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USE OF ERTS DATA FOR MAPPING SNOW COVER IN THE WESTERN UNITED STATES

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ABSTRACT

The purpose of this investigation is to evaluate the application of ERTS data for mapping snow cover, primarily in the mountainous areas of the western United States. The specific objectives are to determine the spectral interval most suitable for snow detection, to determine the accuracy with which snow lines can be mapped in comparison with the accuracies attainable from other types of measurements, and to develop techniques to differentiate reliably between snow and clouds and to understand the effects of terrain and forest cover on snow detection.

1. INTRODUCTION

The earth's snow cover is a resource that directly or indirectly affects most of the world's population. As written in a recent report on the needs for polar research (Committee on Polar Research, 1970):

> "Snow forms a transient, sedimentary veneer on much of the earth's land surfaces. The diverse economic effects of this snow layer are incalculable. It is a major and renewable hydrologic reservoir; in many areas of North America more than half of the utilized water is derived from melted winter snow. Flood damage from spring snow melt is a recurring hazard in many river basins. The obstacles and hazards to ground transportation alone are formidable ..."

In mountain areas, such as the southern Sierra Nevada in California, the hydrologic importance of snow accumulations requires accurate monitoring of the snow pack distribution. As pointed out by Anderson (1963), the annual stream flow in the areas adjacent to the southern San Joaquin Valley is the most variable of any California watershed, due mainly to a large variability in the number and intensity of the winter storms crossing the region.

In his report on the management of California's snow-zone lands for water, Anderson discusses two important characteristics of the Sierra Nevada snow pack: (a) maximum accumulation of snow, and (b) rate of melt of snow water from the pack. The first characteristic is a good indicator of total water yield, and the second of when the resulting water is delivered. Both of these characteristics may be related in some degree to the snow extent. In a study using aerial photographs, Leaf (1969) found that for each of three Colorado watersheds a functional characteristic exists between extent of snow cover during the melt season and accumulated runoff. He reports that snow-cover depletion relationships are useful for determining both the approximate timing and the magnitude of seasonal snowfall peaks.

Despite the economic and scientific implications of snow cover, existing data collection methods often cannot provide either the desired areal coverage nor observational frequency. Except in limited areas where aerial survey is used, the significant parameters are usually measured at ground stations or at widely scattered snow survey courses. Now, the capabilities of remote sensing from earth-orbiting satellites offer promise for the development of a more cost-effective means for monitoring snow cover.

2. APPLICATION OF ERTS DATA

Considerable research has been carried out in recent years to determine snow survey and other hydrologic applications of environmental satellite data (McClain, 1970). Through studies performed by Barnes and Bowley (1970, 1972) techniques to map snow cover from existing photographic and thermal infrared measurements have been developed. These studies have shown that valuable information on snow extent can be derived from spacecraft observations.

Nevertheless, limitations in the use of satellite systems designed primarily for meteorological purposes do exist. Cloud interference, which limits the number of usable satellite observations, remains a problem (for hydrologic purposes, however, daily snow observation is not normally required). Also, since mountain regions are commonly forested, vegetation effects may also influence the location of the snow line in satellite photographs. Of greater significance is that the mapping accuracy that has been attainable from the relatively poor-resolution cameras is only marginal for optimum hydrologic use. Now, ERTS-1 is providing the first opportunity to investigate the application of high-resolution multispectral data for snow survey. Through use of these data, many of the previous problems can be alleviated.

Data from some 50 ERTS passes have been received for use in the current investigation. These data cover various mountain areas in the western United States during the period from late July 1972 through early January 1973 and the relatively flatter terrain of the Upper Midwest during late November and December. Additionally, a sample of ERTS data from the Arctic has also been available.

Examination of the MSS data and the limited sample of RBV data has shown that the contrast between snow-covered and snow-free terrain is greatest in the MSS-4 (0.5 to 0.6 μm) and MSS-5 (0.6 to 0.7 μm) spectral bands. The MSS-5 data appear to be the most useful of the two bands for snow mapping, because in some instances snow-covered areas are near saturation in the MSS-4 data, causing a loss of some detail in the snow pattern. In the longer wavelengths, especially the MSS-7 near-IR band (0.8 to 1.1 μm), snow cover is more difficult to detect. However, the near-IR band may provide useful information for certain purposes such as detecting melting conditions. As discussed later in this report, MSS-7 data have been found extremely useful for studies of glaciers in the Arctic.

