PROGRESS REPORT ON SNOW AND ICE OBSERVATIONS FROM TIROS SATELLITES

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The U. S. Weather Bureau's National Weather Satellite Center, located in Suitland, Maryland, has been charged with the responsibility of developing an operational meteorological satellite system capable of providing realtime weather observations on a global scale. Partly to implement such a program, the National Aeronautics and Space Administration has successfully placed six TIROS satellites in orbit since April 1960, while a seventh is expected to be launched some time within the next few weeks*. The first four were placed in a nearly circular orbit approximately 450 miles high, with the plane of the orbit inclined 48° to the equator. For TIROS V and VI, the orbital inclination was 58°. Each carried two TV cameras, and during their functional lifetime, all of them have photographed ice and snow.

The possibility of obtaining wide-area coverage of ice and snow features on a real-time basis has both direct operational as well as research value to many organizations. The obvious economic advantages of obtaining such coverage from satellites will depend largely on our ability to interpret pictures and radiation data obtained from such vehicles, and to depict this interpretation in terms which are familiar to the meteorologist, hydrologist, oceanographer or other user in the field or in the laboratory.

Except for the meteorological analysis of cloud forms, the interpretation and application of satellite ice photography is perhaps the most intensely studied aspect of TIROS photographs thus far conducted. These studies have been in progress since shortly after TIROS I was launched in April 1960. Recently, the United States and Canada participated in a joint exercise, Project TIREC (TIROS Ice Reconnaissance), in which aircraft, ship and land station observations of sea ice and weather were collected simultaneously with passes of the TIROS IV meteorological satellite over the Great Lakes and Canadian east coast waters. Much of this data remains to be analyzed; however, it is already evident that operational ice reconnaissance and surveillance may be begun within the next few years. A discussion of Project TIREC, its aims and objectives, and some of the preliminary findings are covered later in this paper.

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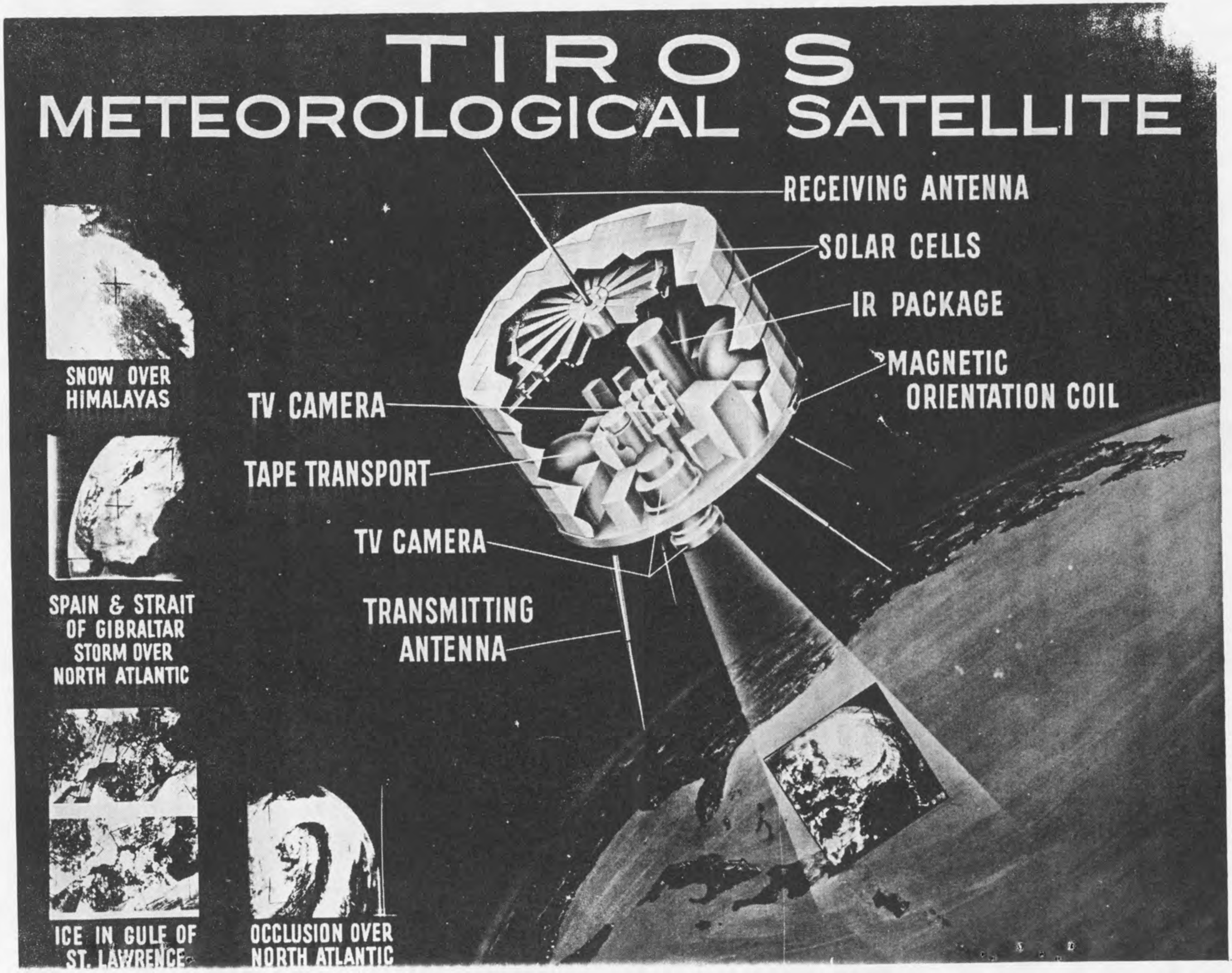
* TIROS VII was launched on June 19, 1963.


