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U. S DEPARTMENT OF COMMERCE
WEATHER BUREAU

METEOROLOGICAL SATELLITE LABORATORY
REPORT NO. 8

Ice Photography from the Meteorological Satellites TIROS I and TIROS II

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WASHINGTON, D. C.
MARCH 1962

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U. S. DEPARTMENT OF COMMERCE

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U.S. WEATHER BUREAU

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METEOROLOGICAL SATELLITE LABORATORY

REPORT NO. 8

ICE PHOTOGRAPHY FROM THE METEOROLOGICAL SATELLITES TIROS I AND TIROS II

by D. Q. Wark and R. W. Popham

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National Oceanic and Atmospheric Administration
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ICE PHOTOGRAPHY FROM THE METEOROLOGICAL SATELLITES TIROS I AND TIROS II

I. INTRODUCTION

The Meteorological Satellite Laboratory of the U. S. Weather Bureau and the U. S. Navy Hydrographic Office, with support from the National Aeronautics and Space Administration and the Commander Barrier Forces Atlantic, have cooperated on a program to determine to what extent TIROS meteorological satellite photographs can be used for ice surveillance and to lay a foundation for further TIROS and NIMBUS satellite ice surveillance studies. This report summarizes the observational program, presents the results graphically, and discusses analytically a limited portion of the material.

With the exception of two sets of satellite photographs showing portions of the Great Lakes, all observations used in this investigation were in the vicinity of the Gulf of St. Lawrence. In addition to the satellite photographs, ice observations were obtained from aircraft: U. S. Navy ice reconnaisance flights were conducted coincident with the passages of TIROS II, so that the observations could be used for comparison with and evaluation of the satellite photographs; some of the routine observations taken by the ice patrol of the Canadian Meteorological Service were included when they coincided geographically with, and were obtained within a few days of the TIROS II photographs. Aircraft observations were visual, with the exception of an aerial photographic mapping survey conducted over a small area on March 24, 1961. Satellite and aircraft observations were obtained in April 1960 (TIROS I) and in January and March 1961 (TIROS II).

Section VII contains the graphic material compiled for this study. The satellite photographs have been pieced together as mosaic strips, and the visual observations are presented in map form; a mosaic from the March 24, 1961 aircraft photographs is not included in section VII, but is shown in figure 5 of section VI. Appendix I contains definitions of some terms used in this report.

Section VI is a discussion of several interesting and enlightening features to be observed in the satellite photographs. The five illustrations are taken from the material in section VII. Large-scale ice features are apparent; details of the ice, such as concentration, presence of leads and openings, and sometimes the type of ice present, can be distinguished in the photographs taken by the TIROS II narrow-angle (12.7° in the diagonal) camera. Floe ice, abundant in March 1961, is particularly striking. Comparisons are made of satellite photographs of a given area at intervals of months, days, or, in one instance, one hundred minutes.

II. BACKGROUND

The first few pictures taken by TIROS I on April 1, 1960 showed areas in the Gulf of St. Lawrence and the St. Lawrence River which appeared to be partly ice covered. This evaluation was later confirmed (Wark and Popham,

About a month after launch the satellite was programmed to take pictures in the South Atlantic, where the Antarctic ice pack might be expected to extend to about 53°S. latitude (see USNHO No. 705 [6]). The absence of land features, the lack of repeated observations, separate pictures without overlap, and the presence of extensive cloudiness prevented a definite identification of the Antarctic ice pack boundary. The Gulf of St. Lawrence, on the other hand, was far more suitable for a study of ice: picture quality was better; geographical features such as islands, bays, rivers and lakes were easily identifiable in the satellite pictures; and overlapping pictures provided the vital space continuity needed. An interesting aspect of photography at the "top" of the orbit is that the probability of viewing the same area on successive orbits is enhanced; this feature is used to advantage in figure 5.

When the satellite ice photography program was formulated, it was apparent that simultaneous visual or photographic aircraft and satellite observations were indispensable. The Weather Bureau therefore sought the cooperation of the U. S. Navy Hydrographic Office as one of the agencies most concerned with sea ice. A coordinated program for observation of ice from aircraft and from TIROS II was established: responsibility for arranging the satellite photography and for advice to the participating aircraft lay with the Meteorological Satellite Laboratory; the Hydrographic Office arranged for the aircraft flights and provided observers. Reconnaissance was made by U. S. Navy Patrol Squadrons 11 and 23, based at the U. S. Naval Air Station, Argentia, Newfoundland. Lieutenant W. A. Dotson and Ensign K. S. Colaw of the Ice Observation Section of the Hydrographic Office flew as ice observers; R. W. Popham of the Meteorological Satellite Laboratory flew on several missions and acted as the MSL representative at Argentia. In addition to the data gathered in this effort, routine observations conducted in the area by the Canadian Meteorological Service were available for use in the analysis of the satellite photographs.

III. COORDINATION OF TIROS AND AIRCRAFT OBSERVATIONS

To direct aircraft to the area to be viewed by the satellite, it was necessary to predict the path of the satellite picture principal point. The useful area in the strip mosaics constructed from the satellite photographs was only about 70 miles wide, or 35 miles on each side of the principal point track. Therefore, the most accurate prediction possible from the data was required. During the January operations a graphical method for predicting the principal point track, described below, was employed. In March an equivalent procedure was used on an electronic computer.

When the position of the satellite is known relative to the earth, and the orientation of the satellite is adequately known in a specified coordinate system, the position of the principal point can be calculated. From tracking station data the orbit can be determined with sufficient accuracy to allow a statement of the predicted position of the satellite within a very few miles. However, the orientation of the camera axis cannot be pre-

dicted with equivalent accuracy; it is determined mainly by photogrammetric methods (see Hubert [4]), but because of observational errors and precession terms, including some which are not accurately known, a long range prediction is subject to rather large errors. The Goddard Space Flight Center produces a "World Attitude Map" which contains a fortnight prediction of TIROS orbital and picture area information. Latitude and longitude coordinates for minute-by-minute sub-satellite points, solar and camera axis nadir angles, and the wide-angle camera viewing areas are given. These data are sufficiently accurate for computations involving routine planning of weather observations by the wide-angle camera, but are inadequate to meet the requirements for ice observation. Because only the narrow-angle camera was used in the present study, small errors of the predicted principal point track could lead to directing the observation aircraft to areas outside of that viewed by the satellite. Therefore, the predictions used were made on the basis of data gathered the day prior to planned operations. The track positions were computed by Meteorological Satellite Laboratory personnel in Suitland, Md. and transmitted to Argentia for immediate use.

The graphical method of principal point track determination used during the January operations is demonstrated in figure 1. The sub-satellite point (SSP) track passing through the area of interest was plotted on a 51° Transverse Mercator chart so that it lay parallel to the center line, the great circle of tangency; this chart had been prepared in anticipation of the slightly greater orbital inclination, but the error introduced by its use is very small. The spin axis point (SAP) on the earth, calculated from the most recent data was plotted on the chart; it was considered to be stationary during the short time of the satellite passage. Great circle arcs (in this case it was sufficient to draw straight lines) from the spin axis point to points on the sub-satellite point track were equal to the nadir angle of the camera optic axis. From the nadir angle thus determined and the known height of the satellite the arc between the sub-satellite point and the principal point (PP) was calculated and laid off on the extension of the SAP-SSP line (the spin vector defining the spin axis point lies in the opposite direction from the camera view). The line connecting the resulting principal points gave the geographical coordinates of the anticipated picture centers. Every effort was made to conduct the satellite photography at times of minimum nadir angle.

The graphical method was satisfactory in January, but in March the maximum accuracy in predicted principal points was required in order to deploy the aircraft photographic missions properly. The Swath Code, formulated by M. H. Frankel of the Meteorological Satellite Laboratory for earlier TIROS I and TIROS II picture programming was used. From the predicted orbital and spin axis data, the digital computer calculated the anticipated principal points without resorting to the approximations of the graphical method.

IV. AIRCRAFT OPERATIONS - JANUARY

Satellite orbital information and picture-taking times were relayed to Weather Bureau and Hydrographic Office personnel in Argentia for aircraft flight track planning. Aircraft operations were coordinated through the COMBARLANT Staff Meteorologists, Cdrs. Albrecht and Woolums. Seven flights

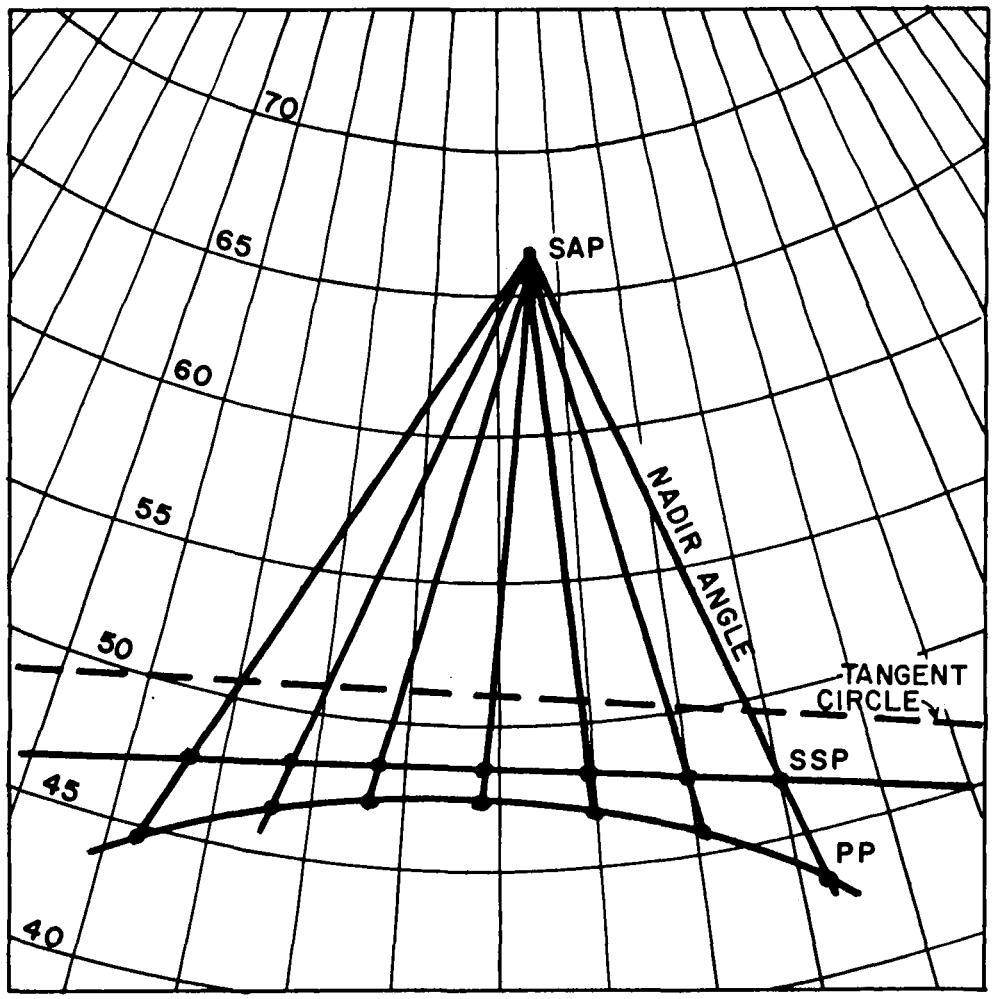


Figure 1. Graphical determination of the principal point on a transverse mercator chart.

were conducted, four of which were coincident with the satellite's orbit. The other three flights were for auxiliary information.

The first flight was on January 19. Ice conditions in the area north of Newfoundland were observed, and the ice pack boundary identified and mapped. The second flight was on January 20, but no satellite pictures were obtained on this day. Flight operations were also planned for the 21st and 22nd, but bad weather over the proposed reconnaissance area forced postponement of these flights.

On Monday, January 23, a U. S. Coast Guard iceberg patrol flight was conducted over the waters north and east of Newfoundland. On the same day, a U. S. Navy P2V patrol flight was made east of Newfoundland with a Weather Bureau observer aboard.

The most valuable observations during this period were made on the following day, Tuesday, January 24. A P2V, with an ice observer and a Weather Bureau observer aboard, traversed an area about 140 miles in length, parallel to and almost along the principal point track (picture center track of the satellite photographs). The aircraft was about 5 miles from Natashquan Point, and approaching it from the east, when the satellite passed overhead taking pictures. The aircraft continued along the pre-arranged flight tracks and surveyed the ice over most of the Gulf of St. Lawrence. Another aircraft from VW-11 had also traversed a portion of the picture-path of the satellite about an hour prior to the satellite's passage; only visual observations of the ice pack boundary were made.

The final flight during the January operations was made on January 25. Weather conditions along the predicted satellite path were not favorable for ice reconnaissance observations; however, observations of the type and thickness of the clouds present were made. As on the previous day, part of the aircraft's flight track was parallel and very close to the observed picture-center track of the satellite photographs. Further operations were suspended after this flight because of adverse weather conditions.

Although the Canadian Meteorological Service routinely conducts ice reconnaissance in the Gulf of St. Lawrence, the relatively short period of time between the formulation and execution of the short-period TIROS-aircraft ice observation program precluded establishment of a joint observation program. The U. S. Navy aircraft flights required for the program were made possible by the excellent cooperation of the Hydrographic Office, COMBARLANT Staff, and the participating squadrons. Aircraft were provided on an "as available, not to interfere" basis; observations were tied in with routine ice reconnaissance flights in the Atlantic and with aircraft flight crew training programs which are normally conducted.

V. AIRCRAFT OPERATIONS - MARCH

Shortly after the January operations, TIROS II picture quality had deteriorated considerably, and plans for further coordinated satellite-aircraft operations were suspended. Early in March, however, quality improved substantially, and a second ice observation program was scheduled.

An analysis of the January satellite pictures indicated that aerial photography obtained coincident with the satellite photography might substantially aid this study. The satellite pictures in January indicated that cracks and leads of sufficient size could be readily identified and positioned, and a more critical determination of the limits of the system could be made using aerial photographs for comparison. The aerial photography could also serve to determine the minimum size of other ice features, such as floes, which the satellite might detect.

To obtain aerial pictures, a standard K-17 aerial camera was mounted in a P2V aircraft from Patrol Squadron 23 based at NAS Argentia, Newfoundland. A point within the predicted picture-taking swath of the satellite cameras was chosen and its coordinates were relayed to the VP-23 Operations Officer. The aircraft was requested to take pictures covering a 600 square mile rectangular

[8]) by satellite photographs of the area taken on three consecutive days, and with Canadian ice reconnaissance data a week earlier and a week later. It was concluded in that study that the possibility of ice surveillance from satellites was promising, and that the major limitation would be the presence of clouds over the ice. The southward precession of the viewing axis of the camera precluded obtaining further pictures in that area until late in May, when the ice was gone.

A new program was planned for a systematic study of the ice in the vicinity of the Gulf of St. Lawrence with the next TIROS satellite. This region was selected because it represents the most extensive area of sea ice in the Northern Hemisphere within the latitudes which can be observed by TIROS. The inclination of the satellite orbit (48°) places an absolute limitation on the latitudes observable; camera orientation, and the undesirability of oblique views, placed a practical limitation of about 50° or 51° on the northernmost observable latitude. Another consideration in the selection of a study site was the location of the readout station: overlapping narrow-angle photographs were possible only when the satellite was in direct contact with readout station; remote pictures, recorded on tape, were taken at a mandatory non-overlapping interval of 30 seconds, whereas direct pictures taken at an alternate interval of 10 seconds available during readout met the requirement for overlap (see Astronautics [1] for a discussion of the TIROS system). The Gulf of St. Lawrence lay within the radius of direct communication with the readout station at Fort Monmouth, N.J., and was therefore the only sea ice area meeting the requirements set forth above. On these bases, a program of satellite photography and aircraft reconnaissance was planned in the selected area for the winter of 1960-1961.

TIROS II was launched from Cape Canaveral on November 23, 1960 into a nearly circular orbit inclined 48° to the equator, with a mean altitude of 690 kilometers. The launch vehicle was a Thor-Delta rocket. Equipment aboard the satellite included a wide-angle camera (105°), a narrow-angle camera (12.7°), and two radiometer experiments (see Bandeen et al. [2]). A defect in the wide-angle camera, as yet unexplained, made its use undesirable, so that the narrow-angle camera was used exclusively in this study. The latter camera views an area approximately 100 miles across the diagonal when pointed straight down.

TIROS satellites are spin stabilized in space, with the optic axes of the cameras parallel to the spin axis. The combined effect of the precession of the orbit and the precession of the spin axis (due mainly to the magnetic coupling between the magnetic moment of the satellite and the earth's magnetic field - see Bandeen and Manger [3]) act to move the area viewed by the satellite from the Northern Hemisphere into the Southern Hemisphere and back again (see Hubert [4]). For a TIROS satellite inclined 48° to the equator, this cycle is completed in about two months. Thus, pictures of the Gulf of St. Lawrence were obtainable shortly after launch in November, again near the end of January, and a third time in late March.

area, 10 miles east and west and 15 miles north and south of the designed point. The area to be photographed was chosen so that a land mass would border on one side of the rectangle to provide a location reference. When two satellite picture-taking passes over the area were programmed, the point of intersection of the principal-point (PP) tracks was chosen.

The aircraft photographic missions extended from March 24 through March 29. Aerial photographic reconnaissance coincident with two satellite passes was carried out only on the first day of the operations. A mosaic of these aircraft pictures is shown in figure 5, which also shows pictures taken from the satellite.

During the following four days two additional flights were made, but thick clouds prevented aerial photography. The satellite pictures, however, indicated that photographs could have been obtained if the aircraft had been diverted. To satisfy air traffic regulations, four operating areas were selected on the last day of the project. Arrangements were made with the readout station to relay information on weather conditions in these four areas to Suitland, based on the satellite pictures taken as the aircraft approached the primary area. With only 100 minutes between satellite passes, 30 minutes of which were required for photographic processing and study of the photographs at the readout station, the schedule was extremely tight. Because the hastily set up communication system was slow, and because the weather in the operating areas was poor, the operation was only partly successful. Although no aerial photographs were taken, the aircraft was eventually contacted in flight and told to look for specific ice and weather features along its proposed flight track. In the pilot's post-flight report, it was indicated that these specific features were observed and were consistent with the satellite observations. Midway between Cape Whittle and Natashquan Point, his primary area and his turnaround point, the pilot reported significantly better weather to the southwest, and the existence and orientation of the broad ice field seen to the east of Anticosti Island in figure H(2).

VI. DISCUSSION OF SPECIALLY SELECTED AREAS

A few examples have been selected from the photographs in section VII to illustrate certain features, and to show changes in the character, concentration, and distribution of ice. The Canadian Meteorological Service ice reconnaissance chart in figure 2 and the mosaic of U. S. Navy aircraft photographs in figure 5 are not included in section VII.

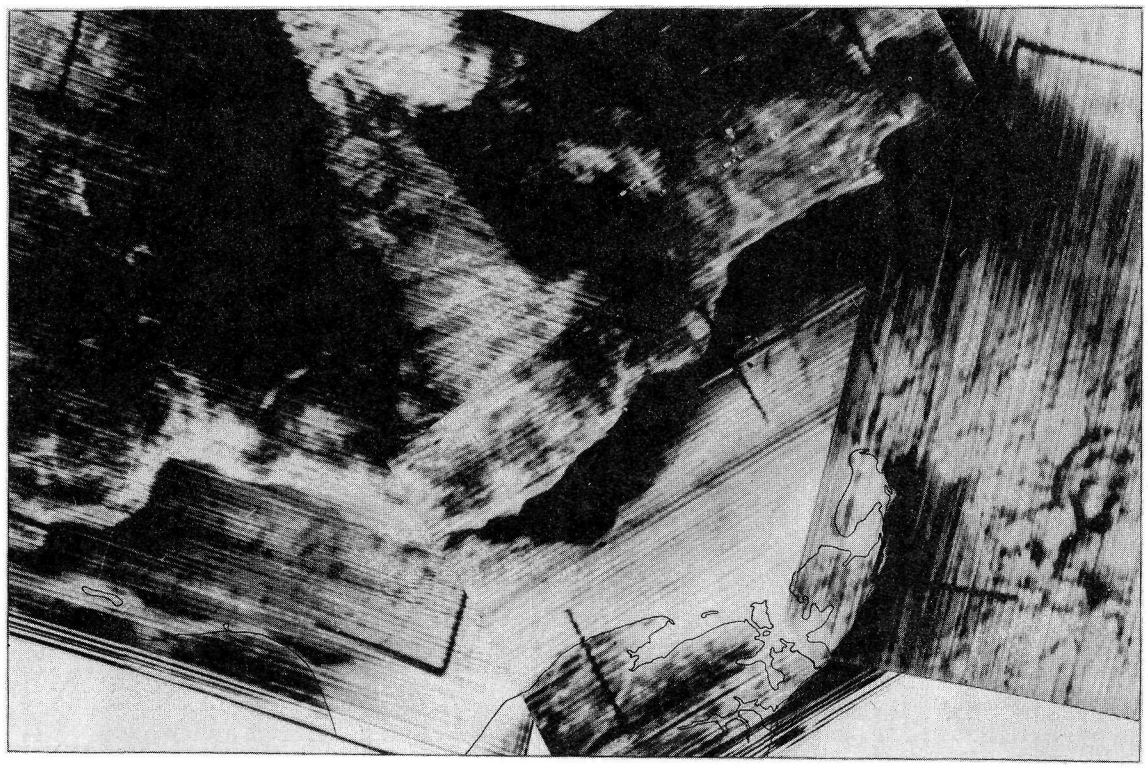
Figure 2

Satellite pictures taken during pass 941 on January 26, 1961 present a fine example of the relation between ice concentration and the prevailing wind. In the upper part of figure 2 is a mosaic of photographs from pass 941 showing Chaleur Bay, which is on the south side of the Gaspé Peninsula. The southern shore line and several islands have been outlined for clarity; the northern shore line is outlined by fast ice west of New Carlisle, and by a narrow strip of fast ice or by snow-covered ground to the northeast. The map in the lower part of this figure is from a Canadian Meteorological Service ice reconnaissance chart of January 23, three days prior to the satellite pictures.