Snow cover can be identified in the MSS-5 data because of its greater reflectance than the surrounding snow-free terrain. Although snow and clouds have similar reflectances, mountain snow cover can be differentiated from cloud primarily because the configuration of the snow patterns is very different from cloud fields and can be instantly recognized. The snow boundaries are also sharper than typical cloud edges, and snow fields usually appear with a more uniform reflectance than do clouds, which have considerable variation in texture. Furthermore, cloud shadows are usually visible, especially with cumuliform clouds, and various terrestrial features can be recognized in cloud-free areas. In fact, in the images from the flatter terrain of the Midwest that are completely snow covered, recognition of terrestrial features is the principal means to establish cloud-free areas. Because of the high resolution of the ERTS data, numerous terrestrial features that are not visible in lower resolution meteorological satellite photographs can be recognized. In addition to natural features, such man-made features as roads, electric power lines, and cultivated fields are detectable. In the heavily forested areas of the Cascades, timber cuts are clearly visible.

3. MAPPING OF SNOW LINE ELEVATION

Mean snow line elevations have been determined for a part of the Olympic Mountains in Washington (for 29 July and 4 September), the Mt. Rainier area in Washington (28 July and 2 September), the Three Sisters Mountains in Oregon (28 July and 2 September), the White Mountains in California (16 September, 21 October, and 27 November), and the Salt-Verde Watershed area in Arizona (21 November). For each area, significant changes in snow line elevation occur during the time intervals between the ERTS observations.

For each case analyzed, the snow limit was mapped from the 9.5" prints using a transparent acetate overlay. The snow line was located at the edge of the brighter area without regard to changes in brightness within the overall area deduced to be snow covered. Although the snow-covered areas in most of the cases analyzed exhibited fairly uniform brightness, some variations in tone were observed. The relationships between these variations and factors such as terrain and forest cover will be examined as the study progresses. Also, the accuracy of the snow line locations will be evaluated when additional correlative snow data are acquired. As the snow line elevation lowers into the more heavily forested areas as the winter progresses (in areas such as the Cascades), the snow line may not be as clearly defined as it is in the late summer and fall cases analyzed so far. To determine the snow line elevation, reference was made to charts from the National Topographic Map Series (Scale 1:250,000). Although the scale of these charts is larger than that of the 9.5" ERTS prints, charts of this scale were found to be very useful for matching the amount of detail in the ERTS data.

Olympic Mountains (Washington)

Analysis of ERTS-1 data for 29 July and 4 September 1972 reveals a 900 ft snow line retreat over the eastern two-thirds of the Olympic Mountains in northwestern Washington near 47°45'N and 123°15'W. The RBV-1 (0.475 to 0.574 μm) data for 29 July (Image ID 1006 - 18313) indicates that significant snow is still present in the eastern two-thirds of the Olympic Mountains on this date (the western third was not visible in the imagery). The snow limit mapped from the ERTS data, after being transferred to the corresponding topographic map, fits extremely well with the shape of the 5000 ft contour throughout the several narrow ridges comprising this region of the mountain range. Maximum elevation of these ridges ranges from 6000 to 7800 ft.

Analysis of MSS-5 data for 4 September (Image ID 1043 - 18372) shows that a considerable retreat of the snow line has occurred during the preceding five weeks. The mean snow line elevation measured from a considerable number of points on the contoured topographic map is at the 5900 ft level, a retreat of 900 ft from the previous observation. Actually, because the slopes in this area are not as steep as in some other areas, the 900 ft change is associated with a significant change in snow extent.

