SATELLITE PHOTOGRAPHY FOR SNOW SURVEILLANCE IN WESTERN MOUNTAINS

By

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Introduction

In the western United States a large percentage of the water supply is produced by snow that accumulates in the mountainous areas. Although an accurate determination of the areal snow distribution is required both for flood forecasting and for water supply prediction, current snow survey methods are costly and at times inadequate. The earth-orbiting satellite is inherently capable of alleviating several of the snow survey problems because of its ability to collect data regardless of the remoteness of a region or the type of terrain.

Previous Studies

Several early investigations, such as those reported at the Western and Eastern Snow Conferences in 1963, [2] [3] demonstrated that mountain snow cover could be identified from spacecraft altitudes. Little operational application could be achieved with the earlier data, however, owing in part to the uncertainty of obtaining an observation over a specified region. The daily global satellite coverage now available has eliminated this problem.

More recent studies [4] [5] of operational uses of satellite photography for snow hydrology have been carried out principally for the region of flat terrain within the Upper Mississippi and Missouri River Basins. These studies have shown that snow cover distributions can often be mapped in greater detail from satellite data than is possible from existing station networks. In non-forested areas, qualitative estimates of snow depth can be obtained for accumulations up to about four inches.

Application to Mountainous Terrain

The research described in this paper has been carried out to determine the application of the previously developed satellite techniques to mountainous terrain. The results have indicated that mountain snow can be mapped with an accuracy at least equivalent to that attainable in flat terrain regions. The retreat of the snow line elevation can be monitored through the runoff period by satellite surveillance.

Nevertheless, current satellite data have limitations and should not be expected to satisfy completely the various operational requirements for snow-cover and depth information. Regardless of the type of terrain being surveyed, cloud interference, limiting the number of useable satellite observations, remains a problem. With the camera systems currently being flown, mapping accuracies are marginal for optimum hydrologic use; this is particularly true for mountain snow, where a small error can result in a significant difference in snow line elevation. Estimation of snow depths of more than a few inches or of the water equivalents common in mountain snow packs is not currently possible.

Satellite Data Sample

The data used to map snow cover consisted principally of ESSA-3 AVCS (Advanced Vidicon Camera System) photographs from January through June 1967. More recent data, particularly that from the 1967-68 winter season, although from similar satellite systems, have not been of comparable quality. Several ESSA-6 APT (Automatic Picture Transmission) pictures from 1967 and 1968 were also examined. Both the AVCS and APT cameras have a ground resolution of about 2 n mi.

Since correct geographical location is essential for obtaining accurate mapping from satellite photography, the accuracy of the initial placement of the latitude-longitude grid must be carefully checked through comparison with known geographic reference points.

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This requirement applies both to APT pictures, which must be gridded after they are received, and to AVCS pictures, which are electronically gridded. In the AVCS pictures, major geographic features and state boundaries are given in addition to the latitude-longitude grid lines. Although these grids have been assigned an accuracy of ± 30 n mi, they may at times be in error by as much as 60 n. mi. or more. Also, the superimposed grid lines and coordinates often obscure detail that may be significant for mapping mountain snow.

Techniques for Identifying Snow Cover

Since snow and cloud can have nearly identical reflectivities, differentiation between the two can be a serious problem when analyzing satellite photography. This is equally important for meteorological purposes; in more than one instance, cloud-free snow-covered areas have been mapped in operational analyses as being cloud-covered.

Four techniques for differentiating between snow and cloud were found useful in flat terrain. These are: (1) reference to cloud observations, (2) recognition of terrestrial features, (3) pattern stability, and (4) pattern appearance. The applicability of each technique to mountainous terrain is discussed in the following sections.

Reference to Concurrent Cloud Observations

Reference to standard weather observations can be used principally to determine when major cloud systems cover the region of interest. Under such conditions, little useful snow cover information can be anticipated from satellite photography. Because of the lack of reporting stations and the variability of cloudiness common in mountainous areas, partially cloud-covered conditions, for which useable satellite data may be possible, often exist.

Recognition of Terrestial Features - Pattern Recognition

Recognition of terrestrial features is perhaps the most important technique for identifying snow, since it immediately indicates that no clouds are present in the vicinity of the visible feature. Coastlines, lakes and rivers are easily recognized features that can be readily verified on standard maps. Other features not so obvious on conventional maps afford equally reliable assistance in snow identification. Among these are boundaries between forested and non-forested areas and boundaries between areas with different land usages.