The most notable feature of these TIROS II pictures is the low reflectivity of water areas lying to the east and south of land areas (and, conversely, the high reflectivity of those to the west and north). This is seen in three portions of the mosaic: at the lower left; in a line from just below the center toward the upper right; and at the lower right. Although there is considerable agreement between the Canadian ice reports and the satellite pictures, particularly in regard to the fast ice along the southern shore at the far left and to the right, the variable concentration seen in the January 26 satellite photographs differs from the more uniform distribution of ice observed by aircraft on January 23. During the intervening three days the winds over this region were predominantly from the west to northwest, as indicated by the wind rose for that period in the lower part of the figure. The wind rose was derived from 6-hourly surface weather observations at Chatham (N.B.), Campbellton (N.B.), Mont Joli (P.Q.) and Seven Islands (P.Q.). It is apparent that the wind has carried the ice away from the leeward shores leaving areas of water which is either clear of ice or contains only newly formed ice with low reflectivity. This becomes even more obvious by comparing the ice in Chaleur Bay with that in the Gulf at the far right; with no impeding shore in the latter area to block the motion of the wind-driven ice, the concentration is less. In figure B(2), the entire mosaic from this pass, this feature is also seen in the St. Lawrence River, around the Magdalen Islands, and near the northern tip of Cape Breton Island.

Figure 3

TIROS II photographs of the same area taken on one day in January and on five days in March 1961, are compared in this figure to illustrate long and short period changes which take place in the ice near the mouth of the St. Lawrence River. Pointe des Monts appears in the upper right in the pictures for passes 1749, 1778, 1807, and 1821, the Manicouagan Peninsula lies near the center of each, and the limit on the left is about at Forestville (48.8° N., 69°W.).



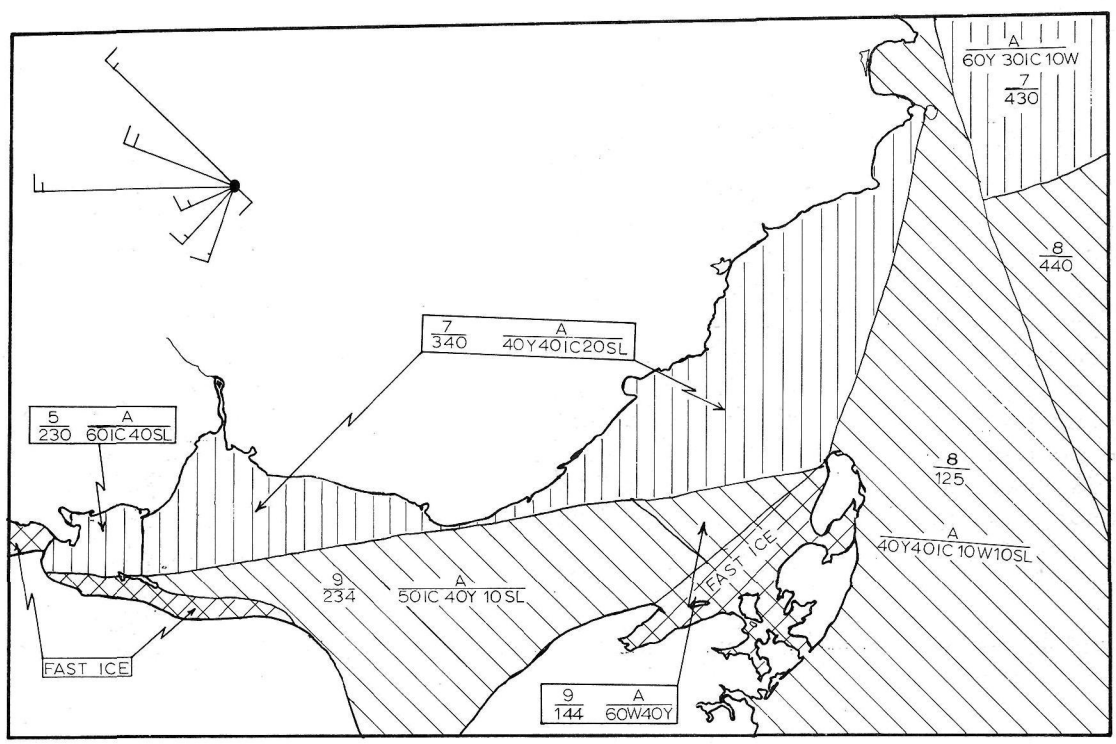


Figure 2. Chaleur Bay; TIROS II photographs on January 26, 1961 and Canadian ice reconnaissance on January 23, 1961.

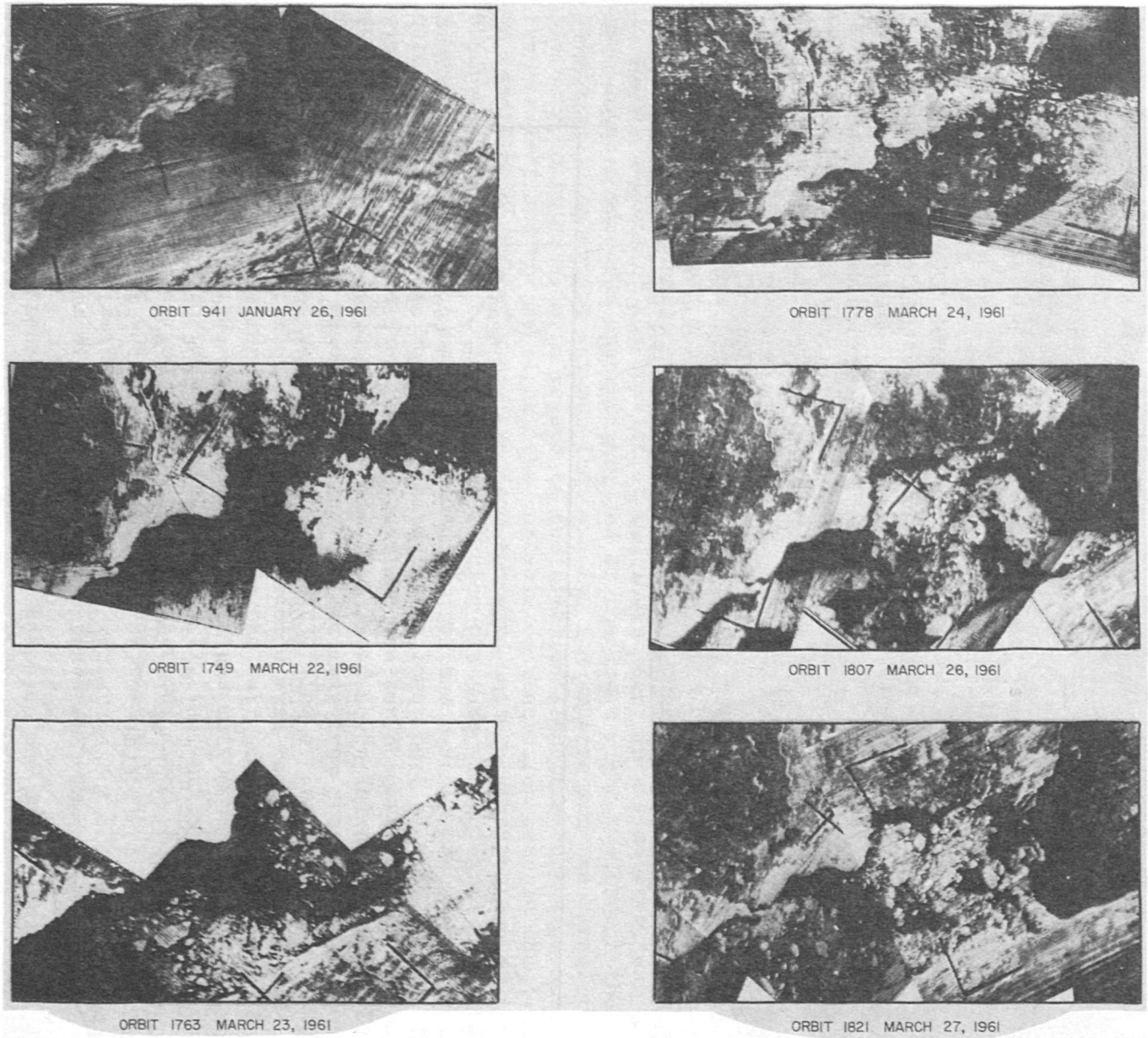


Figure 3. St. Lawrence River near Manicouagan Peninsula; TIROS II photographs on January 26, 1961 and on March 22, 23, 24, 26 and 27, 1961.

Pictures from pass 941 on January 26 show fast ice along the north shore, and particularly around Manicouagan Peninsula. Just south of the fast ice the river appears quite dark, as though it might be free of ice or contain only thin young ice; the southern two-thirds of the river area is bright, though not so bright as the clouds and the snow-covered ground on the Gaspé Peninsula at the bottom of the picture; there is a protrusion of the darker area below the Manicouagan Peninsula. As seen in figure 2 showing Chaleur Bay, and in figure A(2) showing the entire mosaic from this pass, the wind has probably been the main influence in carrying the thicker ice to the south and east. This protrusion of the darker area indicates that tides or currents deflected by the peninsula may also have an important role in determining the ice concentration in this area.

The other five illustrations show the area on March 22, 23, 24, 26, and 27. Fast ice is seen along the north shore from Forestville to the Manicouagan Peninsula, as in January, and the shore is largely free of ice from there to Pointe des Monts. The ice fields are of particular interest in this sequence. On March 22 the north shore is almost entirely free of floating ice, though there are extensive fields to the south. On March 23 some floes have been carried to the west, and by March 24 widely dispersed floes are found over the entire river, with a dense field of floes along the north shore between the Peninsula and Pointe des Monts. By March 26 and March 27 this field has moved to the southwest, leaving open water once more along most of the north shore, and has mixed with another ice field which can be seen at the far right on March 24. There appears to be an upstream motion during the period of these pictures, which might be due to tidal shifts rather than a secular movement. More could have been learned about the ice motions if the area had been photographed on successive passes.

In many cases, individual floes can be identified on more than one day; the giant floe seen at the bottom center near the north coast of the Gaspé Peninsula on March 26 and 27 is probably the same one seen a bit to the right on March 24. Not all of the floating ice is floe ice. In some areas the ice appears to be in belts and patches; this is more difficult to discern in the River, where very sizable floes predominate. At the far right of the March 27 mosaic is an ice field of a different character, much darker than the floes and with the wandering fingers and shapeless areas characteristic of belts and patches.

Comparison of the January and March photographs illustrates to a degree the use which can be made of satellite photographs not only to determine the amount but also the type of ice seen. Shading and shape are not the only criteria. From considerations of continuity, time of year, and weather, one can place different interpretations on a dark water area; in the January case the dark areas probably have young ice in considerable amounts, whereas in the March cases they are probably ice free.

Figure 4

The upper figure, part of the mosaic from pass 1763 of March 23, 1961, shows ice-filled Gaspé Bay, the ice pack between the tip of the Gaspé Peninsula and Anticosti Island, the apparently open water area south of Anticosti

Island, and the heavy concentration of ice between the island and the Newfoundland coast which is seen just on the edge of the picture on the far right. This is an excellent demonstration of the capabilities of existing television cameras; with new cameras now being developed, future satellites will be able to conduct high quality ice surveillance on a large scale. It would require an ordinary ice reconnaissance aircraft approximately 3 hours to cover the area shown in the upper portion of this figure; this coverage was obtained in a 60 second interval and could have been available for use within 30 minutes.

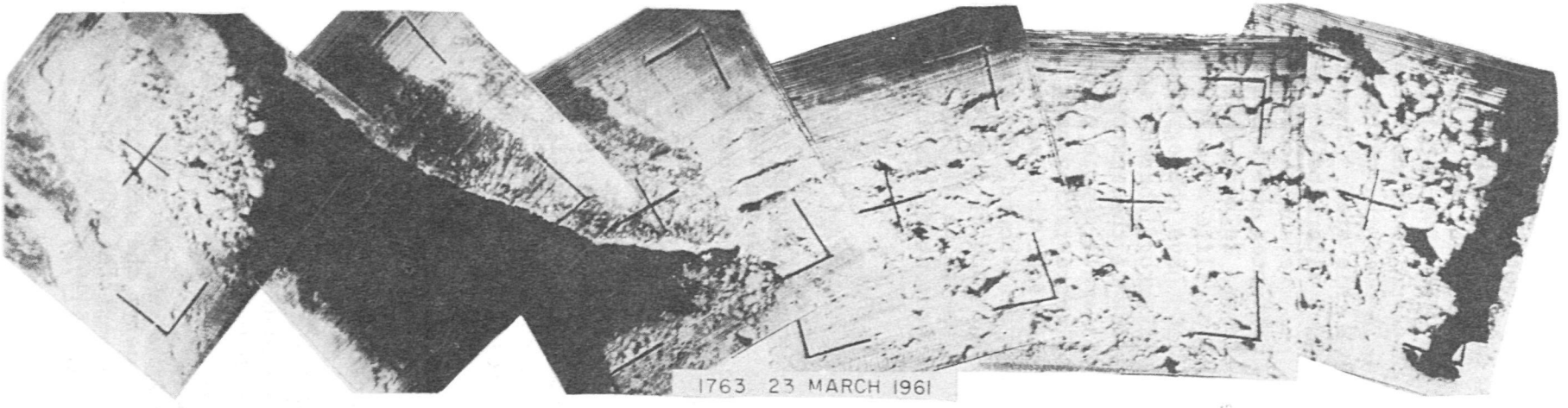
In the picture at the far left the ice concentration can be determined easily. The change in ice concentration in this area from about 0.8 or 0.9 winter ice along and north of the peninsula to 0.7 or 0.8 winter ice toward Southwest Point on Anticosti Island is also easily discernible; there is a distinct line of demarcation between these two different ice ages. Although the area south of Anticosti Island appears mostly ice free, a close scrutiny of the pictures reveals very faint traces of ice.

The bright spot near the center of Anticosti Island is the same one which has been seen in TIROS I photographs and also in several of the TIROS II pictures of the island.

The area off the northeastern shore of Anticosti Island is rather interesting from several standpoints. The cracks in the ice in this area appear to be some type of pressure pattern in the ice. They are widest and parallel to each other in the southern portion, and become narrower and more bent in the upper area with the apices pointing toward the north-northwest. A change of gray tone is also noted along a line through these pressure openings, indicating that the ice in the upper portion of the figure may be younger. Fast ice extends for approximately 3 miles out from the island, ending at a flaw lead. This flaw lead is about 1 to 1 1/2 miles wide and about 15 miles long. A floe about 3 miles across appears within the lead.

The rest of the ice seems to consist mainly of giant ice floes and fields varying in concentration from about 0.7 to 0.9; some of the fields are approximately 15 miles across. The dark area at the right hand side of this picture is an open-water lead between the Newfoundland coast and the ice pack, and is approximately 6 to 8 miles in width. The lower part of this lead ends in an oval shaped area a few miles north of Port au Port Peninsula. The dark area at the top of the picture near the center of this mosaic seems at first to be due to a change in the electronic signal level. However, visual ice reconnaissance just north of this area (which will be discussed later) indicated that this was an area of open-water.

The lower figure, part of the mosaic from pass 1850 of March 29, 1961, shows the 6-day change in ice conditions above the northern coast of Anticosti Island. In particular, the relatively ice free area north of the island appears to be an extension of the open-water area north of Anticosti Island on March 23. Also the ice has apparently broken off along the line of demarcation between the dark gray and light gray ice which can be seen in the third frame from the left in the March 23 mosaic. The flaw lead can also be discerned, but not so clearly as on the March 23 mosaic.



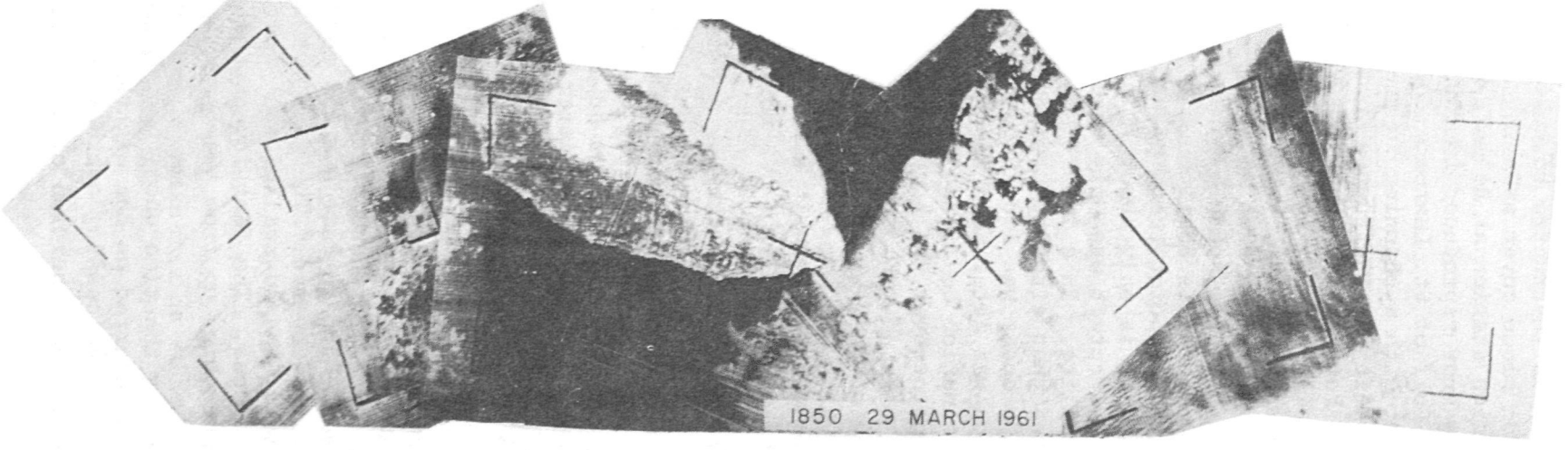


Figure 4. Gulf of St. Lawrence between the Gaspe Peninsula and west coast of Newfoundland; TIROS II photographs on March 23 and 29, 1961.

Pass 1850 pictures were obtained on the day when a photo-reconnaissance aircraft was instructed to take photographs at four different points, dependent upon cloud cover existing at each. Personnel of the satellite data acquisition station at Belmar, N.J. indicated that the pass 1849 satellite pictures (not reproduced in this report) showed thick cloud cover over the eastern Gulf of St. Lawrence; clouds were also extensive over the western Gulf, but with a thinning in the overall cloud cover in this area. Therefore, the aircraft was instructed to take pictures at its third alternate position near Old Post Point. The crew was also requested to observe and record details of a band of ice approximately 60 miles wide, oriented north-northeast south-southwest, touching the eastern tip of Anticosti Island; this band of ice can be seen in the pass 1850 mosaic. The satellite area shown here was slightly south of the area which the pilot would have photographed had he reached his destination, revealing the degree of error inherent in the principal point track predictions. The picture width of the narrow-angle camera is only about 70 miles, but even with this small degree of tolerance the aircraft was only about 15 miles out of the picture-taking area of the satellite. In a letter written by the pilot 2 days after this operation, he stated that after he crossed the Newfoundland coast west-bound, the area along the coast was ice-free, but that he did notice the band of ice below him which was later seen in the satellite picture. Although he did not reach his destination he stated that the weather west and southwest of his turn-around point over the band of ice was clear.