TIROS
METEOROLOGICAL SATELLITE
RECEIVING ANTENNA
SOLAR CELLS
IR PACKAGE
MAGNETIC
ORIENTATION COIL
TV CAMERA
TAPE TRANSPORT
TV CAMERA
TRANSMITTING
ANTENNA
SNOW OVER
HIMALAYAS
SPAIN & STRAIT
OF GIBRALTAR
STORM OVER
NORTH ATLANTIC
ICE IN GULF OF
ST. LAWRENCE
OCCLUSION OVER
NORTH ATLANTIC

Relatively little has been done to develop techniques for analyzing satellite observations of snow cover, although more attention has been focused on this problem recently. Some of the earliest work [1] in this field involved the interpretation of TIROS I photographs of snow and cloud cover over the Alps; in his report, S. Fritz discusses the important meteorological problem of distinguishing clouds from an underlying snow surface. In a more recent article[2], R. Tarble shows, among other excellent photographs, examples of TIROS IV pictures of the snowpack in the Sierra Mountains of California and the central Rocky Mountain region, bringing closer to home the practical applications of satellite snow cover observations to Hydrology. Both ice and snow observations are discussed in this paper since many of the interpretation problems are quite similar.

Before discussing satellite observations, however, a brief discussion of the observation vehicle itself would appear appropriate so that the reader may more fully appreciate the capabilities and limitations of the satellite system. Figure 1 shows the major components of the TIROS satellite. This is a space-oriented, spin-stabilized satellite* rotating about an imaginary axis through the geometric center of the top and base. The two TV cameras are located on the base plate, the optical axis of each camera parallel to the spin axis. Pictures may be acquired by either of two modes. Using the tape mode, a maximum of 32 pictures per camera, at a nominal 30 second interval, may be obtained and stored on magnetic tape within the vehicle. Either of two ground stations, one located in California and the other in Virginia, may acquire these pictures when the satellite is within a line-of-sight bearing from the station, usually a radial distance of less than 1,000 miles. At the same time, the satellite may be commanded to take and transmit pictures directly to the ground station. Under optimum conditions, 50 to 60 pictures at 10 second intervals may be obtained using this direct mode. Canadian east coast waters and the Great Lakes are within direct read-out range of the Virginia station, which accounts in part for the selection of these areas as huge outdoor "laboratories" to develop satellite ice surveillance techniques.

In addition to the two TV cameras carried aboard all of the TIROS vehicles, TIROS II, III and IV carried IR sensors, as shown in figure 1. These consisted of a medium resolution multi-channel scanning radiometer[3] which viewed in three terrestrial and two solar regions, a hemispheric radiometer[4] and a cone radiometer[5]. Power for these and other subsystems is provided by nickel cadmium batteries charged by solar cells around the side of the vehicle. The magnetic orientation coil shown in figure 1 was introduced after TIROS I; it provides a certain amount of control over the attitude of the vehicle in space.

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* For a more detailed description of the TIROS vehicle, refer to NASA TR R-131, Final Report on the TIROS, I Meteorological Satellite System, Goddard Space Flight Center, Greenbelt, Maryland, 1962.

