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SNOWCOVER MAPPING BY MACHINE PROCESSING OF SKYLAB AND LANDSAT MSS DATA

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ABSTRACT

SKYLAB and LANDSAT MSS data were analyzed using computer-aided analysis techniques (CAAT) developed at LARS. Results indicated that the middle infrared wavelength bands of the SKYLAB S-192 scanner would allow effective discrimination between snowcover and water-droplet clouds, whereas the limited spectral response of the LANDSAT-1 or 2 scanners do not allow such spectral discrimination. In the next phase of the current investigation, five spectral classes of snowcover were defined and mapped. These classes were found to be related to differences in the proportion of snow and forest cover in the individual resolution elements. In addition, topographic data (elevation, slope, and aspect) were digitally registered onto the SKYLAB and LANDSAT data to determine their influence on snowpack characteristics. Combining these results with the digital topographic data allowed acreage estimates of the various classes of snowcover to be tabulated according to elevational zones for either the entire data set or on an individual watershed basis.

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INTRODUCTION

The water supply for much of the southwestern United States comes from snowmelt in the watersheds of the Colorado Rocky Mountains. Information on the amount of snow accumulated during the winter months is necessary for making accurate predictions of spring runoff. Leaf and Haeffner (1971) have pointed out that an important index of runoff during the snowmelt season is the areal extent of the snowcover.

For more than thirty years snow hydrologists have made innumerable attempts to correlate the areal extent of snowcover and subsequent runoff. Parshall (1941) and Potts (1944) have estimated the areal extent of snow fields for runoff forecasting using ground photography. From the late forties to date, many studies have included use of aerial photography to measure the areal extent of snowcover (Parsons and Castle, 1959; Finnegan, 1962; Leaf, 1969). However, it was not until the early 1960's that one could attain a synoptic view of large geographical areas through earth orbiting satellites. Today, a wide variety of environmental satellites are collecting an astronomic amount of data that potentially could be utilized to map the areal extent of snowcover in a repetitive mode. Wiesnet (1974) has stated that "our capacity for collecting data on snow and ice far exceeds our ability to analyze the data". Therefore, in order to keep up the pace with the existing and highly advanced data collection technology, computer-aided analysis techniques (CAAT) need to be further developed and evaluated.

The Laboratory for Applications of Remote Sensing (LARS) was organized at Purdue University in 1966 with an overall goal of applying modern computer technology and pattern recognition theory to the quantitative analysis of multispectral earth resources data. Several analysis techniques have been developed since that time and applied to a variety of disciplines. However, it was not until LANDSAT-1 MSS data became available that any of these computer-aided analysis techniques were applied to snow-hydrology studies.

The results of the work with LANDSAT-1 data indicated that the areal extent of snowcover could be obtained from these data, but that spectral variations within the snowpack area could not be reliably determined because of detector saturation problems. Another major limitation of the LANDSAT data was the inability to discriminate between snow and clouds.

Analysis of SKYLAB S-192 multispectral scanner data indicated that the above limitations of the LANDSAT data could be overcome. The increased spectral range of the SKYLAB S-192 MSS offered significant advantages over the LANDSAT-1 data.

The purpose of this paper is to report some of the results obtained in the application of computer-analysis techniques to the SKYLAB multispectral scanner data for purposes of mapping snowcover in mountainous terrain. Two major facets of the investigation will be discussed. The first phase involves the multispectral classification of snowcover, including both snow/cloud differentiation and the definition and classification of different spectral groups of snowcover. The second major phase of the investigation consists of combining spectral data with topographic data in order to obtain a product having a greater degree of flexibility and utility than could be obtained using spectral data alone.

TEST SITE DESCRIPTION

The San Juan Mountains test site is located in a mountainous area of southwestern Colorado, containing a complex association of forest types, rangeland, alpine tundra, agricultural fields, water bodies, snow, and various man-made features. This area is fairly typical of the Rocky Mountains Region in terms of forest, water, and recreational resources.