In mountainous areas, the snow pattern itself often forms a recognizable terrestrial feature. Because the snow line tends to follow elevation contours, distinct patterns exist; once these are identified as being associated with certain features, they can easily be recognized in later pictures. This technique cannot be used in flat terrain, where the snow pattern results from individual storm characteristics.

Cloud-free mosaics of the western United States, which can be used for reference purposes, are shown in Figures 1 and 2. The mosaic in Figure 1, made up of four passes from late February and early March, is typical of winter snow conditions.

In Figure 2, a similar cloud-free mosaic, compiled from May and June passes, is shown. By this time of year, the snow has retreated to higher elevations. Several features, such as the Sierras, Cascades, and Canadian Rockies, can still be easily recognized. With snow at lower elevations gone, some ranges, such as the Wasatch and Wind River, actually stand out more clearly.

Pattern Stability

Since clouds seldom retain the same shape for more than a few hours, stable patterns viewed by satellite are indicative of snow cover. To employ this technique, observations a day or more apart are required, unless several observations per day from an earth synchronous satellite are available. Two observations on the same day only a few hours apart must be used with caution, since the apparent stability of slow-moving cloud patterns may be mistaken for snow. When the observations are several days apart, the possible changes in snow cover, due to either melting or a storm passage, must be taken into consideration.

The mountain snow patterns identified in the background charts were first established through pattern stability. In addition to reference to the background charts, this technique should be employed, whenever possible, to differentiate more definitely between cloud and snow, particularly snow which may have fallen at lower elevations.

Pattern Appearance

Although having nearly the same reflectivities, snow may appear "smoother" than clouds in satellite photographs. The lumpy texture is due to shadows of higher clouds on lower clouds or shadows from clouds with greater vertical development; occasionally, cloud shadows can be detected on an underlying snow surface.

This technique is not as useful in mountainous terrain as in flat terrain. Although large scale cloud systems, characteristic of winter storms, can often be identified by their pattern and texture, convective type cloudiness, more common in the spring, may appear very similar to mountain snow.

Mapping of Snow Cover Distribution

Placement of Snow Line - Mapping Accuracy

In the analysis of satellite photography over flat terrain, all cloudfree areas with a continuous brightness distinctively greater than the normal dark background were mapped as being snow-covered. The snow line enclosing such areas was found to represent the limit of a snow accumulation of one inch or more.

In mountainous terrain, the snow line can be located in a similar manner. Because of the roughness of the terrain and the rapid buildup of snow with elevation, the snow line as determined from the satellite photograph probably represents an accumulation of several inches. (The exact snow depth represented by the apparent snow line is difficult to establish because of the lack of ground truth data.)

The results of tests carried out in the previous studies indicated that the snow line can be mapped from satellite photography with an accuracy of within 10 n. mi. In mountainous terrain, however, landmarks can often be used to establish more accurate geographic referencing than is possible in flat terrain. Therefore, the mapping accuracy of mountain snow is believed to be at least as good as, and possibly better than, that in non-mountainous areas. Nevertheless, the accuracies possible from existing data are marginal for attaining the one to two mile accuracies desired for optimum operational use.

Determination of Snow Line Elevation

Once the snow line has been mapped, the snow line elevation can be determined by map-matching. The snow line as analyzed from the satellite picture can be transferred to a base map and compared with an overlay of elevation contours or with the elevations of reporting stations. Transparent overlays of elevation contours can also be placed directly on the pictures; however, the slight differences in perspective in each pass received from a polar orbiting satellite present a significant problem.

Good agreement has been found between the snow line elevation as determined from the satellite data and from ground truth. Further analyses are currently in progress to determine more exactly the accuracy with which the snow line elevation can be established.

Examples of Sattellite Snow Surveillance

(a) Snow Line Retreat

The snow line retreat during the spring of 1967 within the area in Idaho just north of the Snake River Plains was continuously monitored through satellite surveillance. The decrease in snow amount is evident in the photographs taken on 8 April and 16 May (Figs. 3a and 3b) when compared with the winter background chart (Fig. 1).

In the photograph used in the mosaic, taken on 5 March, the area is completely snow covered. The snow line in southwestern Idaho is estimated from the photograph to be at the 3-4,000 foot level; near the eastern end of the Snake River Plains it is estimated to be near the 5,000 foot level. By early April, the North-South mountain ranges (Beaverhead Mountains, Lemhi Range, Lost River Range) begin to appear as separate ranges as the snow at lower elevations melts. By 16 May, the snow cover is confined solely to the higher elevations. The snow line mapped from this picture fits well with the 9,000 foot contour.

