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Applicability of ERTS for Surveying Antarctic Iceberg Resources

John L. Hult and Neill C. Ostrander

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16. Abstract

This investigation explores the applicability of ERTS to (a) determine the Antarctic sea-ice and environmental behavior that may influence the harvesting of icebergs, and (b) monitor iceberg locations, characteristics, and evolution. Imagery sampling in the western Antarctic between the Peninsula and the Ross Sea is used in the analysis. It is found that the potential applicability of ERTS to the research, planning, and harvesting operations can contribute importantly to the promise derived from broader scope studies for the use of Antarctic icebergs to relieve a growing global thirst for fresh water. Live Antarctic readout will permit timely acquisition of imagery on every orbital pass, which will be necessary to achieve adequate glimpses through the 80 percent cloud cover. Thermal sensor bands will provide coverage in daylight or darkness. Several years of comprehensive monitoring will be necessary to characterize sea-ice and environmental behavior and iceberg evolution. Live ERTS services will assist harvesting control and claiming operations and offer a means for harmonizing entitlements to iceberg resources. The valuable ERTS services will be more cost effective than other means and will be easily justified and borne by the iceberg harvesting operation.

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PREFACE

This is a report on *Applicability of ERTS for Surveying Antarctic Iceberg Resources*, a project that was accepted for participation in NASA's first Earth Resources Technology Satellite program (ERTS-1). Most of the data analysis and work reported herein were supported by the Directorate of Research Applications, Office of Exploratory Research and Problem Assessment of the National Science Foundation, under an ongoing program entitled *A Feasibility Study of Polar Ice as a Fresh Water Resource*. A recent report from the program, *Antarctic Icebergs as a Global Fresh Water Resource* (R-1255-NSF), provides background orientation and preliminary concepts for using Antarctic iceberg resources, and is a basis for evaluating the potential application for ERTS.

This investigation was exploratory in nature. Only enough imagery sampling was requested to determine the applicability of ERTS for surveying Antarctic iceberg resources and to confirm estimates of the general abundance of icebergs with suitable characteristics for economic global transport as a source of fresh water. Much more comprehensive imagery, supplemented with ground truth data, during several yearly seasonal cycles will be required to provide an adequate inventory of Antarctic icebergs, their characteristics, and their evolution, and to characterize confidently the sea-ice and environmental behavior critical to the design and planning of iceberg harvesting operations.

This report should be useful for planning future ERTS programs and in the collection of imagery for the harvesting of Antarctic iceberg resources, as well as for potential users and suppliers of Antarctic icebergs and governments or agencies concerned with the development or control of these resources.

The authors wish to acknowledge the assistance, comments, and sources of information provided by Edward W. Crump of the Goddard Space Flight Center, NASA; the review and comments of Rand colleagues Jeannine V. Lamar, Charles Schutz, Ralph E. Huschke, and S. M. Olenicoff; the collection of statistical details from the imagery by F. Y. Katayama; and the editorial assistance of Jeanne Dunn. The authors accept the responsibility for any errors of fact or interpretation.

SUMMARY

This report gives the results of an ERTS-1 investigation entitled *Applicability of ERTS for Surveying Antarctic Iceberg Resources*. The very limited sampling of the orbital passes over Antarctica from which imagery was obtained provided enough information to satisfy the objectives.

This investigation is one of a series exploring various aspects of the feasibility of using Antarctic icebergs as a global fresh water resource. Related investigations that have explored concepts for transporting and using the icebergs indicate great promise for this continuous yield resource. However, icebergs of appropriate size and shape must be available for assembly into trains for economical transport, and methods must be found to cope successfully with the surrounding sea ice. Also, ways of harmoniously harvesting this international resource must be developed. These problems have been the concern of this investigation.

The results from ERTS-1 for the period from November 1972 through March 1973 reveal a general prevailing cloud cover more than 80 percent of the time over the Antarctic coastal and sea areas of interest. However, openings in the cloud cover can be exploited to piece together imagery of a large fraction of the earth's surface off Antarctica every few weeks, if every ERTS imaging opportunity is taken.

The sea-ice belt girding Antarctica was very evident, but there was insufficient imagery to refine previous descriptions of its seasonal behavior. Many images of iceberg clusters were obtained that confirm the general abundance and dimensional characteristics of icebergs and that identify differing characteristics with different sample areas. However, the sea-ice and iceberg environment should be comprehensively and continuously monitored for several years in order to acquire enough information to confidently plan and design efficient iceberg harvesting operations. A wealth of additional information for mapping, resource exploration, and research can also be obtained when imagery for iceberg resources is collected.

The potential application for ERTS would be greatly enhanced with live Antarctic readout to enable the timely acquisition of complete imagery on every orbital pass. Also, use of thermal bands should provide better imagery in daylight or darkness throughout the year. With these improvements in ERTS performance, the long-term monitoring for planning and design as well as the quick-use requirements for control of harvesting operations and the registering of claims and entitlements could be achieved. ERTS has capabilities that could support new concepts for claiming service and establishing entitlements that would drastically reduce the costs, conserve the resources, harmonize the operations, and reserve the opportunity for anyone to acquire any entitlement in the future.

The iceberg harvesting operations can easily bear the costs of the ERTS services that appear to be essential to the success of economical large-scale use of the continuous Antarctic iceberg yield that otherwise melts and returns to sea water without benefit to man in the process.

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I. INTRODUCTION

This investigation uses data from the first Earth Resources Technology Satellite (ERTS-1)(1) to determine the characteristics, abundance, and accessibility of Antarctic iceberg resources and also to evaluate the potential role and application of ERTS types of sensing systems to the future harvesting of Antarctic resources. Preliminary studies of the feasibility of moving icebergs to areas that need fresh water and cooling indicate that Antarctic icebergs should become attractive as a fresh water source (compared with desalting or interbasin transfer) for any area in the world that is near deep-water ocean access.(2,3) The economics of exporting the icebergs will depend on their sizes and shapes and the ease with which they might be assembled into trains of uniformly small width (preferably in the lower portion of the range 300 to 1200 m in width) and extracted from the surrounding sea ice. This report first presents the pertinent results obtained from ERTS-1 imagery and then discusses the ERTS system potential and development action needed to facilitate the harvesting of Antarctic iceberg resources.

Because the prevailing cloud cover in Antarctica presents a serious problem to optical sensors, its analysis is important for assessing the potential role of optical sensors and thermal imaging devices. This study interpreted over 900 scenes and used 2900 catalog listings of Antarctic scenes in the temporal and geographic analysis of the cloud cover from November 1972 through March 1973.

Sea-ice behavior (coverage and movement) as a function of geography and season is determined as well as the limited imagery will permit and is correlated with historical data. The role of sea ice in the harvesting of Antarctic icebergs is described and evaluated.

Data on iceberg dimensions and behavior are compiled from sampled iceberg cluster scenes. Iceberg characteristics relevant to their harvest and transportation are discussed.

Considerable Antarctic topography that can be used to update and refine maps of Antarctica is revealed in the imagery. A listing of the scenes with the most useful information is provided.

The section on ERTS system potential first describes the concept of using Antarctic icebergs as a global fresh water resource and the possible role of ERTS in this application. The requirements of live imagery are developed along with possible ground readout system configurations, performances, and costs. The potential of thermal imagery and micro wavelengths is discussed, including such factors as cloud cover, resolution, seasonal influences, contrasts with sea ice, and the possibilities of iceberg height determinations by temperature differences.

The application of ERTS to the long-term continuing collection of information on sea-ice behavior and iceberg evolution is discussed, and the requirements for real-time information for control and access purposes are defined. A claiming and monitoring service is described that would be very practical should competing harvesting operations develop in the same general area. Based on the use of such a claiming and monitoring service, a concept is proposed for establishing entitlements to Antarctic iceberg resources that does not deny anyone the opportunity to acquire such resources at any future time.

The section on ERTS system potential concludes with estimates of the economics of using an ERTS type of system to aid in the harvesting of Antarctic icebergs. Estimates include the costs of the desired ERTS information, the costs that iceberg harvesting systems could bear, and the increased costs of harvesting icebergs without ERTS information or by other means.

The final section on author-identified significant results includes suggestions for program measures that could greatly enhance the benefits that might be derived from an ERTS program applied to the Antarctic and the harvesting of its resources.

II. RESULTS FROM ERTS-1 IMAGERY

The applicability of ERTS for surveying Antarctic iceberg resources was evaluated by studying images of the ocean and coastal areas of the western Antarctic between the Antarctic Peninsula and the Ross Sea. The test site was bounded by the four coordinates in clockwise order: 65°S, 160°E; 65°S, 75°W; 75°S, 75°W; 79°S, 160°E. Imagery was requested for the period 30 October 1972 through 9 April 1973; however, data were obtained only from November through March. Any cloud cover was accepted and imagery from bands 5 and 7 of the Multispectral Scanner (MSS) covering wavelengths of 0.6 to 0.7 and 0.8 to 1.1 micrometers, respectively, was used in the analyses. The standing order was for bulk black and white, 9.5-in. positive paper prints, from which most of the analyses were made. For detailed determination of iceberg characteristics, selected scenes were requested for bulk black and white 70-mm positive transparencies from band 7. The transparencies were readily magnified to a scale of about 1:150,000 to obtain detailed visual measurements of iceberg surface dimensions.

The ERTS systems are described in detail in the *Data Users Handbook.*(1) The satellites are placed in a sun syncrhonous orbit which very nearly reproduces the same earth coverage and sun illumination angles every 18-day period. The orbital inclination is approximately 99 deg from equatorial (about 9 deg from polar) and therefore covers most of Antarctica that is of interest for icebergs. The satellite altitude over Antarctica is about 930 km (500 n mi), and the orbital period of 103 min provides approximately 14 orbits per day. The field of view or scene size of the imagery is approximately 185 km (100 n mi) on a side. Consecutive images along an orbital track overlap to provide a continuous coverage swath. The orbital program provides cross-track sidelap of about 14 percent on successive days at the equator and greatly increased overlap at high latitudes, e.g., the Antarctic.

The *Data Users Handbook* indicates that the theoretical ideal ground resolution approaches 80 meters; however, effective resolution of the bulk products typically may exceed 100 meters.(1)

The operational properties of the first experimental Earth Resources Technology Satellite, ERTS-1, are not likely to be incorporated in a future system; however, they do provide experience for the design of future systems. ERTS-1 was inaugurated with live readout stations only in North America. Imagery obtained from other parts of the world was stored on wideband video tape recorders on board the satellite. The 30-min storage capacity of the recorder was programmed and shared world-wide until it could be read out at opportune times by the North American readout stations that were not preoccupied with live readout. The data collected at remote stations such as Alaska or the west coast were then mailed to the processing center at Goddard Space Flight Center, from which the prepared imagery was mailed to the investigators. Under ideal circumstances, the user obtained the imagery weeks after it was taken; however, in many cases it was not received until months later.

Imagery for more than 900 scenes was interpreted in this investigation. The scene centers were plotted on a map of Antarctica as illustrated in Fig. 1. It is seen that they were fairly well distributed over the originally defined test area. However, the analyses revealed that the useful *coverage* (openings in cloud cover) *was spotty both geographically and temporally.* For the purposes of analysis, the Antarctic region was partitioned along orbital parallels as illustrated in Fig. 1. The sector boundaries are specified at latitude crossings as follows:

Sector 1	109°E to 170°E at 70°S
Sector 2	160°E to 165°W at 75°S
Sector 3	165°W to 142°W at 75°S
Sector 4	142°W to 118°W at 75°S
Sector 5	118°W to 97°W at 75°S
Sector 6	97°W to 73°W at 75°S
Sector 7	73°W to 50°E at 70°S
Sector 8	5°W to 50°E at 70°S
Sector 9	50°E to 109°E at 70°S

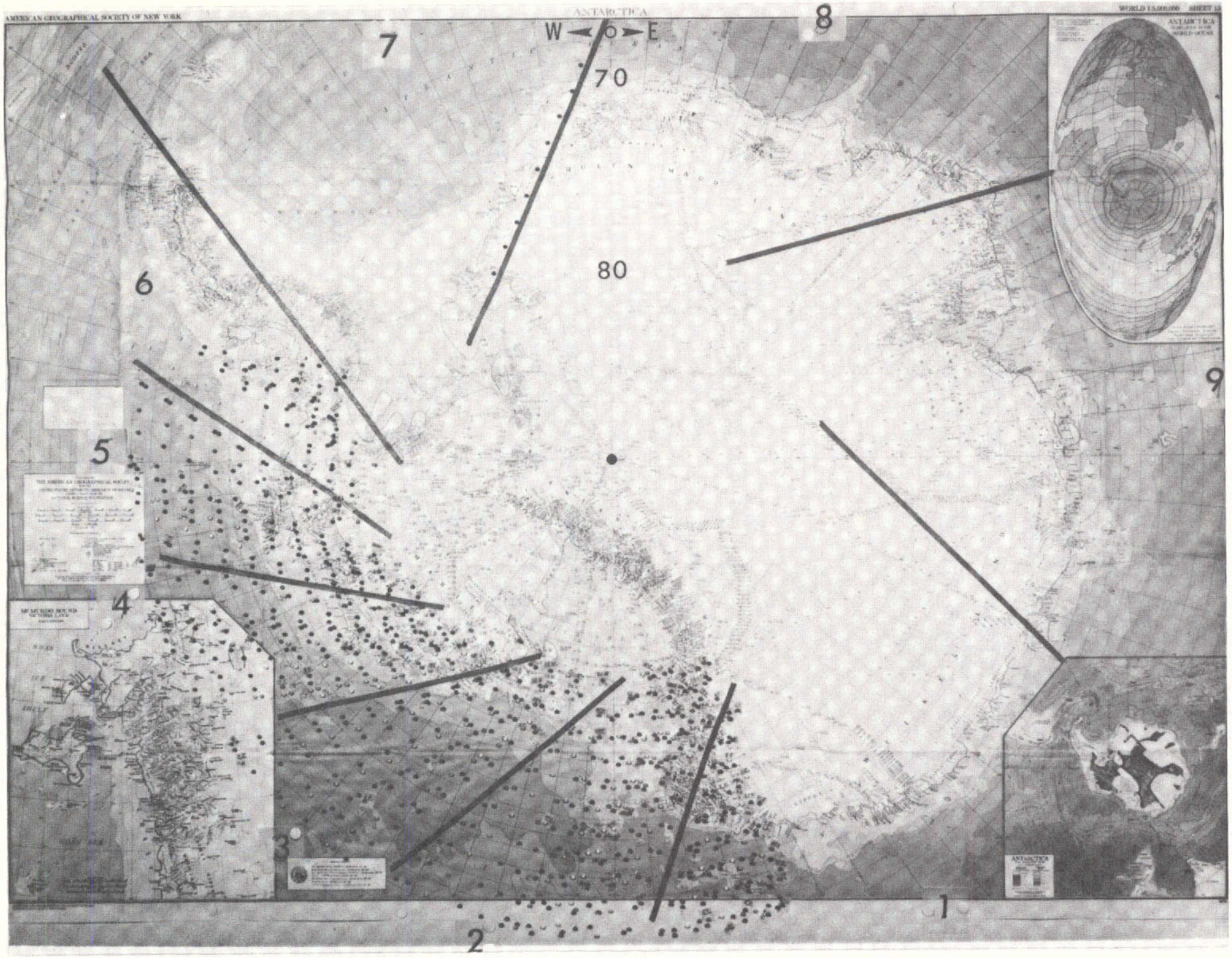

Fig. 1 — Division of Antarctica into 9 sectors and distribution of images

All the imagery analyzed was obtained during the period from 16 November 1972 to 27 March 1973 and can be found listed in *Earth Resources Technology Satellite, Cumulative Non-U.S. Standard Catalog No. N-9.*(4) In some of the analyses the imagery for the above period was further partitioned into time periods to examine changes with time during the limited period of observations.