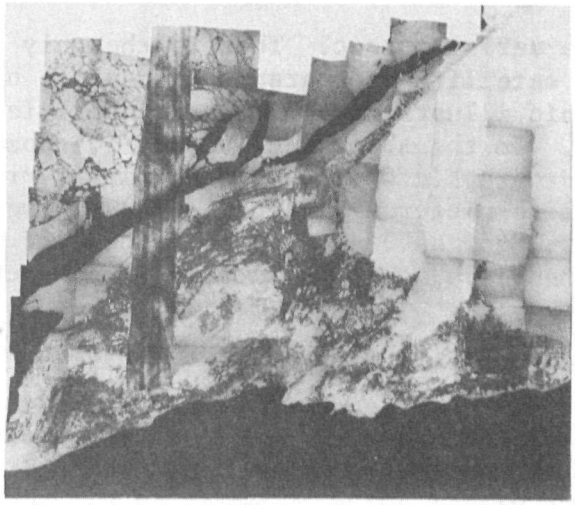
Figure 5

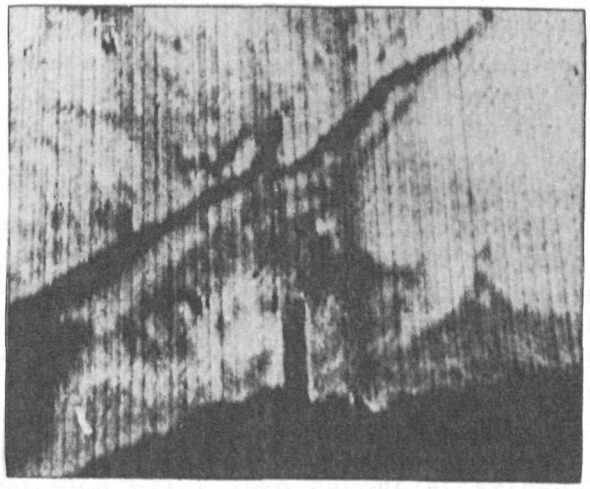
The upper figure is a mosaic of aircraft pictures from 10,000 feet obtained on March 24, 1961 by a P2V aircraft from Patrol Squadron VP-23. A K-17 aerial camera was used to obtain these pictures. The area shown is Port au Port Peninsula on the southwestern coast of Newfoundland.

The middle picture is an enlargement of part of a frame taken from pass 1777 on the same day, during the time when the aerial photographs were being taken. The lower figure is an enlargement of a frame from pass 1778 taken approximately 101 minutes later than the picture immediately above it, and approximately 30 minutes after the aircraft had left the area. The broad black lines in the TIROS photographs are part of the fiducial marks of the pictures.

Many of the features seen in the aircraft mosaic can also be easily distinguished in the satellite pictures. For example, there is an absence of ice in the northern part of St. George's Bay (the lower portion of each picture). Port au Port Bay, on the right hand side of each picture, is completely ice covered. The fast ice on the west coast of the peninsula, the shore lead, and several of the ice floes can be distinguished in the satellite pictures. The fast ice extends from the peninsula to Red Island (far left, one third up from the bottom).

During the time when the aircraft was taking pictures the camera malfunction occurred on the eighth run. Quite fortuitously, the satellite happened to be passing overhead taking pictures at almost the time of this malfunction so a portion of the picture from this pass (1777) has been





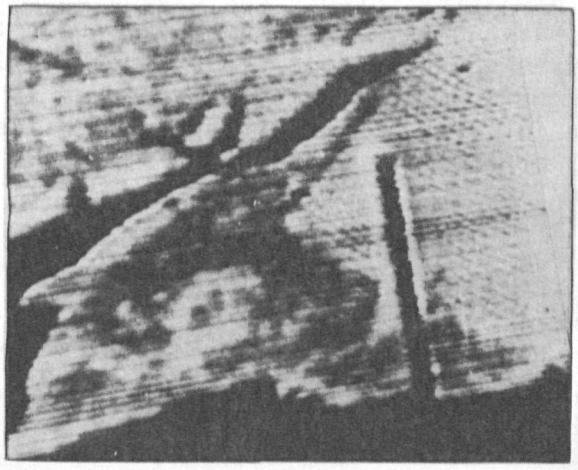


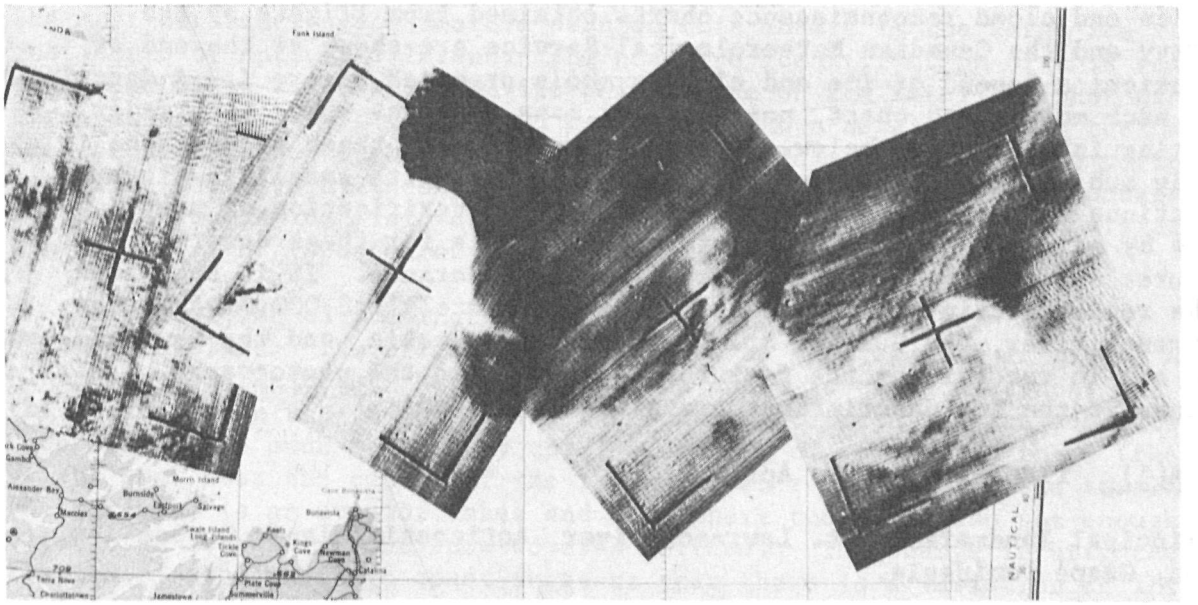
Figure 5. Port Au Port Peninsula on March 24, 1961; Mosaic of aircraft photographs, and TIROS II photographs on Passes 1777 and 1778.

inserted to complete the aerial mosaic. This is the only known case where simultaneous aerial and satellite photographs of sea ice have been obtained. It is considered a graphic illustration of the capabilities of a satellite ice surveillance system. In the absence of visual ice observations in this area, the U. S. Navy Hydrographic Office, Oceanographic Predictions Division, made use of these satellite pictures obtained on these two passes to predict ice conditions in the St. Georges Bay area for the use of the M.S.T.S. MIRFAK on its trip to Stephenville, Newfoundland late in March.

Figure 6

The upper part of this figure shows the eastern end of pass 1763. The absence of clouds over the western portion of this pass permitted fairly accurate positioning of these pictures. The ice pack boundary is rather well defined, and extends within about 40 miles of the Newfoundland coast, and more than 100 miles east into the Atlantic. The ice in the western portion of the upper figure appears to be a 0.9 to 1.0 partially snow covered concentration, of about 0.8 winter ice and 0.2 young ice. This latter conclusion is based upon the relative absence of identifiable sharp coastal features. The absence of these features may be due primarily to snow cover extending over both the land and ice adjacent to the shore. Near the center of this picture, the cloud cover appears to consist mainly of thin cirrus clouds. In the eastern portion there appear to be mainly thin altocumulus or altostratus clouds. Although cloud cover over this area does not permit a high degree of confidence in interpreting the type and age of the ice, the picture nevertheless indicates that ice observation through clouds is sometimes feasible. Ground or aircraft reports of the type and thickness of clouds in this area could aid substantially in the analysis of the ice features viewed by the satellite through the cloud cover.

The lower part of figure 6 shows the eastern portion of pass 1835. Because of the lack of recognizable images over large portions of this pass, it has not been possible to position these pictures as accurately as those shown in the pass 1763 sequence. The ice feature seen in this pass is believed to be part of the same ice pack seen through the clouds on pass 1763. The ice areas are similar in appearance and occur in the same general area. Errors in positioning the pictures shown in pass 1835, together with the southward movement of the ice pack which might have been expected in the intervening 5-day period, places the ice pack boundary roughly 50 miles south of the position in which it was observed on pass 1763.



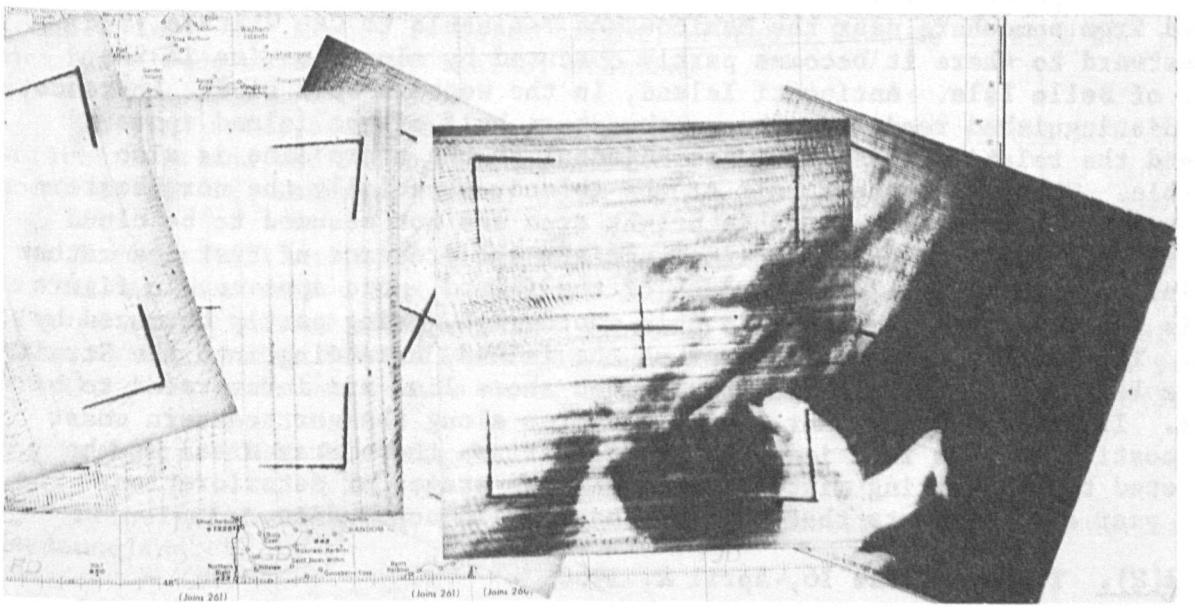


Figure 6. Atlantic Ocean and east coast of Newfoundland; TIROS II photographs on March 23 and 28, 1961.

VII. TIROS I AND TIROS II ICE PHOTOGRAPHS

The satellite ice photographs obtained by TIROS I and TIROS II and the aerial ice and cloud reconnaissance charts obtained from flights by the U. S. Navy and the Canadian Meteorological Service are shown at the end of this section; a legend of ice and cloud symbols precedes figure K. A description of each mosaic and chart, pointing out many features which the reader may distinguish, is given below. The interpretation of these photographs is partially subjective. The experience of the authors with satellite pictures, consultations with experts in ice observation, and verification of many features by aircraft reconnaissance formed the basis for these descriptions. The figures are numbered in the order of their appearance. It is suggested that the reader obtain a large scale map (approximately 1:2,000,000) of the St. Lawrence River, the Gulf of St. Lawrence, Nova Scotia, and the Newfoundland area to aid in recognizing the features identified in the photographs. The terms used in the ice descriptions are given in Appendix I.

Figure A(1). TIROS I, Pass 2, April 1, 1960

Principal landmarks: St. Lawrence River, Anticosti Island, Quebec Mainland, Gaspé Peninsula.

This is a composite of wide-angle pictures obtained from the TIROS I satellite on the day of launch. The horizon can be seen in the upper left hand corner. The dark area running lengthwise in the picture is the upper Gulf of St. Lawrence; the lower portion of the Gulf is mostly cloud-covered. The picture distortion is due to the oblique angles from which these pictures were obtained. The most readily identifiable features are the curvature of the Gaspé Peninsula, and the upper part of the St. Lawrence River. The northern Quebec shore appears relatively cloud-free, and the Quebec coast line can be followed from somewhere near the Manicouagan Peninsula to Cap Whittle, and northeastward to where it becomes partly obscured by clouds or ice in the Straits of Belle Isle. Anticosti Island, in the western Gulf of St. Lawrence, can be distinguished readily. The northwestern half of the island appears dark, and the relative absence of ice adjacent to the shore line is also noticeable. The southeastern half of the island, especially the northeastern shore, appears much brighter. This bright area was not assumed to be cloud cover; the sharpness of the shoreline suggests the presence of fast ice rather than clouds. The ice field just south of the island, more apparent in figure A(2), is not readily discernible in this photograph, being partly obscured by clouds. The light gray patterns east of the island, extending into the Straits of Belle Isle roughly parallel to the Quebec shore line are interpreted to be sea ice. If it is assumed that the bright area along the northeastern coast of Anticosti Island is fast ice, then by comparison these gray areas may be interpreted to be floating winter ice in various stages of deterioration. The time of year also suggests that this may be a valid conclusion.

Figure A(2). TIROS I, Pass 16, April 2, 1960

Principal landmarks: St. Lawrence River, Gaspé Peninsula, Anticosti Island, Newfoundland.

This figure is a composite of narrow-angle TIROS I pictures. The small light spots on the pictures are due to radio interference.

Clouds partly obscure the lower part of the St. Lawrence River near Quebec, but the remainder of the area appears to be almost free of clouds. The most outstanding ice feature seen in this mosaic is the large ice field just south of Anticosti Island. The positive identification of this feature as an ice field was based upon its persistence on the satellite photographs of three consecutive days (the third day is not shown here) and upon the Canadian ice reconnaissance flights made a week before and a week after the period of satellite photography (see Wark and Popham, [1]). The earlier reconnaissance reported a large ice field attached to the southeastern end of the island; the later flight reported only very young ice in this same region.

Of nearly equal prominence is the ice along the northern coast of Anticosti Island. The brighter ice can also be seen clearly in figure A (1). Along most of the coast the outline of the coast is quite distinct, but near the southeastern tip of the island the contrast between sea ice and snow-covered land is much reduced by the low density of vegetation there (the bright spot near the center of the island, seen repeatedly in the satellite photographs, is an area of lakes and burn where there is also not enough vegetation to obscure the snow-covered surface). The change in brightness of the ice off the northern coast suggests that there is a variation in its age or its concentration, with the latter being more likely in April.

The oblique angle at which these photographs were taken considerably distorts the Gaspé Peninsula, but Gaspé Bay and Chaleur Bay can be seen without difficulty. The southern side of Gaspé Bay appears to be covered by ice, but a distinct shore lead can be seen on the north side; Chaleur Bay appears to be covered by ice except for a protrusion of open water north of Miscou Island. Mirimichi Bay, to the south, is barely discernible because of the lack of contrast between the snow-covered land and the solid ice in the bay. Newfoundland, on the right, is quite bright, probably because of snow and the cumulus clouds reported by weather stations.

Several areas of belts and patches of ice can be seen in the Gulf between Anticosti Island and Newfoundland, north of Cape Breton Island, and near the mouth of the St. Lawrence River; other belts and patches are seen in the river.

Figures A(1) and A(2) demonstrate that a considerable amount of ice information can be obtained from satellite photographs, even those taken under the adverse conditions of oblique angle view and unfavorable gain setting of the video system. With TIROS II most of the photographs were taken in the vertical, and the video gain was set to favor better contrast in areas of low reflectivity.

Figure B(1). TIROS II, Pass 911, January 24, 1961

Principal landmarks: Trinity Bay area, Anticosti Island, and northern Newfoundland.

This was the best overall pass of the January series of satellite pictures. Virtually all of the northern part of the Gulf of St. Lawrence, with the exception of a small area of the Newfoundland coast, is seen to be covered by ice.

A heavy ice concentration, with numerous cracks and leads, appears near the mouth of the St. Lawrence River north of the Gaspé Peninsula; it appears to be about 0.8 winter ice. Elsewhere in the Gulf, with the exception of the area off Newfoundland, there appears to be 0.6 to 0.9 winter ice, also with numerous cracks and leads. Fast ice outlines the shore of Anticosti Island, whereas there is a shore lead along much of the Quebec shore. Parallel cloud bands, north and south of the island and near the northeastern coast of Newfoundland, are identifiable by the patterns which are more regular than those exhibited by the ice. Belts and patches of ice lie in the more open area west of Newfoundland.

Visual aircraft observations of ice and clouds were made in the Gulf and in the Atlantic at about the time of the satellite pass; they are shown in figures K(1) and K(2). Scattered cumuli lay off the northeastern coast of Newfoundland, and broken stratocumuli lay along the northern coast of Anticosti Island; between was a large clear area. Ice observations indicated that there was winter ice west of Natashquan Point, young ice and slush immediately north of the fast ice along the shore of Anticosti Island, and young and grease ice between the island and the Newfoundland coast. Areas of pancake ice and of belts and patches were seen in the open water area off the western Newfoundland coast.

The ice pack boundary in the Atlantic northeast of Newfoundland can be seen clearly in the eastern part of the mosaic. The boundary lies roughly east and west to the north of Notre Dame Bay, then curves somewhat to the southeast farther off the coast, becoming less discernible there because of the greater amount of cumulus and statocumulus clouds. Belts and patches are prominent south of the boundary in Notre Dame Bay; open water areas and belts and patches within the pack are less distinguishable because of the greater ice concentration and the greater cloud cover. Comparison of the visual reconnaissance and the satellite pictures gives good agreement for the ice and cloud features. In both the Gulf and the Atlantic clouds limited the ice observations by the satellite, but some information was obtainable everywhere and in most areas the type and concentration of ice could be discerned quite well.

Figure B(2). TIROS II, Pass 941, January 26, 1961

Principal landmarks: The St. Lawrence River near the Manicouagan Peninsula, Chaleur Bay, and the Magdalen Islands.

This mosaic picturing the central area of the Gulf of St. Lawrence, provides one of the finest views of this area obtained during the TIROS II operation. The picture swath crosses the St. Lawrence in the vicinity of the Manicouagan Peninsula, which is surrounded by a bright patch of fast ice. Other ice in the River is gray in appearance, with a distinct concentration on the southern shore. On the northern shore the River is dark, and an elongated dark area extends most of the way across the River below the Peninsula. To the east-southeast of this dark area are some faint parallel bands oriented west-northwest-east-southeast and extending almost to the extreme western part of Chaleur Bay; these are almost certainly bands of scattered cumulus or stratocumulus clouds.

The lower two-thirds ofChaleur Bay is covered with ice of high reflectivity.

but the northern and western parts, as in the River, are dark and are therefore free of ice or have thin ice of low reflectivity. This pattern is repeated in the Gulf; the reflectivity is low to the east of Shippigan and Miscou Islands, in a broad stream southeastward from the Gaspé Peninsula, on the eastern side of the Magdalen Islands, and east of the northern tip of Cape Breton Island. Reflectivity is high on the western side of the Magdalen Islands, and is intermediate elsewhere. The Gulf ice, in the 100 miles to the east of Miscou Island, has many large leads, giving it a mottled appearance. Farther to the east, near the bottom, are some very distinct bands, parallel to the satellite track, which are again interpreted as scattered to broken cumulus or stratocumulus clouds. These clouds are probably present everywhere in the eastern part of the mosaic, even over the dark area east of the Magdalen Islands and Cape Breton Island, but the dark lines in this area, with other orientations, are quite likely leads in the ice.

The open water areas represented by the dark areas on these photographs are caused by the action of persistent winds carrying ice away from leeward shores. (See also the discussion of figures 2 and 3). Although there is a considerable amount of cloudiness in the Gulf, the ice is not completely obscured as it would be by an overcast, and interpretation of ice features is still possible.

Figure C(1). TIROS II, Pass 1734, March 21, 1961

Principal landmarks: Saguenay and St. Lawrence Rivers, Gaspé Bay, Anticosti Island.

The lower part of the Saguenay River appears to be open, while the upper part is frozen and probably snow-covered. Across the St. Lawrence from the Saguenay River, the ice appears thin and not snow-covered. It is possibly dissipating, with puddling on the surface. Most of the ice in this area is concentrated near the southern shore of the St. Lawrence River.

A very small part of Chaleur Bay is seen in the lower part of the sixth frame from the left. It shows fast ice extending a short distance out from the land near New Richmond, with an ice-free area south of the fast ice. The entire Gaspé Peninsula area (fourth frame from right) appears to be cloud free, so that the ice covered rivers stand out quite sharply against the darker land areas. Snow cover over portions of the land is also seen in these pictures.

The ice in Gaspé Bay and Mal Baie appears somewhat brighter than the ice just to the east of the bays. One explanation for this difference is that landlocked ice tends to be more even, especially when snow-covered, than ice which is more exposed to the action of wind and water currents. Northeast of the peninsula (third frame from right) the ice is more broken and appears to consist of giant floes up to 5 miles across, with numerous open water leads, some a half mile or more in width and several miles long. The lower part of the open water south of Anticosti Island (second and third frames from the right) is partly obscured by a thin layer of clouds extending northward from the ice pack, at this point approximately 35-40 miles south of the island. The edge of the ice pack is rather uniform. Gradations of gray along the southeastern portion of the ice pack edge suggest a possibility that this is a mixture of both young and winter ice.

Figure C(2). TIROS II, Pass 1748, March 22, 1961

Principal landmarks: Miramichi Bay (N.B.), Magdalen Islands, Prince Edward Island, St. Georges Bay (Nfld.)

Miramichi Bay (ninth frame from right) is ice covered, but there is a relatively large open water area east of the bay. Several curving, short leads appear in Northumberland Strait, but most of the area around the western end of Prince Edward Island appears solidly ice-covered.