(b) Sierras Storm

In 1967 a mid-March storm produced nearly 100 inches of new snow in parts of the Sierras. The resulting changes in snow cover distribution were mapped from the satellite observations. Cloud-free photographs taken before the storm (7 March), just after the storm (14 March), and a few days later (19 March) are shown in Figures 4a, b and c.

A dramatic increase in areal snow amount can be seen in Figure 4b. At this time, Lake Mono (in the eastern Sierras near 38N) is completely surrounded by snow; in Figure 4a, the area to the east of the lake is snowfree. The snow distribution around Lake Tahoe (dark spot just south of 40N, 120W) has also greatly increased. By 19 March, however, much of the new snow at lower elevations has apparently melted, as the snow pattern is similar to the observation taken before the storm.

The snow cover distributions as mapped from these pictures are verified by concurrent snow reports. Several lower elevation stations, that had been snowless on 7 March, reported substantial snow-on-the-ground on 14 March (more than 20 inches in some cases). By 19 March, the snow had completely disappeared at most of these stations.

Estimation of Snow Depth

In the studies of flat terrain regions, an analysis of satellite observed brightness and reported snow depth was carried out. The results indicated that, in non-forested areas, brightness can qualitatively be related to snow depth for accumulations to about four inches. For accumulations greater than four inches, no change in brightness is detectable; in forested areas, little variation in brightness occurs with increasing snow depth.

It is apparent, therefore, that little information on the snow depths common in mountainous regions can be obtained from satellite photography alone. For example, no significant change in brightness can be detected in the central Sierras in the pictures in Figures 4a and 4b, although in some areas snow depths have increased by more than 60 inches.

Even in non-forested, flat terrain, the relationship between brightness and snow depth can be affected by several factors, including the age of the snow, rainfall, type of terrain, and type of vegetation. Reflectivity decreases with the age of the snow cover, such that two inches of new snow may appear as bright as four or more inches of old snow. Similarly, rainfall may reduce the reflectivity of the snow, although a significant decrease generally results from a complete melting of a part of the snow cover, rather than a decrease in reflectivity of the snow itself. For small snow accumulations, the roughness of the terrain can influence the reflectivity; the height of the grass or grain stubble can also be a factor determining the snow depth that will appear as continuous cover in a satellite picture.

Two additional factors are also significant for identifying and mapping snow cover, both in flat or mountainous terrain. The first is the camera system itself; characteristics of the cathode ray tube and lens of the satellite camera system can result in a non-uniformity of film density, such that the brightness of a source of certain intensity may vary over the resulting picture. 6/ The second is the solar angle; since snow is not symmetrical in reflectance, 7/ the apparent brightness is a function of sun angle (especially for angles below 45°), and therefore is dependent on the camera angle of the satellite, the time of day, and the time of year.

The Outlook for Satellite Snow Surveillance

The ESSA system of operational satellites is now providing reliable twice per day global coverage, with one of the satellites having direct readout APT capability. In addition to data in the analog form, such as that used in the studies described in this paper, the satellites equipped with AVCS camera systems provide data in the form of digitized brightness values. Automatic identification and mapping of snow may be possible from these data, enabling more quantitative results to be obtained.

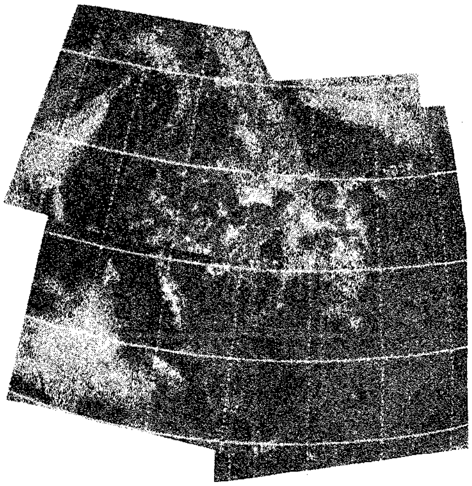


Figure 1 Cloud-free mosaic of the western United States compiled from ESSA-3 photographs taken in late February and early March 1967. The snow cover distribution is typical of winter conditions.

