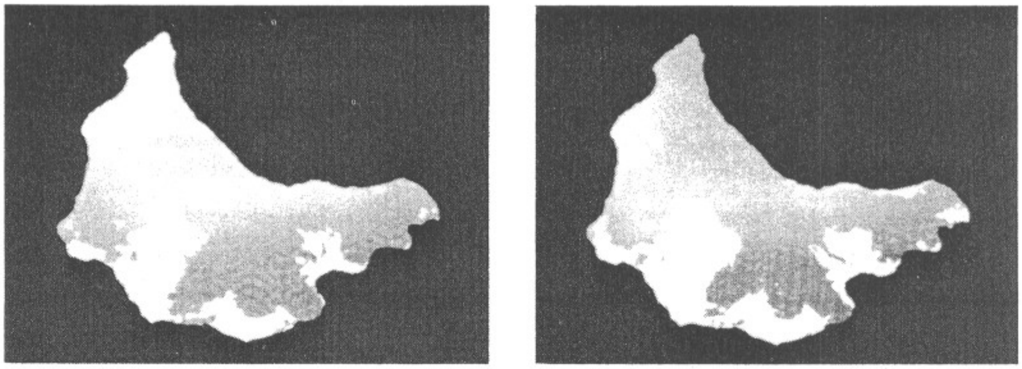


Figure 3. ERTS Image No. 1041-18253 for 2 September 1972. North Cascade Mountain region of Washington and Canada. (Location shown shaded in Figure 2.) Map shows several drainage basin outlines and a rectangular area to be enlarged (in Figure 4). Slide used in oral presentation was in color.



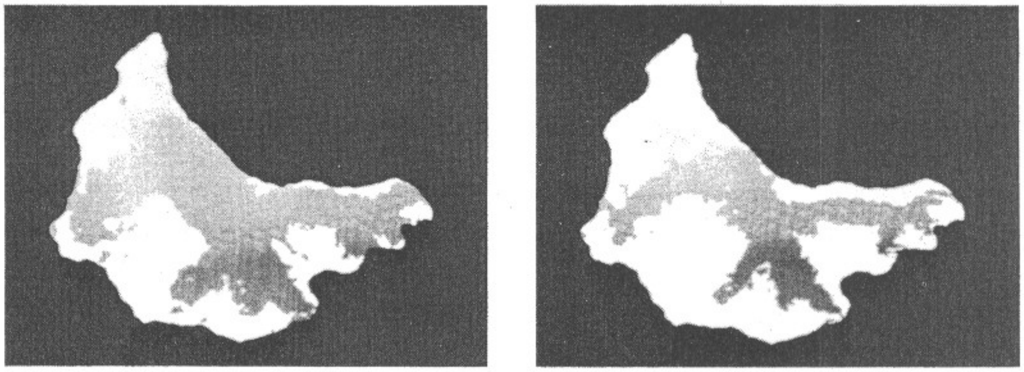
MSS-5 IMAGE 26.8Km HIGH SECTION OF E1041-1823-5. (Thunder Creek Drainage Basin Outline Superimposed)

GRAY STEP 10 15.6% OF BASIN



GRAY STEP 8 21.4% OF BASIN

GRAY STEP 6 31.0% OF BASIN



GRAY STEP 4 35.0% OF BASIN

GRAY STEP 2 52.5% OF BASIN

Figure 4. Areal Distribution of Brightness Above Threshold for 2 September 1972 (Band 5, .6-.7μ)

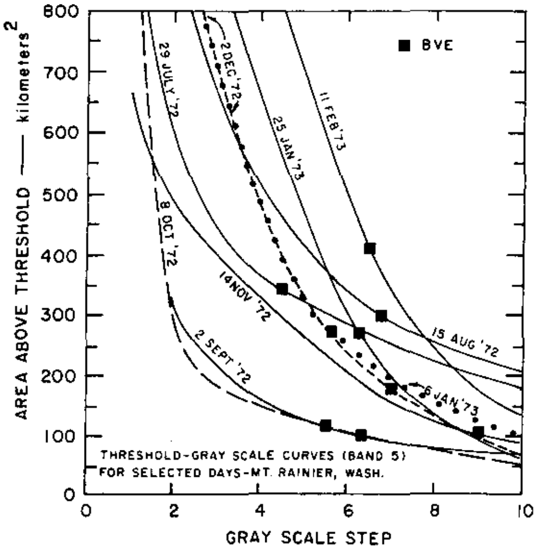


Figure 5. Area vs. Threshold Level for Nine Dates. Region counted was 45 km diameter circle centered on Mt. Ranier. Plotted points are Best Visual Estimate (BVE) averages for two operators.

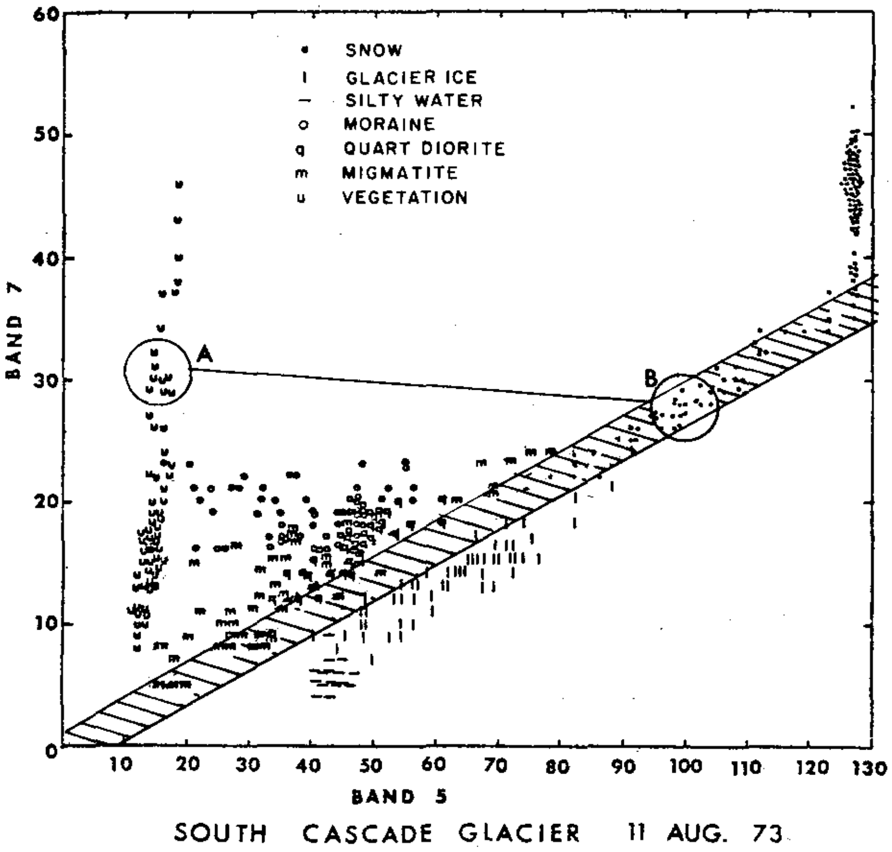


Figure 6. Two Band Radiance Diagram Showing Responses from Snow and from Relatively "Pure" Patches of Selected Competing Themes. Ratio slicing can be used to extract snow within the shaded band. Data from digital tape of ERTS scene 1384-18311 (11 August 1973).