Another major ice opening occurs near the Magdalen Islands (sixth frame from right). Although the ice is cloud-covered immediately east of this opening, the outlines of the ice are still discernible. The ice southwest of St. Georges Bay (third and fourth frames from right) appears to be gray where partly obscured by clouds; St. Georges Bay itself is relatively ice-free, while the land mass to the south is mostly cloud-covered.

Figure D(1). TIROS II, Pass 1749, March 22, 1961

Principal landmarks: Manicouagan Peninsula, Gaspé Peninsula, Anticosti Island, Port au Port Peninsula (Nfld.)

This is one of the best series of pictures obtained by TIROS II. Fast ice surrounding the Manicouagan Peninsula (second frame from left) extends several miles into the St. Lawrence River. A relatively large ice field may be seen east of the Peninsula in the St. Lawrence River. This ice pack was seen on subsequent satellite passes to be approaching the Manicouagan Peninsula area.

An extensive field of ice surrounds the northwestern shore of the Gaspé Peninsula (third, fourth, and fifth frames from left) and extends almost to Anticosti Island (sixth and seventh frames from left). The gradations in these pictures from very bright ice adjacent to the shore to barely discernible, gray ice features farther out in the river are well marked.

A very narrow strip of fast ice outlines Anticosti Island. Several of the ice floes seen south of Southwest Point (seventh frame from left) were seen on subsequent mosaics of the area. The bright area seen near the center of Anticosti Island has also been observed by both TIROS I and TIROS II. The area south of Anticosti Island remains ice-free. Ice floes lie near the eastern tip of the island; the gradual approach of these floes to the southeastern coast can be noted in subsequent picture mosaics of the area. Between the tip of Anticosti Island and the Newfoundland coast is an extensive ice field with numerous large cracks and leads. There is a shore lead along the Newfoundland coast, varying in width from 3 to 6 miles (third frame from right). The many inlets and lakes in western Newfoundland appear to be ice-covered and snow-covered. Several land features are covered by highly reflective snow, and contrast noticeably with adjacent wooded areas.

Although Port au Port Peninsula is partly obscured by the fiducial mark on the satellite photograph (third frame from left), there is no shore lead visible adjacent to the northwestern coast of this peninsula. Port au Port Bay is ice-covered, but St. Georges Bay to the south appears to be mostly open

water. Glover Island, inland from St. Georges Bay, is a particularly distinguishable landmark, as is Red Indian Lake. The noise and interference patterns at the top of the pictures preclude the identification of clouds in this area.

Fast ice outlining the southern coast of Anticosti Island extends abour a mile off-shore, except for the area a short distance west of Cormorant Point where it is perhaps 2 to 3 miles wide; this is seen also in figure C(1). The greatest concentration of ice lies north and east of Anticosti Island and extends almost to the Newfoundland coast. Most of this area is covered by a thin overcast, but several rather wide cracks and leads can still be observed.

Figure D(2). TIROS II, Pass 1762, March 23, 1961

Principal landmarks: Halifax, Cape Canso (N.S.), Burin Peninsula (Nfld.)

The southeastern Nova Scotia coast is barely discernible (first six frames from left). Thin ice appears to be forming along this coast. The small white dots seen east of the Darmouth area (third frame from left) are either small cumulus cloud formations or small patches of snow. Farther up the coast the land becomes more distinguishable. Halfway between Halifax and Cape Canso (fourth to sixth frames from left) and just off shore is an area of broken to overcast clouds, presumably cumulus. These clouds partly obscure a large ice field east of Cape Canso (fifth frame from left). The western side of this ice field is very sharply defined, while the easttern part is very ragged with numerous belts and patches trailing off from it. A small part of Cape Breton Island may be seen just north and west of the ice pack; several miles east of the pack, scattered and banded thin clouds appear, increasing in thickness toward Newfoundland. St. Pierre Island and the lower part of the Burin Peninsula stand out quite sharply against the water background (last two frames on right). There appears to be very little ice below the clouds which appear from this point east. No recognizable landmarks can be seen from this point east. However, the last photograph in this mosaic shows what appear to be medium or giant floes below the cloud cover in the lower portion of this picture.

Figure E. TIROS II, Pass 1763, March 23, 1961

Principal landmarks: Saguenay River, Gaspé Bay, Anticosti Island, Newfoundland.

A favorable camera angle, excellent camera performance and an almost cloudless day combined to make this the best overall series of photographs

obtained during the March series. Again, the Saguenay River is visible; the lower part remains ice-free, while the upper part still remains ice-covered and snow-covered (frames one and two from left, upper mosaic). There has been little change in the ice across from or just south of the mouth of the Saguenay River since March 21 (see figure C(1)). The entire northern shore line of the Gaspé Peninsula is visible in pass 1763, whereas just a small portion was visible in pass 1734. The ice in the lower part of the St. Lawrence River is gray in appearance, in contrast to the brighter appearing ice farther up the river. An ice floe in the middle of the river and about 75 miles down-river from the Saguenay may be the same one seen in pass 1734 on the south shore; it is surrounded here by several smaller floes. The conglommeration of ice east of this floe may be seen rather faintly in pass 1734.

Of particular interest is the ice around the northeastern tip of the Gaspé Peninsula (6th, 7th and 8th frames from left, upper mosaic). This is a rather solid and extensive field with numerous cracks and leads which stand out sharply against the bright ice. There has been no significant change in the amount of ice between the Gaspé Peninsula and Anticosti Island in the previous 48 hours, but individual floes are more distinguishable than in the pass 1734 pictures, probably mainly because of better picture quality.

The area immediately south of Anticosti Island is still ice-free, except for the previously noted fast ice along the coast. The ice south of the eastern tip of the island, seen near the center of the right hand picture in pass 1734, has moved northward and is now almost adjacent to the shore (2nd frame from left, lower mosaic).

North of the island the ice is not so broken up as it is farther east, but several large cracks lie just east of the island, oriented ENE-WSW. A lead, apparently refrozen, runs parallel to the northeastern coast of the island from a point near Prinsta Bay to Natiskotek Bay. The lead is about 3 miles off-shore and is about 2 miles wide; there are several floes within this lead, one of them considerably larger than the others. About 20 to 30 miles north of the island the ice becomes darker, which suggests the presence of a different type, age, or concentration of ice. A further comparison of this area and the refrozen lead is made in the discussion of pass 1850 (fig. H(2)).

The ice east of Anticosti Island is broken into large floes and fields, some of which are estimated to be 12 to 15 miles long and several miles across. This heavy ice concentration ends abruptly 6 to 10 miles from Newfoundland, leaving a large ice-free area along most of the coast (fifth and sixth frames from left, lower mosaic). This open-water area widens to the north near Lobster Cove, and narrows slightly to the south, ending in a large oval-shaped area just west of Shag Island.

The Bay of Islands with its many coves and inlets, Deer Lake and Grand Lake are all iced over and are probably covered by several inches of snow. The southern end of White Bay and most of the area visisble in Notre Dame Bay are ice filled also, with the notable exception of a polynya in Notre Dame Bay (8th frame from left, lower mosaic).

The ice pack boundary in the Atlantic contrasts sharply with the water in the third picture from the right. Small belts and patches of ice immediately adjacent to the ice pack in this area are also readily discernable. The boundary curves eastward under a thin overcast and runs out into the Atlantic in an irregular line, still visible through the progressively thicker cloud layers. The ice visible through the thicker overcast appears as extensive fields, rather than a solid pack such as that observed nearer the land. The pack boundary is never less than 30 miles from the coast in these pictures, and the large fields shown there extend more than 100 miles into the Atlantic.

Figure F(1). TIROS II, Pass 1777, March 24, 1961

Principal landmarks: Miramichi Bay (N.B.), Port au Port Peninsula and St. Georges Bay (Nfld.)

Thin clouds partly obscure some of the ice in the Gulf, but many giant floes and fields are readily observed. Port au Port Bay is completely iced in (upper right, 3d frame from right). On the northwestern coast of Port au Port Peninsula a small island, one-and-a-quarter miles off-shore, forms the tip of the hook-like appendage which extends out into the Gulf near the beginning of a wide lead. Fast ice along this coast ends abruptly just south of the island and curves sharply back to shore. The lead, more than a mile wide where it begins near the island, parallels the coast and lies between the floes in the Gulf and, the fast ice along the shore. The lead becomes indistinct near Long Point.

St. Georges Bay is void of ice except for a small area around Sandy Point and Stephenville. Glover Island is easily identified, as is Grand Lake, Red Indian Lake, and Humber Arm, near Corner Brook (last 2 frames on right). A thin layer of clouds between Buchans and Grand Lake almost obscures Hinds Lake. The bright areas on land appear to be associated with the higher elevations, such as Lewis Hills north of Stephenville. It is believed that these are snow-covered areas of sparse vegetation and therefore more highly reflective than the more wooded areas.

Figure F(2). TIROS II, Pass 1778, March 24, 1961

Principal landmarks: Maincouagan and Gaspé Peninsulas, Anticosti Island, Port au Port Peninsula, St. Georges Bay.

The western part of this pass shows large floes and fields in and near the mouth of the St. Lawrence River. Clouds which obscure part of the ice appear to be oriented in NW-SE bands. The area near Southwest Point on Anticosti Island is still free of ice (sixth frame from left). A few of the floes south of here were observed on the previous day during pass 1763. Thin clouds covering the water south of Anticosti Island also appear to be oriented in bands. Ice east of the island is visible through thin clouds and through breaks in the overcast. The ice off Heath Point (7th frame from left) has the same concentration observed farther south one and three days earlier. The same features seen in figure H(1), 100 minutes earlier, are seen in the frames on the right.

Figure G(1). TIROS II, Pass 1807, March 26, 1961

Principal landmarks: Manicouagan Peninsula, Gaspé Bay, Anticosti Island.

Clouds obscure most of the land in the central part and the ice in the eastern part of this mosaic. However, many individual floes can be seen north of the tip of the Gaspé Peninsula. The breakup of the ice is very noticable when this mosaic is compared with some of the earlier passes. Gaspé Bay is still ice-covered, while the area south of Anticosti Island remains ice-free. The concentration has increased sharply near the Manicouagan Peninsula.

Figure G(2). TIROS II, Pass 1821, March 27, 1961

Principal landmarks: Manicouagan and Gaspé Peninsulas, Anticosti Island

The ice in the St. Lawrence River consists mainly of ice floes, but east of the mouth of the river and north of the coast of the Gaspé Peninsula, a few ice fields as well as floes are visible (2d, 3d and 4th frames from right). The concentration is not so great between the Gaspé Peninsula and the island as when viewed on March 23. The bays and inlets along both shores of the river are closed by ice. Fast ice along the northern shore extends outward into the river about 4-5 miles in the area around Manicouagan Peninsula (2d and 3d frames from left), but for the most part extends less than a mile from the shore. The area south of Anticosti Island is partly cloud-covered but still ice-free (last two frames on right).

Figure H(1). TIROS II, Pass 1835, March 28, 1961

Principal landmark: Chaleur Bay

Most of the area seen in this mosaic is cloud-covered; however, it does reveal that ice is visible through certain types and thicknesses of clouds. A small part of the St. Lawrence River can be seen at the far western end of this mosaic. The Gaspé Peninsula is largely covered with thin to occasionally thick clouds. Chaleur Bay is seen near the lower edge of the first four frames from the left. The bay is open near the north shore at the western and eastern ends, but elsewhere the ice extends almost to the shore. A very narrow shore lead is visible along the north shore between the two open areas (3d and 4th frames from left). Some clouds in NNW-SSE bands lie over the

eastern bay area (4th frame from left). Some ice floes can be seen through the clouds just off shore in the Gulf. From these ice floes to an area south of Anticosti Island, thick cloud decks predominate. Although Anticosti Island itself cannot be seen, no ice is evident through the thin clouds south of the island. This area was noted to be free of ice on seven days prior to this pass. In the center of the mosaic, the broad north-south band of ice visible through the clouds was observed by aircraft on the following day (see Section V). Just west of Newfoundland are banded, presumably cumulus, clouds. The area below these clouds appears to be relatively ice-free. No landmarks are visible over Newfoundland under the dense cloud cover. Although the ice pack seen off the Newfoundland coast cannot be located precisely, it closely resembles the ice seen off the coast just east of Cape Canso during passes 1762 and 1763, March 23.

Figure H(2). TIROS II, Pass 1850, March 29, 1961

Principal landmark: Anticosti Island

Anticosti Island appears somewhat foreshortened in this sequence because of the more oblique angle of view than on earlier passes.

A major change has now taken place north of Anticosti Island; the heavy ice concentration observed in this area by the satellite on several earlier passes is greatly reduced, and much of the area is now open water. There is a distinct break 2 to 3 miles off the north shore of the island which may possibly indicate the point at which fast ice ends and floating sea ice begins.

In comparing this area with the same area viewed on March 23 it is interesting to note how the remaining ice seems to coincide with the light grey area mentioned in the discussion of pass 1763, while the open water area appeared darker on that pass. Also, the refrozen lead seen in 1763 has become the line of separation between fast ice and sea ice (center frame).

Elsewhere, ice is still visible through thin spots and breaks in the overcast both east and west of the island although it is difficult to tell whether ice exists beneath the clouds near the Newfoundland coast, but the darker areas visible through the clouds are thought to be ice-free.

Figure I(1). TIROS II, Pass 1865, March 30, 1961

Principal landmark: Saguenay River

The lower Saguenay River (extreme lower left) is clearly ice-free. In the St. Lawrence River, ice floes can be distinguished, although clouds limit the amount of detail visible over a large part of the area. This figure covers some of the area shown in the figure 3 of the section VII.

Figure I(2). TIROS II, Pass 1879, March 31, 1961

Principal landmark: Manicouagan Peninsula

The St. Lawrence River is free of clouds from the Manicouagan Peninsula southwestward, but dense clouds largely obscure the ice features to the east.

Nevertheless, the clouds are thin enough in places, such as in the area immediately east of the Gaspé Peninsula (in the right third of the mosaic) to allow a view of many large and giant floes.

Figure J(1). TIROS II, Pass 897, January 23, 1961

This figure shows a part of Lake Superior. Solid ice is seen at the left near the bottom; the northern limit extends eastward from a point just above Duluth. A shore lead is seen at the western end of the Lake. The upper part of the Lake is either ice-free or contains ice of low reflectivity; this characteristic extends eastward, but around Isle Royale at the right, dense clouds obscure both land and Lake features. Bands of clouds lie across the central part of the Lake. No fast ice on the north shore of the Lake is evident in these pictures.

Figure J(2). TIROS II, Pass 1705, March 19, 1961

This photograph shows the southern part of Georgian Bay on the eastern side of Lake Huron. Fast ice surrounds the islands and invades the bays and inlets along the eastern shore. This ice is probably snow-covered, as evidenced by its brightness. On the south and western shores there appears to be little fast ice. Most of the water area is covered by darker ice, except for open water within 2 to 5 miles of shore in most places. Large leads 2 to 5 miles across separate the individual ice areas.

Figure K(1). U. S. Navy ice reconnaissance, January 24, 1961

Ice data obtained from U.S. Navy reconnaissance aircraft in the Gulf of St. Lawrence and in the Atlantic east of Newfoundland on January 24, 1961 are shown in this figure. The key to the symbols is given in Appendix II. The aircraft operations leading to this chart were described in Section IV. TIROS II photographs taken during pass 911 on the same day can be compared directly with this chart (fig. B(1)).

The fast ice shown west of Natashquan Point does not appear to be so extensive in the photographs; it shows clearly immediately west of the Point, but appears to end about 5 miles to the west. Cracks in the preponderant winter ice to the southwest show clearly in the photographs, but south of the mid-point between the mainland and Anticosti Island east-west bands of broken stratocumulus clouds are seen and little can be told about the ice below. To the east of the Point, the observed shore lead shows in the photographs as a dark line. The younger ice observed to the south appears to be about as bright as the somewhat older ice already mentioned, but the cracks are not seen so readily. In the eastern Gulf the young ice changes increasingly to pancake and grease, and in the southern limit there are belts. The satellite photographs show the eastward transition as a darkening and finally a breakup into belts. The northward protrusion of the dark area off the Newfoundland coast lies near the limit of the aircraft observations. The boundary of the area with 0.5 to 0.7 concentration and that with 0.8 to 0.9 concentration shows up well in the photographs, and the two are in agreement. There are some clouds in this portion of the Gulf, showing as small dots in frame B1.

In the Atlantic, there is a small area observed by both aircraft and

TIROS II. There, in the upper part, only the boundry between the ice-free area on the south and the area of 0.5 to 0.7 concentration seems to follow the ice outline indicated by the satellite. The clouds over the rest of the area are too numerous to permit positive identification of ice features. The wavy line at the top of the ice reconnaissance indicates that the ice observer found the clouds too thick to permit ice observation to the north.

Figure K(2). U. S. Navy cloud reconnaissance, January 24, 1962

Cloud observations were made by the U. S. Navy at the same time as the ice observations shown in figure K(1). Because more rapid variations occur in cloud patterns than in ice patterns, some disagreement is to be expected between the slowly acquired aerial information and the nearly instantaneous satellite photographs. In the Gulf the aircraft was 5 miles east of Natashquan Point during the satellite passage, and in the Atlantic the observations from the other aircraft were about one hour earlier.

The extension of clouds seen in the photographs (fig. B(1)) between the mainland and Anticosti Island becomes immediately apparent. Clouds along the southern side of the Island are less apparent in these pictures and show up best as bands over the water rather than over the Island; the time difference is probably responsible for this partial disagreement. The clear area in the center and the scattered clouds in the east are well verified in the photographs, although over the more uniform ice areas, clear and scattered conditions are not clearly distinguishable in the photographs. Partly cloudy conditions are most easily identified over darker surfaces.

In the Atlantic, clouds were observed only at the limit of the observation area. These match some dense clouds just above the center of the photograph swath. However, there are also dense clouds over the ice area near the bottom of the swath, so comparison here contributes little. Again, the difference in observation time is probably partly responsible for these inconsistencies.

Figures L(1) through O(2). Canadian Meteorological Service ice reconnaissance, March 19 - April 1, 1961

These figures show ice charts obtained from Canadian Meteorological Service aircraft reconnaissance flights from March 19 to April 1, 1961. On March 21, 22, 23, and 24 these flights intersected areas photographed on the same day by the satellite; in some areas the air reconnaissance was two or three days before or after the satellite photography. Almost the entire Gulf of St. Lawrence was observed visually during this period, as the eight charts show, and a large part of it was photographed by the satellite. Comparison of the photographs with the charts can therefore be made directly in a few instances, and with a time difference of up to several days in others. The charts are self-explanatory, with the help of the key to the symbols, so the following discussion (not given exactly in the order of appearance) will be confined to their comparison with the photographs. It should be mentioned that the preceding interpretive discussion of the March photographs, figures C(1) through I(2), was undertaken without reference to these charts.

Comparison of ice reconnaissance for March 21 (fig. L(2)) and pass 1734 (fig. C(1)). The most interesting area for comparison is the area east of the Gaspé Peninsula. Gaspé Bay consists of fast ice; the coastal area to the south of the bay is 0.7 concentration of mostly slush ice; the satellite shows this as a rather dark area with some ice features discernible. Between Gaspé Bay and Anticosti 0.9 winter ice is reported, and a 0.9 concentration of mostly small and medium floes. The large, dark area south of Anticosti Island seen in the satellite photograph is revealed by the visual reconnaissance to be mostly slush ice near the coast, and a mixture of ice crust and slush farther south. The boundary between this young, or newly forming, ice and the visually recorded 0.8 winter ice appears farther south and is recorded on the ice reconnaissance. A few scattered clouds extend north of the ice pack boundary in this area. It should also be noted that the boundary between the fast ice in the Gaspé Bay and the ice outside of the bay is discernible in the satellite photographs.

Comparison of ice for March 22 (fig. M(1)) and Passes 1748 (fig. C(2)) and 1749 (fig. D(1)). The two satellite passes complement each other; the earlier pass is south of the later pass, and they are very nearly tangent in the St. Georges Bay - Port au Port Peninsula area. Almost all of the ice around the Magdalen Islands is from 019 to 1.0 concentration; most of it is winter ice, and consists mainly of small and medium floes. Thin clouds exist over this area also, as can be noted particularly near the southwestern Newfoundland coast. The area around the Magdalen Islands appears to be open water from the satellite, but the visual reconnaissance indicates there is approximately 0.6 ice cover. No explanation can be given for this discrepancy. The ice concentration drops off near the entrance to St. Georges Bay, but it is still reported as winter ice and is seen by the satellite with partial cloud cover over the ice. St. Georges Bay is reported as open water. In pass 1749, the entire area from Anticosti Island almost to the Newfoundland coast is reported as 0.8 concentration of mostly small or medium floes and winter ice. The satellite photographs are consistent with this observation, and, except for minor variations, so is the observation of the shore lead adjacent to the Newfoundland coast. Fast ice in the Bay of Islands and Port au Port Bay is also seen in the satellite photographs.

