AN ALL-DIGITAL APPROACH TO SNOW MAPPING USING GEOSTATIONARY SATELLITE DATA

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ABSTRACT

This paper describes an all-digital snow-mapping technique that utilizes 4-km resolution visible data from a geostationary satellite, GOES-W. The study area includes nine contiguous river basins in the Sierra Nevada. The snow-mapping procedure uses a brightness threshold for each individual basin pixel to identify snow cover. The method allows for daily and seasonal changes in solar illumination angles and variations in the nature of ground cover across the basins.

INTRODUCTION

Areal snowcover maps and calculations of percent snowcover are now operationally produced at the National Environmental Satellite Service (NESS). The data are disseminated to federal and state agencies for use in runoff forecasting and water resource planning. Selected river basins in the Sierra Nevada have been operationally monitored at NESS since early 1973. One hundred and seventy-eight (178) areal snow-cover determinations were made for the American River basin (above Folsom Dam) between January 1973 and June 1978 and transmitted to the National Weather Service/ River Forecast Center in Sacramento, California. At the request of the California State Department of Water Resources, the Sacramento river basin above Shasta Dam and the Feather above Oroville Dam were added to the NESS operational snow-mapping program in January 1977. In February 1978, the U.S. Soil Conservation Service Office in Reno, Nevada, requested that operational coverage be extended to three river basins on the eastern slopes of the Sierras, the Tahoe-Truckee, Carson, and Walker.

Snowcover analyses at NESS are presently done through photointerpretation of satellite images using optical rectification techniques and density slicers

(Schneider et al., 1976). This method of analysis is time-consuming and its accuracy is dependent upon the skill of the analyst. To meet user demand, it is important that a faster, more objective method for snow mapping be developed. The digital snow mapping experiment is directed toward this goal.

THE STUDY AREA

The study area includes nine contiguous basins in the central and northern Sierra Nevada. This area is depicted under almost snow-free conditions in Figure 1, a 1-km resolution visible image taken from GOES-W on August 1, 1978. The basins have been outlined on the image using a Bausch and Lomb Zoom Transfer Scope (ZTS) and are labelled for orientation purposes. Six of the rivers (Sacramento, Feather, Yuba, American, Mokelumne, and Stanislaus) drain west from the Sierras and have basins covered with grassy lowlands grading into higher elevation coniferous forests. Light-colored granite is exposed at several locations above the timber line. Each of these western basins delineated on Figure 1 encompasses the drainage area above a dam and reservoir. The remaining three basins, the Carson, Tahoe-Truckee, and Walker, drain east from the Sierras and are covered by low elevation desert shrublands and salt flats interspersed with highlands covered by pine-juniper woodlands. The nine basins range in size from 1,590 km^2 (Mokelumne) to 16,630 km^2 (Sacramento above Shasta).

DESCRIPTION OF THE SATELLITE AND SENSOR

Two geostationary meteorological satellites operated by NESS, the geostationary operational environmental satellites (GOES), view the Earth's disk through Visible and Infrared Spin-Scan Radiometer (VISSR) instruments. A description of this dual geostationary satellite system can be found in *Technical Memorandum NESS 64* (Bristor, 1975). The satellites, GOES-E and GOES-W, are fixed over the equator at 75°W and 135°W, respectively at an altitude of about 36,000 km. The VISSR instrument provides concurrent observations in the infrared spectrum (10.5 to 12.5 μm) and in the visible spectrum (0.55 to 0.75 μm). The visible data which are used in snow mapping are expressed as 6-bit count values measuring relative brightness.