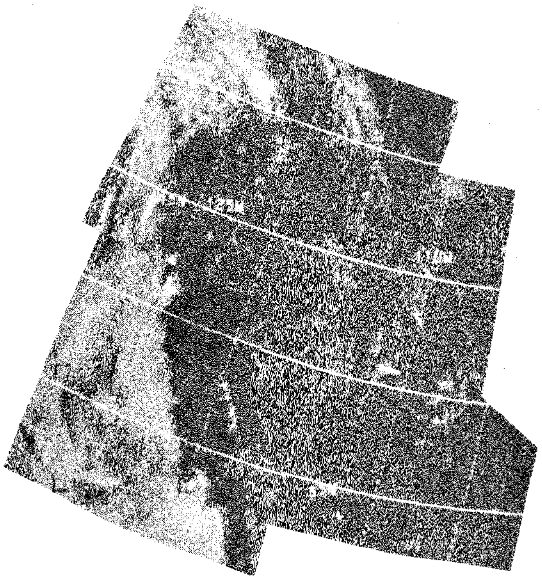
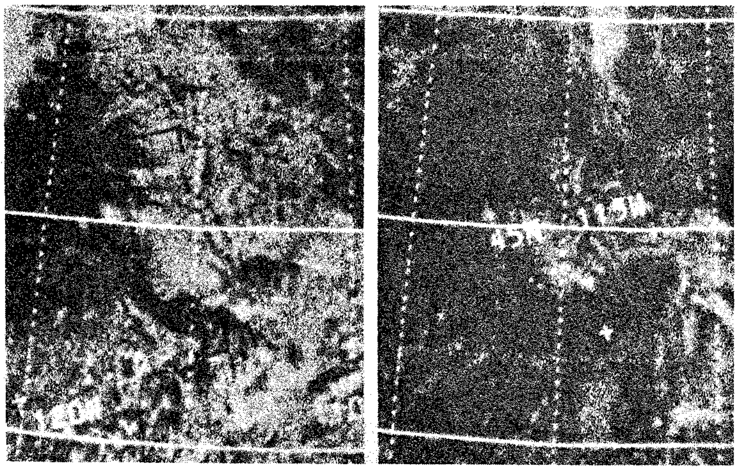


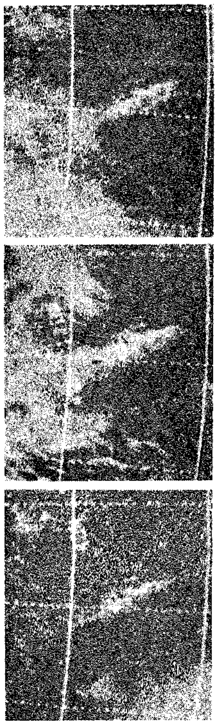
Figure 2 Cloud-free mosaic of the western United States compiled from ESSA-3 photographs taken in late May and June 1967. The decrease in snow amount is evident when compared with Figure 1.



(a) 8 April 1967

(b) 16 May 1967

Figure 3 ESSA-3 photographs showing the snow line retreat in the area north of the Snake River Plains.



(a) 7 March 1967

(b) 14 March 1967

(c) 19 March 1967

Figure 4 ESSA-3 photographs showing changes in snow cover distribution in the Sierras resulting from a major storm.

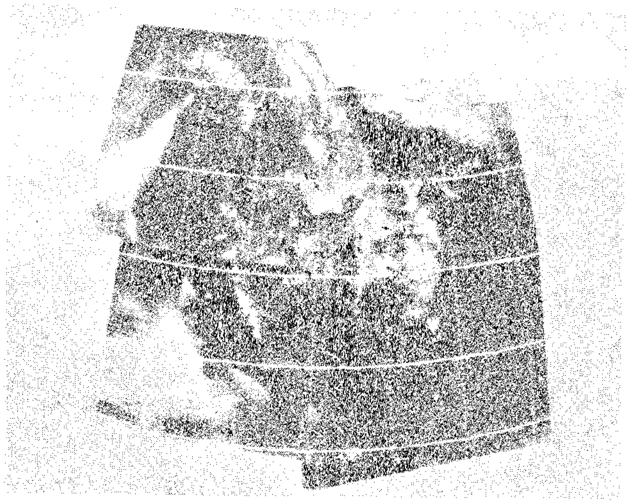


Figure 6 Relationship between satellite-observed brightness and snow depth in non-forested areas.