Comparison of ice reconnaissance for March 23 (fig. M(2)) and Pass 1763 (fig. E). The reconnaissance indicates that the ice in the northern part of the St. Lawrence River is a 0.7 concentration, mostly ice crust, and concentration of mostly winter ice. The discrepancy between the satellite photographs and the visual ice reconnaissance may be accounted for in part by the inability of the satellite cameras to discern thin or newly forming ice. This appears to be particularly true of the March pictures. On the other hand, there was only one good visual reconnaissance flight made on the same day as the satellite pass, so perhaps an unfair comparison is made in this case. The ice boundaries as seen in the satellite pictures are not consistent with the visual reconnaissance data, perhaps because the boundaries may be difficult to plot, since the ice pack is rather randomly oriented in this area and the boundaries are not sharply defined. An interesting comparison in changes in ice age can be made in the area to the northeast of the Gaspé Peninsula. The visual ice reconnaissance indicates a change in ice age from 0.9 winter to 0.7 winter (in the same area the ice concentration

varies from 0.9 to 0.8). The position of this line agrees with the satellite photographs, which show a relatively bright, highly concentrated ice area changing toward the northeast to a slightly darker area of less concentration along a very discernible line. All of this occurs between the land mass just north of the Gaspé Bay and Southwest Point on Anticosti Island. The area south of Anticosti Island has 0.7 concentration, 0.4 brash and block ice and 0.3 small and medium floes. This area, reported as 0.6 ice crust, appears to be ice-free in the satellite photographs.

Comparison of ice reconnaissance for March 19 (fig. L(1)) and Pass 1762 of March 23 (fig. D(2)). The satellite photographs reveal a large ice field east of Nova Scotia, near the center of the mosaic, which appears to be a 0.9 to 1.0 concentration of mostly winter ice, with ice of less concentration and perhaps of a different age near the southern and eastern edges. There are scattered to broken clouds to the left of this ice field. The visual reconnaissance indicates that this area was mostly winter ice (0.7 to 0.8), varying from 0.4 near the southern and eastern edges to 0.9 near the center. The visual reconnaissance indicates the ice to be in the vicinity of Cape Breton Island, while the satellite photographs taken 6 days later indicate the ice field to be farther south. The visual reconnaissance shows the area to be surrounded on three sides by open water and the satellite photographs show it as a completely detached ice field.

Comparison of ice reconnaissance for March 24 (fig. N(1)), April 1 (fig. O(2)) and Pass 1763, March 23 (fig. E). These were the only two visual reconnaissance flights made off the eastern Newfoundland coast; one the day after pass 1763 and a second, eight days later. In both cases substantial amounts of fast ice are indicated in the area of Notre Dame Day. This is a 1.0 concentration of winter ice. The reconnaissance flights of March 24 and April 1 were made in tactical support of a ship operating in the area north of Notre Dame Bay. The ice reconnaissance data obtained from the satellite on March 23 indicated that the ice pack boundary extended well out into the Atlantic. The captain of the ship had to decide whether it would be better to go south from his operating area north of Notre Dame Bay around Newfoundland and into his port in the western Gulf of St. Lawrence, or to go by the shorter route through the Strait of Belle Isle. No TIROS photographs from the satellite were possible in the Strait of Belle Isle area because of orbit limitation. If satellite ice surveillance had been available in conjunction with this operation, the flight around the eastern and northern Newfoundland coast might have been eliminated, and a single reconnaissance flight made into the Strait of Belle Isle area instead. The satellite photographs in the area indicated the presence of an opening shore lead along the Newfoundland coast, and if a passage through the Strait of Belle Isle had been possible, based on data obtainable from the aircraft, the TIROS photographic information probably would have been sufficient to reduce the number of reconnaissance flights into the Gulf significantly.

The above discussion comparing satellite photography with visual ice reconnaissance data has been brief, and a much more detailed analysis could be made. However, this report is intended to indicate some of the surveillance capabilities of satellites rather than to present complete research results. It is left to more experienced ice analysis to make a thorough comparison of the data provided in this report.

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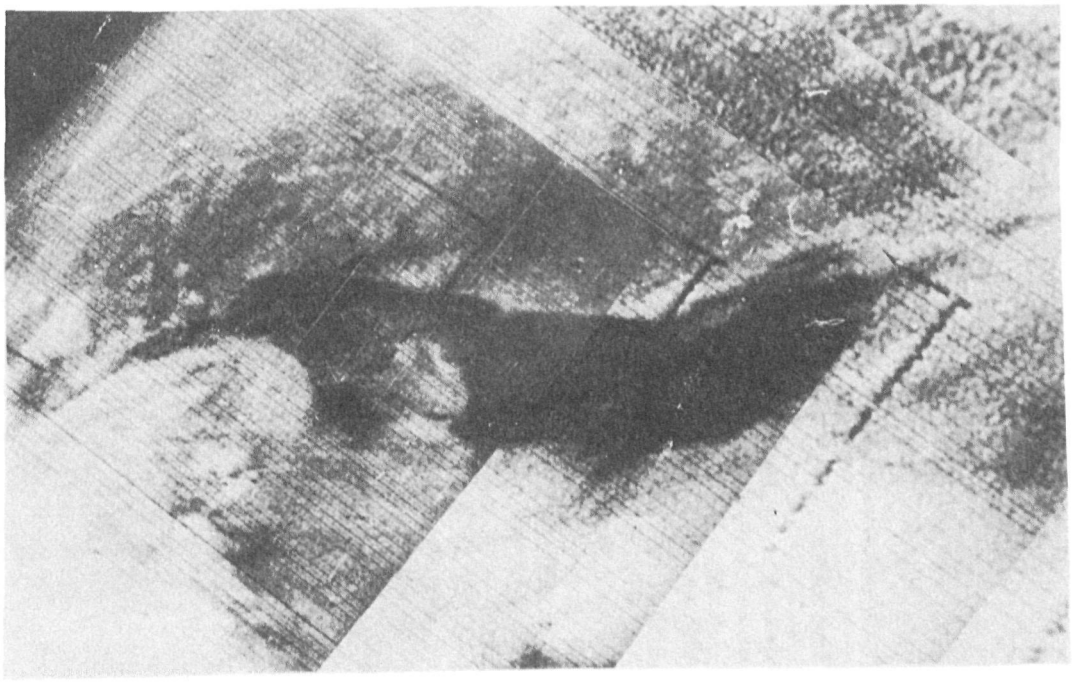

FIGURE A(1) PASS 0002 TIROS I APRIL 1, 1960

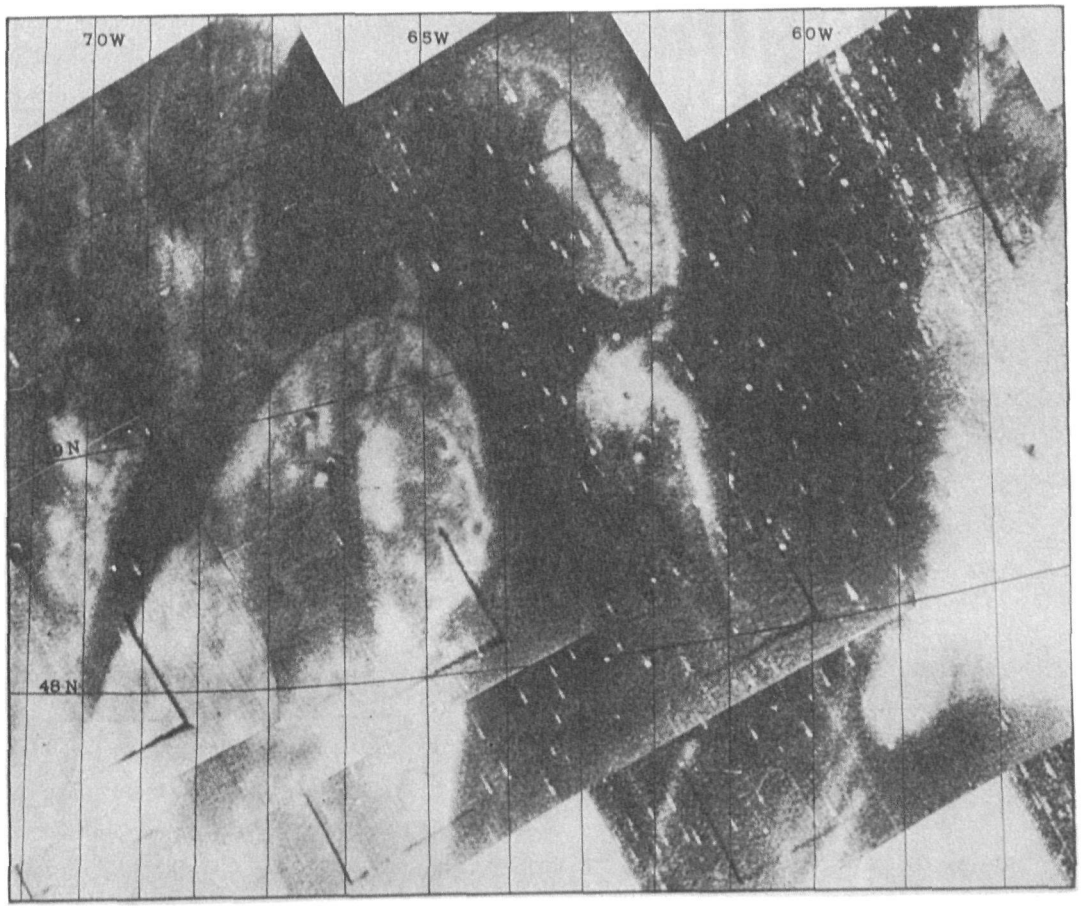

FIGURE A(2) PASS 0016 TIROS I APRIL 2, 1960

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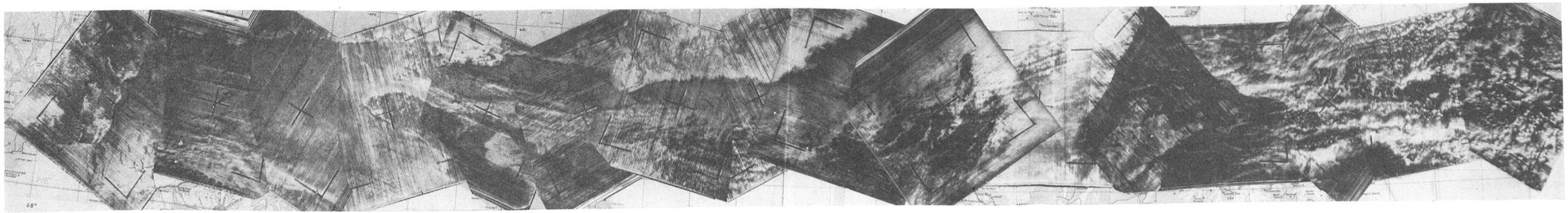
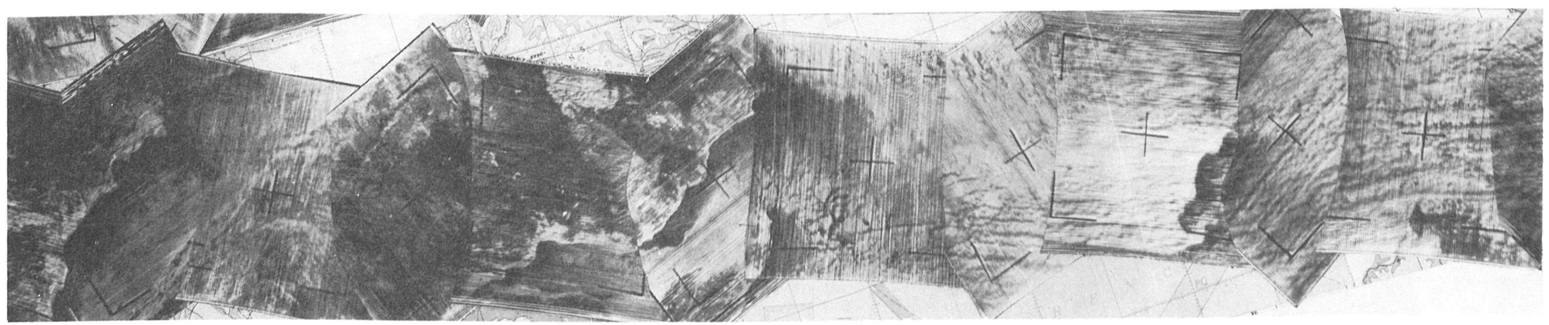


FIGURE B(1) PASS 911 JANUARY 24, 1961



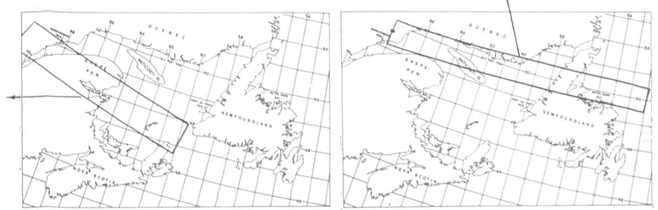


FIGURE B(2) PASS 941 JANUARY 26, 1961

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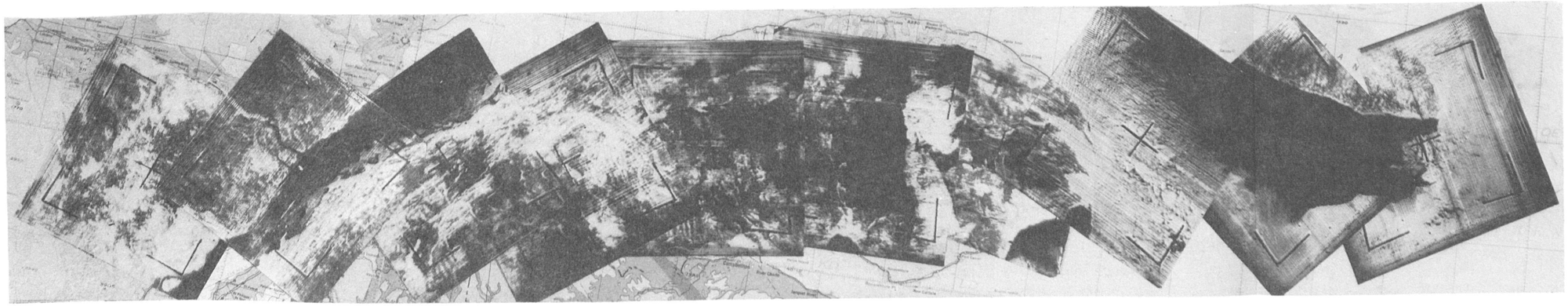


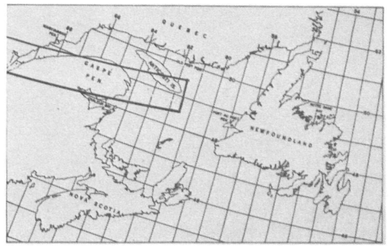
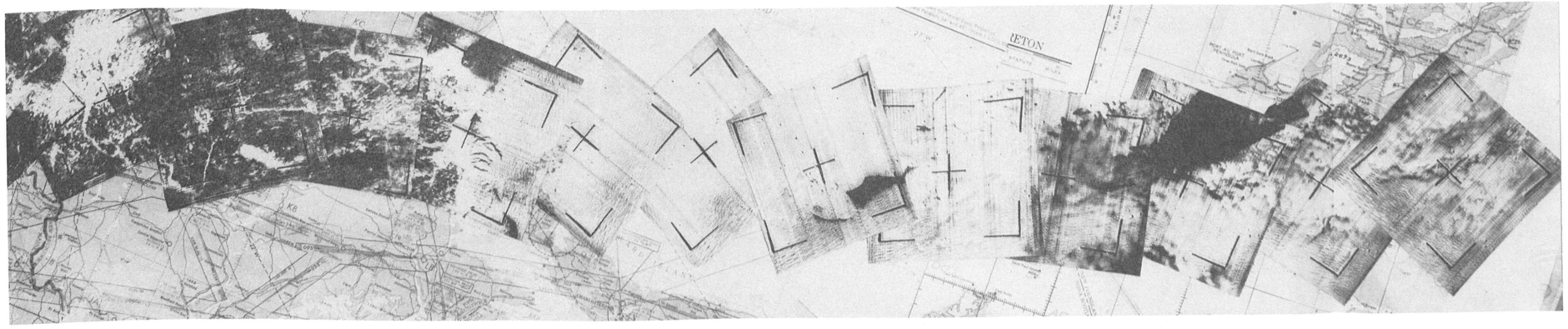


FIGURE C(1) PASS 1734 MARCH 21, 1961



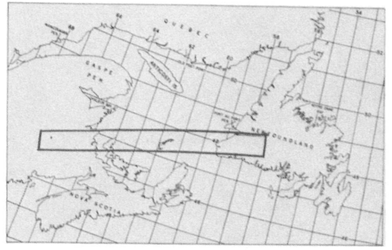


FIGURE C(2) PASS 1748 MARCH 22, 1961

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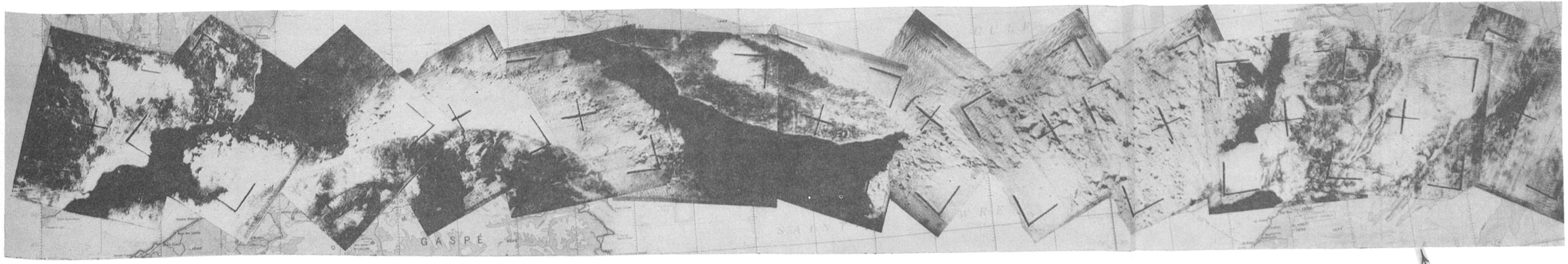
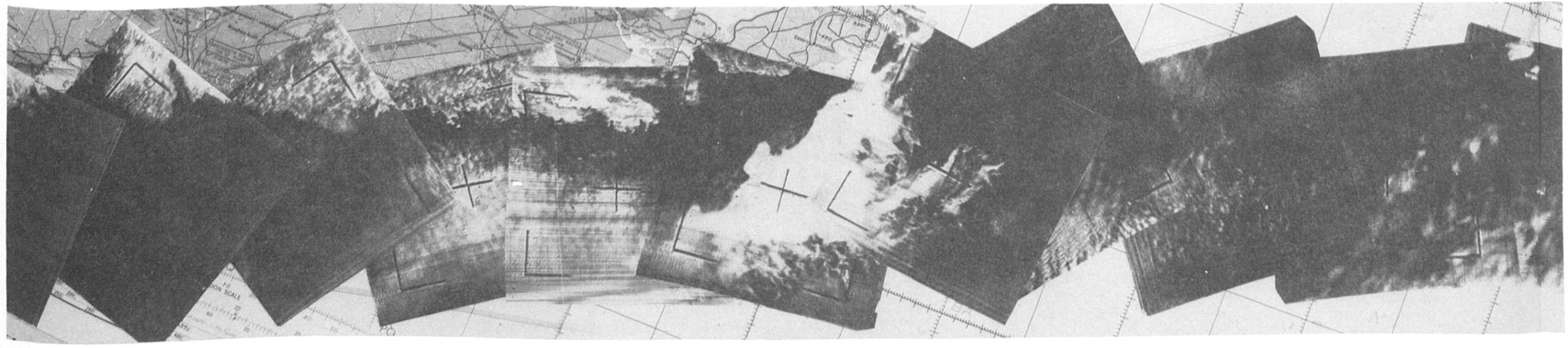