Imagery obtained for this investigation that contained useful information other than cloud coverage has been described and submitted to the Image Descriptor Data Bank file under one or more of the following descriptors: Ice, Sea Antarctic; Icebergs, Antarctic; Antarctic Topography.

CLOUD COVER

Previous climatological data on cloudiness in the southern hemisphere indicate a total cloudiness that reaches maximum values in the coastal regions surrounding the Antarctic continent.(5) The mean cloudiness exceeds 80 percent most of the year over most of the region extending 1000 km north of the coast. Climatology also indicates that cloudiness is the most extensive during the daylight season when it persists to the high interior regions of the Antarctic with 50 percent likelihood as compared with perhaps only 20 percent during the night season. The primary area of interest for the harvesting of iceberg resources is in the regions of drift ice where cloud cover greater than 80 percent appears to persist, and it becomes essential to determine the potential utility of sensors that must exploit openings in cloud cover as well as to examine the characteristics of the openings themselves.

Cloud-cover information was obtained from more than 900 Antarctic scenes that were interpreted according to the authors' subjective estimation of the fraction of the scene area over which the obscuration was sufficient to degrade the ability to find icebergs and to measure their dimensions at the full resolution capability of the sensors. These interpretations can be compared with the cloud-cover values assigned to more than 2900 Antarctic scenes (including those interpreted in this study) in the *Cumulative Non-U.S. Standard Catalog No. N-9.*(4) Most frequently the scene areas were totally obscured and there was no question that the cloud cover was complete. Some scene areas had very thin cover through which the general nature of the sea ice below could easily be discerned, but the contrast needed to find imbedded icebergs and measure their dimensions was obscured. Such areas were interpreted to be cloud-covered. However, any scene with 90 percent or more of cloud cover through which a positive determination could be made about the presence or absence of sea ice below was arbitrarily assigned a value of 90 percent cloud cover. The cloud cover of scenes was then partitioned into categories of 0-40, 50-80, 90, and 100 percent. The tabulated data of cloud cover over drift-ice areas within the study test site are displayed in Figs. 2 and 3. They are tabulated by sector and sector combinations and by time period and time period combinations. Also the cloud-cover interpretations as defined for this study are compared with the catalog listings. The catalog listings of cloud cover are the routine subjective impressions of the processing crew that was operating at the time; they do not represent any precise interpretation of any particular cloud-cover definition, especially for the highly ambiguous scenes of the Antarctic involving so much cloud cover over the snow and ice. The scene-to-scene comparisons of cloud cover by the interpretations of this study are frequently at great variance with the catalog listings; however, the averages seem to have fairly consistent differences.

The season average of cloud cover over drift ice in sectors 2 through 6 as interpreted in this study was 0.84. The corresponding average as obtained from the catalog listing was 0.74. The season average of cloud cover over fixed ice for the same sectors was 0.70 as interpreted in this study and 0.60 as obtained from catalog listings. Similarly, the season average of cloud cover over drift ice in sector 1 as interpreted in this study was 0.91 whereas the corresponding average obtained from catalog listings was 0.81. Thus the averages of cloud cover as interpreted with the definitions of this study are about 0.1 greater than the corresponding averages obtained from the catalog listings. This comparison is illustrated in Fig. 4 (I and C

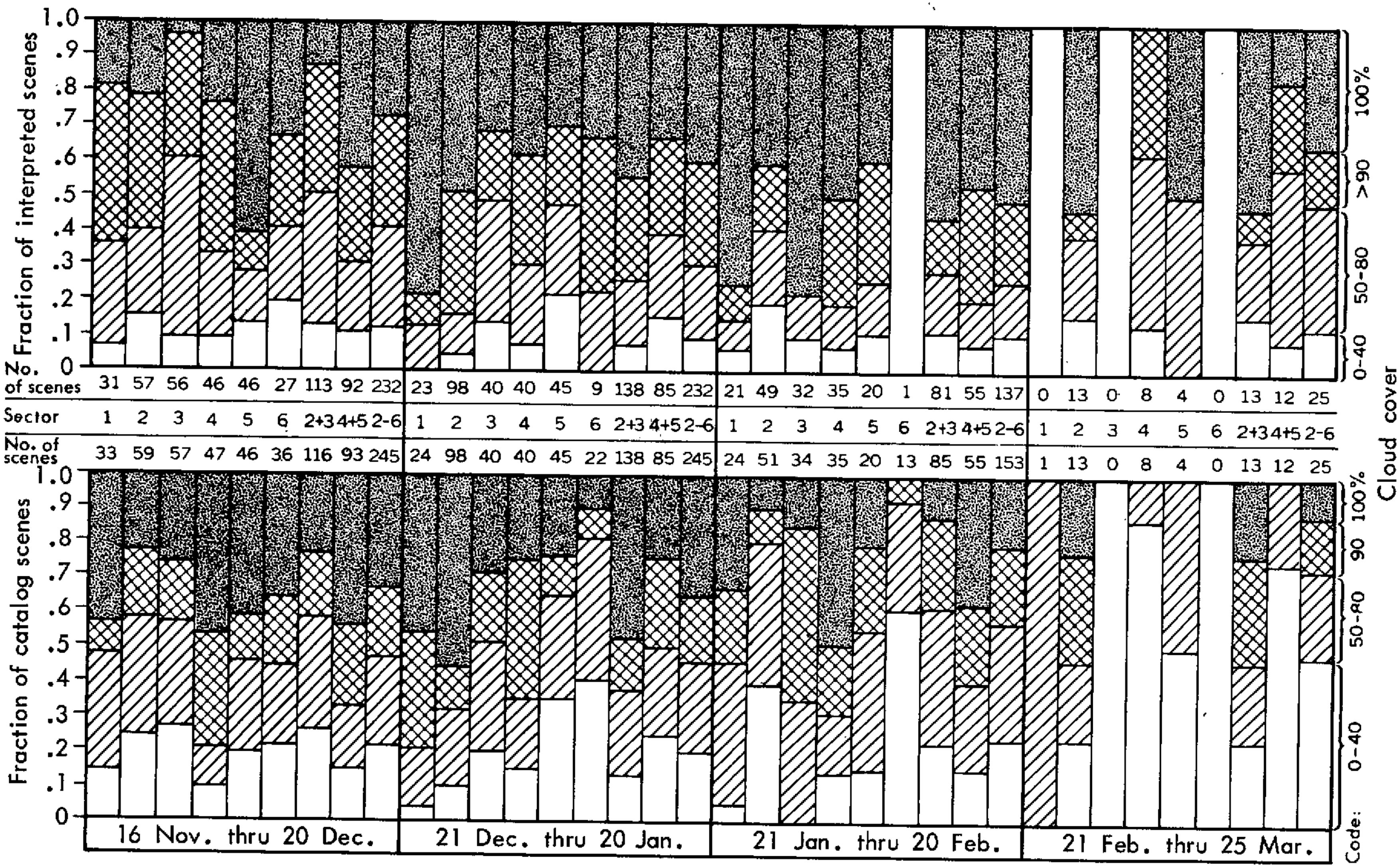

Fig. 2 — Cloud-cover comparison over drift-ice areas: (Special interpretation and catalog, four different periods)

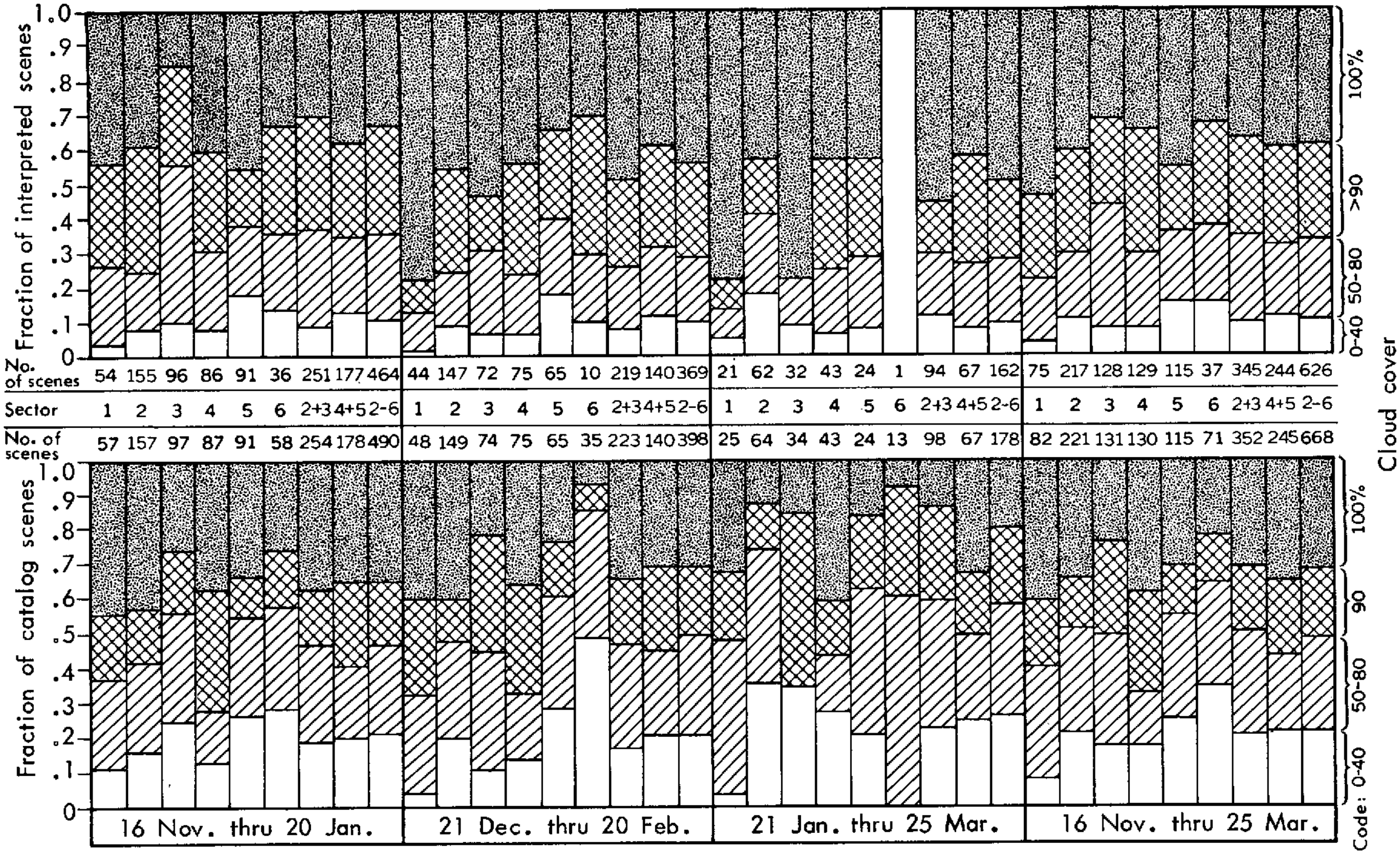

Fig. 3 — Cloud-cover comparison over drift-ice areas: (Special interpretation and catalog, various period combinations)