The topography of the test site area is rugged, ranging in elevation from less than 2000 meters to over 4200 meters. Timberline in the region is at approximately 3600 meters, and extensive areas of tundra are found above this elevation. In the data set analyzed in this study, this tundra area was completely covered by snow. Below timberline, there are several different forest cover types that are distributed as a function of the topography (elevation, slope and aspect). There are many variations in stand density between and within the different forest cover types. Such stand density variations become important in interpreting the spectral characteristics of the SKYLAB S-192 MSS data for snowcover mapping purposes, as will be discussed later.

DATA UTILIZED

The present study involved an unusual and particularly valuable set of data that were obtained over the test site during the SKYLAB-2 (SL-2) mission. On June 5, 1973, both SKYLAB and LANDSAT-1 data were obtained over the test site within an hour of each other, and the following day color-infrared photography was obtained from 18,288 meters (60,000 feet) by NASA's WB-57, and both photographic and multispectral scanner data were obtained from 11,186 meters (30,000 feet) by NASA's NC-130 aircraft. In addition, ground observation data were gathered throughout the week to complete the data set.

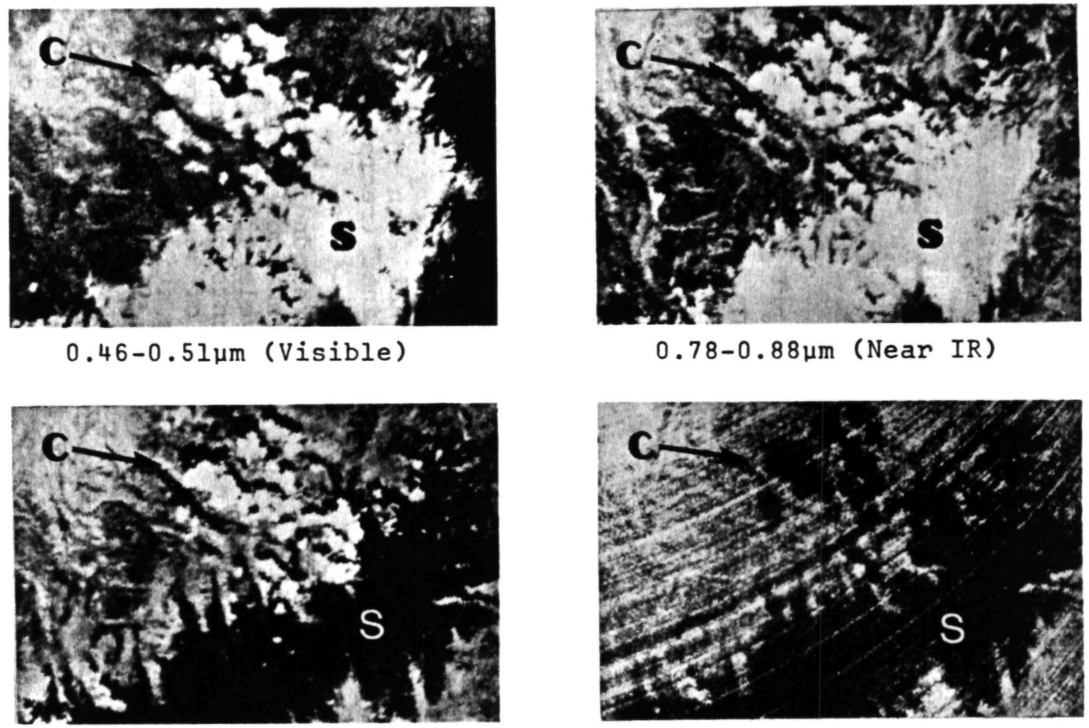
MULTISPECTRAL CLASSIFICATION OF SNOWCOVER

As previously stated, computer-aided analysis of LANDSAT multispectral scanner (MSS) data has indicated that it is possible to map and perform quantitative estimations of the areal extent of snowcover. However, cloud-cover and saturation of the LANDSAT MSS detectors limited the accuracy of the results. In most cases it was found that it was impossible to separate clouds from snow-covered areas using LANDSAT spectral information only (Hoffer and staff, 1975).

Snow and Cloud Differentiation

The problem of discriminating cloud formations from snow-covered areas was long ago identified by those researchers interpreting the early meteorological satellite images (Conover, 1964).