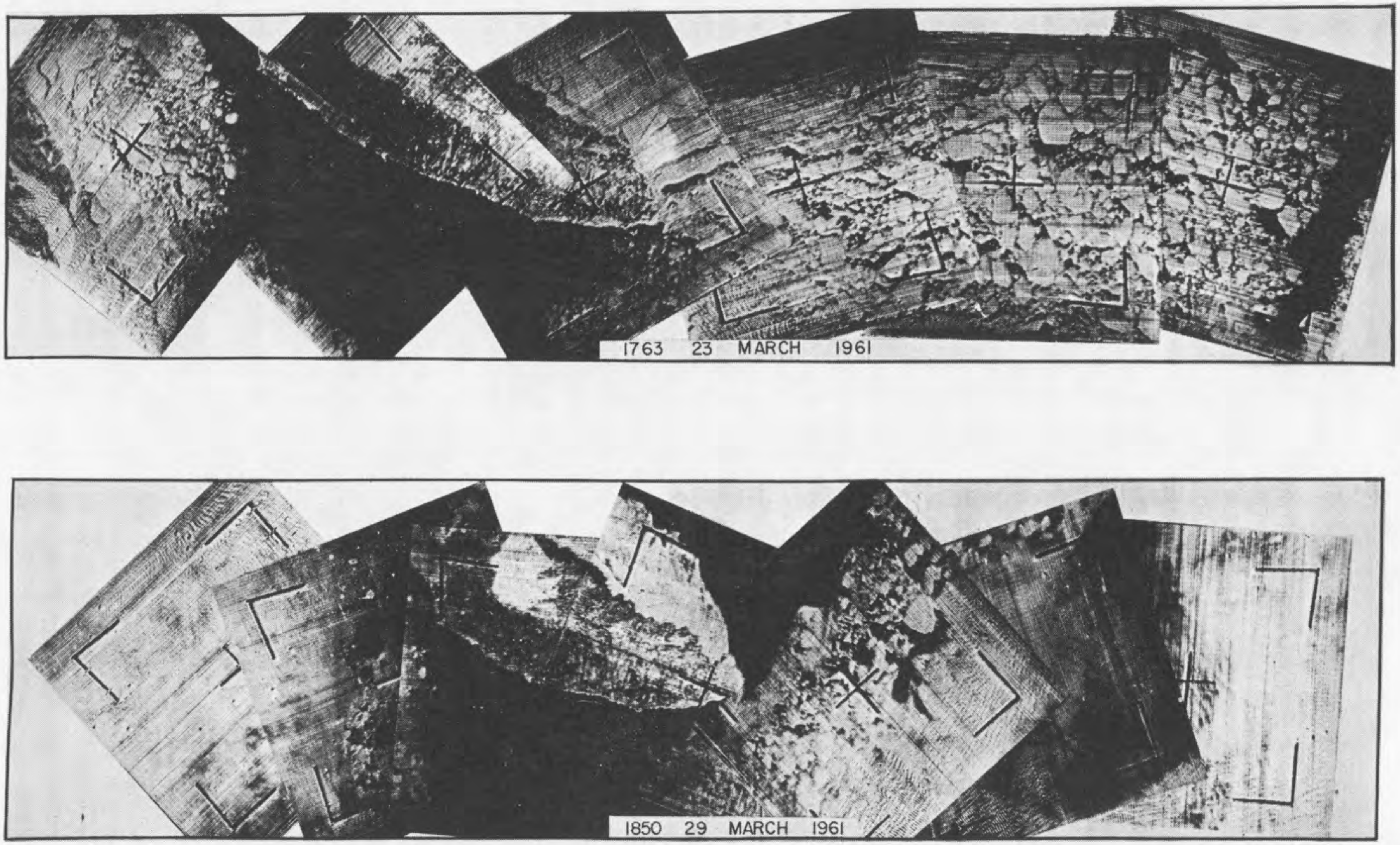


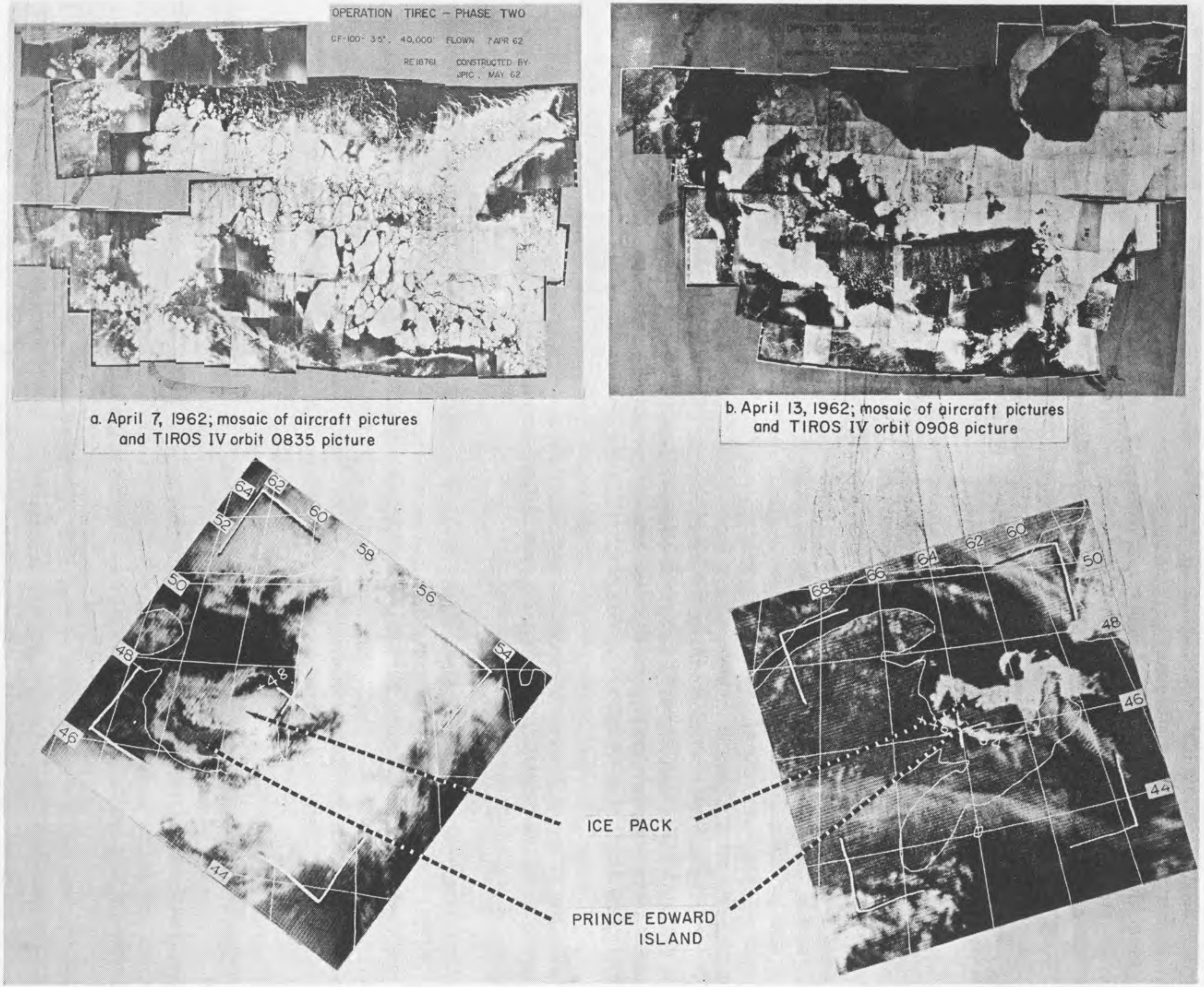
Figure 2. A series of TIROS II photographs taken with the narrow-angle camera, showing changes in ice conditions around Anticosti Island in the Gulf of St. Lawrence.

Ice covers approximately 15,000,000 square miles or about 10% of the earth's surface. For this reason it has major climatological significance, and enters into any consideration of the earth's total heat budget. More apparent perhaps are local changes in precipitation type and amount due to the growth or disappearance of ice in lakes or other large bodies of water. Since ice also constitutes a major hazard to navigation, it has an important bearing on the economy of many countries, especially in the northern hemisphere. Visual aerial ice reconnaissance missions are flown largely in support of ship operations, to provide the ice forecaster or ship routing officer with ice information needed to route ships through such areas as the Gulf of St. Lawrence or Hudson Bay.

One of the first steps in determining if satellites could provide usable ice information was to establish the requirements of the user, and next, to investigate the possibility of using satellite observations to satisfy any of these requirements. In most areas of the world, merely knowing the location of ice boundaries is enough during much of the year to predict the advance or retreat of the ice pack. In the fall, the ice pack advances; as areas begin to freeze, ice thickness and concentration becomes increasingly important. In winter, when most of the area is covered by ice, the location of leads or open water areas within the ice are of major significance. During this period pressure ridges may develop, and the ice may build up to thicknesses of 30 feet or more. For this reason, ice topography is important. With springtime warming the ice begins to break-up; following the break-up pattern is necessary to determine which areas will become free of ice first.

The requirements for ice information are, therefore, seasonal and include observations of ice boundaries, concentration, thickness, topography, and the presence of ice leads and open-water areas.