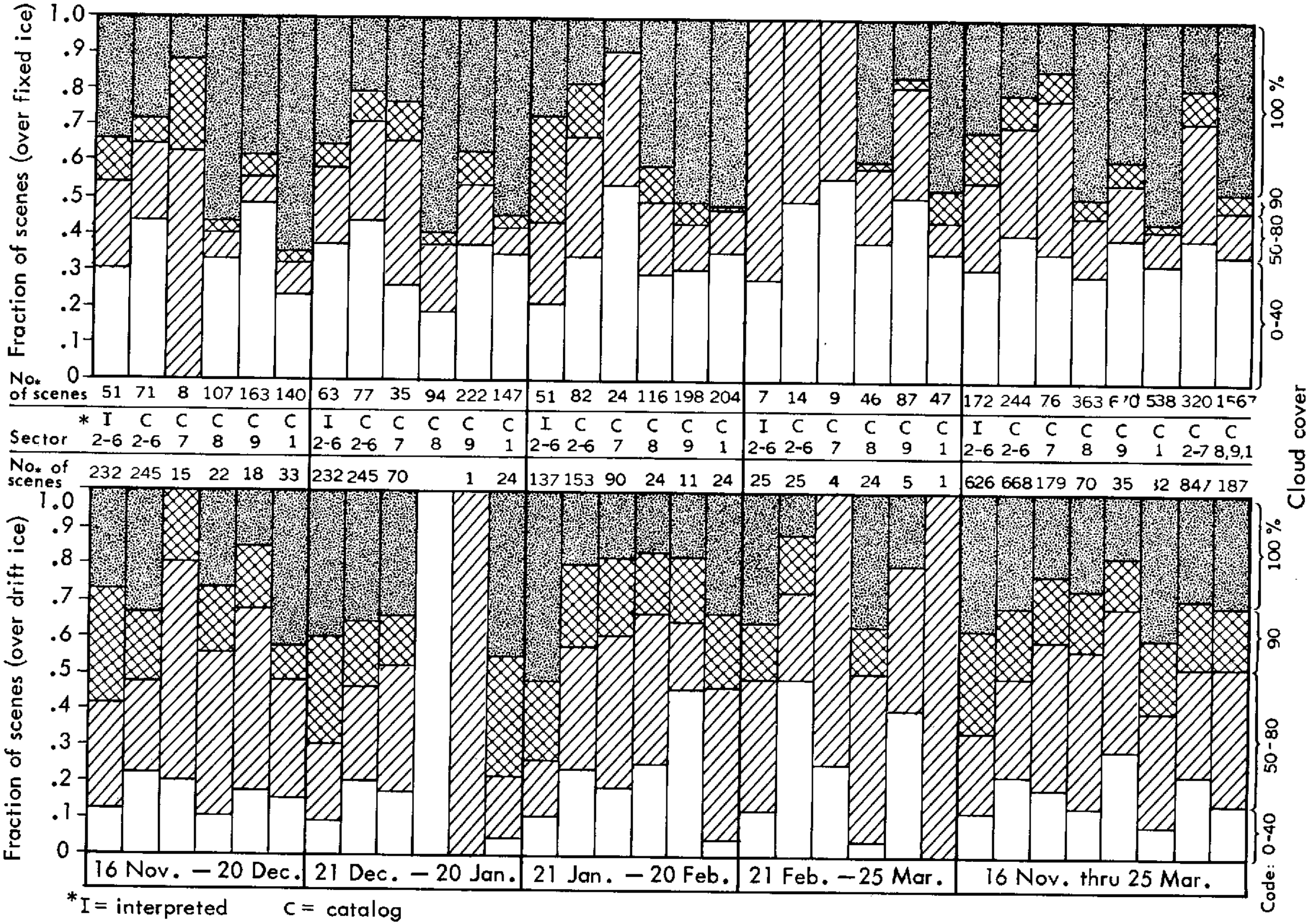

Fig. 4 — Cloud-cover comparisons (over fixed ice and drift ice)

above the sector number refer to Interpreted and Catalog, respectively) and should be kept in mind for the illustrations of catalog averages for all of Antarctica shown in Fig. 4. From the data in Figs. 2, 3, and 4, it is concluded that for the daylight period from November 1972 through March 1973, the cloud cover over most of the drift-ice areas where iceberg harvesting operations are most promising exceeded 0.8 as interpreted by the definitions of this study. This is in substantial agreement with the climatological cloud cover described in other references,(5) which also indicate only very slight reductions in cloud cover over the drift-ice areas during the seasons of darkness.

There was inadequate sampling of scenes to provide conclusive evidence of cloud-cover variation with period or with sector. However, there seems to be a slight tendency for increased average cloud cover in the middle of the daylight season compared with the ends, and for decreased average cloud cover in sectors in which drift-ice areas extend farther south (sectors 2 and 3 including the Ross Sea and sector 7 including the Weddell Sea).

It is difficult to define the characteristics of the "openings" to be expected in the prevailing cloud cover over Antarctic iceberg scenes of interest. However, most open areas are comparable to or smaller than a scene of 185 km diameter, and in the small sample of this type of data there seemed to be no recognizable correlation between openings on scenes obtained 24 hours apart with average geographical overlap of 0.7 between scenes. Thus it is assumed that if complete imagery was obtained on every ERTS pass, the cloud-cover openings on successive passes would be statistically independent events, and the probability of a cloud-cover opening in all the potential ERTS images over a specified iceberg area should range between 0.3 and 0.7 in each 18-day cycle (or in each 9-day period when using a thermal sensor capable of operating in the dark during either the ascending or descending nodes). This estimate assumes a cloud-cover average between 0.8 and 0.9 and a day-to-day scene overlap between 0.7 and 0.8.

SEA ICE

In order to harvest Antarctic icebergs efficiently and to assemble them into trains for movement to using areas, it will be necessary to contend with the sea ice that surrounds Antarctica and the icebergs most of the time. The seasonal and geographical extents of the Antarctic sea ice have been described in various publications.(5,6) Also valuable are the historical accounts of sea-ice obstructions to navigation in these regions.(7) The descriptions of the various forms of ice that may be encountered and how they evolve are helpful to the understanding of the nature of this barrier to the otherwise easy access to the densest iceberg clusters.(8) ERTS types of observations over several years with scene sampling at nearly every orbital-pass opportunity should provide a valuable record of sea-ice behavior that could be very useful in planning the harvesting of iceberg resources. The very limited sampling obtained with ERTS-1 (less than 10 percent of the opportunities for October through March) was inadequate for a comprehensive interpolation of the sea-ice behavior over a daylight season. A much more complete sampling over two or more years and preferably over the full year (in darkness as well as daylight) seems highly desirable to gain a confident understanding of the sea-ice behavior and its potential influence on ocean operations in the Antarctic.

The sea ice observed in the portion of the western Antarctic from which this investigation obtained imagery consisted of a huge belt extending more than 1000 km northward from the coast in the early daylight season. By February, after erosion during a few months of the daylight season, the northern edge of the sea-ice belt had receded to about 70° south latitude over much of the western Antarctic lying within the test site. At the same time the ice belt seemed to withdraw from the coast in many areas, with considerable erosion of coastal fast ice. The dissolution of the belt from both north and south seemed to be most severe in the Ross Sea in the vicinity of 180° longitude, where the belt separated in Feburary to open the Ross-Ice-Shelf front and much of the coast eastward to the Getz Ice Shelf (~130°W) to access without the necessity of breaking through the belt. Most of the Bellingshausen Sea and Amundsen Sea east of Cape Dart on Siple Island seemed to be closed off throughout the season by the sea-ice belt. However, the belt became the narrowest in this sector and would have required breaking through about 300 km or less of belt width to reach open-water areas near the coasts. The approximate boundaries of the sea-ice belt in December and in February are shown in Fig. 5 as estimated from the small amount of ERTS-1 imagery that was unobscured by cloud cover. The behavior of the belt seemed to be more consistent with that depicted in Ref. 5 than in Ref. 6; however, it may change from year to year without always following a detailed standard pattern.

During the daylight season when the sea-ice-belt width is receding, the deteriorating ice debris along the northern edge of the belt appeared to feather out into wisps as viewed with ERTS resolution (see Fig. 6).[*] The central portion of the belt may be consolidated

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[*] The annotation that appears on the ERTS imagery illustrated in this report is described briefly with reference to Fig. 6. The ERTS orbit is parallel to the sides of the image and the spacecraft motion is toward the bottom. The alphanumeric annotation appearing on the line above the grey scale at the bottom provides the following information from left to right:

28 NOV 72	Date of image
C S65-19/E178-40	Format center - latitude and longitude - degrees and minutes
N S65-22/E179-01	Earth location directly below satellite
MSS 7R	MultiSpectral Scanner, band 7, stored data R
SUN EL 34 AZ062	Sun elevation 34 deg, azimuth 62 deg
200-1786-A	Spacecraft heading 200 deg, orbit revolution 1786; "A" is Alaska ground recording station
I-N-D-IL	Codes identifying a variety of processing factors

(Continued on page 16)

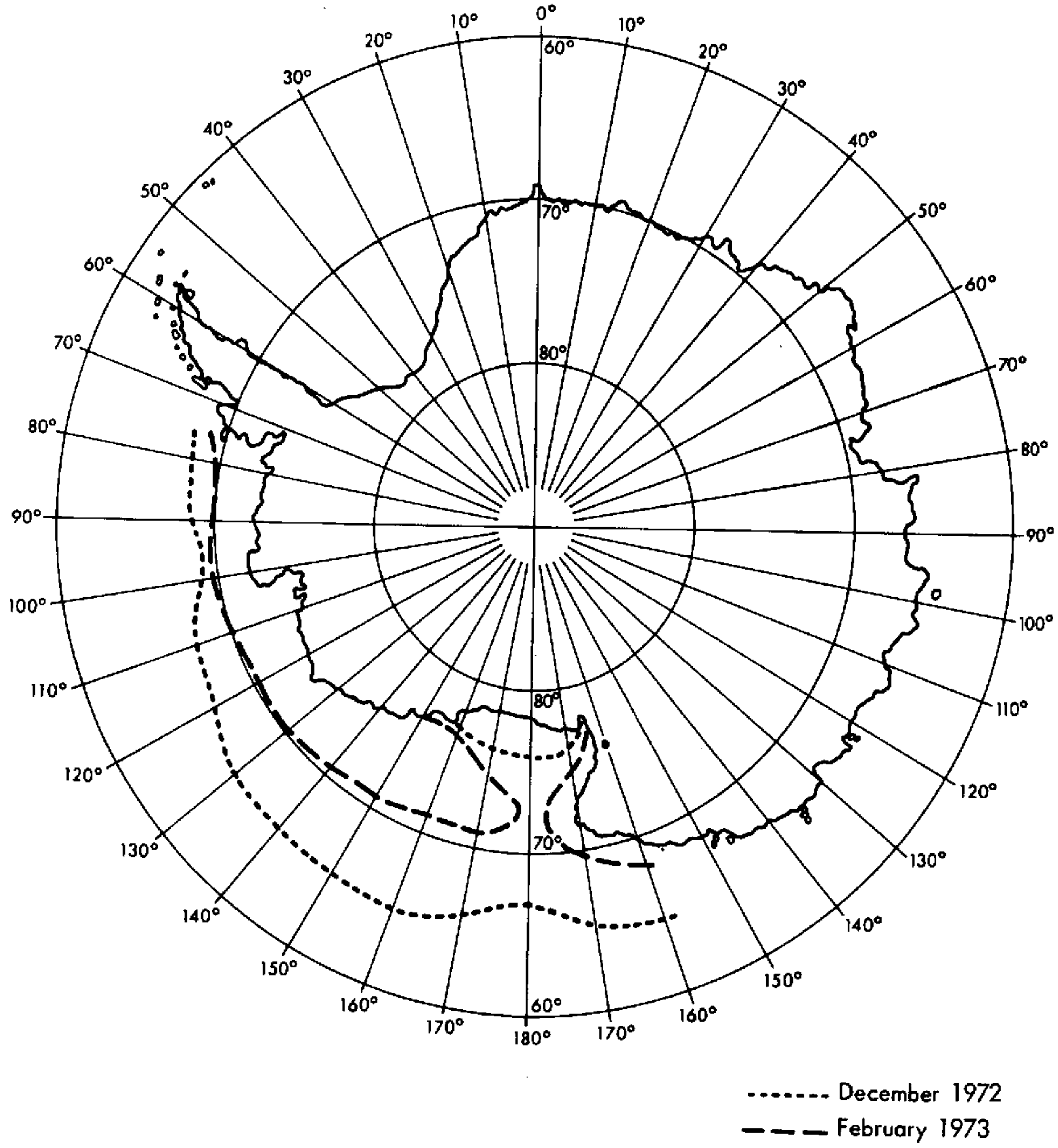

Fig. 5— Boundaries of sea-ice belt

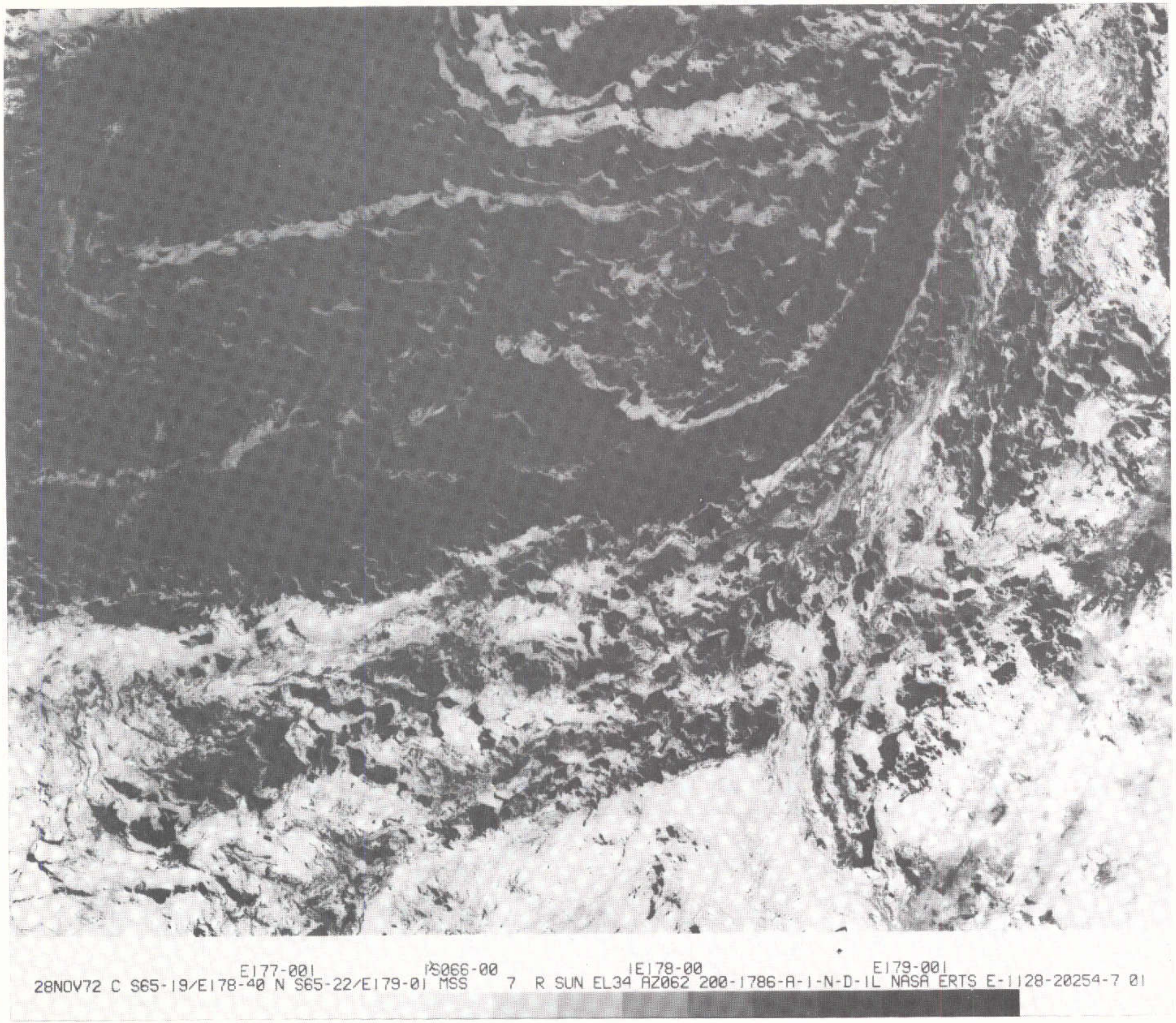

Fig. 6—Debris-ice wisps in northern edge of sea-ice belt

into a continuous snow-covered surface that may crack and then break up into floes of mixed and varied sizes and erosion shapes. Figures 7 and 8 illustrate some of the forms of sea ice to be found in the belt.