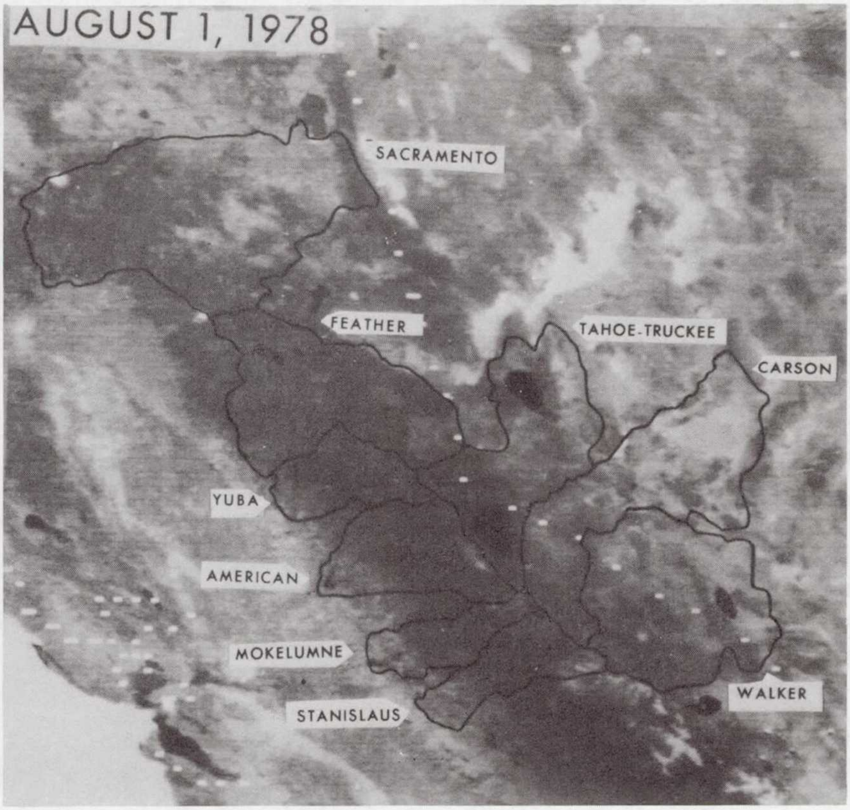


Fig. 1--GOES-W image of the Sierra Nevada test area

THE VISSR DATA BASE

The digital VISSR data, at reduced resolution from the eastern and western satellites, are being processed into an experimental VISSR Data Base (VDB). Data may be obtained from each satellite at 30-minute intervals. About 18 minutes are required for the VISSR to produce the digital image or "picture" of the full disk. The western satellite data are normally acquired at 15 minutes and 45 minutes after the hour, while the eastern satellite data are acquired on the hour and half hour. Digital data from the full Earth disk are currently restricted to areas extending from 50^{o}N to 50^{o}S latitude and approximately 50^{o} longitude east and west of the satellite subpoints.

The VDB is formed by processing data received in real time from the GOES and ingested onto computer disks, where the resolution of the visible channel is reduced from 1 km to 4 km. The VDB contains 12 selected 4-km visible pictures, six from each satellite. Data are maintained on the VDB for 24 hours before being overwritten with current data. The visible pictures from the western satellite are the source of data for the digital snow-mapping experiment described in this paper.

PROCEDURE

The digital snow-mapping technique processes on a pixel-by-pixel basis an array of 4-km resolution GOES data containing the nine snow basins. For each pixel, a computer program performs the following operations:

1. Determines which river basin, if any, the pixel is in.
2. Calculates the clear brightness of the pixel, that is, its brightness in the absence of snow or clouds.
3. Checks whether or not the pixel brightness exceeds its clear brightness by more than a set theshold. If so, the pixel is classified as snow-covered. The snowcover in the basin is then determined as the percent of basin pixels that exceed their computed clear brightness by more than the threshold value.

Construction of the Digital Mask

Determination of which pixels are located in a particular basin required creation of a digital mask. An example of a 129x129 array of 4-km GOES digital data can be seen in Figure 2. Basin outlines from standard hydrologic maps were converted to a GOES-W projection and drawn on the printout using a ZTS. A digital basin mask was then constructed by identifying each basin to the computer by line and pixel. The mask, shown in Figure 3, contains blanks in the pixel locations outside all river basins and an appropriate number from 1 to 9 indicating locations of the nine basins. Bodies of water in and adjacent to the basins (Lake Tahoe, Pyramid, Walker, Eagle, Almanor, and Mono) are indicated by the letter A for use as location landmarks. The mask is permanently stored on computer disk and can be used as long as GOES-W remains fixed at $0^{\circ}N$, $135^{\circ}W$. Movement of the satellite to another position would require construction of a new digital mask.