While all of the TIROS satellites have photographed ice, the pictures obtained from TIROS II and TIROS IV have contributed most to our knowledge of what we can see of ice conditions from satellite altitudes. On TIROS II a narrow-angle camera system was used to obtain some very excellent pictures of ice in the Gulf of St. Lawrence. This camera had an angular field of view of 12.7° and a resolution of 0.25 mile. Figure 2 shows an example[6] of the type of ice detail seen with the narrow angle camera. These pictures were taken from an altitude of approximately 470 miles, and show clouds and ice around Anticosti Island in the Gulf of St. Lawrence. In the upper series of pictures, taken March 23, 1961, large ice floes and fields around the eastern tip of the island can readily be seen. Paralleling the north coast is a flaw lead, or refrozen lead, about two miles across and about 50 miles long. This lead separates fast ice along the shore from the large ice field to the north. Within this field, and about 40 miles off-shore, the brightness (or reflectivity) of the ice changes abruptly along a line running roughly NNW-SSE. This line appears to intersect the apex of each of the broadening V-shaped open-water areas.



a. April 7, 1962; mosaic of aircraft pictures and TIROS IV orbit 0835 picture

b. April 13, 1962; mosaic of aircraft pictures and TIROS IV orbit 0908 picture

Six days later, as the lower mosaic of pictures show, the area north of this line is ice-free. Apparently the change in albedo was an indication of the breaking-up of the ice. This change was very probably due to a difference in ice age, type or concentration. Such a difference would normally be detected by an aerial ice observer, whose report would be used by the forecaster to predict the break-up of the ice. If this and other sea ice information could be obtained by examining a series of satellite photographs, the need for regular long-range aircraft ice reconnaissance flights could be substantially reduced, while the amount of knowledge about ice conditions over any part of the globe could be substantially increased.

While the pictures obtained with the TIROS narrow-angle camera system appear to satisfy many of the users' requirements for detail, the picture-taking swath is only about 90 miles wide and 1000-1500 miles in length. In an area such as the Gulf of St. Lawrence, several satellite passes would be needed to obtain complete coverage. For operational meteorological purposes, a wide-angle camera is much more desirable for observing large-scale weather systems. The wide-angle camera used on TIROS II became non-functional within a relatively short period after launch. As a compromise between these two systems, and to provide a degree of redundancy in the event one system failed, a new camera lens was used on TIROS IV. The effective angular field of view with this lens system is 78°; each picture covers an area of approximately 200,000 miles, or roughly 450 miles on a side. This lens system was used almost exclusively to obtain the satellite pictures being analyzed as part of Project TIREC conducted in February and again in April 1962 to study the ice reconnaissance potential of a weather satellite system.

One of the biggest problems in developing a satellite ice reconnaissance capability has been the lack of comparative data needed to determine the limitations of the system and to develop the necessary interpretation techniques. Project TIREC was conducted to obtain this type of information. High-altitude jet photo aircraft from both countries, operating at or near 41,000 feet, obtained photographs for direct comparison with the satellite pictures. Medium and low-altitude photographs were also obtained as a check on the visual ice reconnaissance observations obtained by U. S. and Canadian ice observers. During days of both good and bad weather radarscope photographs were obtained so the boundaries of the ice could be kept under surveillance when clouds obscured the area. Special surface and upper air observations of meteorological parameters were also obtained for comparison with the satellite pictures and with the information obtained with infrared sensors aboard the satellite.

Much of the data collected during this program still remains to be analyzed. Figure 3, however, indicates two types of observations collected, and will also serve to illustrate some of the analysis techniques being employed. In the upper portion of this figure are two mosaics of high altitude aerial photographs obtained five days apart in April 1962 showing sea ice around Prince Edward Island in the Gulf of St. Lawrence. Below each mosaic, for comparison, is a corresponding TIROS IV photograph.

ORBIT 779, APRIL 3, 1962

ORBIT 793, APRIL 4, 1962

ORBIT 808. APRIL 5. 1962

ORBIT 822, APRIL 6, 1962

ORBIT 835. APRIL 7. 1962

ORBIT 908. APRIL 12, 1962

Figure 4. A series of six TIROS IV photographs indicating how the persistence of sea ice features in areas

Sea ice boundaries are perhaps the most easily-determined ice feature in satellite pictures. Here, both satellite pictures have a two-degree latitude-longitude grid superimposed. The ice pack boundaries determined from these pictures were retraced on a 1:2,000,000 scale chart identical to the type used to plot aerial ice reconnaissance reports. This chart was then over-layed on the chart containing the visually observed boundary and the boundary plotted from the high-altitude aerial photos. All three fell within 4-12 miles of each other.

It might also be mentioned that the ice pack boundary, as determined from the aerial photos, generally fell closer to the boundary determined from the satellite pictures than did the visually reported boundary. The differences in distance between these three boundaries may be attributed partially to electronic and optical distortion characteristics of the satellite camera system, errors in picture gridding, and also partly to the time required to obtain both the aircraft photos and the visual ice observations. The Canadian ice observers taking these observations were highly trained, skilled personnel, and had the benefit of Doppler and Antac navigational aids permitting them to map ice boundaries within an accuracy of $\pm$ 500 feet.

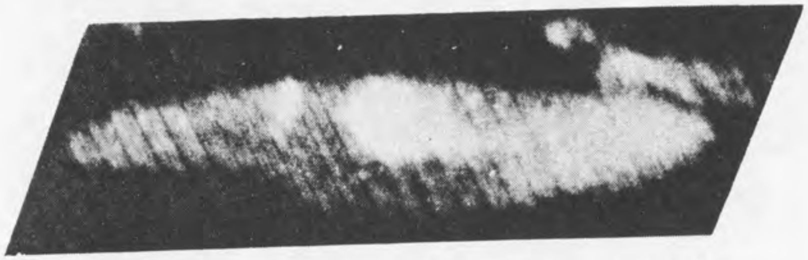
Both objective and subjective techniques are being used to study variations in the reflectivity of the ice. In the former instance an image enhancer is being used to emphasize or differentiate tonal graduations within the ice pack. In the latter case, considerable success has been achieved in matching ice concentration determined from the satellite pictures with that reported by the ice observer. However, it would be premature to state that this could be done routinely until all cases have been throughly investigated.