Mount Rainier (Washington)

An RBV-1 image for 28 July (Image ID 1005 - 18260) was analyzed to determine the mean snow line elevation for the Mt. Rainier area (maximum elevation 14,410 ft). The mean elevation of 65 points along the snow limit for this date is 5200 ft. Analysis of MSS-5 data for 2 September (Image ID 1041 - 18260) shows a considerable retreat in snow line elevation. The mean of 45 elevation points taken from the topographic map overlay is 6100 ft, a change of 900 ft since 28 July. This snow line retreat of 900 ft corresponds exactly to that measured for the same period over the Olympic Mountains located 100 miles to the northwest.

Three Sisters Mountains (Oregon)

ERTS observations on 28 July and 2 September indicate a 1000 ft snow line retreat on the western slope and a significantly smaller retreat of 200 ft on the eastern slope of the Three Sisters Mountains (near 44°N, 121°

45'W). On 28 July the snow line elevation mapped from the RBV-1 image (Image ID 1005 - 18265) is at 6000 ft on the western slope and at 7000 ft on the eastern slope. Five weeks later, however, the snow line mapped from the MSS-5 image (Image ID 1041 - 18265) along the western slope is 7000 ft, a change of 1000 ft from the earlier observation, whereas the mean snow line elevation on the eastern slope is 7200 ft, a change of only 200 ft.

White Mountains (California)

Analysis of three ERTS-1 passes during the period from mid-September through late November 1972 reveals broad changes in snow line elevation for the White Mountains of eastern California. This range, with peaks from 12,000 to 14,200 ft is oriented north-south just east of the Sierras between 37° and 38°N at 118°15'W. On 16 September (MSS-5, Image ID 1055 - 18035) snow cover is restricted to the higher terrain at a mean elevation of 12,800 ft. Five weeks later on 21 October 1972 (MSS-5, Image ID 1090 - 18003), a dramatic lowering of the snow line elevation has occurred, particularly along the western slopes. The snow line elevation is 7000 ft (mean of 25 points) along the western slope, and 10,500 ft (mean of 30 points) along the eastern slope.

The ERTS data on 27 November (MSS-5, Image ID 1127 - 18064) shows, however, that significant snow melt has apparently occurred during the preceding five-week period. The snow line elevation along the western slope has receded some 4000 ft to 11,000 ft (mean of 33 points), whereas measurements of the eastern slope show a retreat of only 500 ft to 11,000 ft (mean of 36 points). Of interest also is that the ERTS data show that during the period from 16 September to 27 November, the Tinemaha Reservoir, located west and just south of the White Mountains in the Owens Valley, increases significantly in size. On the earlier date, the reservoir measures 1-1/2 n.mi. north to south, whereas in late November, the length of the reservoir has increased to about 2 n.mi.

Salt-Verde Watershed (Arizona)

For the Salt-Verde Watershed area in Arizona aerial snow survey charts have been acquired for several dates, beginning 14 November (through the courtesy of the Salt River Project Office). The aerial survey procedures are described in a paper by Warskow (1971). For each aerial survey flight, which is made at approximately two-week intervals, an ocular estimate is made of the snow depth using the logs left from timber operations in the mountain areas, ground and vegetation textural characteristics, and cultural features (such as fences, road cuts) as indicators of the snow depth. Both the areal outline of the snow pack and the observed depths are recorded on a map overlay. The initial chart has been correlated with the ERTS data from a week later (21 November), and the chart of 12 January has been correlated with the ERTS data of 14 January.

Analysis of MSS-5 data from 21 November (Image ID 1121 - 17330) shows a well-defined snow boundary in the Salt-Verde Watershed, a narrow mountainous area extending from 35°30'N, 113°W southeastward to 33°45', 109°15'W. In this analysis the ERTS snow limit was transferred to the aerial snow survey map of 14 November. Although this aerial survey snow line was charted a week earlier than the satellite observation, there is good agreement between the two, especially in the region from about 35°N, 112°W to 34°15'N - 111°W. Differences showing the aerial survey snow line some 2 to 5 n.mi. broader in extent are, however, observed in the region near 34°N and 110°20'W to 111°W. As only light snow amounts (1 to 4 inches) were reported for 50% to 60% of this region on 14 November, it seems reasonable to assume that this 2 to 5 mile difference could well be the result of snow melt over the one-week period between the aerial and satellite observations. The same is undoubtedly true for differences observed along an isolated, narrow ridge just south of 34°N near 111°W, where the aerial survey indicated a trace to 1 inch above the 6200 ft level and 12 inches to 16 inches above 7000 ft. The ERTS snow line is observed close to the small area above 7000 ft in the region of significantly greater snow depth.