The extended spectral range of the SKYLAB S-192 multispectral scanner (0.41-12.5µm) proved to have significant advantages over the more limited spectral range of the LANDSAT MSS system (0.5-1.1µm). One of the advantages offered by the SKYLAB data is the ability to reliably and accurately differentiate snowcover from clouds using spectral information only. Figure 1 shows four SKYLAB-2 S-192 images representing the four different portions of the spectrum (visible, near infrared, middle infrared, and thermal infrared). A close inspection of these images shows that in the visible (0.46-0.51µm), near infrared (0.78-0.88µm), and thermal infrared (10.2-12.5µm) regions the clouds and snowcover have a very similar appearance, thus rendering difficult their discrimination. However, in the middle infrared (1.55-1.75µm) the snow appears black while the clouds still show a white appearance.



0.46-0.51µm (Visible)   0.78-0.88µm (Near IR)

1.55-1.75µm (Middle IR)   10.2-12.5µm (Thermal IR)

Figure 1. SKYLAB S-192 images representing the four major regions of the spectrum. C = clouds, S = snow.

The application of computer-aided analysis techniques to the SKYLAB-2 S-192 digital data has allowed the quantitative determination of the spectral separability and automatic discrimination between snowcover and clouds. Figure 2 shows a SKYLAB-2 S-192 image containing both snowcover and clouds, in which the rectangular outlined areas indicate the selected portions of data representing the snowcover and cloud spectral classes. The areas designated in this way were utilized to quantitatively examine the spectral characteristics of snow and clouds.

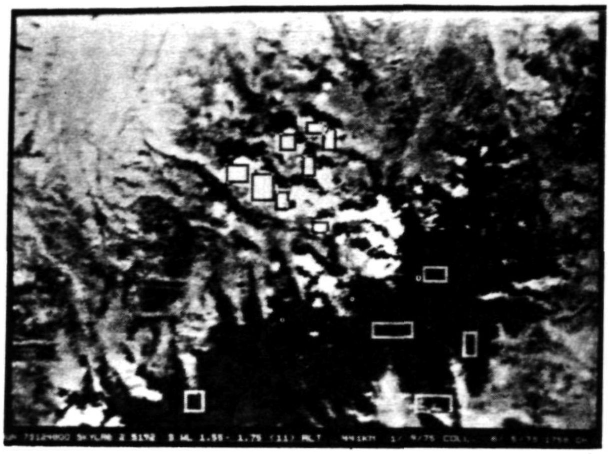


Figure 2. Middle IR wavelength imagery of the SKYLAB-2 S-192 Scanner with snow and cloud areas defined (rectangles).

The mean spectral response and corresponding standard deviation (in digital counts) for snowcover and clouds in the thirteen SKYLAB-2 S-192 wavelength bands is shown in Table 1. The digital counts range from zero to 255, where a spectral response of 255 indicates saturation of the detector. It is evident from Table 1 that the spectral responses for snowcover and clouds are very similar in channels 1 through 7, and in channel 13. It is only in channels 8 through 12 that the spectral response of the snowcover differs (in various degrees for each channel) from that of clouds. However, in order to measure accurately the degree of spectral separability between the snowcover and clouds, the LARSYS transformed divergence algorithm (Swain et al., 1971; and Swain and staff, 1972) was utilized. Figure 3 is a bar graph showing the spectral separability (based on transformed divergence values) between snowcover and clouds in the 13

SKYLAB-2 S-192 MSS bands. Values of transformed divergence greater than 1750 (the shaded area in Figure 3) indicate a reliable separability between the spectral classes in question (Swain and King, 1973).

Table 1. Mean Spectral Response and Standard Deviation for Snowcover and Clouds. SL-2 S-192 Data, 5 June 1973.