The presence of clouds also presents a major problem to the satellite ice analyst except in areas of high background contrast. Here, the problem is less serious, since the persistence of ice features allows us to distinguish the ice from the more transient cloud systems. Figure 4 shows six TIROS IV pictures obtained during the April phase of Project TIREC. The position of the ice around Prince Edward Island remains essentially unchanged during the nine-day period encompassed by these photographs, while cloud systems appear and disappear almost from day to day.

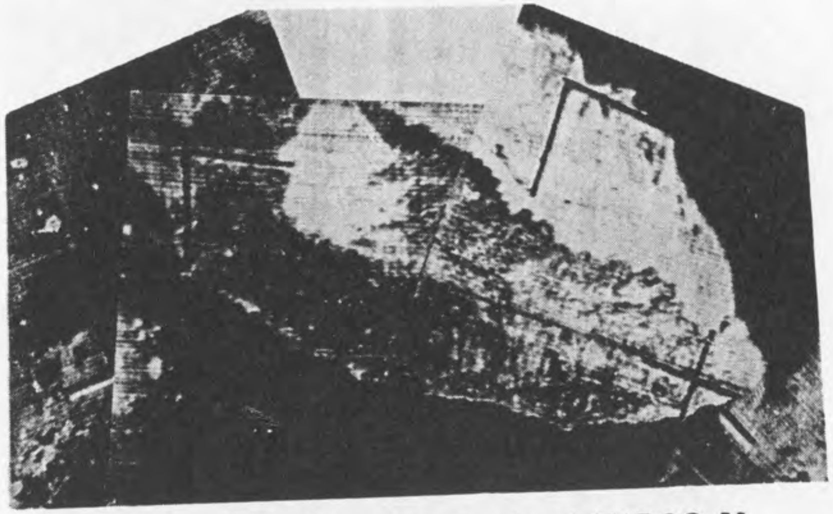
Over the polar regions the problem will be more acute, since background contrast is essentially nil. For this reason, stereoscopic methods of distinguishing clouds from the underlying surface are being investigated, as is the use of satellite-borne radiation sensors.

Summarizing to this point, it now appears that the mapping of sea ice features observed by satellites can be done operationally to the accuracy required for broad-scale, and in some instances, detailed ice reconnaissance. Ice concentration can also be estimated quite accurately, except where young or newly-formed ice is present. Much can be inferred about ice thickness where historical data exists. Ice topography may be the most difficult to determine. All-in-all, however, a satellite system appears quite capable of providing much of the information normally required by the ice forecaster or ship routing captain.

a. Mosaic of aircraft pictures obtained from 41,000 feet on April 13, 1962.



b. Enlargement of TIROS IV wide-angle(78°) photo obtained on Orbit 0793, April 4, 1962.



c. Enlarged portion of a mosaic of TIROS II narrow-angle (12.7°) photos obtained on Orbit 1850, March 29, 1961.

As indicated earlier, the analysis of satellite photographs of snow cover has not been pursued as vigorously as the study of ice. More attention has been focused on this aspect of satellite observations in recent weeks, however, and it presently appears that a major effort will be made this spring, again as a joint Canadian-U.S. program, to correlate surface observations of snow cover with pictures to be obtained from TIROS VII. Final plans have not been made at this time, however, so little more can be said at present.*

The amount of winter snow accumulation and the rate of snow-melt run-off in spring influence river and flood forecasting, hydro-electric power output, water reservoir storage, game management, recreation, and many other areas of major economic significance. Snow survey teams, aircraft surveillance, and instruments strategically placed in basin drainage areas provide much of the input data used to calculate and predict the amount and rate of run-off.

Satellite applications to this field would initially be restricted to observing the aerial extent of the snow cover. That this is, in itself, an important application may be illustrated by pointing to the hydrologic forecasting problem created by a heavy snowfall occurring in 1960 near the headwaters of the Missouri in eastern Montana and the Dakotas. In this instance the heaviest snowfall occurred in the mountains; snow depth observations, recorded mainly at gages at lower elevations, reported a much lighter accumulation. The problem, a typical one, was to forecast the amount of discharge which would occur with a sudden spring warming trend.

It is very conceivable that an experienced interpreter, familiar with snow reporting procedures and hydrologic requirements, and trained to observe and map snow features seen in satellite photographs, could have detected an error in the estimated reports of the amount of snow which had fallen in this region. With the development of better camera systems, and with refinements in interpretation techniques, it may also be possible to qualitatively estimate the rate of snow melt.

To determine how accurately the extent of snow cover might be measured from satellite altitudes, two satellite pictures and a mosaic of aerial photographs were examined (figure 5). These pictures were all of Anticosti Island in the Gulf of St. Lawrence. All showed a large bright area near the center of the island, the result of a 1957 forest fire. The area was gridded, and also planimetered as a double-check on the measurement. In the aerial photo, which served as a control, the bright area covered approximately 300 square miles. In the narrow-angle TIROS II photograph, a value of 290 ($\pm$ 10) square miles was arrived at, while in the medium-angle (78°) TIROS IV photograph a measurement of 300 square miles ($\pm$ 40) was obtained.

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* This study was not conducted. Weather Bureau hydrologists have since determined that the resolution achieved with TIROS wide and medium angle camera systems would not be adequate for the type of detailed study proposed.