In the January case (Image ID 1175 - 17324), the aerial survey snow line also correlates well with the ERTS snow line. In fact, the principal difference seems to be that the ERTS snow line is more detailed, implying that the observer may smooth the snow line somewhat when compiling the aerial survey snow chart. In the areas where the snow line was estimated rather than actually observed from the flight, the differences are greater, with the snow extent mapped from the ERTS data being consistently less than that depicted on the corresponding chart.

Analysis of Arctic Data

A considerable amount of ERTS data over the Arctic has been received for use in a separate study (SR126: Evaluate the Application of ERTS-A Data for Detecting and Mapping Sea Ice). These data show the seasonal increase in snow cover in several areas such as the islands of the Canadian Archipelago and northern Alaska. For example, in late July, Banks Island in the Canadian Archipelago is completely snow-free; in late September, however, snow covers the higher elevations of the central portion of the island, and in late September the entire island is snow-covered. With snow cover, relatively small-scale terrain features, such as isolated hills, stream valleys, gullies, and ridges, are greatly enhanced. This is particularly evident in the MSS-7 band where large differences in brightness exist between sunlit features and shadows in the low-sun angle imagery.

In other Arctic data, considerable detail is evident in glaciers located along the east and west coasts of Greenland (for example, 23 September, Identifier 1062 - 16504). Detectable features include imbedded sediment trails (medial moraines), crevassed areas, and apparent limits of new snow cover over older glacial ice. Furthermore, significant differences are apparent in the various spectral bands. Several glaciers exhibit a uniform reflectance in the MSS-4 band, whereas in the MSS-7 band the lower elevation portions appear much darker than the higher elevation portions. This difference in reflectance is believed to be due to the existence of melt-water on the surface of the glacier at the lower elevations.

4. CONCLUSIONS

The results of the analysis of the initial sample of ERTS data covering the specified test sites in the western United States indicate that the MSS-5 spectral band (0.6 to 0.7 μm) is the most useful for detecting and mapping mountain snow cover. Snow cover can be readily detected and can be distinguished from clouds because the configuration of mountain snow patterns is very different from that of clouds, snow boundaries are sharper than typical cloud edges, snow fields usually appear with a more uniform reflectance than do clouds which often have considerable variation in texture, cloud shadows are often visible, and terrestrial features can be recognized in cloud-free areas. At the ERTS resolution, numerous terrestrial features not visible in lower resolution meteorological satellite data can be detected. In addition to various natural features, man-made features such as roads, electric power lines, cultivated fields, and timber cuts are visible.

In the four mountain areas for which data have been analyzed on at least two different dates, changes in snow line elevation ranging from 200 to as much as 4000 ft have been mapped. In these analyses topographic charts of a scale of 1:250,000 have been found to be useful for measuring snow line elevation. In two cases analyzed for the Salt-Verde Watershed in Arizona good agreement is observed between the location of the snow line as mapped from the ERTS data and as depicted on aerial snow survey charts. A single ERTS frame covering much of the Salt-Verde Watershed can be analyzed in a few hours, whereas the combined flight time and time to plot the aerial survey chart is considerably longer. Thus, it does appear that snow extent can be mapped from ERTS data on a cost-effective basis.

Although a thorough investigation of the multispectral characteristics of snow has not yet been undertaken, examination of data from the Arctic has revealed that the multispectral approach can provide information on glacial conditions that cannot be ascertained from observations in a single spectral band. Several glaciers along the coasts of Greenland exhibit a uniform reflectance in the MSS-4 (0.5 to 0.6 μm) band, whereas in the MSS-7 (0.8 to 1.1 μm) band the lower elevation parts appear much darker than the higher elevations. This difference in reflectance is believed to be due to the existence of melt-water on the surface of the lower parts of the glaciers as opposed to snow cover on the upper parts.

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