Wavelength Region	Wavelength Band (μm)	Snowcover Mean	Snowcover S.D.	Clouds Mean	Clouds S.D.
Visible	0.41-0.46	255	0	254	4
Visible	0.46-0.51	250	16	248	19
Visible	0.52-0.56	229	38	229	37
Visible	0.56-0.61	255	0	254	1
Visible	0.62-0.67	254	6	254	8
Near Infrared	0.68-0.76	246	22	246	22
Near Infrared	0.78-0.88	230	38	230	35
Near Infrared	0.98-1.03	181	44	222	41
Near Infrared	1.09-1.19	165	33	228	32
Near Infrared	1.20-1.30	106	22	210	43
Middle Infrared	1.55-1.75	33	16	163	33
Middle Infrared	2.10-2.35	39	15	160	31
Thermal Infrared	10.2-12.5	67	18	61	14

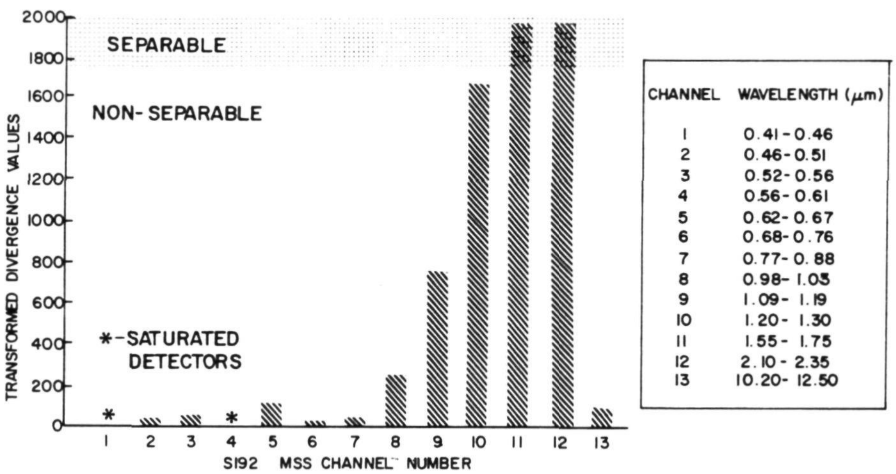


Figure 3. Spectral separability based on transformed divergence values between snowcover and clouds in the 13 SKYLAB-2 wavelength bands.

The most relevant aspect of Figure 3 is that it clearly shows that snowcover and clouds can be spectrally separated in only the two middle infrared bands (1.55-1.75μm and 2.10-2.35μm).

The data in Figure 3 shows a definite trend in the separability values as a function of wavelength. The separability between clouds and snow starts to increase in band 8 (0.98-1.03μm) or near IR region, and continues to increase with increasing wavelength throughout the reflective portion of the spectrum. However, in the thermal infrared band (10.2-12.5μm) the separability measure between the snowcover and the clouds drops sharply to a very low value. The thermal data indicates that the temperatures of the clouds and the snow are very similar. Therefore, at least for this data set, one cannot reliably discriminate snowcover from cloud formations based on their thermal response only.

The above results clearly show the advantage of obtaining multispectral scanner data in the middle infrared (1.3-3.0μm) portion of the spectrum for snowcover mapping applications. These results are significant in defining the appropriate wavelength bands to be included in future earth observation satellite systems.

Spectral Definition and Classification of Snowcover

An inspection of the 13 wavelength bands of SKYLAB-2 data shown in Figure 4 reveals that the areas of snowcover have a high reflectance throughout the visible wavelength bands (channels 1 through 5, from 0.41 to 0.67μm). On data in the near infrared wavelengths (channels 6 through 10, from 0.68 to 1.30μm), the areal extent of the snowpack seems to decrease in size with increase in wavelength. In the middle infrared region (channel 11, 1.55 to 1.75μm, and channel 12, 2.10 to 2.35μm), the snowcover is very low in reflectance and appears nearly black. Finally, in the thermal infrared data (channel 13, 10.2 to 12.5μm), the snow is relatively cold in relation to the other earth surface features, so it appears dark in tone on the imagery.