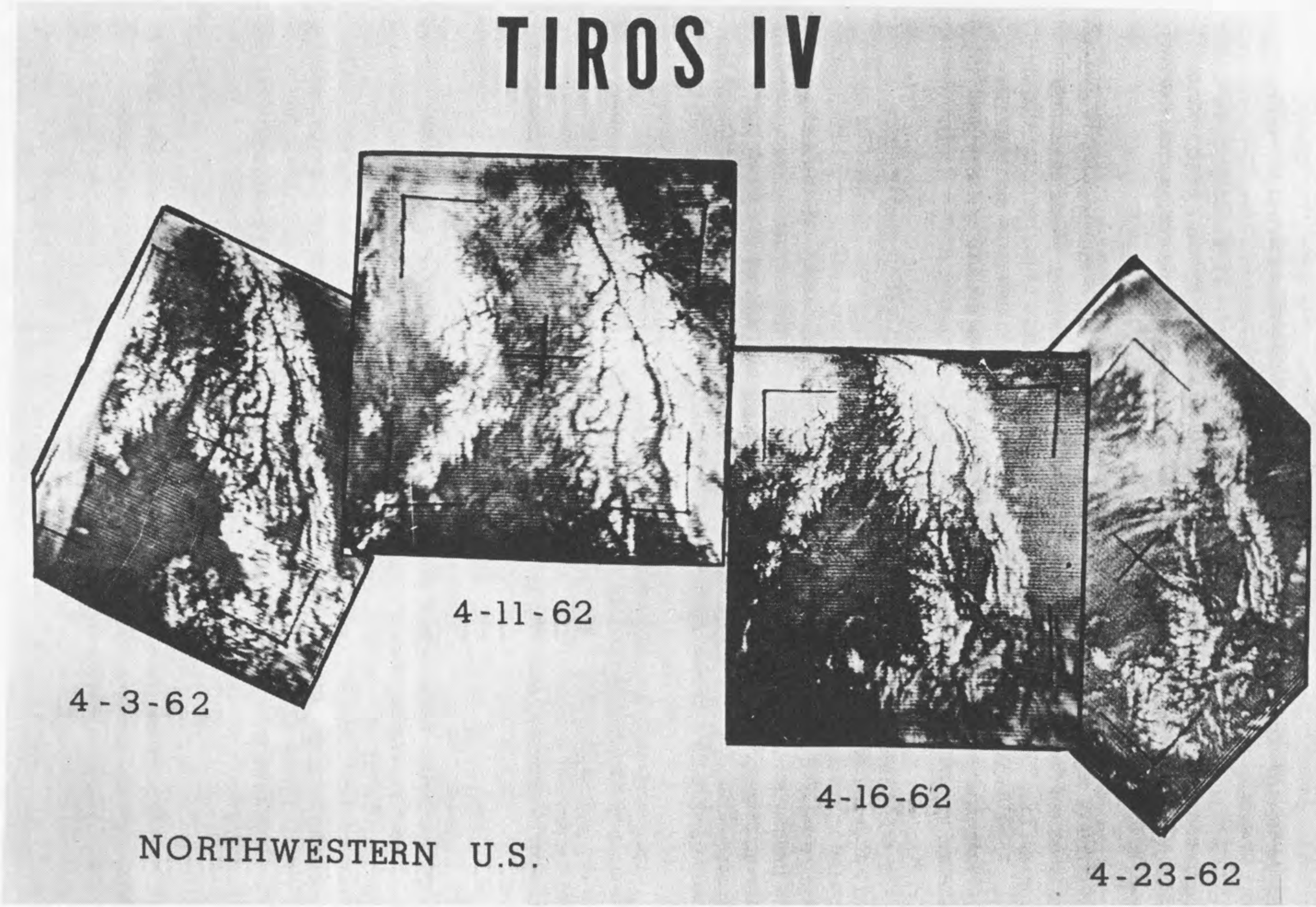


Figure 6. TIROS IV pictures taken in April 1962 showing the dendritic drainage pattern of the Cascade and Rocky