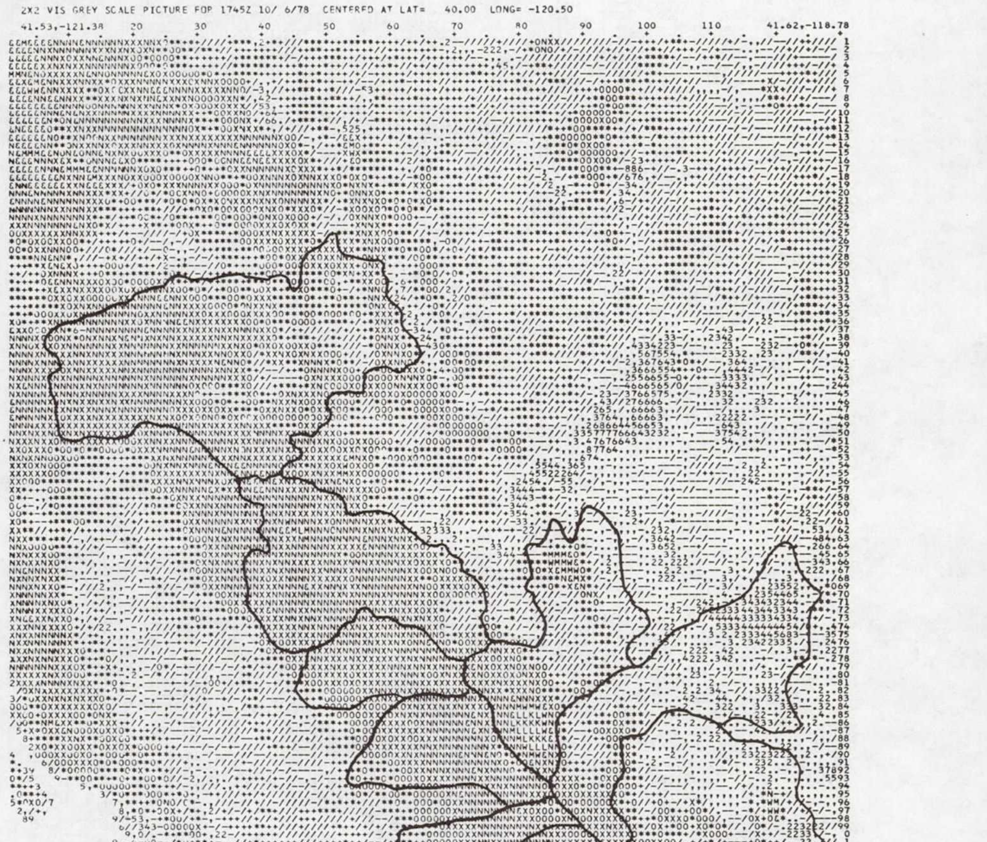


Fig. 2--Alphanumeric printout with each character representing a 4-km pixel element. Basin boundaries drawn with aid of a ZTS.

Fig. 3--Digital basin masks

In processing the digital data for snowcover, it is essential that the digital mask and data array be exactly aligned with respect to one another. Misalignment can easily be detected by comparing location of the aforementioned landmarks on mask and data array. In case of misalignment, the data array can be shifted by line and pixel (up/down or right/left) so that it is properly registered to the mask.