The apparent decrease in areal extent of the snowpack throughout the reflective infrared portion of the spectrum seems to be caused by two factors. First, water in liquid form has very little reflectance above 0.8μm, and since the snowpack was in the process of melting by June 5, particularly at the

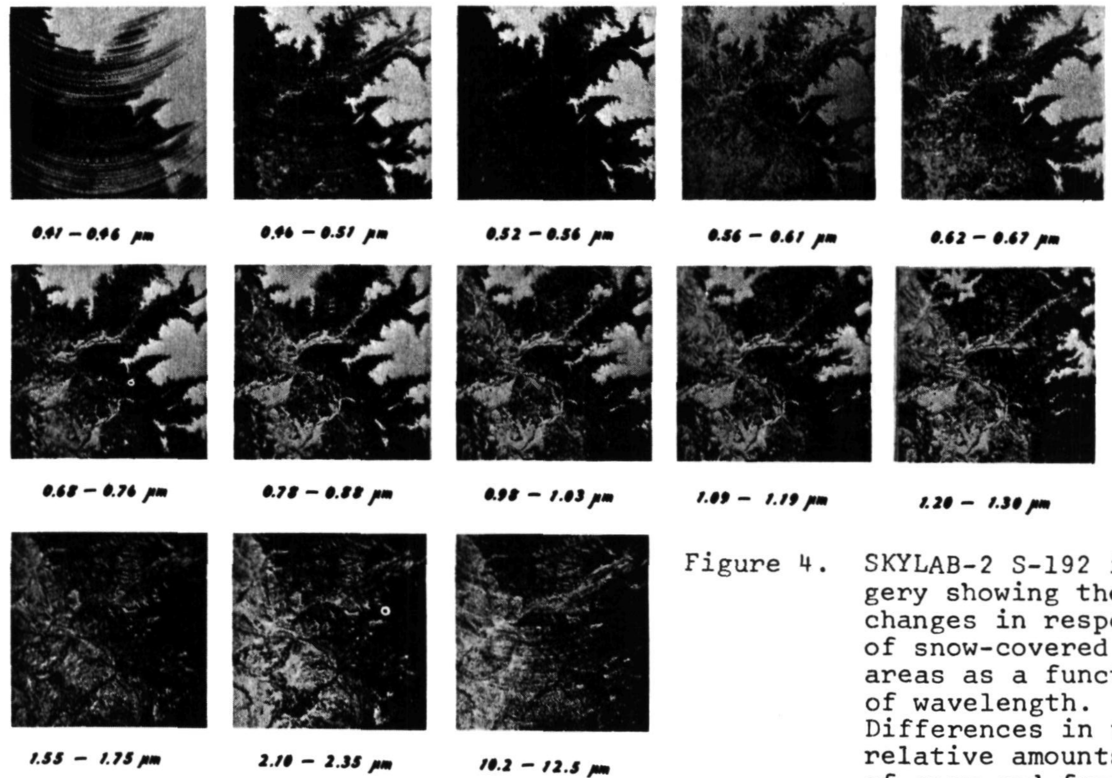


Figure 4. SKYLAB-2 S-192 imagery showing the changes in response of snow-covered areas as a function of wavelength. Differences in the relative amounts of snow and forest canopy, which are closely associated with elevation, are a major cause for the spectral variations observed.

lower elevations, the snow crystals probably have a coating of liquid water which would cause a lower reflectance. The second and perhaps more important factor in this case is that the forest cover is denser at lower elevations, resulting in a higher proportion of forest canopy than snowcover at the lower elevations. Examination of the aerial photos (taken the day after the SKYLAB data were obtained) showed that only the tundra areas at the highest elevations had a pure snow cover, without any trees present to cause a decreased reflectance.

The computer-assisted analysis of the SKYLAB-2 S-192 MSS data for mapping snowcover involved several processing steps. The first consisted of the definition of the maximum number of spectrally separable classes or categories of snowcover present in the scene. A multispectral clustering or "non-supervised" approach was utilized for this phase of the analysis. In this case, five distinct spectral classes of snowcover could be defined. Subsequently, their statistics (means and covariance matrices) were used as training input for the computer classification of the entire data set, utilizing a "supervised" approach involving a maximum liklihood algorithm.

Figure 5 shows the snowcover map resulting from the computer classification of the SKYLAB MSS data. The five different spectral classes of snowcover are shown as different tones of white and gray. The white areas represent "snow-1" spectral class, the four gray tones represent the other four snowcover classes, and the black indicates areas having no snow cover.