Icebergs that calve from the ice shelves and glacial ice streams along the coast may become locked up in coastal fast ice for years, but they tend to leak out of their locked-up coastal clusters and diffuse northward through the sea-ice belt. Most of the icebergs become locked into huge floes in the central portions of the belt for periods of one or more seasons. However, many icebergs may break loose, especially near the edges of the belt or near large fractures or leads, and plow through the sea ice or sweep it up in front of them as the iceberg is driven by deeper sea currents. Figure 7 illustrates four dark streaks in the lower right that are four large melting furrows of sea ice about 18 km in length which had recently been plowed by the icebergs at the eastern terminals. Most of the other icebergs in Fig. 7 remained locked in the sea ice while the four furrows were plowed.

The collection and harnessing of icebergs into long trains will probably be easiest along the northern edge of the belt or in the open-water areas inside (south) of the belt where these operations would not need to contend with crowding sea-ice stresses. The greater density of the iceberg clusters near the coast would facilitate the formation of large trains with more favorable characteristics. Once a train of icebergs has been formed in open coastal waters, it may be feasible in some situations to propel it so as to plow through the belt. The thrust required to move the train in open waters will be

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NASA ERTS	Identifies the Agency and the Project
E-1128-20254-7	Frame identification number giving time of exposure relative to launch; "7" indicates MSS band 7 (0.8-1.1μm)
01	Regeneration number

Latitude and longitude tick marks are indicated around the edge of the image, and registration marks outside the corners aid in alignment of different spectral images of the same scene. All the *images* in this report illustrate ground scenes approximately 185 km in width.

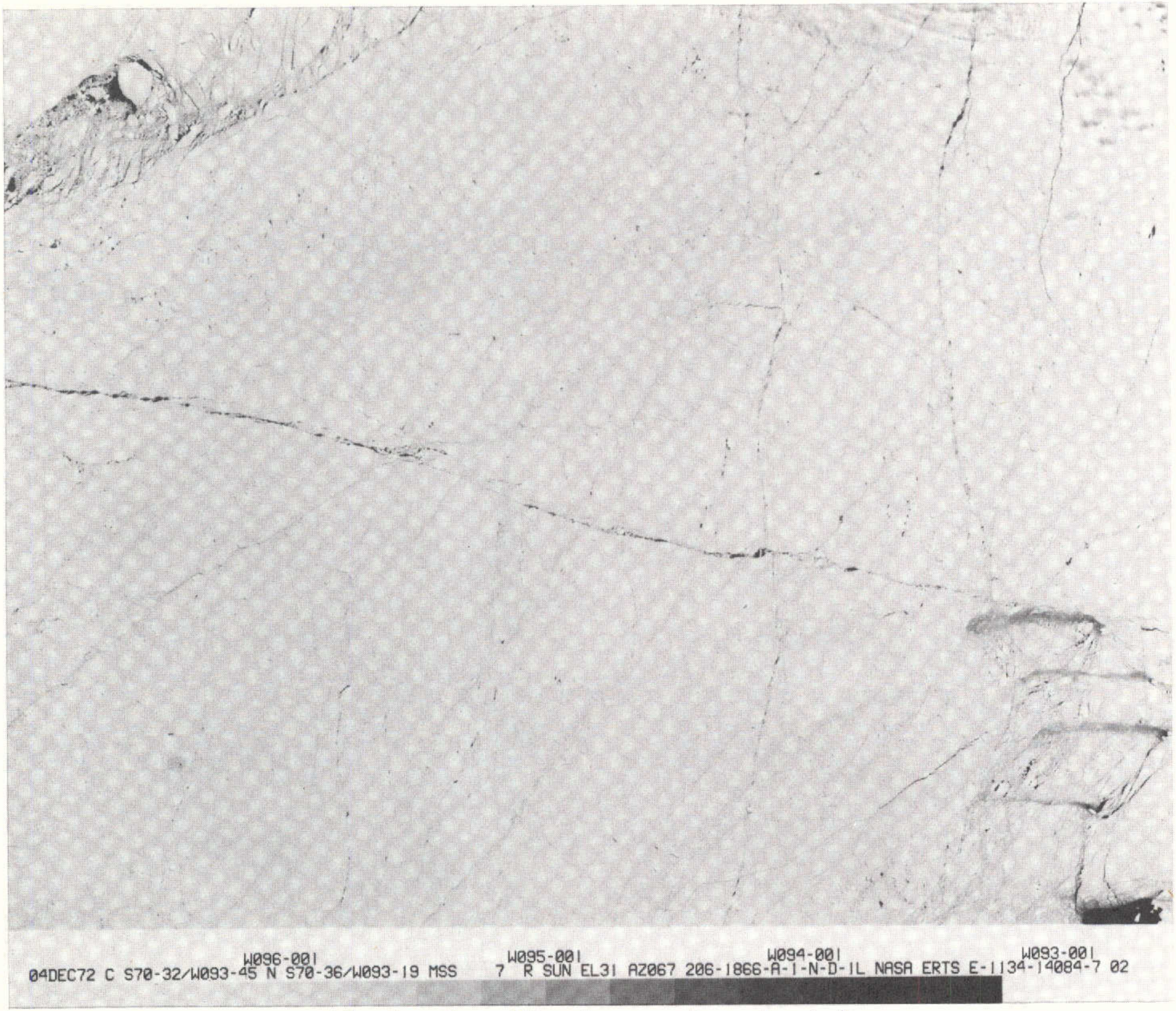

Fig. 7 — Consolidated areas of sea-ice belt

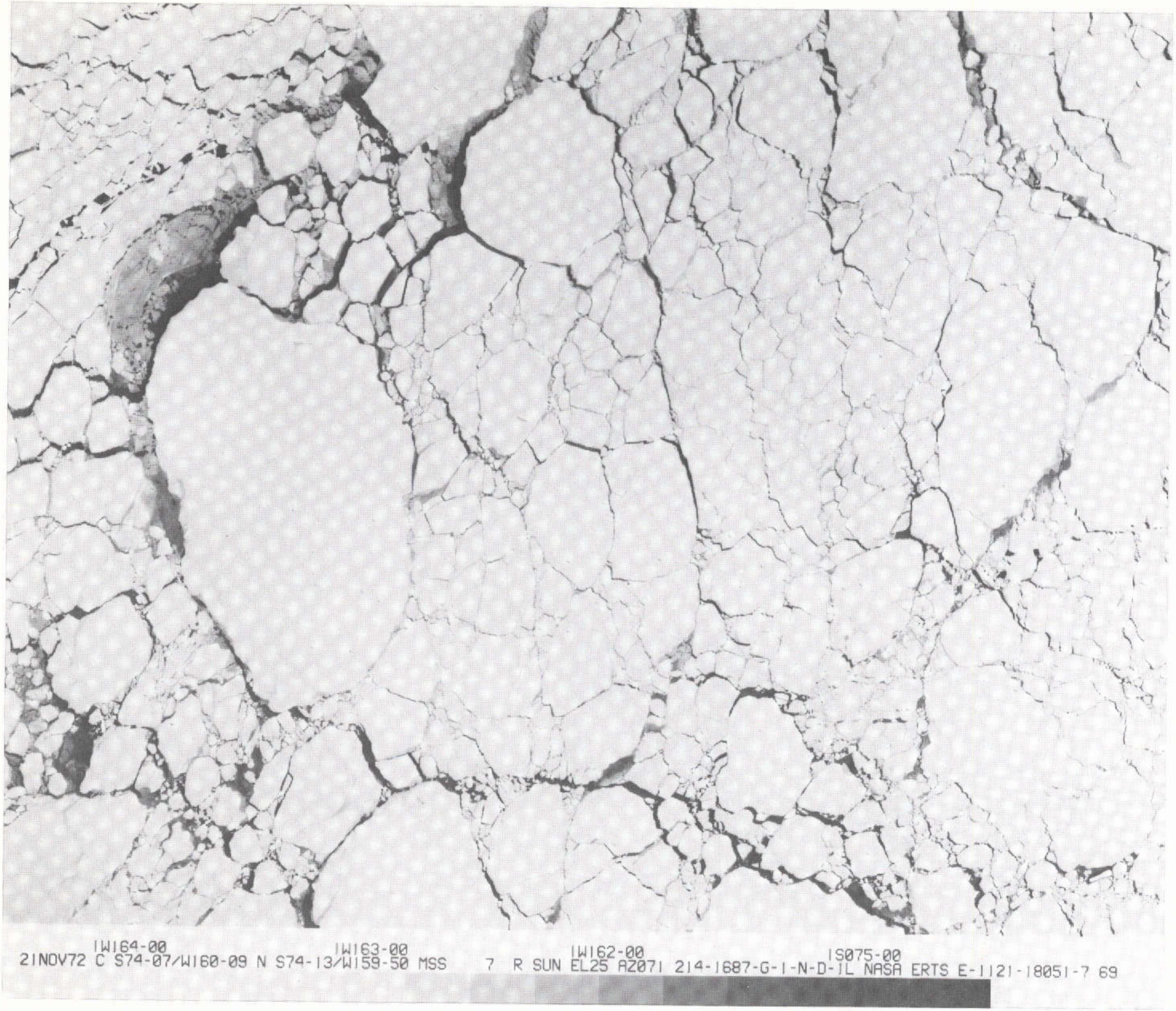

Fig. 8 — Broken floes of sea ice (mixed sizes and shapes)

large compared to that provided by natural currents in these regions. The train should, therefore, have a considerably greater capacity to plow through the belt than do the naturally imbedded icebergs. Techniques need to be developed for controlling the train when attempting to plow through the sea-ice belt in order to move it in the desired direction and avoid collisions with icebergs that are locked in or are themselves moving through the belt.

ICEBERG CHARACTERISTICS

The iceberg characteristics that were of greatest interest in this investigation were the effective widths available that would permit harnessing icebergs snugly together into long trains. Eight dense cluster areas representative of western Antarctica between the Ross and Bellingshausen Seas were selected and the maximum widths of the icebergs and their topside areas were tabulated. Individual visual measurements were made of each iceberg on a projected image with a scale of about 1:150,000. The widths were measured perpendicular to the dimension that appeared to offer the best opportunity for in-line harnessing of each iceberg into train formation. Figures 9 through 14 illustrate the various types of clusters.*

Figure 9 shows a cluster of icebergs locked into the fast ice off Cape Colbeck (eastern edge of Ross Sea at the lower right). The much deeper and higher (~50 m) icebergs stand out in relief against the fast ice and are easily recognized and measured under magnification. Also included in this sample are a number of icebergs in open water west of the locked-in cluster. In the open water the shadows of the higher icebergs do not provide recognizable signatures for distinguishing them from sea ice. However, tabular icebergs (large icebergs with flat tops) tend to break into pieces with crisp looking edges similar to the pieces of a broken window pane, as distinct from the eroded looking edges of many sea-ice floes. Also, the currents at the much greater depth of icebergs tend to move them differently from sea ice and they will frequently dam up or sweep out the sea ice

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*See footnote on pp. 13 and 16 for aid in interpretation.