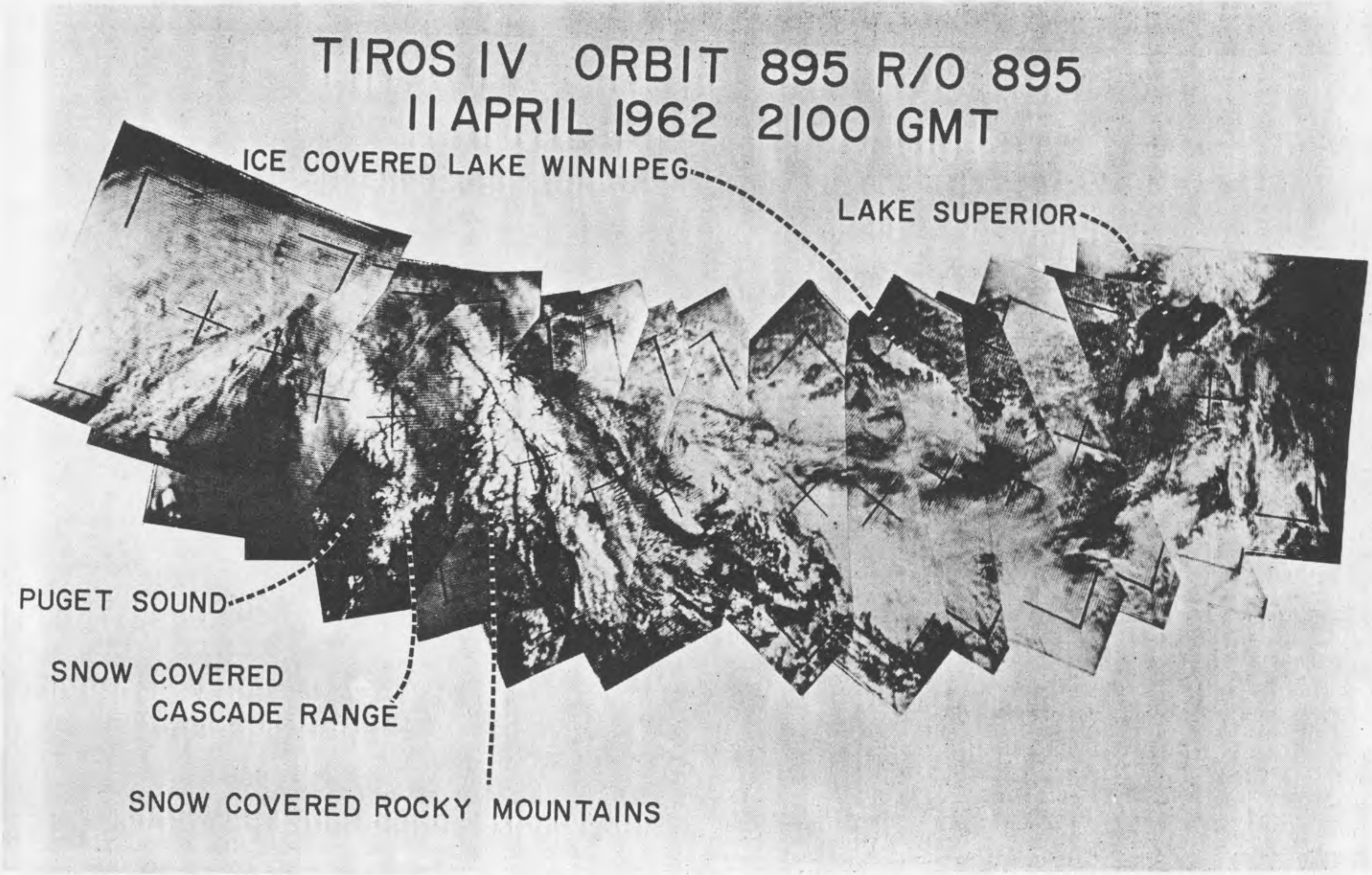
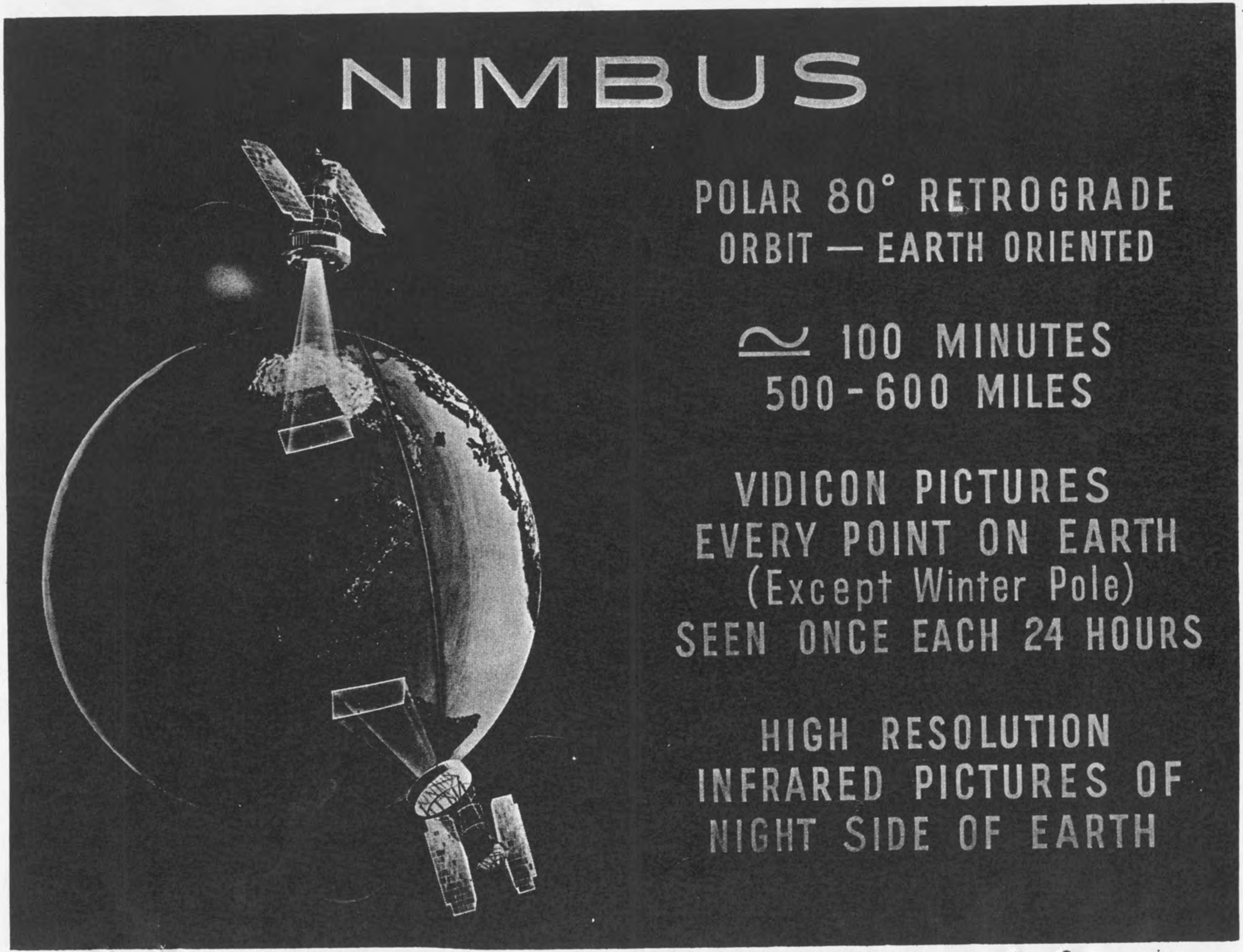


Figure 7. A mosaic of TIROS IV pictures obtained in April 1962, illustrating the broad area coverage and numerous features viewed by the satellite.


NIMBUS
POLAR 80° RETROGRADE
ORBIT — EARTH ORIENTED
≃ 100 MINUTES
500 - 600 MILES
VIDICON PICTURES
EVERY POINT ON EARTH
(Except Winter Pole)
SEEN ONCE EACH 24 HOURS
HIGH RESOLUTION
INFRARED PICTURES OF
NIGHT SIDE OF EARTH

The TIROS IV picture and the aerial photographs were obtained nine days apart; the TIROS II pictures were obtained a year earlier. Since no snow depth reports are available for this region, this raises the question of whether or not variations in snow depth will affect the appearance of snow-cover areas seen in satellite photographs.

The dendritic drainage pattern of the Rockies and Cascade Mountains is especially evident in the series of four TIROS IV pictures obtained in April 1962, and shown in figure 6. This pattern is characteristic of young, and generally higher, mountain ranges observed in satellite pictures. The Himalayas, Alps, Andes and the rugged mountain regions of the Scandanavian countries exhibit this same appearance, largely due to the absence of vegetation at these higher elevations.