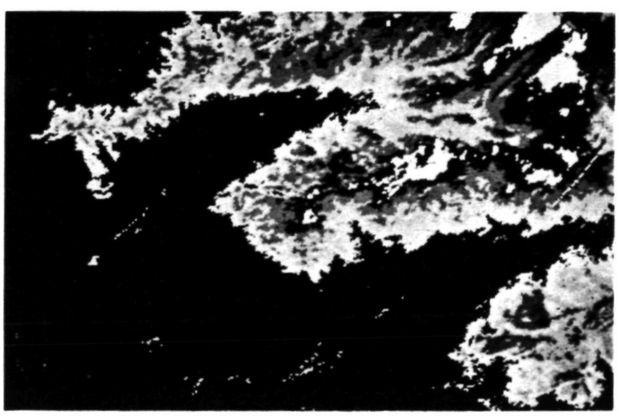


Figure 5. Multispectral classification of snowcover by computer, utilizing the SKYLAB-2 S-192 MSS data.

The five spectral classes of snowcover shown in Figure 5 are related to differences in reflectance in the individual wavelength bands in the near infrared portion of the spectrum, particularly in the 1.09-1.19μm and 1.20-1.30μm band, as indicated in Table 2.

Table 2. Mean Spectral Response of Five Snowcover Classes and a Forest Class

Band (μm)	Spectral Classes					
	Snow 1	Snow 2	Snow 3	Snow 4	Snow 5	Forest
(0.41-0.46)	255*	255*	255*	255*	255*	205
(0.46-0.51)	255*	255*	255*	197	162	110
(0.51-0.56)	254*	252*	219	120	93	56
(0.56-0.61)	255*	255*	255*	253	251	131
(0.62-0.67)	255*	255*	255*	255*	237	72
(0.68-0.76)	255*	255*	255*	240	166	89
(0.78-0.88)	255*	255*	255*	193	148	113
(0.98-1.08)	255*	255*	194	138	108	102
(1.09-1.19)	251	196	137	104	89	92
(1.20-1.30)	185	148	98	76	68	83
(1.55-1.75)	64	61	56	54	59	72
(2.10-2.35)	19	17	14	11	13	21
(10.2-12.5)	99	100	101	105	110	124

* - Denotes detector saturation

For wavelengths from 0.41-1.08, the statistics indicated that there had been detector saturation due to the high reflectance from areas in the Snow 1 and Snow 2 classes, as well as in other spectral classes in some wavelength bands. However, in the 1.09-1.19μm and 1.20-1.30μm wavelength bands, there is a very distinct decrease in reflectance from the Snow 1 to the Snow 5 spectral class.

Comparison of the snowcover classification results with the aircraft (NC-130 and WB-57) photography taken one day after the SKYLAB-2 overpass indicated that the five different spectral classes of snowcover were closely related to the different proportions of snow and forest cover present in the individual resolution elements (pixels) of the SKYLAB-2 S-192 MSS data. The S-192 scanner integrates the reflectance from the entire area on the ground within each resolution element (approximately 0.47 hectares). Therefore, a relatively high proportion of coniferous forest cover and a relatively low proportion of snow within a single resolution element will result in a relatively low reflectance as compared to resolution elements containing fewer trees and a larger proportion of snow.

Figure 6A shows an area of the S-192 classification map containing the five different spectral classes of snowcover. Figure 6B shows a photographic print of the same area (shown in Figure 6A) taken by NASA's WB-57 aircraft from an altitude of 18,288 meters (60,000 feet). Comparison of these two images clearly indicates that the different spectral classes of snowcover shown in Figure 6A correspond to the different proportions of snow and forest shown in Figure 6B.

The spatial distribution of the five spectral classes of snowcover shown in Figures 5 and 6A is highly correlated to the topography of the area. The "snow 1" spectral class is found at higher elevations in the areas of alpine tundra. The other four spectral classes are found at lower elevation ranges. Thus, the statistics for these spectral classes, as given in Table 2, indicate that the decreasing response values among the spectral classes (particularly well shown by the 1.09-1.19μm or the 1.20-1.30μm data) generally correspond to both decreasing elevation and increasing density of coniferous forest cover.