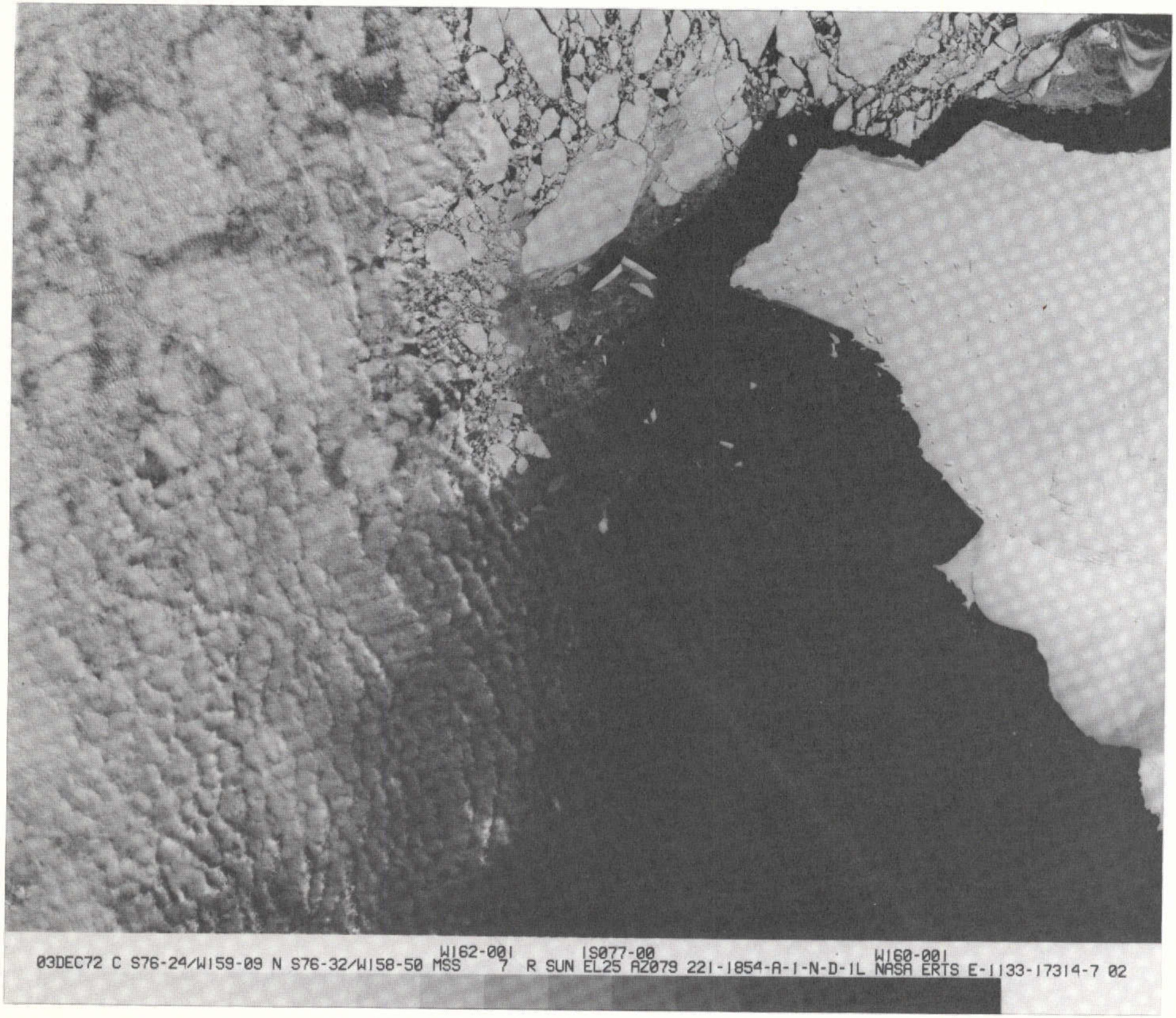


Fig. 9 — Iceberg cluster off Cape Colbeck

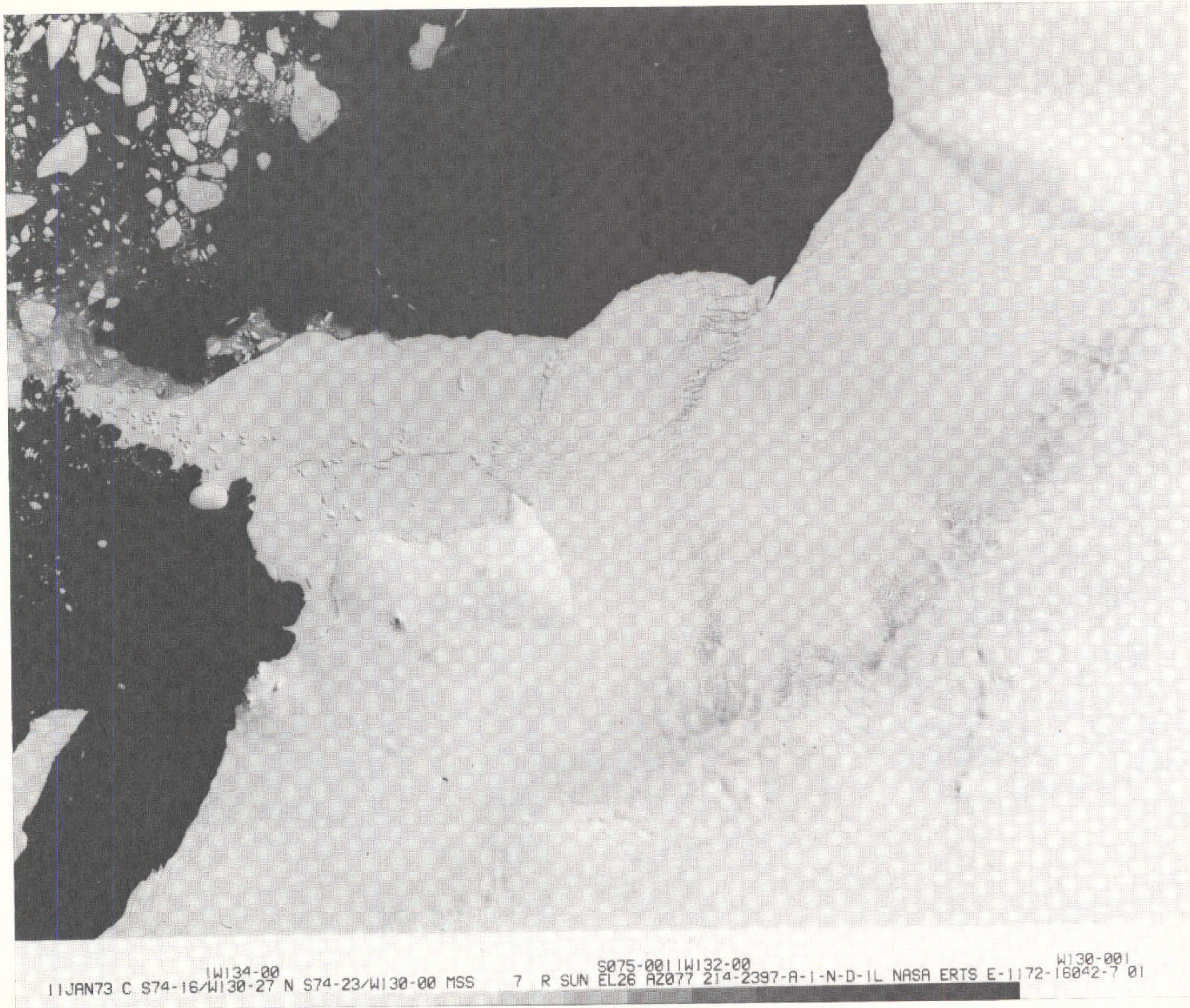


Fig. 10 — Iceberg cluster off Grant Island and western Getz Ice Shelf

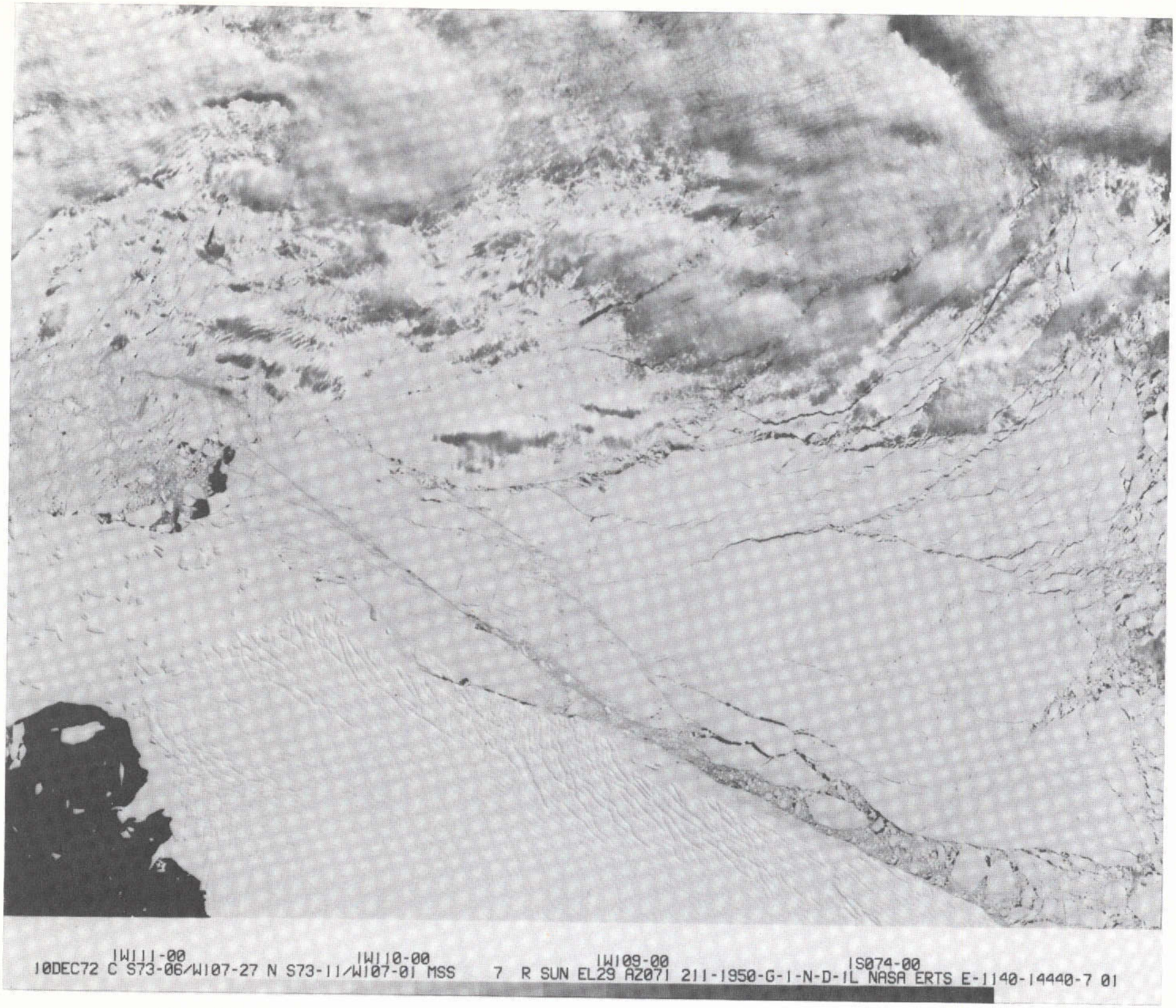


Fig. 11 — Iceberg cluster off the northern tip of Thwaites Iceberg Tongue

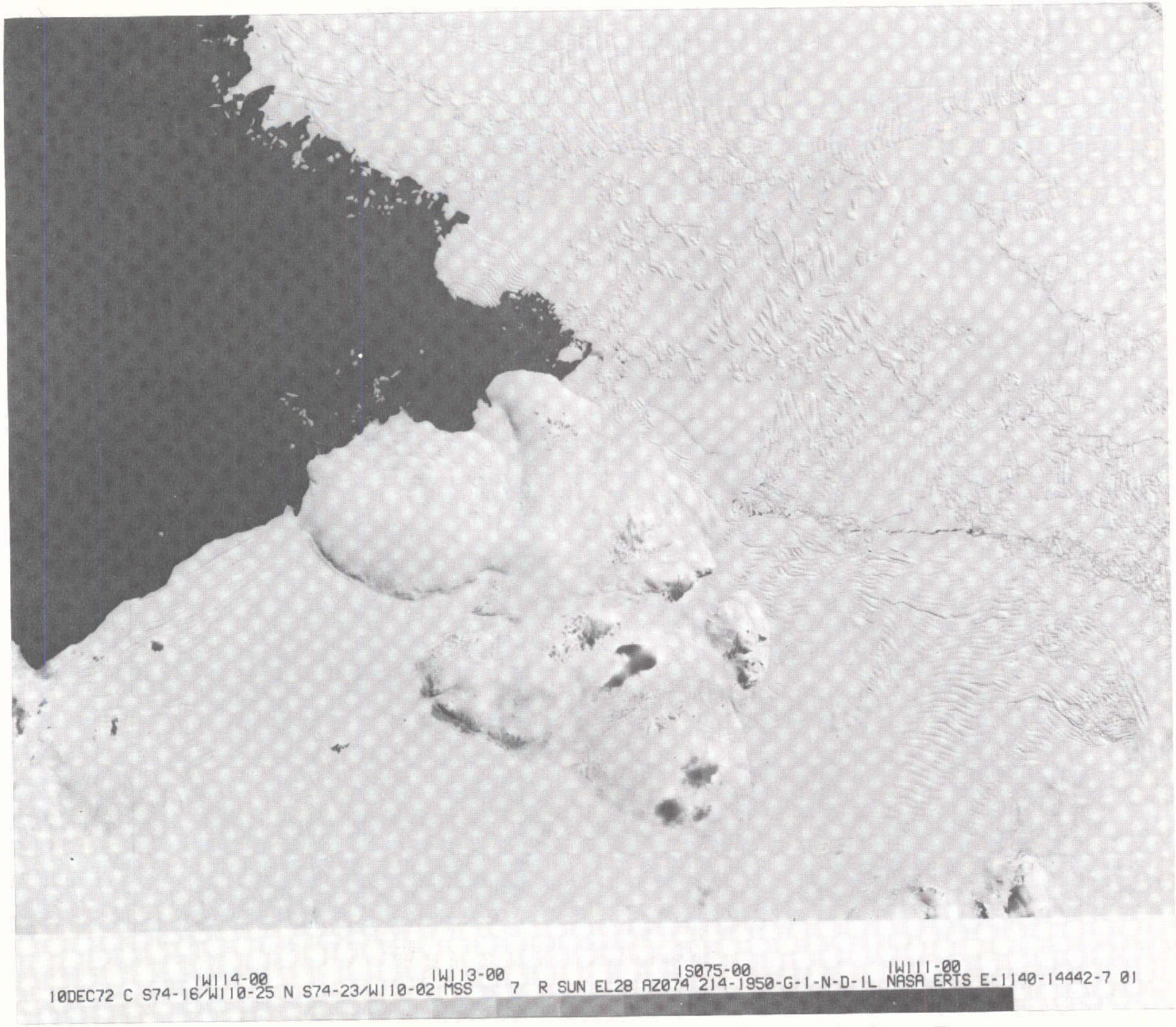


Fig. 12—Iceberg clusters south and west of Thwaites Iceberg Tongue

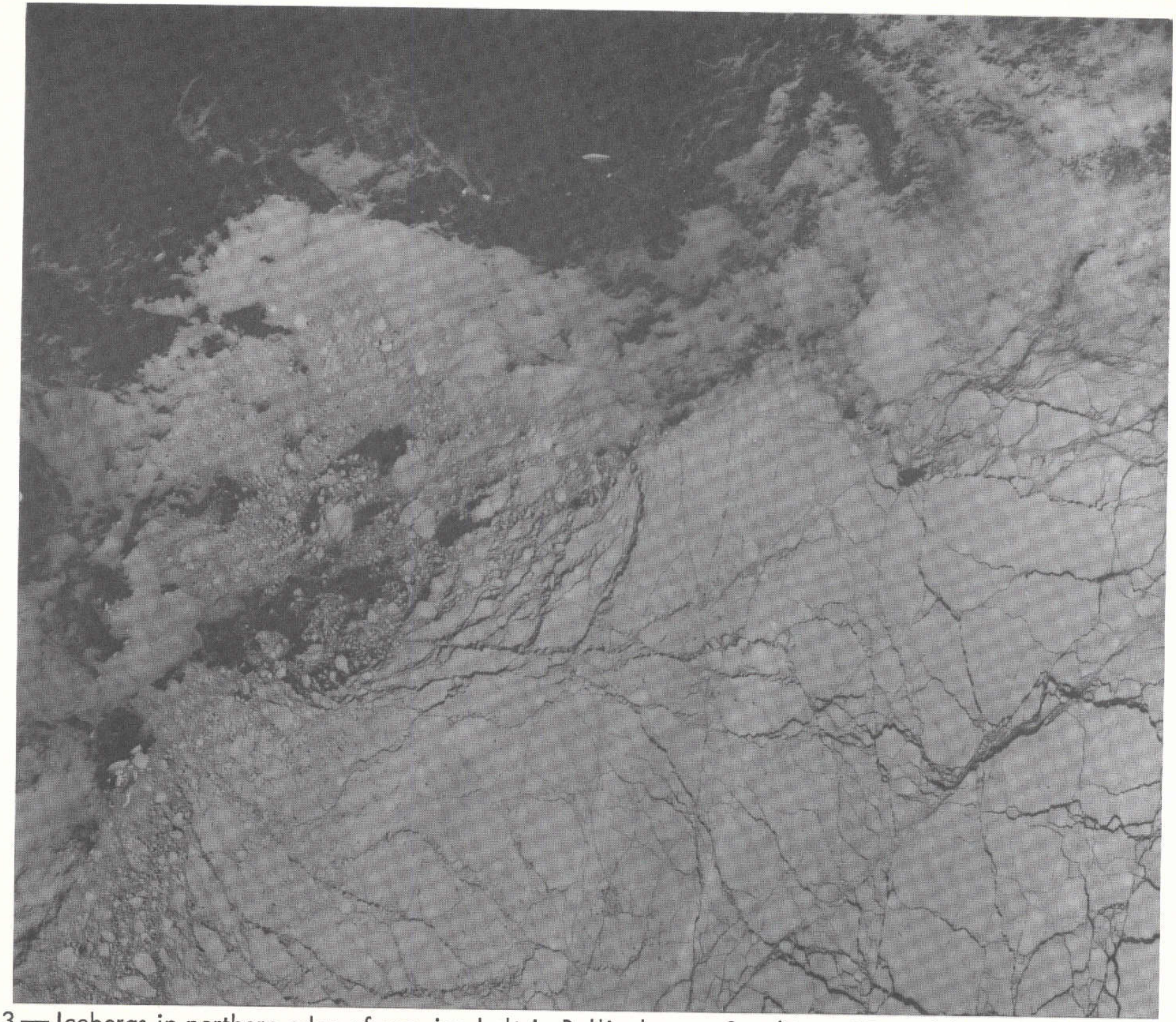


Fig. 13 — Icebergs in northern edge of sea-ice belt in Bellinghausen Sea (East of Peter Island, from 1168-13563-7)

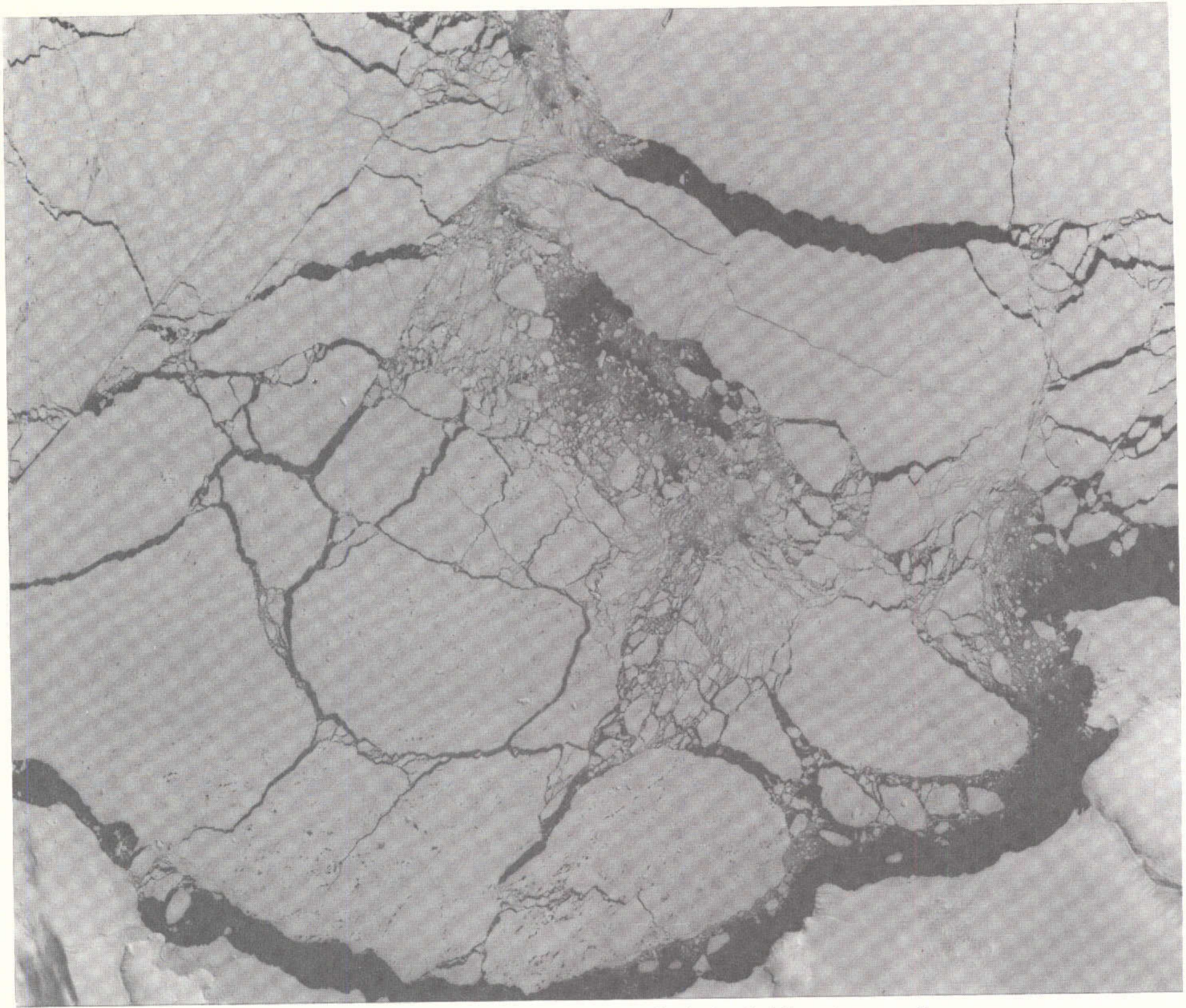


Fig. 14 — Icebergs locked in sea-ice belt in Bellingshausen Sea
(East of Thurston Island, from 1168 - 13572 - 7)

to leave an open-water signature behind them. This is illustrated by the two icebergs, each about 6 km long by 1 km wide, that are about 15 km off the western tip of the fast ice containing the cluster of icebergs (the scene width is approximately 185 km). These two large icebergs were originally joined together end-to-end to form a single ship-shaped iceberg about 12 km long. In this scene, they are sweeping south the melting sea ice, including a bright eroded ice floe of comparable size within their swath. There are a number of other smaller icebergs in the open water to the south and between the pack ice and the fast ice that were also included in the data sample.

Figure 10 shows a cluster of icebergs locked into the fast ice off Grant Island and the western Getz Ice Shelf. In the extreme lower left of the scene is an irregularly shaped glacial ice tongue about 30 km long by 8 km wide that has broken away from its source. The image also indicates that the shelf flow from the DeVica glacier just east of Grant Island extends considerably north of the Getz Ice Shelf as indicated on the 1970 edition of the map of Antarctica by the American Geographic Society of New York.

Figure 11 shows a cluster of icebergs locked into the fast ice off the northern tip of Thwaites Iceberg Tongue. Analysis of their dimensional statistics reveals significant differences from those of Thwaites origin, and their greater widths and shape differences may indicate that many of these icebergs have drifted over from the Dotson Ice Shelf or possibly from Pine Island Bay.

Figure 12 shows many clusters of icebergs in or near the fast ice, south and west of Thwaites Iceberg Tongue. One sample of dimensional statistics was taken from icebergs in the open water on the western edge of the fast ice, and a much larger sample was taken from the icebergs locked in the interior of the fast ice. In both cases, all large multiple-layered iceberg clumps were excluded so that the statistics of the basic layering widths of the Thwaites source would not be distorted.