Determination of Snow-Free Brightness

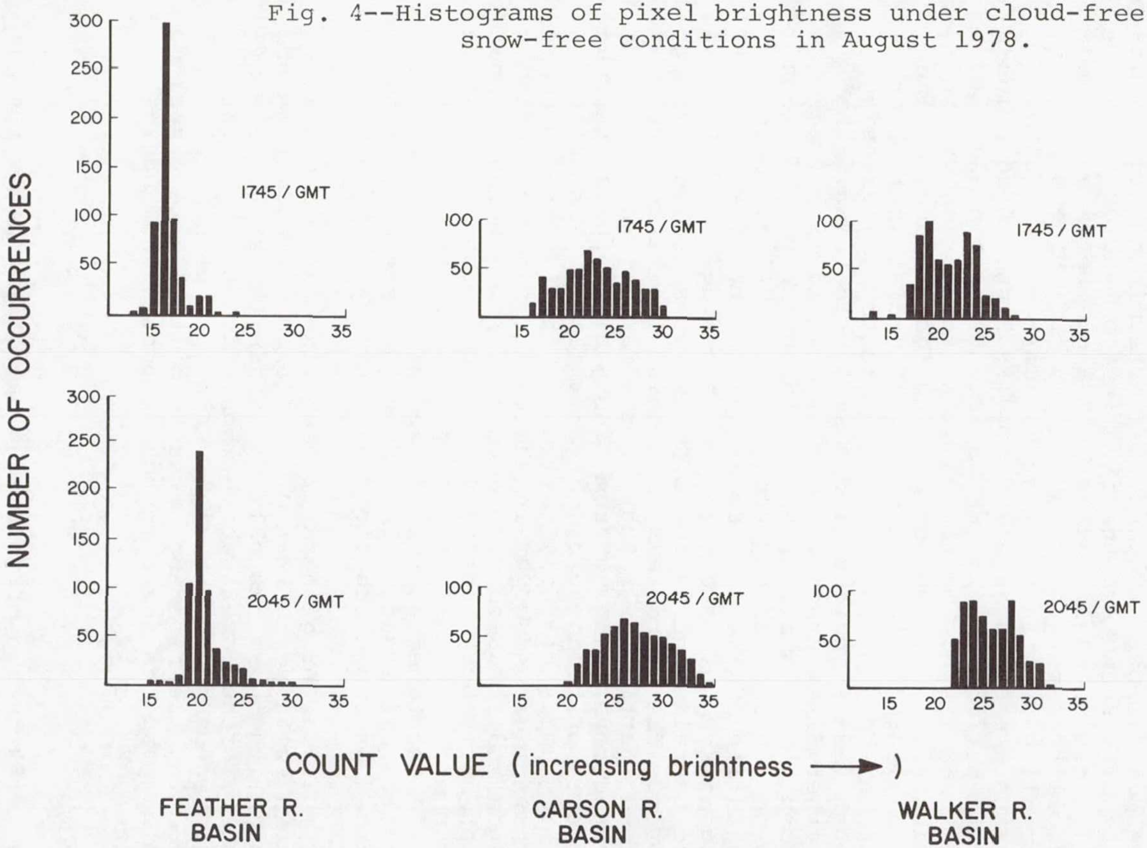
The heart of the automatic snow-mapping procedure is computation of the brightness of each pixel in a basin under cloud-free, snow-free conditions. The most important quantities determining the brightness of a scene are the illumination angles (local solar zenith angle and azimuth angle between sun and satellite) and ground cover. The brightness values for all pixels in the Feather, Carson, and Walker basins are shown as histograms in Figure 4 to illustrate surface brightness variations within basins. For each basin, the histogram at the top shows the brightness distribution at 0945 local standard time on a clear day in August 1978; the distribution on the same day at 1245 is on the bottom. Increasing count values indicate increasing brightness. The Feather River drainage, mostly covered with forest except for a small grassy plain in the southeastern corner, has a sharply peaked distribution, representative of its uniform ground cover. The Carson and Walker basins are on the east side of the Sierra and contain contrasting climate zones and vegetative cover. The histograms from these two basins are broad, particularly that of the Carson, which has ground cover ranging from pine-juniper forest through desert scrubland to bright salt flats. The Walker histogram is bimodel, reflecting the two predominant types of ground cover in the basin, pine-juniper woodlands and scrub-covered desert. From morning to noon, each basin brightens by 4 or 5 counts but the histogram shapes change very little, indicating that the different types of terrain and ground cover brighten by the same amount. This fact suggests a practical method of computing the clear brightness of each pixel.

If the brightness of each pixel in a basin is known relative to that of a reference area within the basin, then one has only to obtain the brightness of the reference area, which when added to the relative brightness gives the clear value for each pixel. Choosing the reference area to be the darkest region, we can express the brightness count of any basin pixel, B_i, as

$$B_i = B_d + R_i \quad ,$$

where B_d is the brightness count of the darkest area and R_i is the brightness of the ith pixel relative to B_d.

Fig. 4--Histograms of pixel brightness under cloud-free, snow-free conditions in August 1978.



To calculate B_d, a regression equation of the following form was used:

$$B_d = a + b \cos\chi + c \sin\chi \cos\phi + d \sin\chi \cos^2\phi \quad ,$$

where χ is the local solar zenith angle, ϕ is the azimuth angle between the sun and satellite, and a, b, c, and d are regression coefficients. Regression coefficients were derived for each basin from clear data collected from August through early November 1978. The regressions are accurate to within 1 count for most pictures as long as the sensor response is stable (Tarpley et al., 1978).

Construction of the Relative Brightness Mask

A relative brightness mask was constructed for each basin from data collected at 0945 local time on a cloud-free, snow-free day in August 1978. The darkest area in each basin (excluding lakes) was chosen by visual examination. In the Sierra, the darkest area is the most densely forested part of the basin. The digital count of the darkest area, B_d, was then subtracted from the value of each pixel in the basin, yielding the relative brightness value, R_i, for each pixel. The relative brightness mask for the Walker basin is shown in Figure 5. These data have the same distribution (excluding lakes) as the 0945 histogram in Figure 4. Note that high numbers in the relative brightness mask correspond to bright features in the picture in Figure 1, while numbers 0 to about 4 are located in forested regions. Since relative brightness in a basin is nearly independent of solar illumination angles, as shown in the histograms, the relative brightness mask was generated for only one hour (0930) but used at other hours during the day.