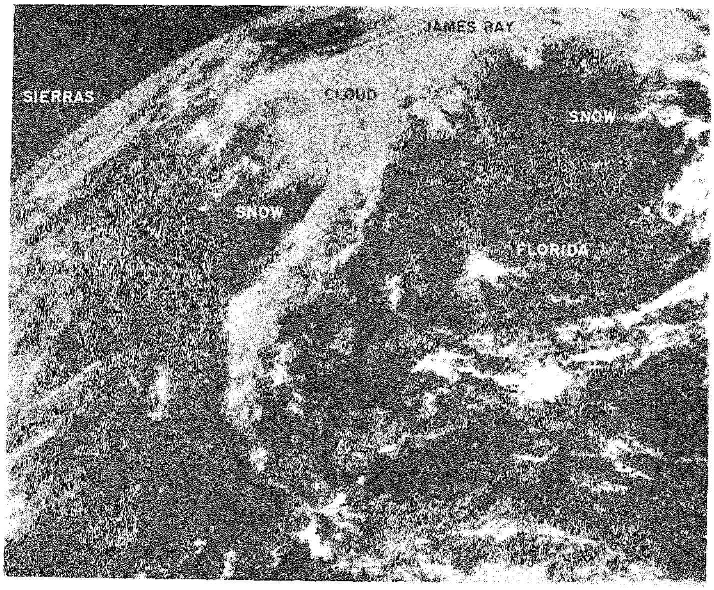


Figure 7 Enlarged portion of an ATS-III photograph (7 May 1968) showing the United States and southern Canada. Snow can be seen in western mountain areas, such as the Sierras. Snow that fell the previous day over northern Maine and the Maritime Provinces can also be identified (Photograph courtesy of NASA and Hughes Aircraft Co.)

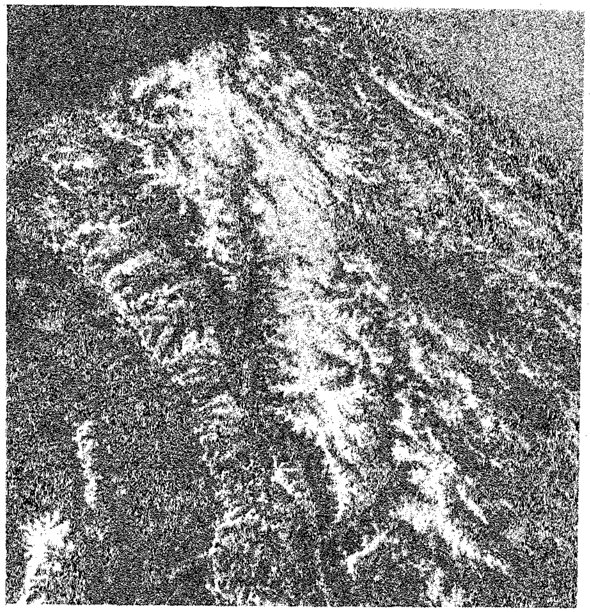


Figure 8 Gemini V photograph (8 August 1965) showing mountain snow cover in the Himalayan region. The ground resolution in this photograph is of the order of that proposed for future Earth Resources Satellite Systems (Photograph courtesy of NASA).

Improved detail in snow cover mapping would result from cameras with higher resolutions and with greater dynamic ranges of gray scale. The resolution of the Nimbus II AVCS camera was about 0.5 miles, but this camera operated only during the summer season (the Nimbus II APT system operated through the winter). Nimbus III, scheduled for launch this month, will carry an Image Dissector Camera, which will have a greater dynamic range than any camera yet flown. Camera systems proposed for the Earth Resources Technology Satellite (ERTS) will be capable of 200 ft. ground resolution, which is comparable to that of the photographs obtained from manned space flights.

Regardless of the type of camera systems developed, cloud interference and estimation of snow depths greater than a few inches will remain major problems in the operational use of satellite photography. The development of systems that can view the earth in other than the visual part of the spectrum may alleviate these problems, at least to some degree. Differentiation between snow and cloud may be easier in the infrared, since even in winter, most clouds would be colder than snow. An infrared sensing system can also complement a video system with nighttime observations, and can measure the surface temperature of the snow cover, a significant parameter for predicting snow melt.

The sensor with perhaps the greatest promise for improving satellite snow surveillance is the microwave radiometer. 8/ Cloud cover interference occurring with visual and infrared observations would be greatly reduced; also some measure of snow depth may be attainable. Some attenuation can, however, be expected from precipitating clouds, and the required resolutions may be difficult to obtain from satellite altitudes.

In summary, satellite photography can already provide the hydrologist with useful information concerning snow cover distributions. From existing data, the horizontal distribution of snow can often be mapped as accurately as, or more accurately than, from a typical ground station network. Future mapping, based on higher resolution camera systems, can be expected to be considerably more accurate than from ground stations, especially in remote areas where the reporting network is sparse. With more sophisticated earth-viewing geophysical satellites planned for the coming years, the outlook for operational snow mapping from satellite data is promising.

Acknowledgment

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