Figure 13 shows a dispersed cluster of icebergs along the northern edge of the sea-ice belt in Bellingshausen Sea east of Peter Island. The icebergs are readily identified in most cases by the clean sweeps of open water in their trails. A similar sample of icebergs was also taken from the northern edge of the belt in the Amundsen Sea.

Figure 14 illustrates a portion of the belt interior south of the area shown in Fig. 13 and east of Thurston Island from which iceberg statistics were collected for comparison with those obtained in the samples from the northern edge of the belt.

Figure 15 displays the statistics of iceberg characteristics obtained from the eight areas sampled. The distribution of iceberg widths is illustrated in terms of the fraction of the total topside area of the sample of icebergs for each 0.1 km of width interval. Each sample area is identified by a geographical name and the ERTS frame from which it was selected. Most of the sample areas came from Figs. 9 through 14. The total number of icebergs included in each sample is given as well as the number in each interval (above the bars). The total topside area of the icebergs in the sample is given in km^2.

Figure 15a, from a sample in Fig. 9, seems to indicate a bimodel distribution. However, major portions of the areas in the 1.0 and 1.1 intervals are derived from the two large icebergs--each about 6 km long--mentioned previously in connection with Fig. 9. If these two exceptional icebergs were excluded from the sample, it would subdue the distribution peak near 1.0 and reduce the average area per iceberg to about 0.6 km^2, which would be more comparable with Figs. 15b and 15c.

The sample represented in Fig. 15d, which comes from north of the tip of Thwaites Iceberg Tongue (see Fig. 11), is anomalous in its distribution of large widths and of an average area per iceberg of 1 km^2. The source of these icebergs is not known, but the shapes and large widths are not characteristic of those from Thwaites.

The small samples represented in Figs. 15e and 15f come from the northern edge of the sea-ice belt. They are biased toward smaller and narrower icebergs, which might be expected for these more northerly samples of icebergs that are probably older and more eroded than those near the coasts.

The icebergs of Figs. 15g and 15h were selected from the Thwaites area discussed with Fig. 12. Sample g is the one from near the western