Determination of Snowcover

A threshold value is added to the predicted clear brightness of each pixel to give a value, T_i,

$$T_i = B_i + \Delta \quad ,$$

where Δ is the threshold. If the measured count exceeds T_i, then the pixel is assumed to be snow-covered. The value of Δ is empirically determined and varies by basin for different illumination conditions and types of ground cover.

Computer-printed snowcover maps, illustrated in Figure 6, are produced by filling a 129x129 array with

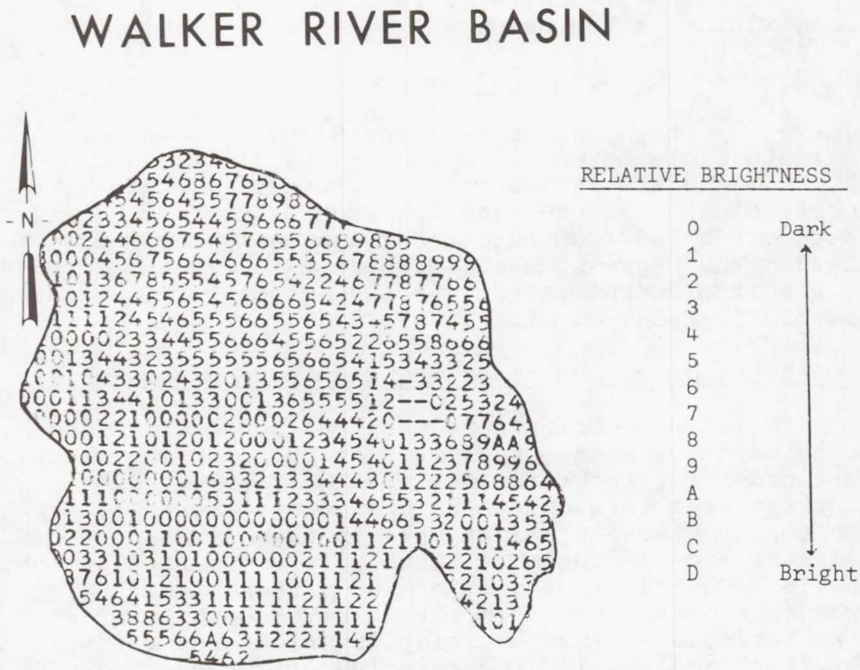
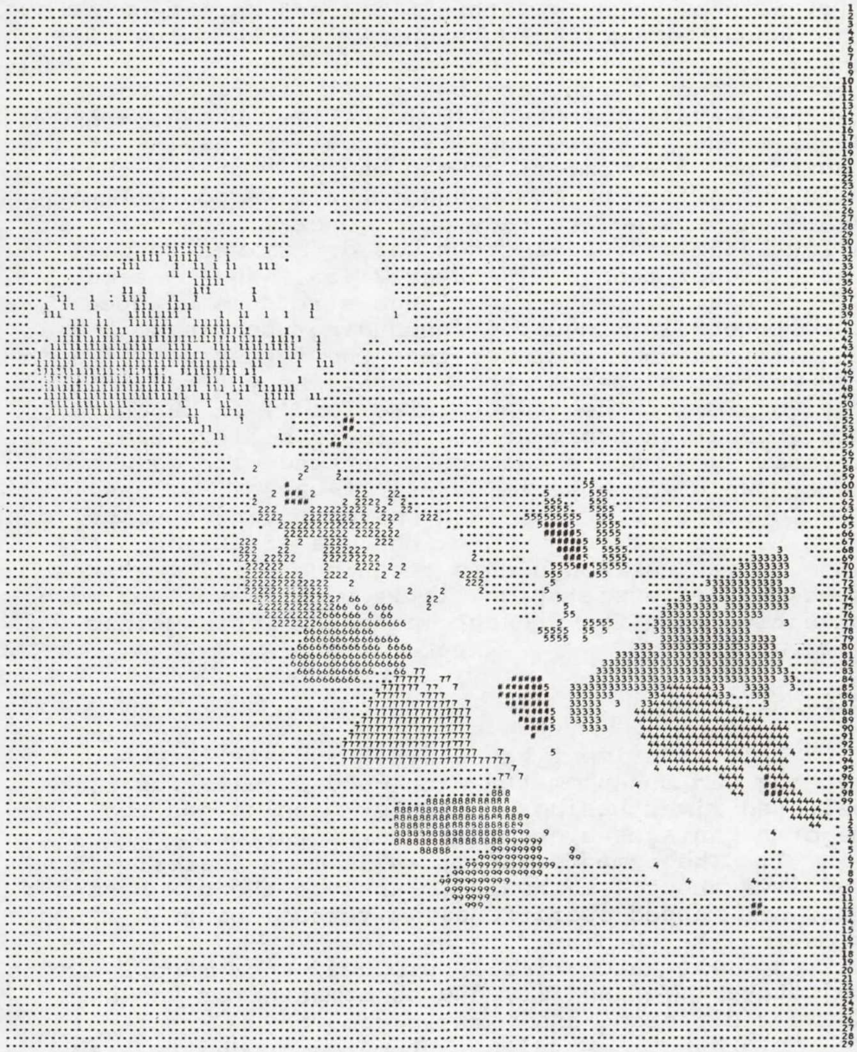