FIGURE D(1) PASS 1749 MARCH 22, 1961



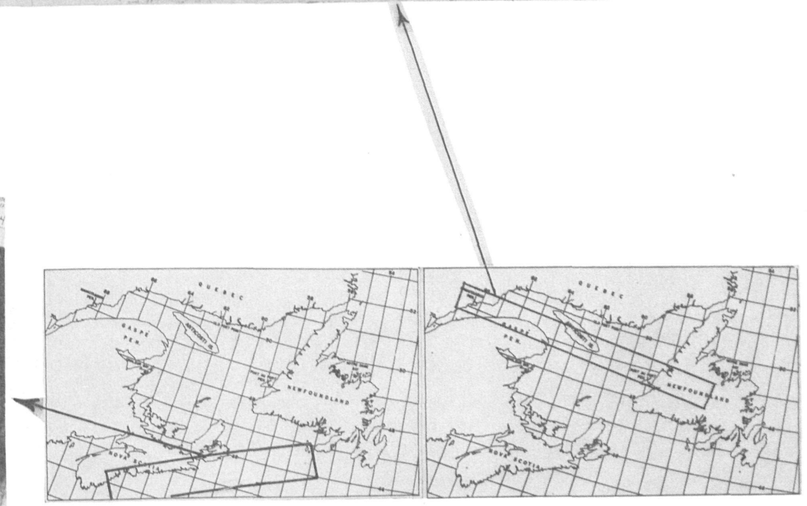


FIGURE D(2) PASS 1762 MARCH 23, 1961

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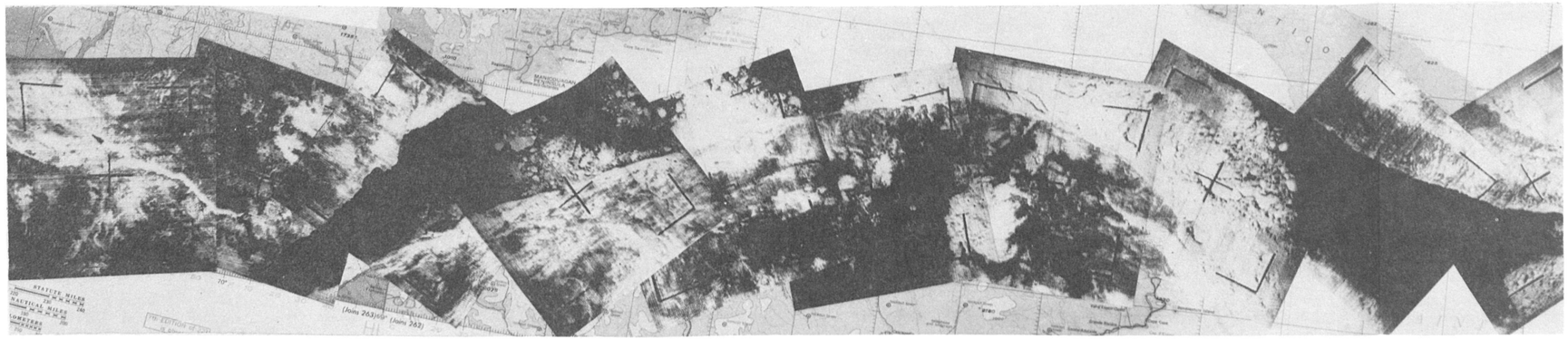

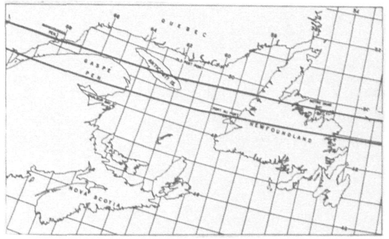

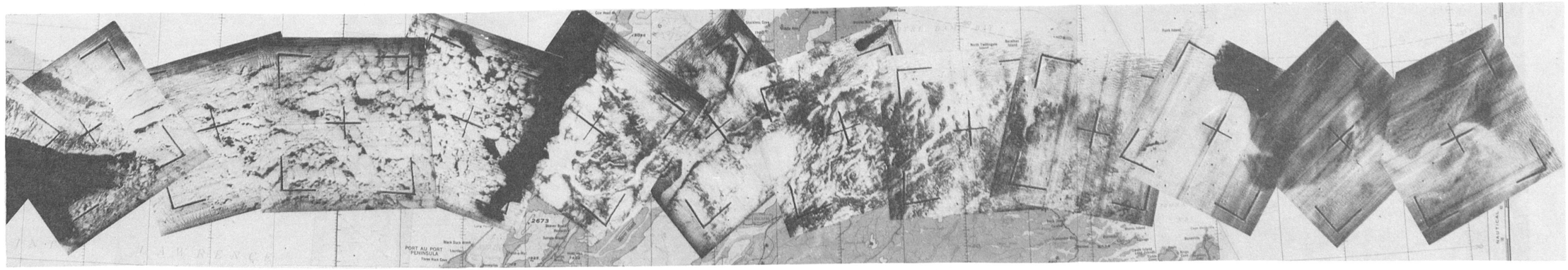

FIGURE E PASS 1763 MARCH 23, 1961

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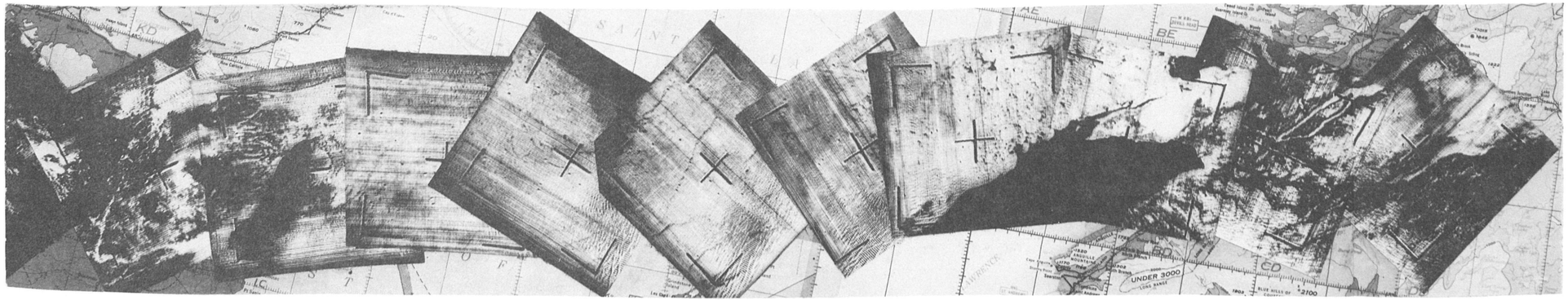

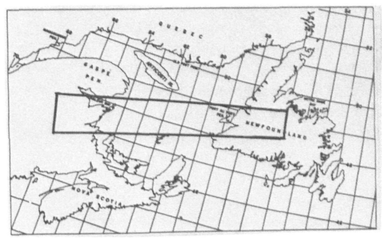

FIGURE F(1) PASS 1777 MARCH 24, 1961

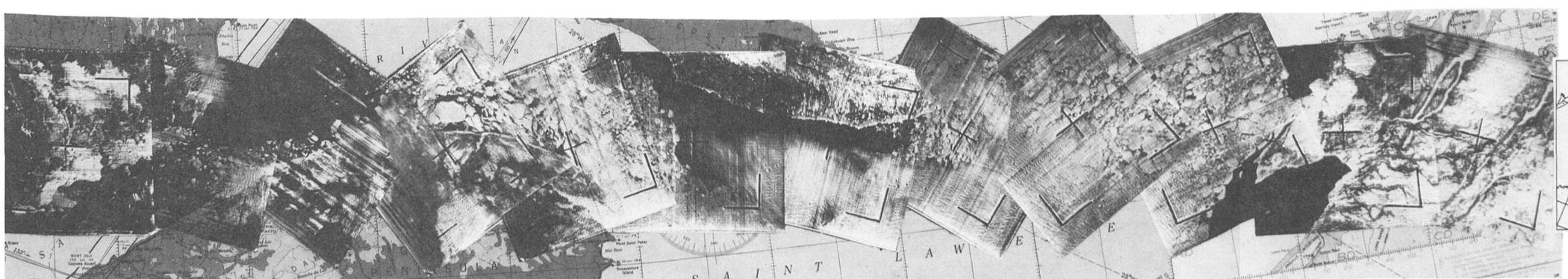

FIGURE F(2) PASS 1778 MARCH 24, 1961

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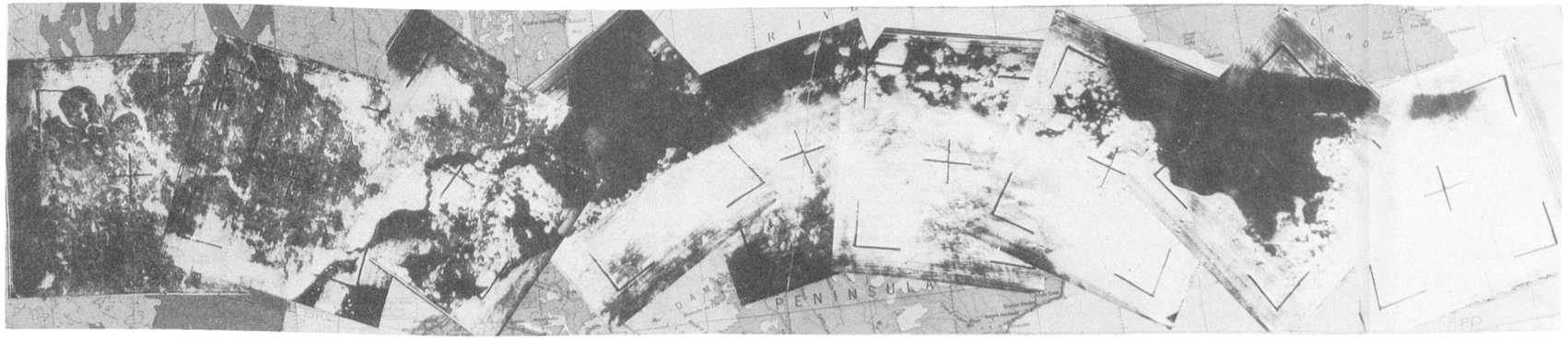


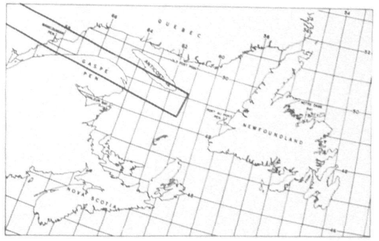
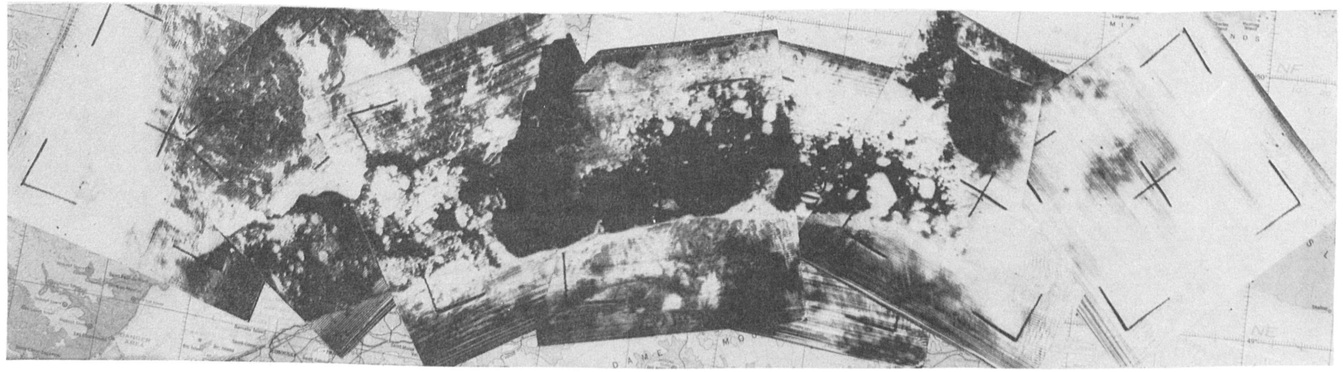


FIGURE G(1) PASS 1807 MARCH 26, 1961



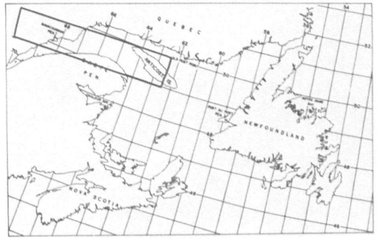


FIGURE G(2) PASS 1821 MARCH 27, 1961

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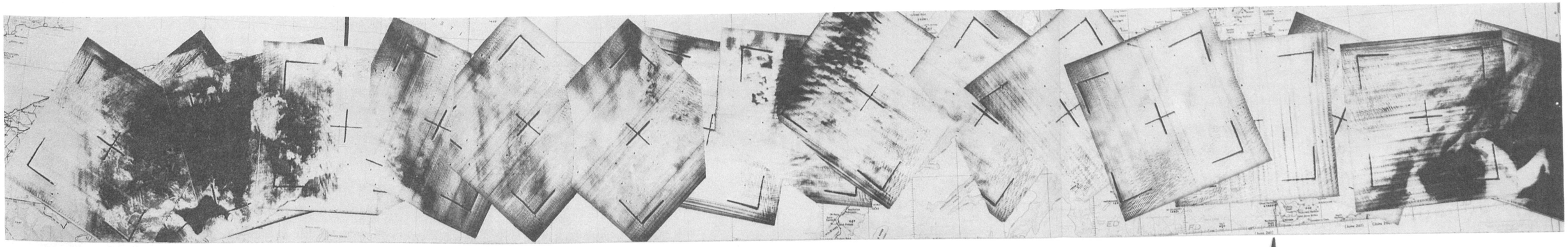
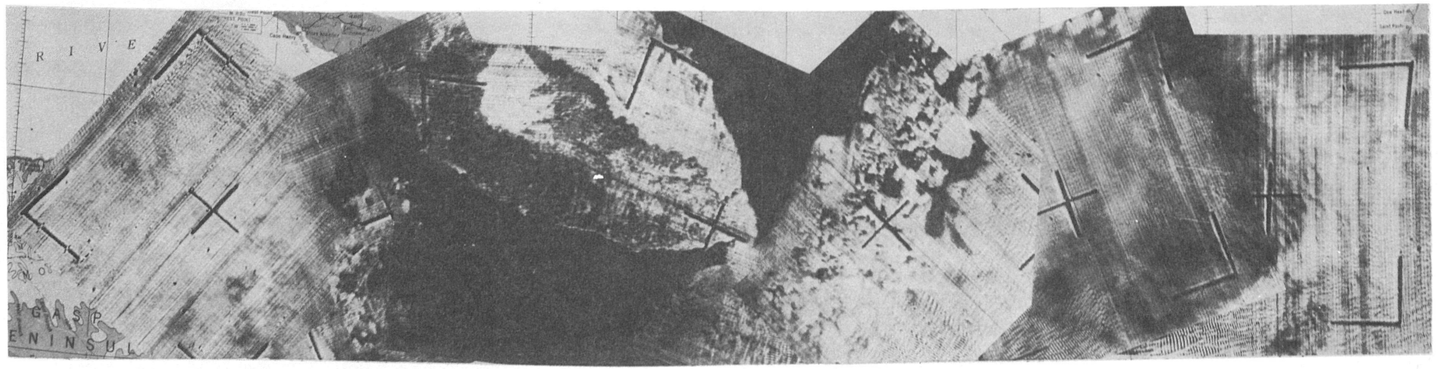


FIGURE H(1) PASS 1835 MARCH 28, 1961



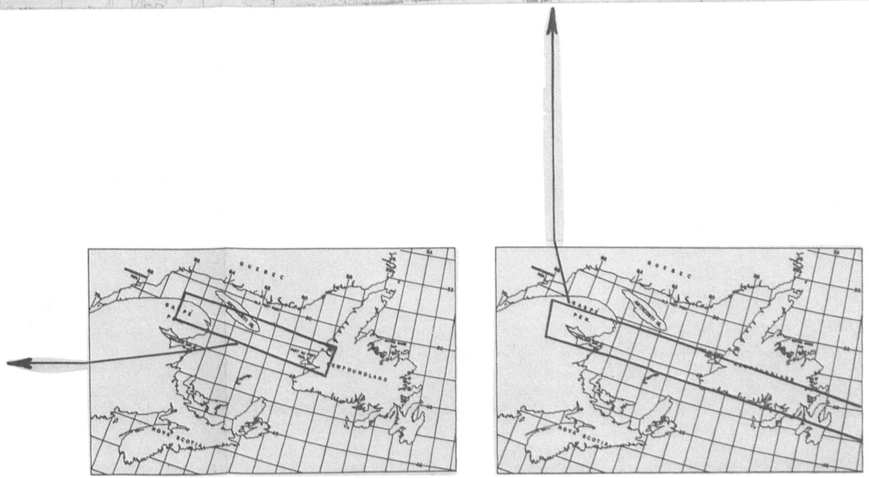


FIGURE H(2) PASS 1850 MARCH 29, 1961

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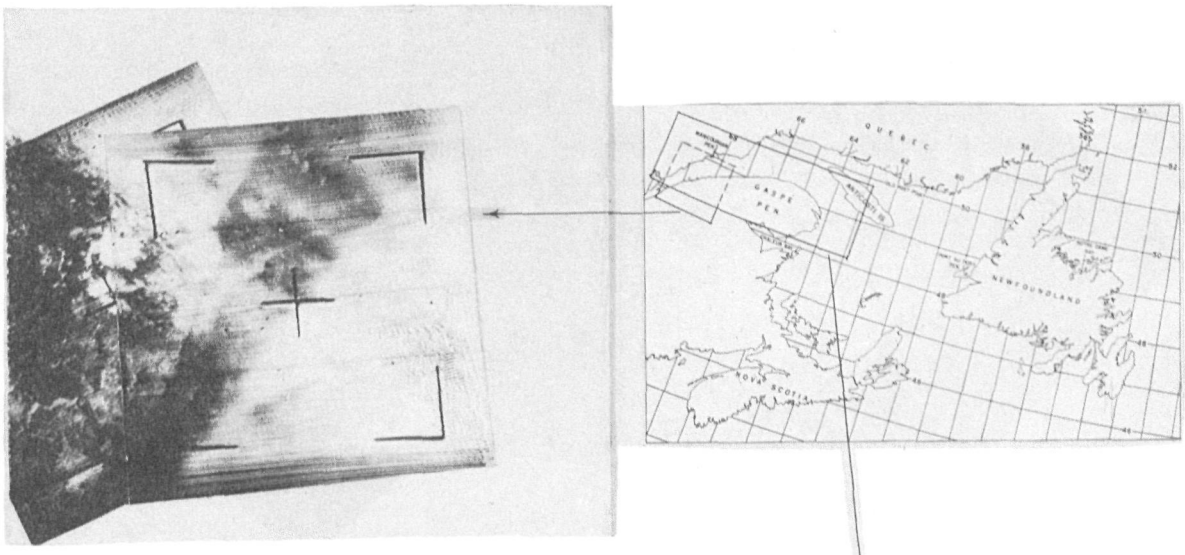

FIGURE I(1) PASS 1865 MARCH 30, 1961

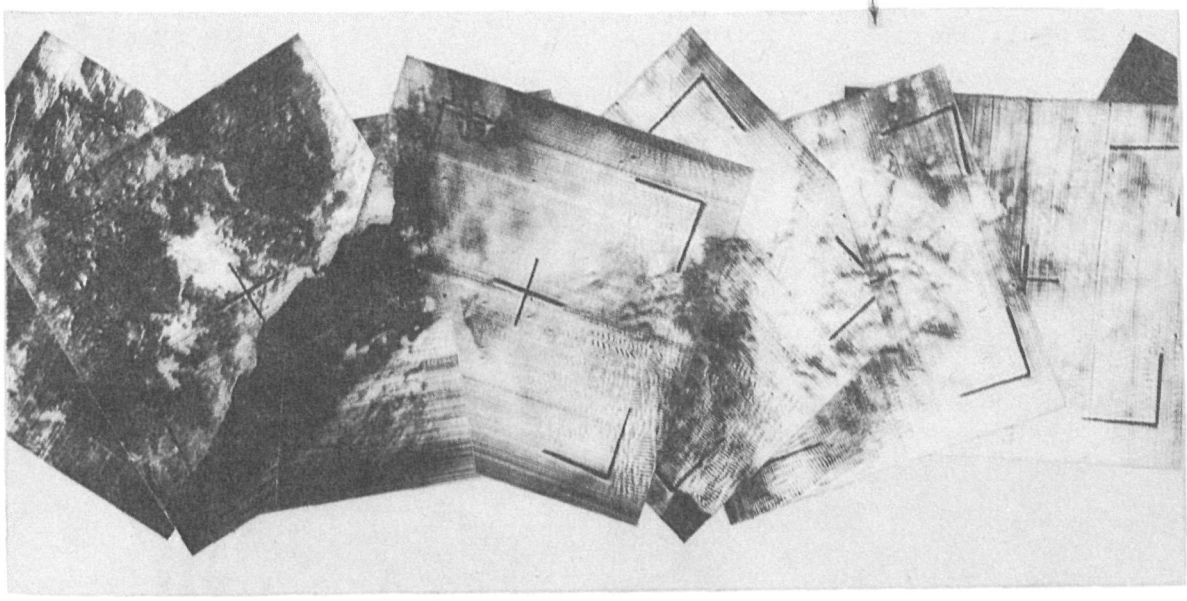

FIGURE I(2) PASS 1879 MARCH 31, 1961

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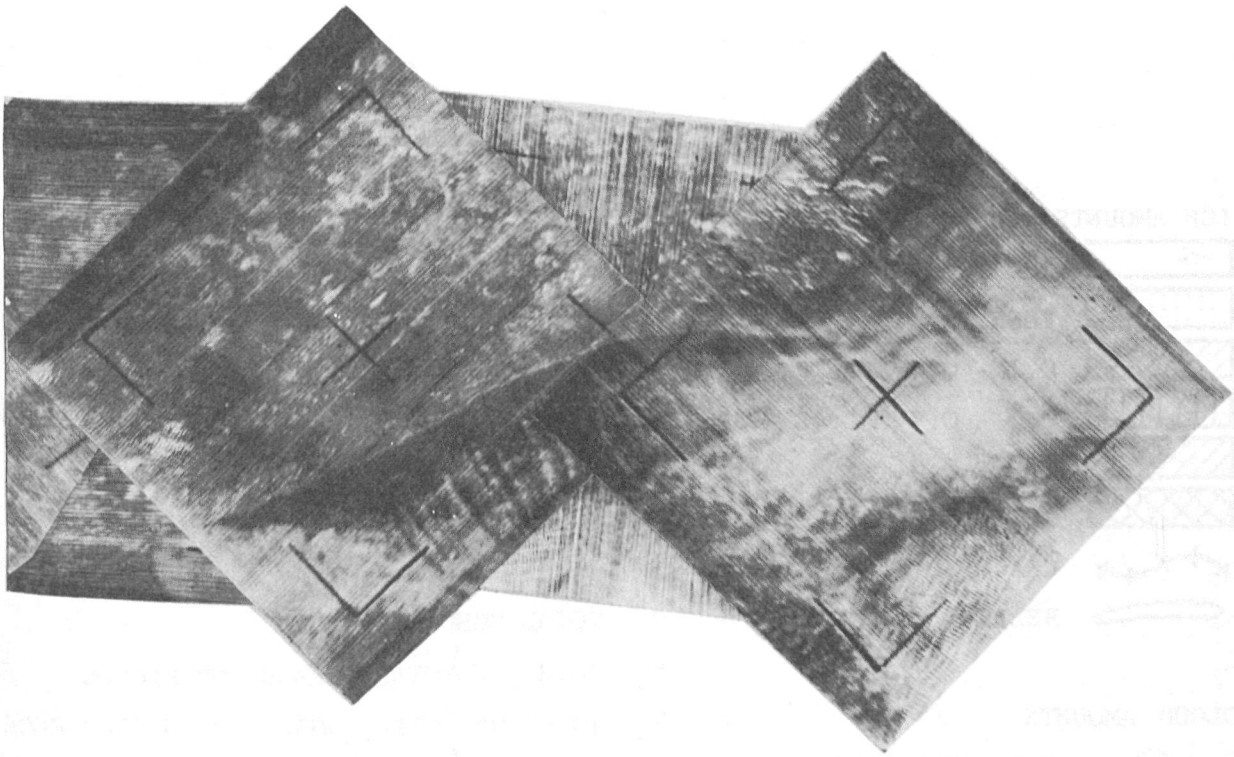

FIGURE J(1) (LAKE SUPERIOR) PASS 897 JANUARY 23, 1961

FIGURE J(2) (GEORGIAN BAY) PASS 1705 MARCH 19, 1961

ICE AMOUNTS AND FEATURES

- ICE FREE
- LESS THAN 0.1
- 0.1 - 0.4
- 0.5 - 0.7
- 0.8 - 0.9
- 1.0 - FAST ICE
- CRACKS
- BELTS

CLOUD AMOUNTS

- LESS THAN 0.1
- 0.1 - 0.4
- 0.5 - 0.9
- OVERCAST
- V VARIABLE

A

% or 10THS TYPE, % or 10THS TYPE, ETC.