DIGITAL TOPOGRAPHIC DATA

To establish a more quantitative correspondence between the spectral classes of snowcover and the topography of the area, digital topographic data were overlaid onto the multispectral scanner data.

Digital tapes containing elevation data had been developed by the Defense Mapping Agency, using 1:250,000 scale U.S.G.S. topographic maps. These DMA elevation data tapes were obtained for the entire San Juan Mountains area and rescaled to match the scale of the SKYLAB and LANDSAT data tapes. From the elevation data, an interpolation procedure was developed to obtain data on slope and aspect for each resolution element. Although the interpolation procedure introduced some error into the data and there are some inherent errors in the small scale maps utilized initially in the digitization process, these errors are not significant for the type of broadscale mapping and analysis involved in this study.

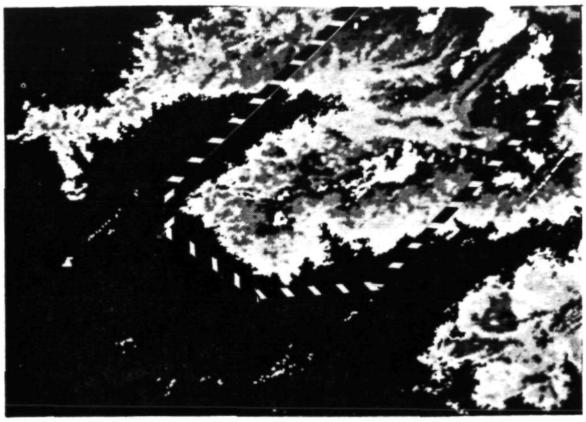


Figure 6a. Portion of the SL-2 S-192 multispectral classification of snow cover.

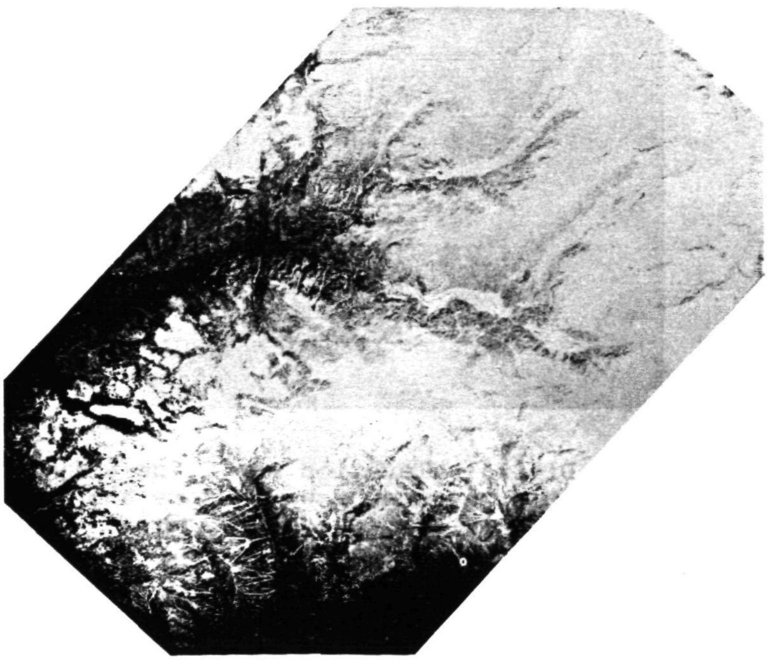


Figure 6b. WB-57 aerial photo of same area shown in Figure 6a.

The final result of this data processing procedure (rescaling and overlay), therefore, was a single digital data tape containing 13 channels of SKYLAB MSS data, four channels of LANDSAT MSS data, and three channels of topographic data (one channel each for elevation, slope, and aspect), all geometrically correct and capable of being displayed at a 1:24,000 scale when displayed on a computer line printer. This data tape was subsequently utilized in all of the analysis sequences for the SKYLAB multispectral scanner data.