Fig. 5--Relative brightness mask for the Walker River basin

dots, basin number, and blanks, depending on whether or not the corresponding pixel in the data array is outside the basins of interest, snow-free (brightness count $\leq T_i$) or snow-covered (brightness $> T_i$), respectively. Snowcover can be determined from any of four pictures resident on the VDB (at 1645, 1745, 2045, and 2145 GMT) and for any combination of the nine Sierra basins. The snowcover in a basin is the number of snow-covered pixels expressed as a percentage of the total number of pixels in the basin.

PRELIMINARY RESULTS

Digital snow maps for the nine Sierra River basins have been generated experimentally at NESS since November 3, 1978. The results are compared to snowcover measurements produced photointerpretively as part of the NESS Operational Snowmapping Program. Over 100 cases have been studied as of this writing. The critical parameter has proven to be Δ, the number of counts by which snow brightens up a basin pixel.



RIVER	PERCENT SNOW COVERED
SACRAMENTO	57.7
FEATHER	57.0
CARSON	42.7
WALKER	61.6
TRUCKEE	64.2
YUBA	34.6
AMERICAN	33.3
MOKELUMNE	22.4
STANISLAUS	47.4

PICTURE TIME 1745

Fig. 6--Printout of digital snow maps with corresponding basin snowcover percentages

In every case, a Δ was identified that brought the digital snow maps to within 5 percent agreement with the manual product. For each basin, the value of Δ producing the correct snow map was found to vary with terrain, snow depth, and solar illumination angles. In the heavily forested American River basin, a Δ of 4 was found to yield the most accurate results at the beginning of November; by the end of December the value of Δ for the basin had to be lowered to 1 to achieve the same accuracy. In general, the value of Δ for 1745Z and 2045Z cases was determined to be 1 count higher than at 1645Z or 2145Z. The eastern Sierra basins, containing large stretches of open desert terrain, required (depending upon season) a Δ from 1 to 3 counts higher than the forested basins on the western slopes of the Sierra. As yet there is no way to predict the proper value for Δ, so in an operational environment the authors believe that several snow maps should be generated with each computer run using a series of first-guess Δ values. The "correct" snow map (and corresponding Δ value) can then be identified by checking it against the satellite image. Although this technique still requires some photointerpretation, it is much faster and more objective than the present manual analysis method used at NESS.

DISCUSSION

This experiment has shown that satellite snow mapping can be automated with good results for selected river basins. Computer mapping has two major advantages over photointerpretation:

1. The computer analysis is much faster. It requires about 4 manhours to analyze the six basins that are mapped operationally, versus about 30 minutes for the automatic technique.
2. The automatically produced snow maps are more objective. Variability due to human error and bias between different analysts is removed.

Disadvantages of the automated procedure are:

1. The program cannot discriminate between snow and cloud or fog, so basins cannot be mapped unless they are completely cloud-free.
2. Very light or patchy snow may not brighten a scene sufficiently to be detected.
3. Digital data are available from the VDB for only 24 hours after the observation so there are deadlines within which the program has to be successfully run. Retrospective snow mapping would have to be done from archived data.

The data used in this study were of sufficient resolution to map snow cover in the Sierra basins. However, it probably would not be possible to use 4-km data to monitor snowcover in basins that are smaller, are farther away from the satellite's sub-point, or have more complex snowlines than the Sierra basins. In order to completely automate snow mapping at NESS, 2-km or even 1-km VISSR data would have to be used to insure good results in all basins.

ACKNOWLEDGMENT

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