A - AGE (IDENTIFIER)	W - WINTER
IC - ICE CRYSTAL	Y - YOUNG
SL - SLUSH	LYPD - LILYPAD
GRS - GREASE	PNK - PANCAKE

C

$N_1N_2N_3$

C - TOTAL CONCENTRATION

N_1- 10THS OF TOTAL, BRASH AND BLOCKS

N_2- 10THS OF TOTAL, SMALL AND MEDIUM FLOES

N_3- 10THS OF TOTAL, GIANT FLOES AND FIELDS

CLOUD SYMBOLS

- NO CLOUDS
- CLOUDS
- OBSERVED CLOUD LIMIT
- OBSERVED BOUNDARY LIMIT

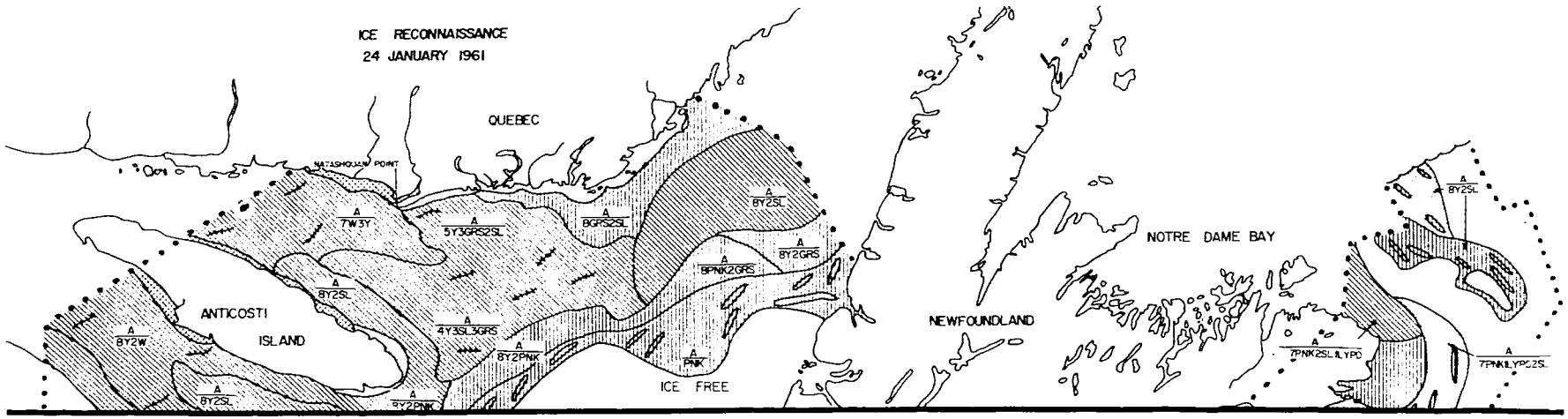

FIGURE K(1) U. S. NAVY ICE RECONNAISSANCE JANUARY 24, 1961

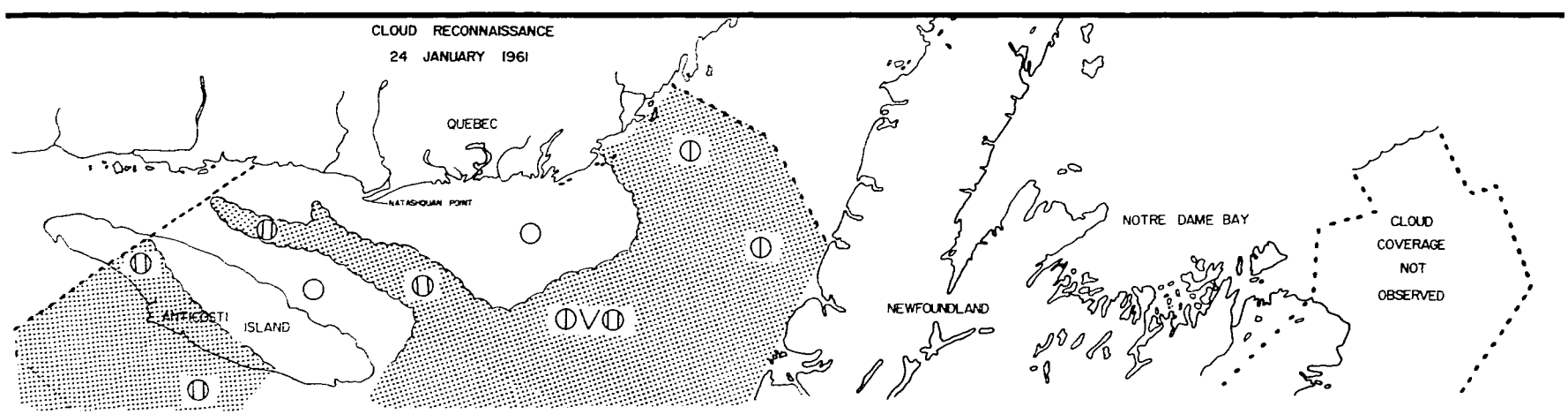

FIGURE K(2) U.S. NAVY CLOUD RECONNAISSANCE JANUARY 24, 1961

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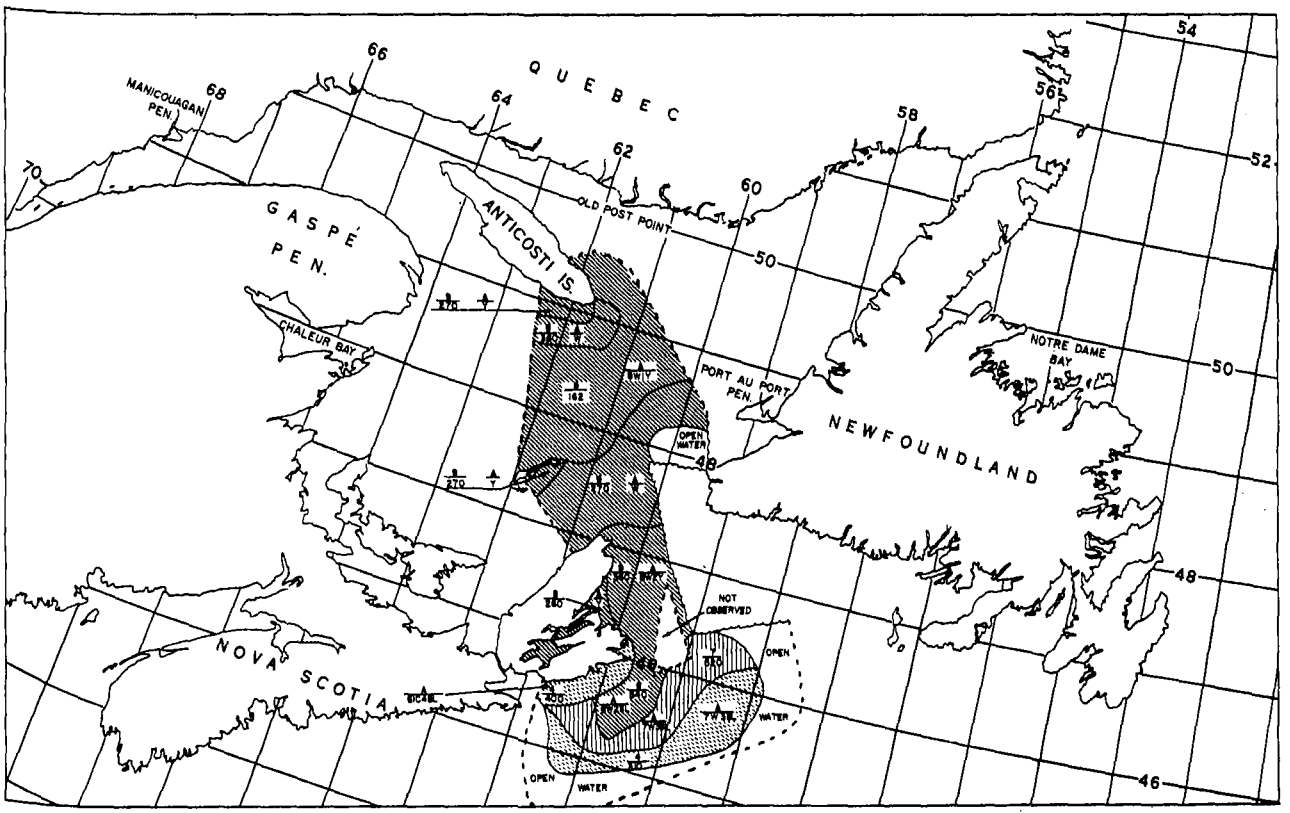

FIGURE L(1) CANADIAN METEOROLOGICAL SERVICE ICE RECONNAISSANCE MARCH 19, 1961

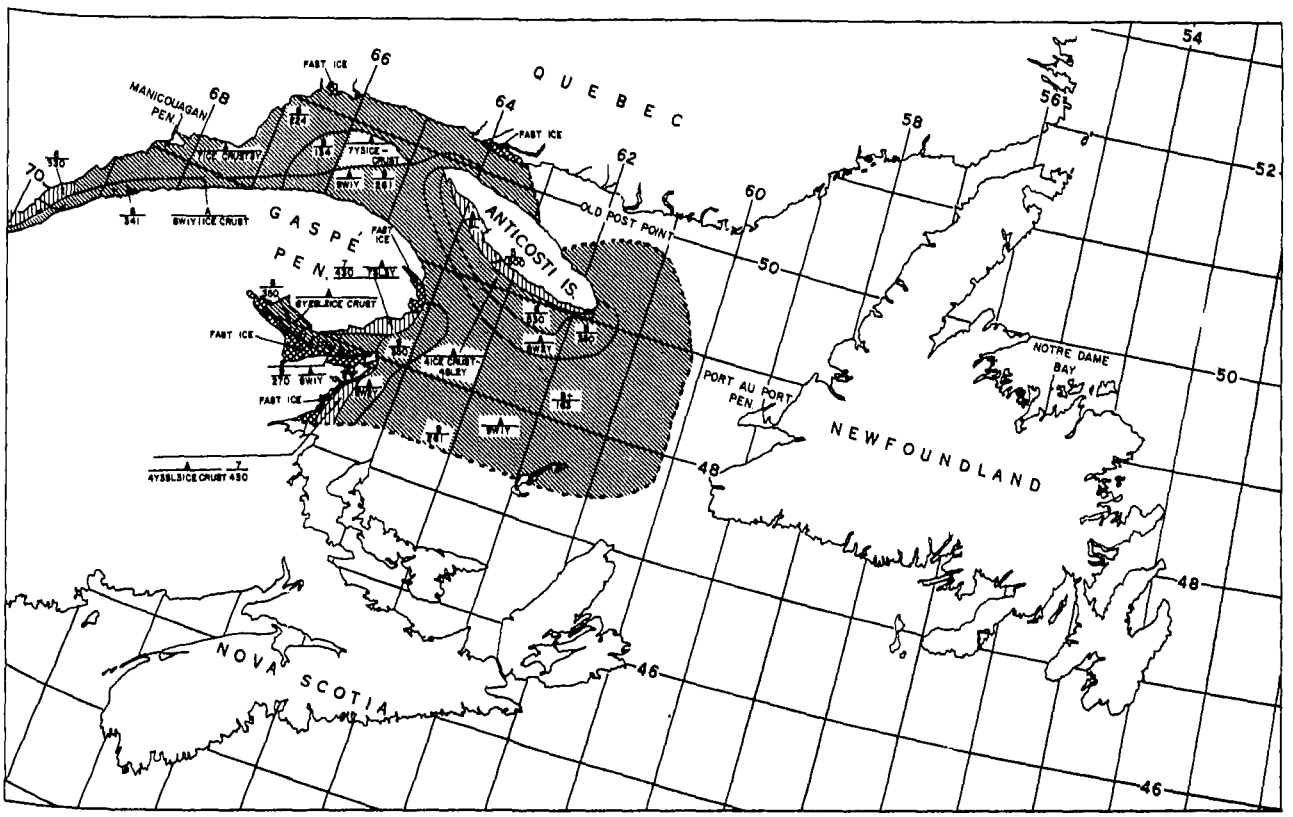

FIGURE L(2) CANADIAN METEOROLOGICAL SERVICE ICE RECONNAISSANCE MARCH 21, 1961

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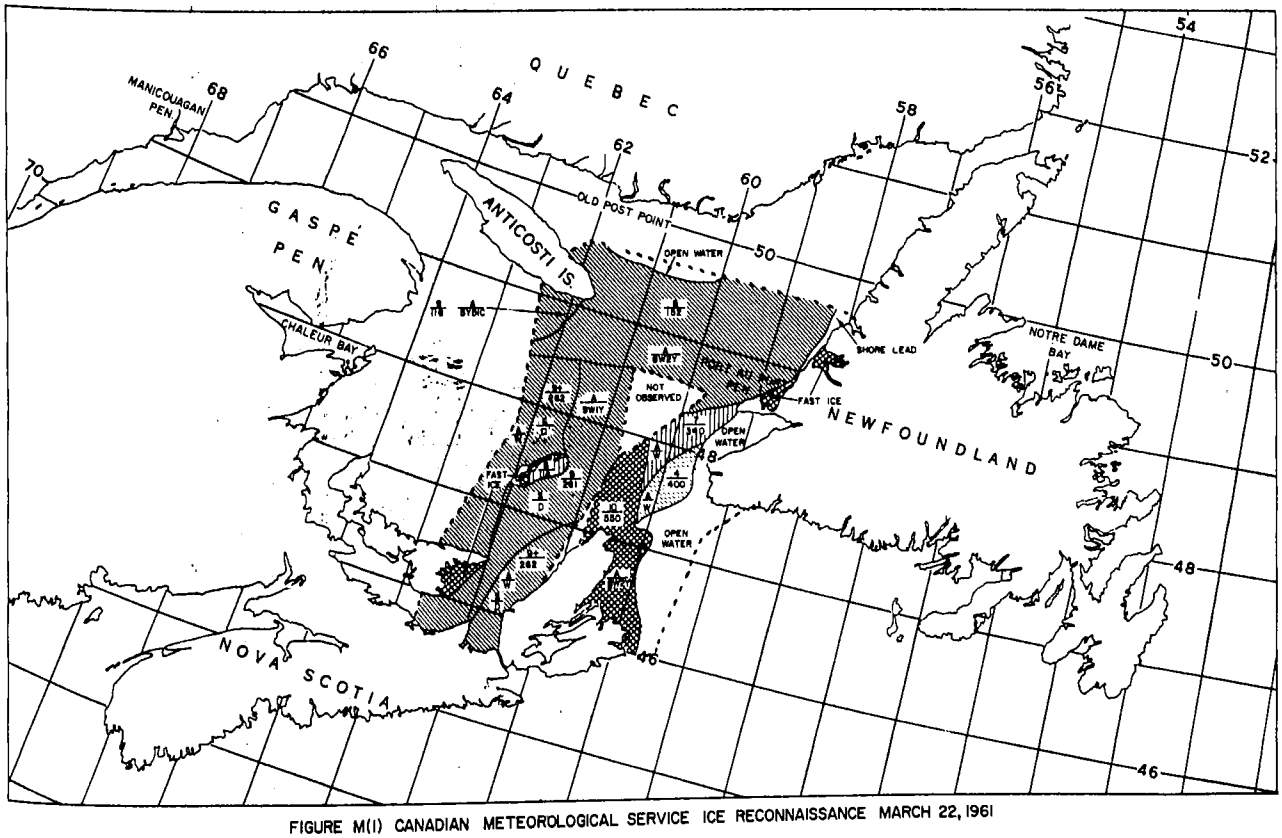