Figure 7 shows a topographic digital map of the San Juan test site, in which the different elevations are shown as different gray tones. The white tone (in Figure 7) represents elevations above 3600 meters, the darkest tone represents areas below 2000 meters, and the intermediate gray tones indicate elevation increments of 200 meters each.

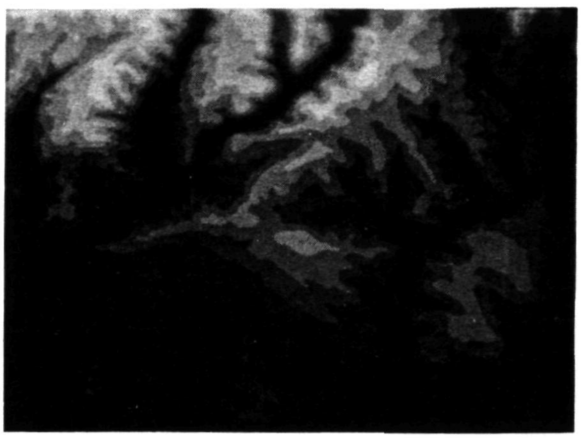


Figure 7. Digital elevation map. The white tone represents elevations above 3600 meters, the darkest tone represents areas below 2000 meters, and the intermediate gray tones indicate elevation increments of 200 meters each.

To further indicate the value of the topographic overlay data, the elevation data were combined with the results of the snowcover classification. The area of each of the five classes of snowcover was determined as a function of elevation using 100 meter elevation increments. This type of calculation can be accomplished rapidly and effectively when an overlay of multiple data sets, such as this one, are available. These results are shown in Table 3.

Table 3. Snowpack Area (in hectares) within 100 Meter Elevation Increments

Elevation (meters)	Spectral Class of Snowcover 1	2	3	4	5	Total Area (hectares)
Above 3700	1179	2464	308	108	7	4086
3600-3700	400	1914	694	135	37	3180
3500-3600	129	1868	1858	517	61	4433
3400-3500	45	904	1858	1266	280	4353
3300-3400	13	378	1305	1417	812	3925
3200-3300	7	94	922	1258	1298	3579
3100-3200	6	22	529	793	1540	2890
3000-3100		9	213	433	1041	1893
2900-3000		1	38	188	535	752
2800-2900			4	54	289	347
2700-2800			1	13	147	181
2600-2700				1	95	96
Below 2600					79	79
Totals	1779	7651	7730	6183	6221	29564

These results of applying computer-aided analysis techniques to a combined set of multispectral and topographic digital data (Table 3) reveal the tremendous potential that these techniques offer to the snow-hydrologist. The utility of being able to rapidly and accurately determine the areal extent of snowcover at different elevations becomes clear when this type of information is used in conjunction with other results such as those obtained by Caine (1975) on the relationship between the peak snow accumulation (water equivalent) and elevation in the San Juan Mountains. Caine's work demonstrated that the normals of peak accumulation in the San Juan Mountains increase with elevation in a predictable fashion. His results suggest a snow accumulation gradient of 65.5 cm of water equivalent per 1000 meter elevation increment, with a no-accumulation level at 2400 meters. Thus, the combination of accurate estimates of the areal extent of snowcover at different elevations and the predictable information on the water equivalent at the various elevations should permit a more accurate estimation of the amount of runoff to be expected during the snow melt season.

SUMMARY OF RESULTS

Computer-aided analysis of the SKYLAB-2 S-192 MSS data showed that:

(1) A reliable spectral separability between snowcover and clouds can be attained only in the middle infrared portion of the spectrum (1.55-1.75μm and 2.10-2.35μm bands).

(2) Five spectrally separable classes of snowcover were defined and mapped. These spectral classes of snowcover were primarily related to different proportions of snow and forest cover contained in the individual resolution elements of the SKYLAB-2 S-192 MSS data.

(3) For the first time, SKYLAB S-192 data were geometrically corrected and digitally overlaid onto a topographic data base from which elevation, slope and aspect data, as well as the spectral data, could be displayed at a 1:24,000 scale.

(4) The results of the spectral classification of snowcover were combined with the topographic data to obtain a table giving the area of each of the spectral classes of snowcover as a function of elevation, using 100 meter increments.

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