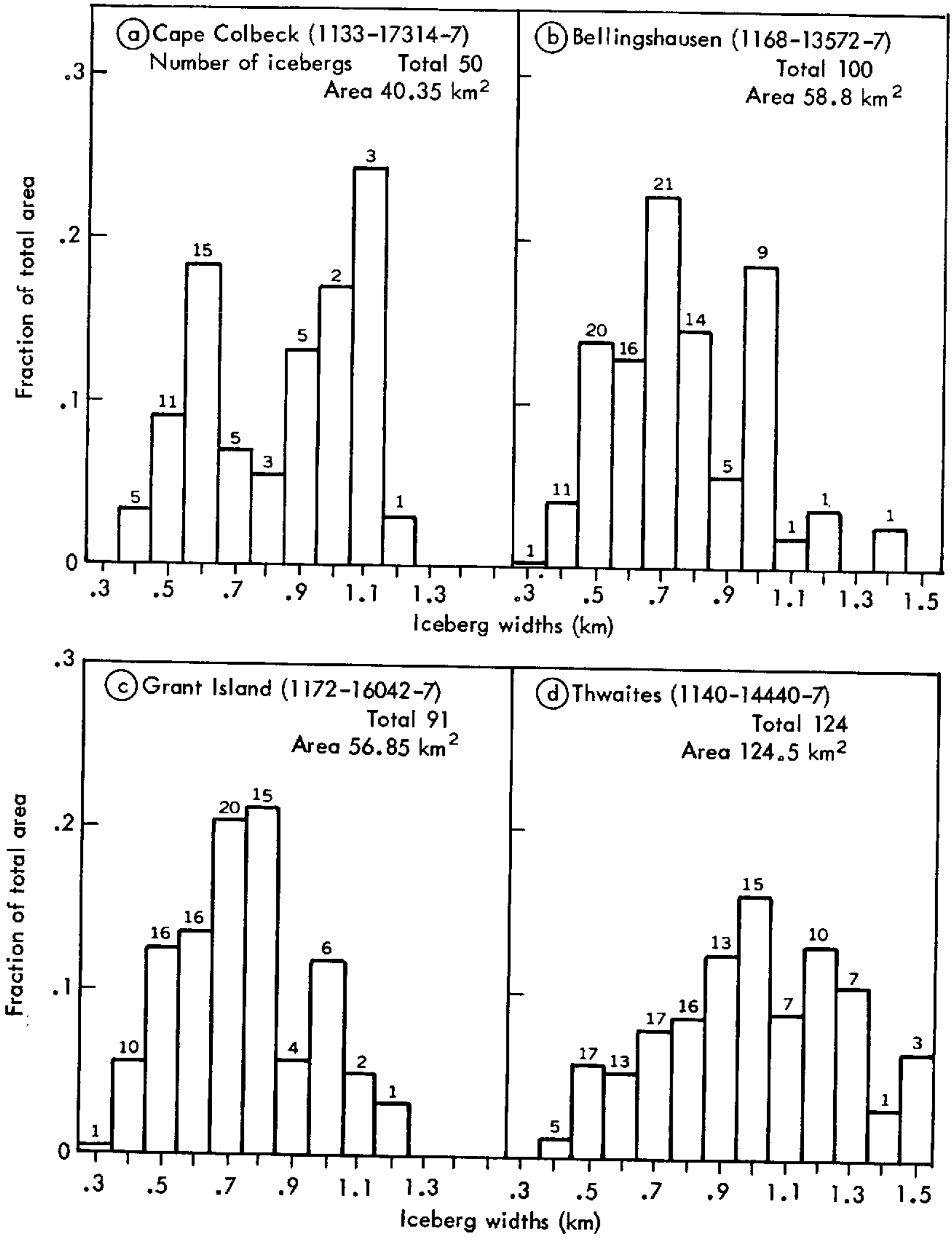


Fig. 15 — Distribution of iceberg widths in sampled areas

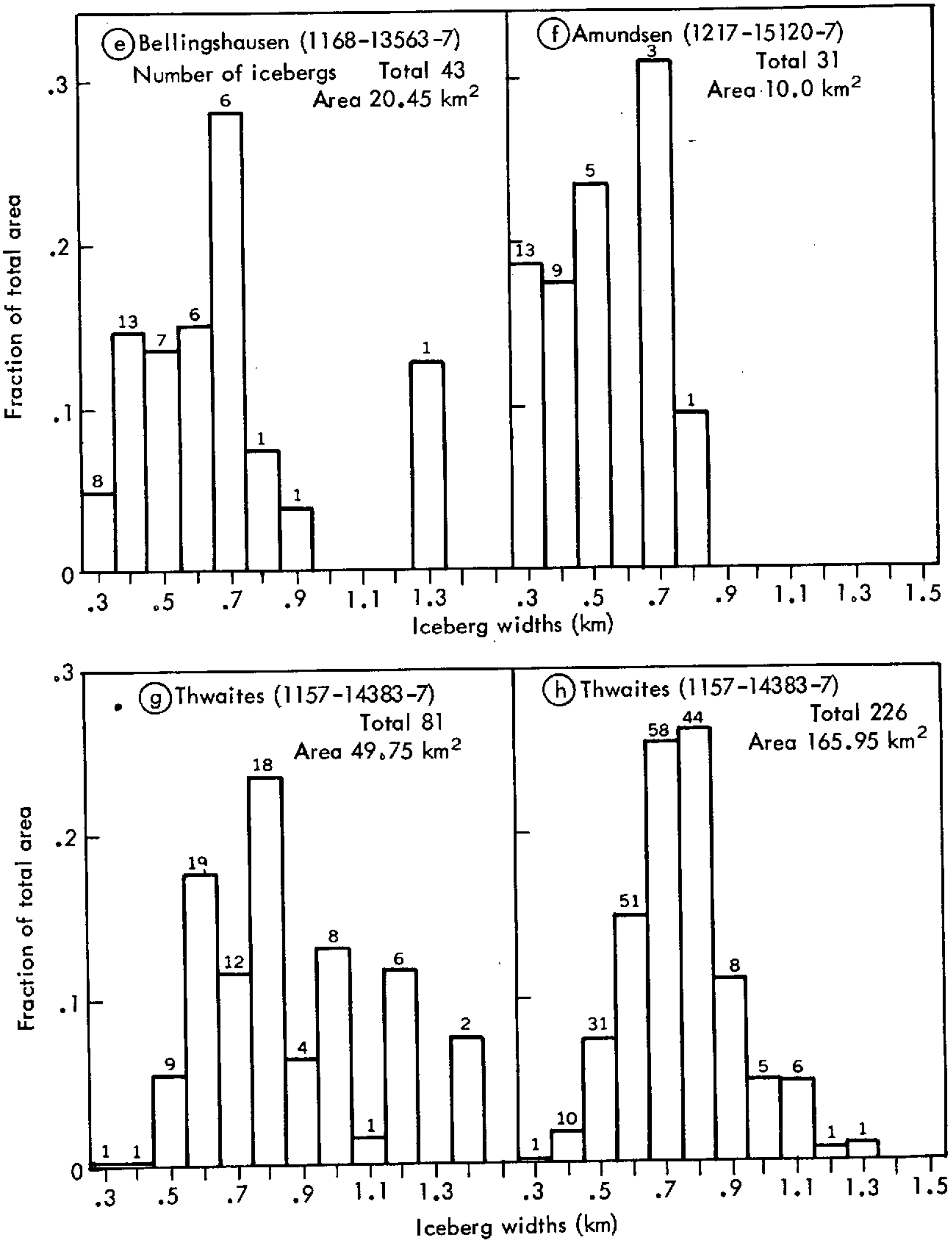


Fig. 15 — Continued

edge of the fast ice and may include some icebergs from other sources than Thwaites. The large sample, h, comes from the interior fast ice and should be a pure representation of Thwaites source characteristics.

The sample statistics of Fig. 15 indicate that until a substantial fraction of the annual iceberg yield is harvested, it may not be necessary to use icebergs of greater than 0.5 km width. However, if the samples of Fig. 15 are representative of all the Antarctic iceberg yield, it may be necessary to harvest icebergs up to 0.8 km wide if much more than half of the annual yield is to be used.

Inadequate data precluded an attempt to inventory the total mass of icebergs in the Antarctic, the annual yield, or the average or typical life of icebergs. The great abundance of icebergs that was observed was not inconsistent with a possible mass balance between the accumulation of precipitation in Antarctica and its discharge to the sea, which has been estimated to yield an average of 10^{12} m^3 of icebergs per year.(2) However, the data samples do indicate that there may be great variability in the life and evolution of the icebergs after they have been calved. In some areas they become trapped near the coast for many years and probably melt much more slowly than icebergs that are swept into oceanic gyres and experience significant current gradients over their immersed depths as they circulate through the belt of sea ice. The significantly smaller dimensions of the icebergs found in the northern edge of the belt as compared with those near the coast indicate that the melting life of the average iceberg in a circulating gyre may be comparable to the circulating period of the icebergs.

The imagery from ERTS-1 did not provide any accurate means of determining height or thickness of icebergs. The shadows produced on surrounding sea ice give an approximate order of magnitude for the height of many of the icebergs (~50 m). However, more accurate determination from satellites will probably require different sensors (such as thermal imaging devices that could measure temperature differences with height, or radio waves using ranging techniques). There probably is some relationship between the thickness of glacial ice streams entering the ocean water and the characteristic widths at which the icebergs tend to break off. Also, the entering flow inclination, tides, and seasons may be influential factors. Additional ERTS data, especially from high-resolution thermal sensors, together with correlation with ground truth, seem desirable for reliable estimates of iceberg thickness.

Some iceberg characteristics, such as the nature and smoothness of the melting submerged surfaces and the expected variations with source and environmental history, will probably never be known without direct physical measurements. Much additional valuable information for achieving efficient harvesting operations will best be gained by experience in the operating environment.

ANTARCTIC TOPOGRAPHY

In addition to the information about iceberg resources that was obtained from ERTS imagery, considerable topographical information was obtained that may be useful for mapping and other Antarctic interests. Figures 16, 17, and 18 illustrate the types of imagery available. Figure 16 shows the McMurdo Sound area and clearly demarks Ross Island, the lead along the edge of the Ross Ice Shelf for ship access to McMurdo station, and many other topographical features. Figure 17 shows the King Peninsula area and islands in the vicinity. Demas Ice Tongue of the Abbot Ice Shelf is outlined and is distinguished from the attached fast ice to the north. The thawing snow surface on top of Abbot Ice Shelf is indicated by the shading tones. Figure 18 shows the Thurston Island area and clearly outlines the complicated structure of the eastern half of the island.

The images that seem to contain the most useful topographical information for possible use in mapping or other activities are listed in the table with ERTS frame identification numbers and a brief geographical description of the exposed area. A much more complete listing of images that contain topographical information unobscured by cloud cover may be obtained from the Image Descriptor Data Bank file under the descriptor: Antarctic Topography.

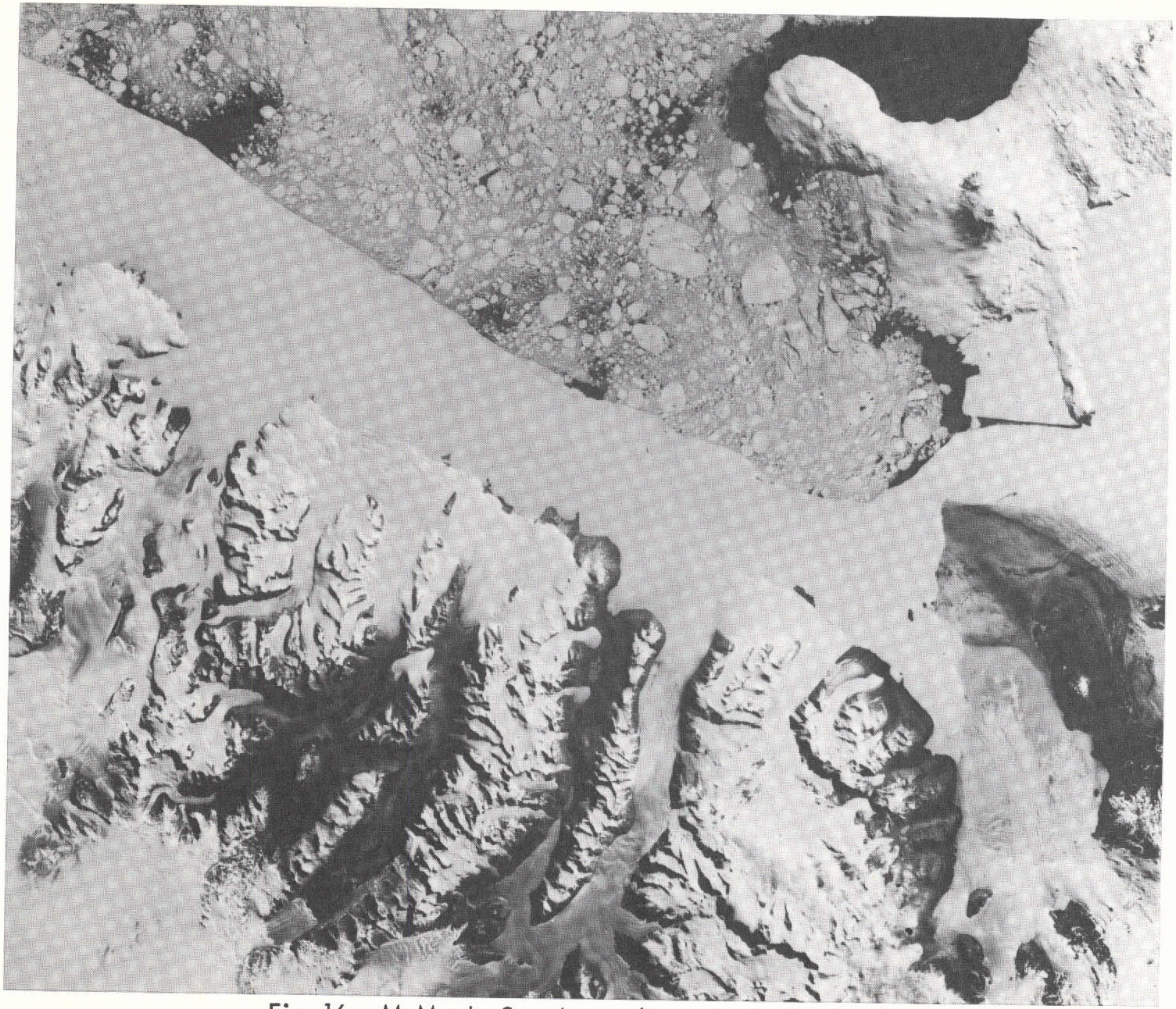


Fig. 16—McMurdo Sound area (from 1174-19433-7)

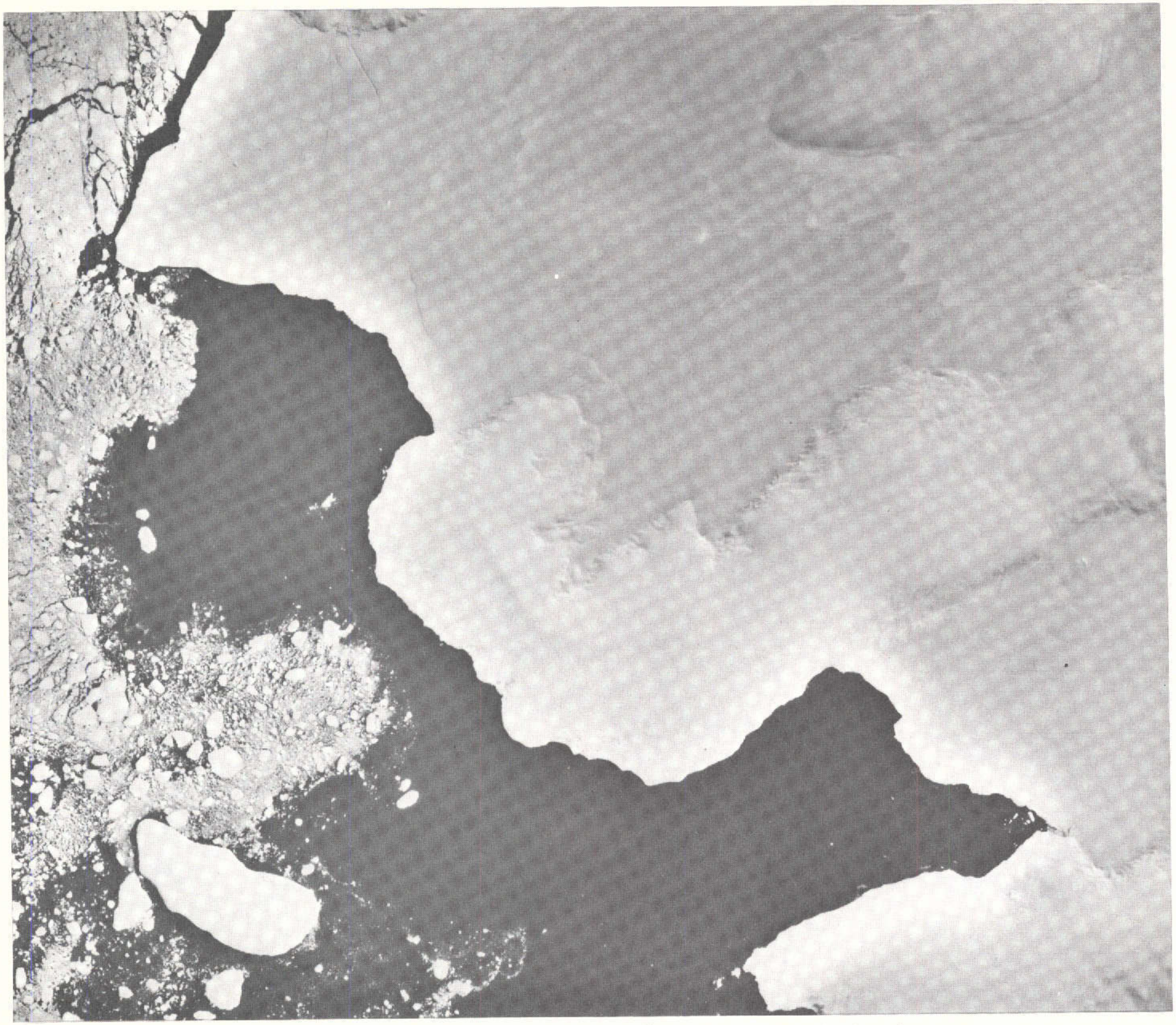


Fig. 17—King Peninsula area (from 1191-14264-7)