FIGURE M(1) CANADIAN METEOROLOGICAL SERVICE ICE RECONNAISSANCE MARCH 22, 1961

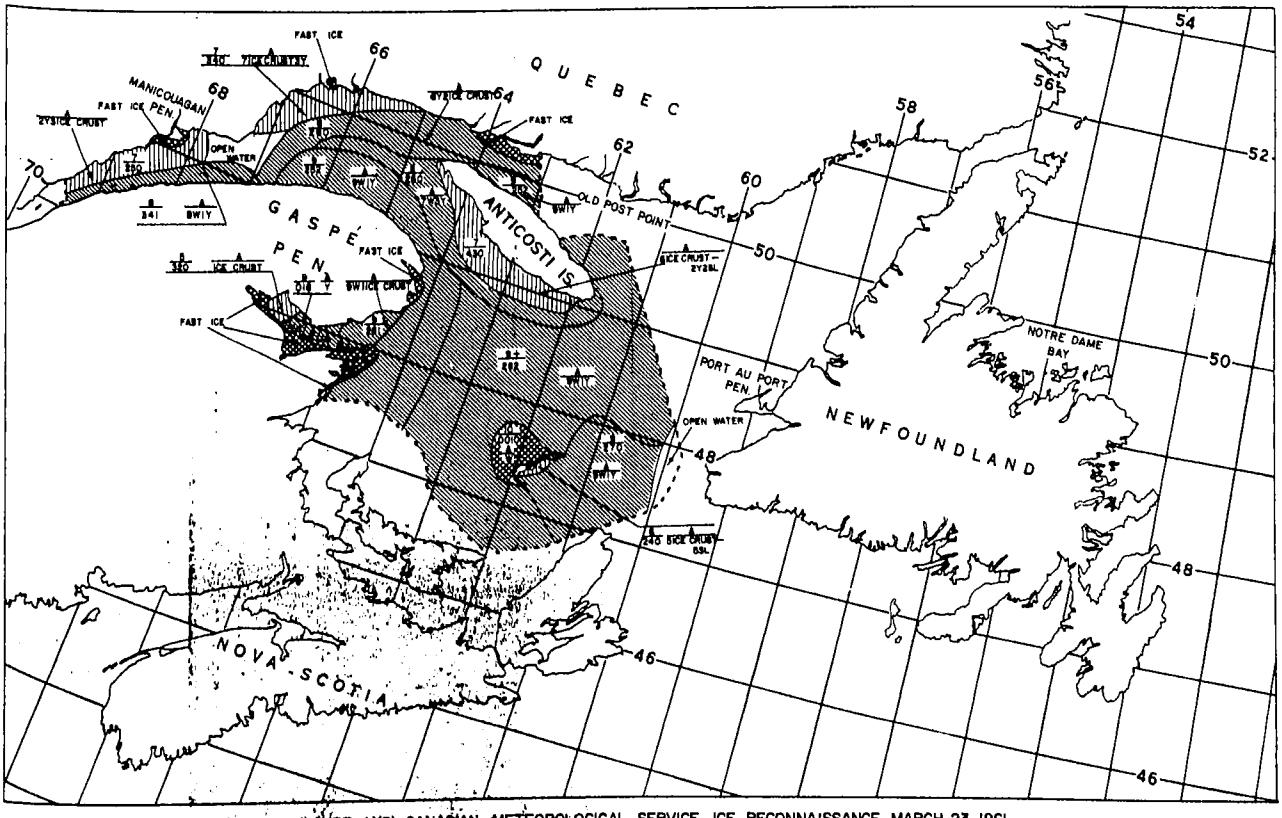

FIGURE M(2) CANADIAN METEOROLOGICAL SERVICE ICE RECONNAISSANCE MARCH 23, 1961

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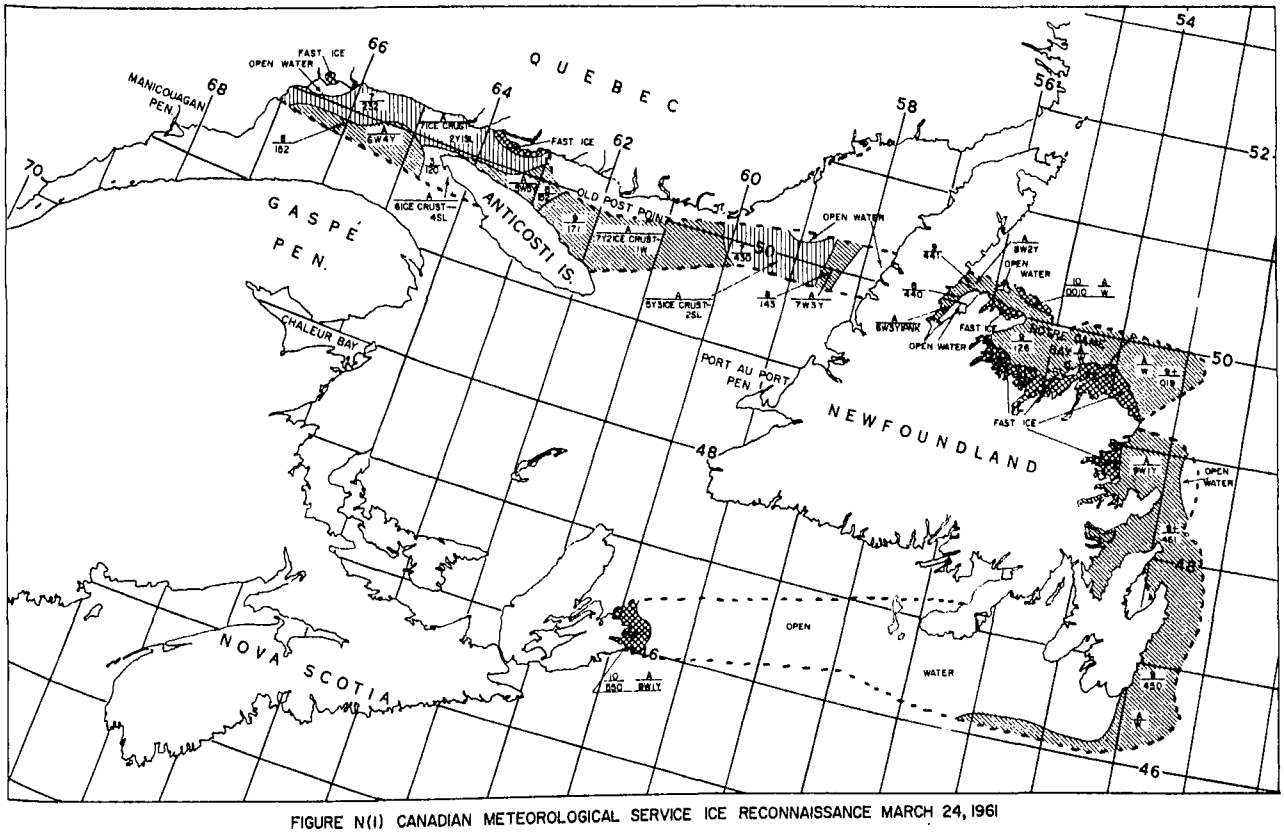

FIGURE N(1) CANADIAN METEOROLOGICAL SERVICE ICE RECONNAISSANCE MARCH 24, 1961

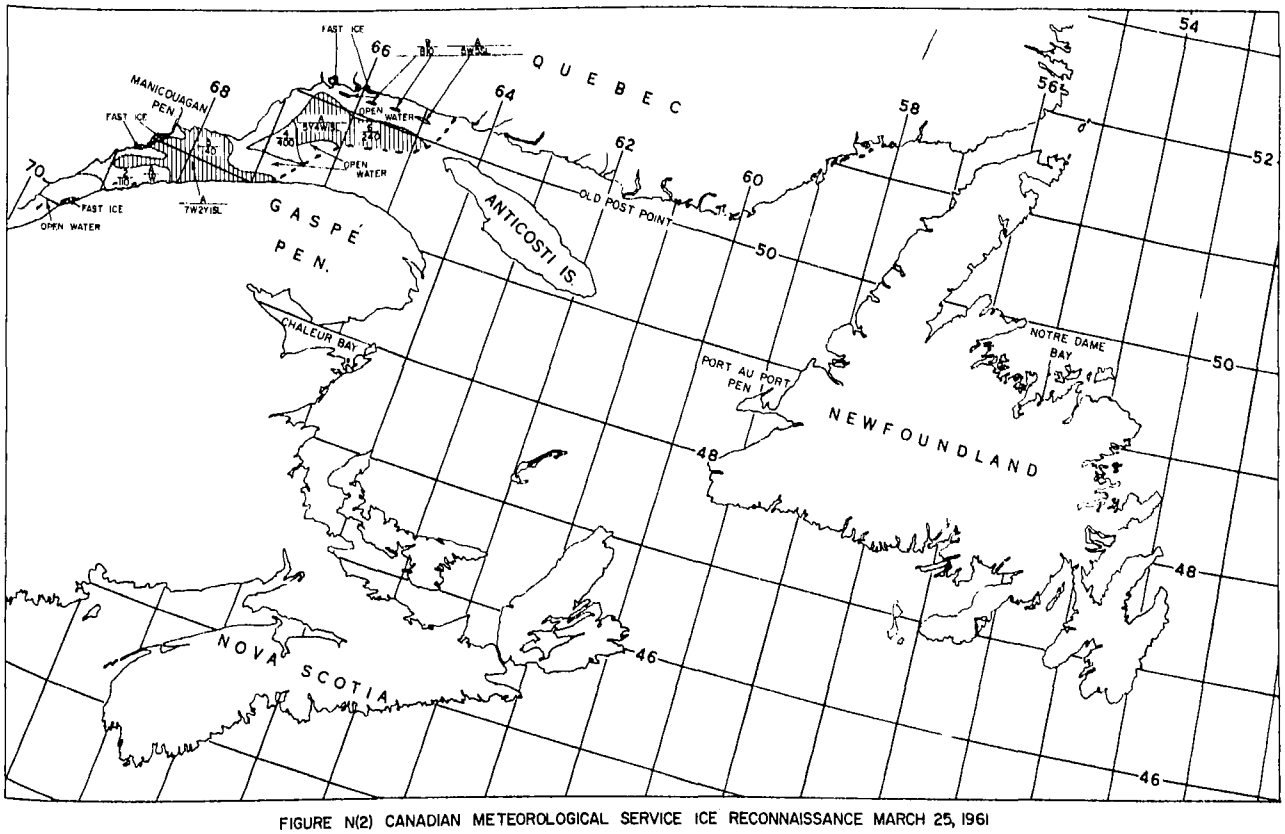

FIGURE N(2) CANADIAN METEOROLOGICAL SERVICE ICE RECONNAISSANCE MARCH 25, 1961

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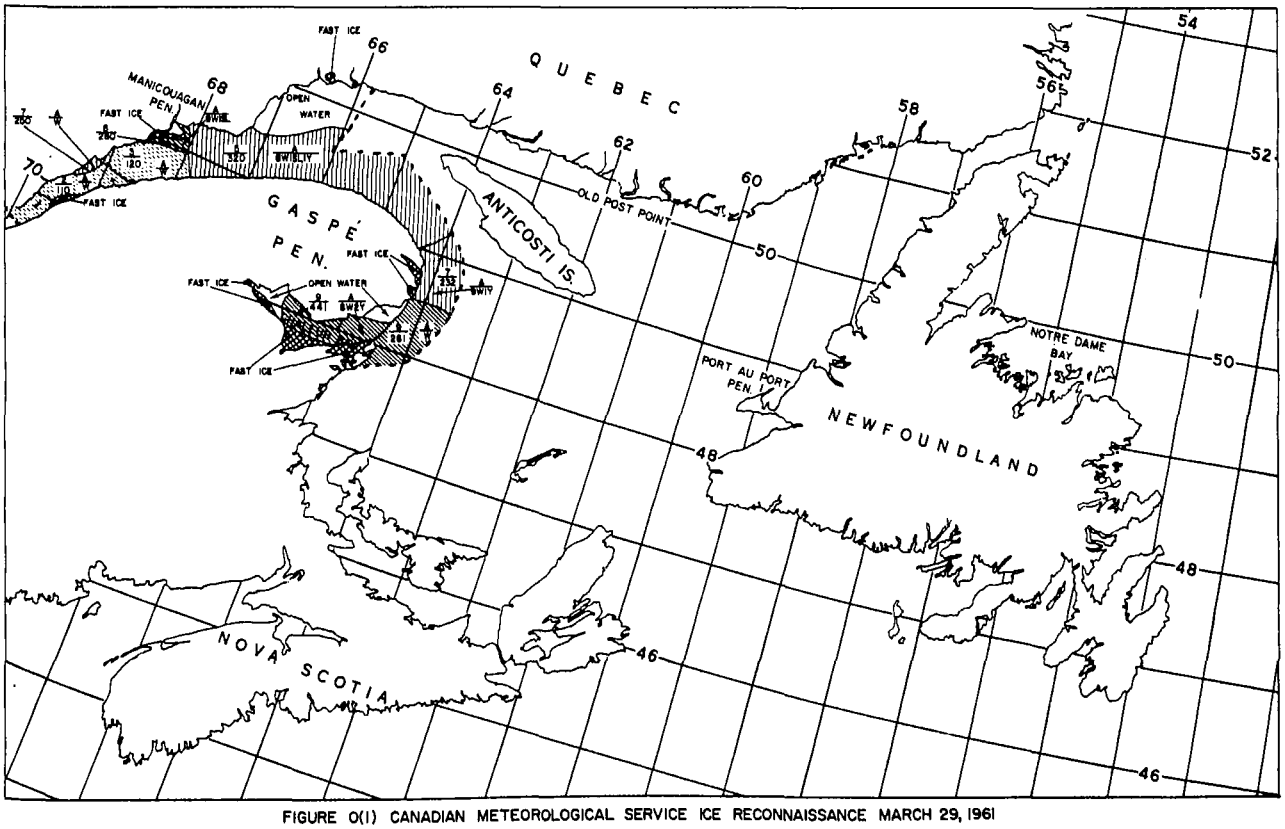

FIGURE 0(1) CANADIAN METEOROLOGICAL SERVICE ICE RECONNAISSANCE MARCH 29, 1961

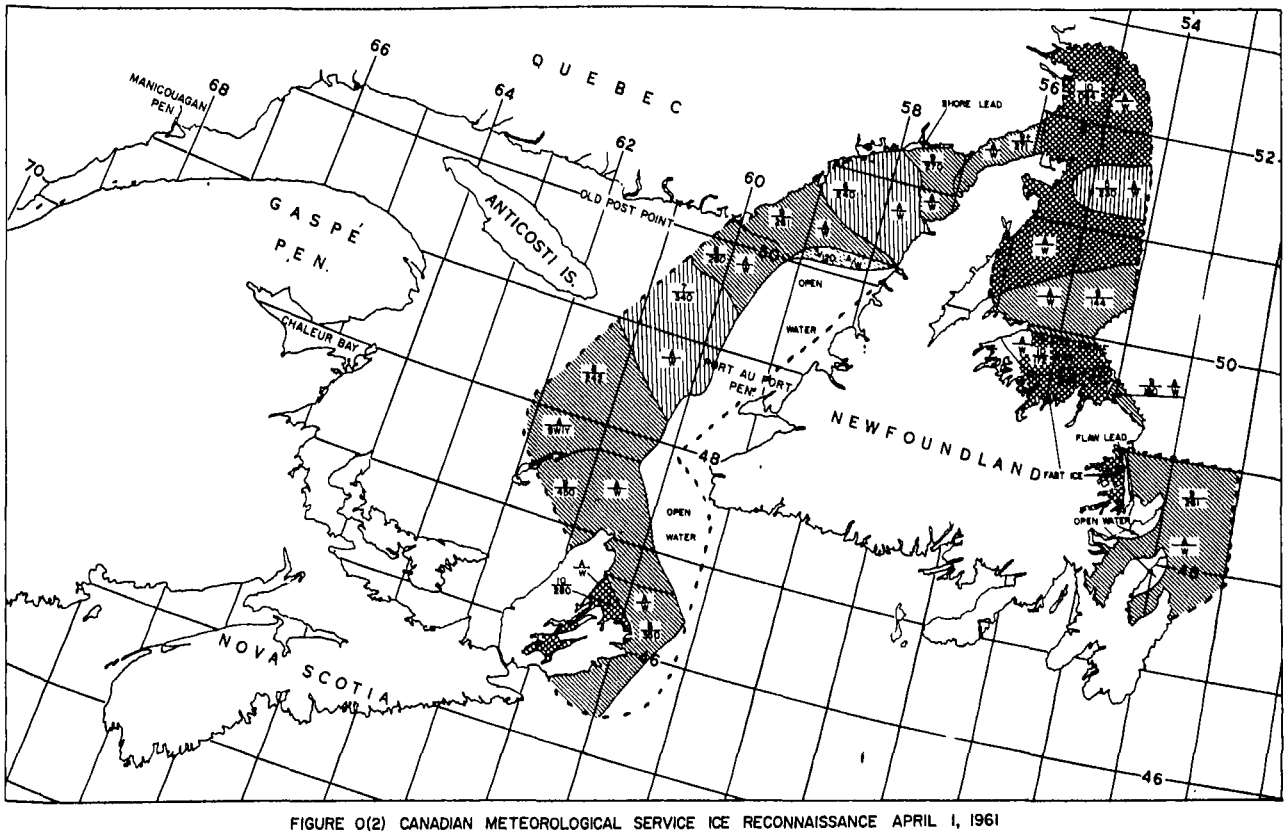

FIGURE 0(2) CANADIAN METEOROLOGICAL SERVICE ICE RECONNAISSANCE APRIL 1, 1961

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ACKNOWLEDGMENTS

In a study such as this to which so many agencies and activities have contributed their efforts, it is not possible to thank all participants individually. We would, however, like to express our special thanks to LT. (jg) W. A. Dotson and Ens. K. S. Colaw of the Aerial Reconnaissance Section, U. S. Navy Hydrographic Office for their part in both the planning and the operations; to U. S. Navy personnel at NAS Argentia, including CDR. R. M. Albrecht, COMBARLANT Staff Meteorologist, CDR. C. R. Champion and CDR. H. A. Willyard, VP-23 Commanding Officer and Executive Officer respectively, and to the rest of the officers and men of VP-23 who flew these missions; to Chief Photographers Mate R. F. Reynolds who took the aerial photographs; to G. Jager and D. M. Mercer of the Meteorological Satellite Laboratory, A. E. Battisfore, Photogrammetry Branch, Nautical Chart Division, U. S. Navy Hydrographic Office, and to Prof. H. L. Cameron, Nova Scotia Research Foundation, Halifax, Canada.

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APPENDIX I

GLOSSARY OF TERMS

The definitions given in the following glossary were taken mostly from Hubert [4] and USNHO No. 609 [5]; those marked with an asterisk (*) have been framed by the authors of this report.

Age (of ice): The stages in the ice cycle from inception to dissolution. Not to be confused with Ice Age, a subdivision of geologic time.

Attitude:* Orientation of the spin axis with respect to a reference frame. It is the practice to use celestial coordinates for TIROS satellites.

Belt: A relatively narrow band of fragments of floating or fast ice of any concentration.

Block: A fragment of sea ice ranging in size from 6 to 30 feet across.

Brash: Small fragments of sea, lake, or river ice less than 6 feet across; the wreckage of other forms of ice.

Camera orientation:* In TIROS satellites the orientation of the optic axis of a camera, usually in celestial coordinates; this may differ slightly from attitude if the optic axis is not parallel to the spin axis.

Crack: A small, unnavigable, narrow break in sea ice that may reveal the sea water surface. Cracks are usually caused by tides, temperature change, current, and/or wind.

Direct picture:* A video picture from a TIROS satellite transmitted immediately to the readout or data acquisition station. See Remote Picture.

Fast ice: All types of ice, either broken or unbroken, attached to the shore, beached, stranded in shoal water, or attached to the bottom of shoal areas.

Fiducial mark:* A reference mark permanently fixed to the front face of the vidicon tube in the TIROS camera. Four marks are placed toward the corners and one near the center; they appear in every photograph.

Floe: The term floe is used for referring to fragments of ice (other than icebergs and other land ice) with no specific size intended. However, unlike the term cake, when floe is used with such qualifying terms as small, medium, or giant, a rather definite size is implied. Terms for describing floes of specific size are: brash, block, small floe, medium floe, giant floe, and ice field. Another distinction is that a floe may consist of a single fragment of ice or many consolidated fragments, whereas cake implies a single unbroken fragment of ice. Floe is also used with such qualifying terms as heavy and light, but these terms imply thickness rather than area limit.

Giant floe: A floe ranging in size from 3,000 feet to about 5 miles across.

Grease ice: A kind of slush formed from congelation of ice crystals in the early stages of freezing. It gives the sea surface a greasy appearance.

Ice crust: Thin, hard sea ice. Ice crust has varying degrees of whiteness depending upon age, thickness, and/or the rapidity of formation.

Ice crystal: The form in which ice always occurs in nature. The shape of ice crystals depends upon the conditions under which freezing takes place.

Ice edge: The boundary at any given time between pack ice and the open sea. It may be a regular line with considerable tightening of the floes along the edge, or may consist of a succession of belts or patches, or may be frayed out into a number of points and bights, with perhaps off-lying isolated fragments. The position of the ice edge depends on wind and tide and varies considerably from month to month and from year to year.

Ice field: The largest of sea ice areas. An ice field is so called because of its size only (more than 5 miles across).

Ice pack:
(1) - Any large area of floating ice driven closely together.
(2) - The entire area of ice in the polar seas and the seas surrounding Antarctica.

Lead: A long, narrow, but navigable water passage in pack ice. A lead may be covered by thin ice.

Medium floe: A floe ranging in size from 600 to 3000 feet across.

Nadir angle: The angle measured at the intersection point at the satellite between some specified line and the local vertical.

Narrow-angle photograph:* TIROS photograph from camera subtending 12.7° in the diagonal, also referred to as Camera 1 on the first two TIROS satellites.

Open water: Water that is less than one tenth covered with floating ice.

Optic axis: The ray perpendicular to the image plane passing through the lens nodal points.

Orbit (number)*: Pass number.

Pancake ice: Pieces of newly formed ice usually between one and six feet in diameter. The raised rims and the circular appearance are a result of the almost constant rotation and collision of the cakes against one another. Small cakes up to about 18 inches in diameter are occasionally called lily pad ice.

Pass (number)*: The number of the passage of the ascending node or northward equatorial passage since the launching of the satellite. All activity of the satellite until the next passage of the ascending node is identified by this number.

Patch: An irregular cluster of floating ice fragments of any concentration.

Picture center:* Principal point. This point is near the center fiducial mark.

Principal point: The image principal point is the point of intersection of the camera optic axis with the image plane. The earth principal point is the point of intersection of the optic axis with the earth's surface.

Puddle: A depression on sea ice filled with melt water. The water in puddles is much lighter in color than sea water. Puddles are a surface feature that may occur on any ice.

Remote picture: A satellite video picture taken beyond range of direct communication with the readout station. It is stored on magnetic tape and transmitted to the ground when the satellite passes near the readout station.

Satellite path:* The track followed by the sub-satellite point.

Sea ice: Ice formed by the freezing of sea water.

Shore lead: A lead between floating ice and the shore or between floating ice and fast ice.

Slush: An accumulation of ice crystals which may or may not be slightly frozen together. Slush has no degree of hardness.

Small floe: A floe ranging in size from 30 to 600 feet in diameter.

Spin axis:* The axis containing the total angular momentum vector of the satellite. It nearly coincides with the major inertial axis and is nearly parallel to the optic axes of the cameras.

Spin axis point: The point of intersection with the earth's surface of the satellite spin axis vector after that vector has been translated parallel to itself to an origin at the earth's center.

Sub-satellite point: Intersection of the local vertical, passing through the satellite, with the earth's surface.

Swath:* A band on the earth's surface encompassing the path followed by the principal point and limited by the area viewed by the camera.

Wide-angle photograph:* TIROS photograph from camera subtending 104° in the diagonal, also referred to as Camera 2 on the first two TIROS satellites.

Winter ice: Sea ice more than 8 inches thick formed and developed in one winter. Winter ice is therefore one year old or less, and is usually less than 12 feet thick. However, if the ice is disturbed by external forces such as wind and current, the thickness of the ice cannot be used to infer its age.

Young ice: Newly-formed ice between 2 and 8 inches thick in the transitional stage of development from ice crust to winter ice.