On the other hand, the more mature peaks in the eastern U. S. appear significantly different; in the northern Adirondacks, snow cover resembles large cumulus clouds, while the ridge-valley complex of the Appalachians, particularly in eastern Pennsylvania, produces a wave-like appearance when covered with snow. A similar pattern has been noted in southeastern Canada, due to the presence of drumlins.

The identification of these features makes it a relatively simple matter to distinguish clouds from the underlying snow surface in mountainous regions. In the northern and central plains regions of the U. S. and Canada, however, it is a different matter. While stands of coniferous forests generally appear dark, deciduous forests appear grey, the darkness or greyness varying with the density and size of the wooded area. Rolling, grass-covered hills and cultivated land appears white, which together with the forests produces a non-homogeneous or mottled effect. In winter it is difficult to accurately depict cloud cover over the plains regions, and equally difficult to map the snow cover except in early winter or late spring.

A good illustration of the broad area coverage and the several types of observations afforded by a satellite system is shown in figure 7. Cloud cover over the Pacific Ocean, snow on the western mountains, snow and clouds over the northern plains regions, and ice in western Lake Superior, are all contained in this one mosaic of TIROS IV pictures obtained on pass 0895 on April 11, 1962. Unfortunately it is not possible to repeat this performance on a daily basis with the space-oriented TIROS vehicle. While TIROS will continue its role as a Research and Development vehicle, the more "sophisticated" Nimbus spacecraft will be used for operational meteorological purposes.

Some of the features of Nimbus are shown in figure 8. The orbital period of 100 minutes is comparable to TIROS; the altitude, however, is 50-150 miles higher. The medium resolution radiometer on TIROS will be replaced with a high resolution IR sensor on Nimbus to provide nighttime cloud cover imagery. Nimbus will also have a camera lens with a variable iris, and 12 calibrated grey scales. A three-camera "fan" will be used, with the axis of the middle camera normal to the earth's surface and the axes of the other two approximaterly 37° from the vertical. Resolution near the center of the vertically-mounted camera will be about .5 miles as compared with 1.2-2 miles with most TIROS camera systems. Later Nimbus vehicles may also have an electrostatic tape camera with a resolution of .1 mile.

Conclusion. The progress which has been made in satellite ice studies indicate that a limited operational satellite ice reconnaissance program could be realized by the time the first Nimbus satellite is launched, while a full-scale capability would probably be realized within a year after launch. If the progress made in this area can be duplicated in the field of Snow Hydrology, it would have major economic implications in many areas, including water conservation and civil engineering. The important thing is to consider satellites simply as new tools, to be evaluated in the same manner as any new piece of equipment, with a mind open to the possibility that entirely new approaches to solving old problems may develop as a result of this evaluation.

Acknowledgements

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DISCUSSION OF

PROGRESS REPORT ON SNOW AND ICE OBSERVATIONS FROM TIROS SATELLITES

By

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It used to be said of scientists, perhaps particularly of scientists attending conferences, that they should be brought down to earth every once in a while. In this day and age - one of rapid technological development - the opposite appears closer to the truth. We must now be reminded to "think big" in order to take advantage of the know-how and hardware that we already have, or are about to receive. We are indebted to authors Popham and Fritz for a very interesting "think big" paper.

There has been a tremendous interest in the TIROS series on the Canadian side of the border witness the co-operation in the TIREC project in the Gulf of St. Lawrence described by Mr. Popham. The first Canadian assessment of this project is a multi-authored paper "Preliminary Report on TIROS Ice Reconnaissance, Eastern Canada" which is in the process of being published by Canada's Defence Research Board. I understand from one of the authors of this report that in summation it states that in the hands of experts ice may be distinguished from cloud, and therefore an assessment of ice conditions of operational significance may be made.

As the program indicates I am pinch-hitting for two associates in the Meteorological Service of Canada - Mr. W. E. Markham, Head of the Ice Forecasting Central at Halifax and Mr. J. P. Bruce, Head of the Hydrometeorological Section to which I belong. Mr. Markham has been closely associated with the TIROS and TIREC projects particularly in the field of ice in the Gulf of St. Lawrence. He informs me that he is "enthusiastic and optimistic of the future". He does however sound two notes of warning - the resolution of the cameras should be improved, and the data should be immediately available to be of operational use. Mr. Popham today has already indicated that the TIROS camera resolution of two miles will be improved to ½ mile in the Nimbus series.

Mr. Bruce is most interested in the authors' use of TIROS photos in the assessment of snow cover in large river basins. Canada has a number of large relatively uninhabited watersheds particularly in the Rocky Mountain area. These are at least partially snow-covered for most of the year and they are of great economic importance for power development. In this case a forecast of snowmelt runoff, day by day, or week by week, allows for the efficient and safe operation of power dams and is most necessary for the provision of timely flood warnings.

Snowmelt runoff is predicted by the use of a degree day index and/or by snowmelt equations based on basin energy balance. In both methods the largest unknown in uninhabited areas is the percentage of watershed covered by snow. Present estimates of this snow cover in the Rockies are suspect of a large error. If Nimbus could improve on the snow cover estimate - as the authors feel it can - this would most certainly assure a marked improvement in the forecast of snowmelt runoff in these major watershed areas. In this connection hydrologists of British Columbia have already indicated interest in assessing the usefulness of photographs from TIROS 7 in the evaluation of snow cover in the Fraser and Columbia River watersheds this spring.

Personally as a hydrometeorologist interested in the lakes of Canada I have an obvious interest in the observation of ice in the Great Lakes since ice cover affects navigation, power development and the weather over the surrounding land areas. Another interesting and potential use of satellite ice reconnaissance may be in the observation, and eventual forecasting, of freeze-up and break-up of larger northern lakes. Recent investigations point to a marked change in the albedo of ice a few weeks prior to break-up. Measurement of albedo correlated with the observed time of break-up may well aid in developing methods for prediction of break-up even in relatively inaccessible lakes.

In conclusion two questions come to mind. (1) Will it be possible to rectify satellite photographs quickly enough to be of operational use in ice forecasting and snowmelt runoff forecasting? (2) Thinking in terms of the forecasting of ice break-up, to what degree can changes in albedo of snow and ice be determined?