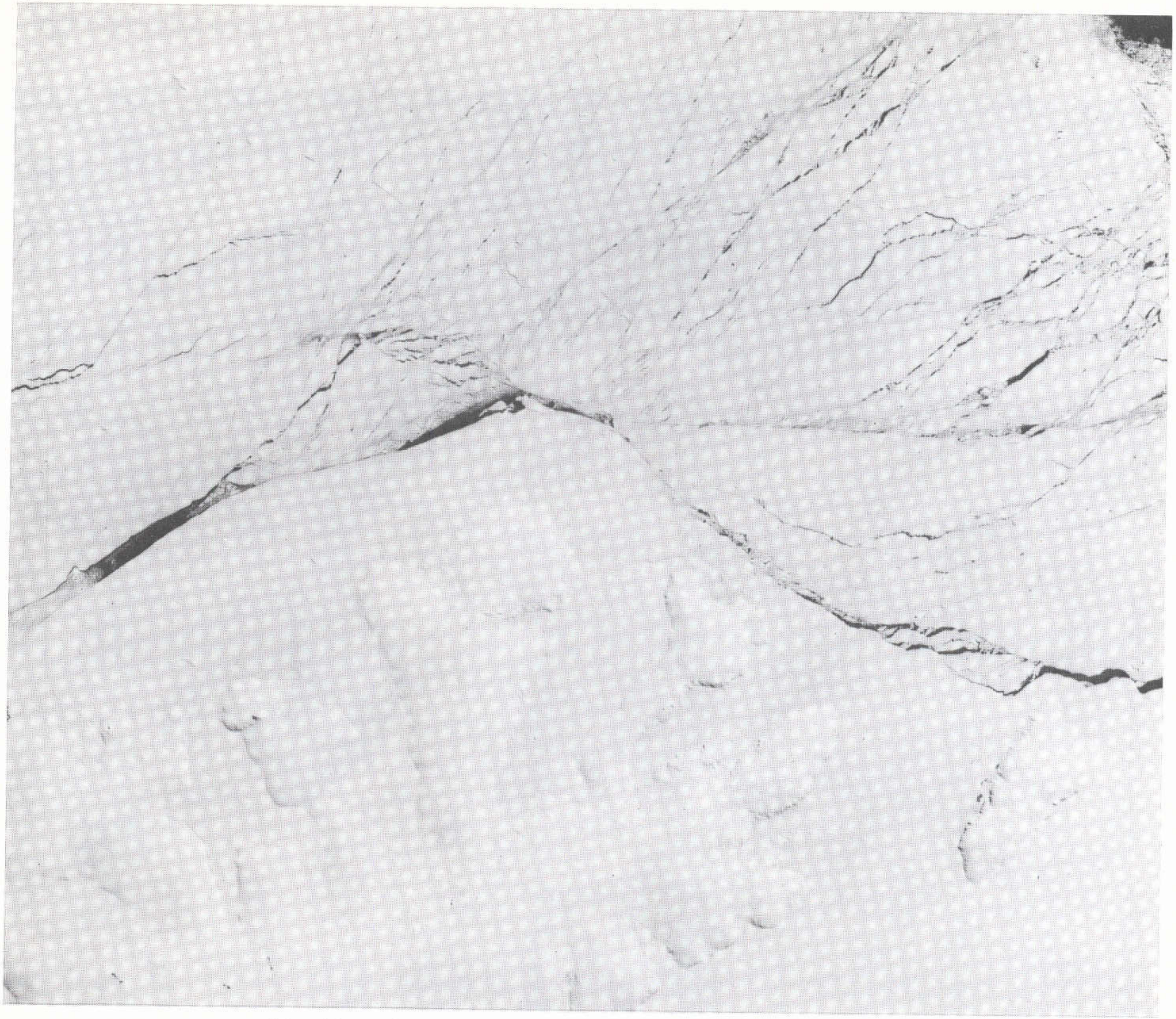


Fig. 18—Thurston Island area (from 1134-14091-7)

ERTS IMAGES EXPOSING TOPOGRAPHY OF POSSIBLE INTEREST

ERTS-1 Frame ID	Geographical Description
1117-21073-7	Rennick Glacier
1117-21075-7	Rennick Glacier
1131-20444-7	Pennell Coast
1131-20450-7	Victoria Land
1131-20453-7	Victoria Land
1131-20455-7	Victoria Land
1149-20443-7	Pennell Coast
1186-20501-7	Pennell Coast
1220-20400-7	Victoria Land
1220-20402-7	Victoria Land
1116-19212-7	McMurdo Sound & Moore Embayment
1128-20275-7	Scott Coast
1128-20281-7	Scott Coast
1128-20284-7	Scott Coast
1128-20290-7	Scott Coast
1130-18580-7	Western Ross Ice Shelf front
1151-19151-7	Western Ross Ice Shelf front
1154-19322-7	Ross Island environs
1157-19493-7	Scott Coast
1163-20224-7	Scott Coast
1163-20230-7	Scott Coast
1165-18520-7	Ross Ice Shelf front @ 178°E
1174-19433-7	McMurdo Sound environs
1177-20001-7	Scott Coast
1177-20004-7	Scott Coast
1200-20290-7	Scott Coast
1214-20055-7	Scott Coast
1214-20062-7	Scott Coast
1214-20064-7	Scott Coast
1214-20071-7	Scott Coast
1121-18065-7	Ross Ice Shelf front
1133-17314-7	Cape Colbeck
1133-17320-7	Ross Ice Shelf front (eastern)
1187-17315-7	Ross Ice Shelf front (eastern)
1187-17321-7	Ross Ice Shelf front (Bay of Whales)
1117-15592-7	Mts. in Marie Byrd Land
1117-15594-7	Mts. in Marie Byrd Land
1120-16161-7	Grant Island environs
1146-15185-7	Carney Island; Bakutis Coast
1146-15194-7	Executive Committee Range
1152-15524-7	Siple Island, Getz Ice Shelf
1152-15531-7	Dean Island, Getz Ice Shelf
1152-15533-7	Flood Range
1152-15540-7	Flood Range

ERTS-1 Frame ID	Geographical Description
1172-16035-7	Siple Island, Getz Ice Shelf
1172-16042-7	Dean Island, Getz Ice Shelf
1172-16044-7	Hobbs Coast
1172-16051-7	Flood Range
1175-16213-7	Grant Island, Hobbs Coast
1175-16215-7	Hobbs Coast
1175-16222-7	Ruppert Coast
1200-15194-7	Executive Committee Range
1200-15201-7	Executive Committee Range
1119-14273-7	Walgreen Coast
1119-14280-7	Mt. Takahe
1134-14091-7	Thurston Island
1137-14265-7	Walgreen Coast
1137-14271-7	Walgreen Coast
1140-14440-7	Thwaites Tongues
1140-14442-7	Walgreen Coast
1157-14374-7	Thwaites Tongues, Walgreen Coast
1157-14380-7	Thwaites Tongues, Walgreen Coast
1157-14383-7	Thwaites Tongues, Walgreen Coast
1160-14551-7	Thwaites Iceberg Tongue
1160-14554-7	Bear & Martin Peninsulas
1166-13572-7	Thurston Island
1166-13574-7	Eights Coast
1174-14314-7	Thurston Island
1174-14320-7	Walgreen Coast
1174-14323-7	Thwaites Glacier
1174-14325-7	Walgreen Coast
1177-14494-7	Thwaites Iceberg Tongue
1177-14500-7	Dotson Ice Shelf environs
1185-13530-7	Pine Island Glacier
1191-14264-7	Abbot Ice Shelf
1191-14270-7	Walgreen Coast
1205-14044-7	Pine Island Bay
1121-12541-7	Alexander Island to English Coast
1121-12543-7	Alexander Island to English Coast
1121-12550-7	Alexander Island to English Coast
1139-12541-7	Alexander Island to English Coast
1139-12543-7	Alexander Island to English Coast
1139-12550-7	Alexander Island to English Coast
1170-12260-7	Ronne Entrance Islands
1173-12430-7	Smyley Island and Carroll Inlet
1182-13345-7	Fletcher Peninsula and coastal environs
1190-12374-7	Ronne Entrance environs
1190-12380-7	Carroll Inlet

III. ERTS SYSTEM POTENTIAL

In order to explore the possibilities of future ERTS systems as aids for harvesting Antarctic iceberg resources, it is important first to understand the potential use of Antarctic icebergs.

RELEVANCE OF ANTARCTIC ICEBERGS

A feasibility study of *Antarctic Icebergs as a Global Fresh Water Resource*(2) indicates that global needs for fresh water and the abatement of thermal pollution are rapidly growing with increasing populations and standards of living, and are becoming acute in a number of regions that include the Pacific Southwest of the United States and parts of Mexico, Chile, Australia, the Middle East, and North Africa. In some of the thirsty regions, other water resources may be available by transfer from river basins having abundant water, or by desalting. The costs of transferring or desalting (which may be \$100 or more per thousand m^3 ($k{\cdot}m^3$) or per acre-ft) tend to severely limit such use. Icebergs might become a very attractive fresh water resource if the technology can be devised that will deliver the melt water at much less cost than desalting and with acceptable environmental impact.

The idea of using Antarctic icebergs has been considered and even tried a number of times during the past century. The abundance of icebergs has long been recognized (annual yield of about a million million cubic meters or a thousand million acre-ft). They might be floated to any point accessible by a deep-water route (at least 200 m of water depth). If a way can be found to move the icebergs and control their melting so as to deliver 10 percent of the *annual* yield economically, it could satisfy the direct needs of an urban population of 500 million (with a usage of 200 m^3 per person). The potential direct economic impact of 10 percent of full exploitation is estimated to be as much as \$10 billion annually.

Past exploration of the Antarctic has indicated that a major portion of the sea ice that forms and builds up during the dark Antarctic winter months thaws out during the daylight season. By March of each year most of the tabular icebergs naturally formed from ice shelf discharges become accessible for acquisition and exporting operations. Although the sea ice is mostly less than 2 m thick as compared with a few hundred meters for most tabular icebergs, the sea ice formed and thawed each year is thousands of times the total area of icebergs and about ten times the mass. Thus sea ice is a major factor to contend with in the acquisition of icebergs. Its moderating influence on the climate (together with that of the continental icecap) is so much more than that of the icebergs that little climatic effect is expected even with the removal of most of the annual iceberg yield. Man should be able to process and use this valuable iceberg resource (which is otherwise wasted) for high-quality fresh water and thermal pollution abatement (before it again becomes sea water) without adverse effects on the global or Antarctic climate.

The theoretical exploration of the feasibility of moving icebergs and controlling their melting involved the modeling of transport operations from the Ross Sea to Southern California, and included the available environmental data on currents, winds, and temperature.(2) Although these data are very crude and limited, they are adequate to test the first-order feasibility. The model shows that the transport effort required is not very sensitive to the winds, can benefit from the currents but is not dependent on them for feasible operations, is not too sensitive to the route selected, and will require insulation of the icebergs for acceptable survival en route to the northern hemisphere. It is found that the Coriolis forces provide the principal resistance to the transport operations. The Coriolis forces are proportional to the momentum (mass x velocity) and the sine of the latitude. These forces are applied at right angles to the velocity and involve a large fraction of the propelling effort to counteract their effects, particularly at more southerly latitudes.

The cost of delivering the icebergs will be determined by the design of the transport operations and the configuration of the iceberg trains. Narrow trains (300 to 600 m wide) are desirable because they are estimated to reduce the net Coriolis effects to a fraction of the direct effects on icebergs. Also, when these trains are propelled at an angle with respect to the resultant velocity, they can more effectively obtain "lift" to counteract Coriolis forces. Minimum transport cost per unit of iceberg is approached for iceberg trains longer than about 20 km. Greater lengths increase the mass, movement resistance, and insulation costs proportionately. The costs of insulation can be estimated without specifying many of the details of operational techniques for applying the insulation, which need empirical test. Essentially, the iceberg surfaces exposed to ablation from the flowing sea water can be wrapped by unrolling film that is designed to trap pockets of melt water to form a quilting of still water between the iceberg and the flowing sea water. A quilt water thickness of 3 cm will limit the iceberg melting to less than 10 percent per year.

Delivering a large iceberg train (1.22 x 10^{13} kg) to California in one year is estimated to cost about \$8 per thousand m^3 (\$10 per acre-ft). It is also estimated that designing operations for more nearly optimum speed or better train configurations will not significantly reduce these rates. On the other hand, these delivery costs can be approached for a variety of operations that would depart significantly from the asymptotic one that was costed.

Before designing an operational system, and for refining cost estimates, a pilot test program would be desirable to: determine the nature of the submerged surfaces of icebergs, test techniques for insulating and harnessing icebergs, measure the towing environment and performance, determine how well the Coriolis forces can be controlled, and test the performance of modeling to simulate operational control and performance.

The conversion of the icebergs for fresh water and heat sink was explored in a very preliminary way in order to uncover promising concepts and to estimate cost limits based on general physical principles. This exploration indicated that iceberg conversion to fresh water at sea level in a timely manner should be achievable in a variety of ways for about \$8 per k•m^3 (\$10 per acre-ft). An engineering study and comparison of the more promising conversion techniques is needed to develop better cost estimates and to provide a basis for the design of pilot test systems that could evaluate alternative approaches for operational systems.

The total cost for delivering Antarctic iceberg water in large quantities to wholesale distribution terminals in coastal areas with deep-water access is estimated to be about \$24 per k•m^3 (or \$30 per acre-ft). This appears to be much less than the costs for interbasin water transfers of a few hundred km or for desalting or costly water reclamation operations; the energy required is correspondingly less and can be supplied without competing for fossil fuel resources. Thus it should become an attractive alternative for obtaining fresh water (in areas close to deep-sea-water access for icebergs) while conserving depleting energy resources and minimizing the burden on the environment.

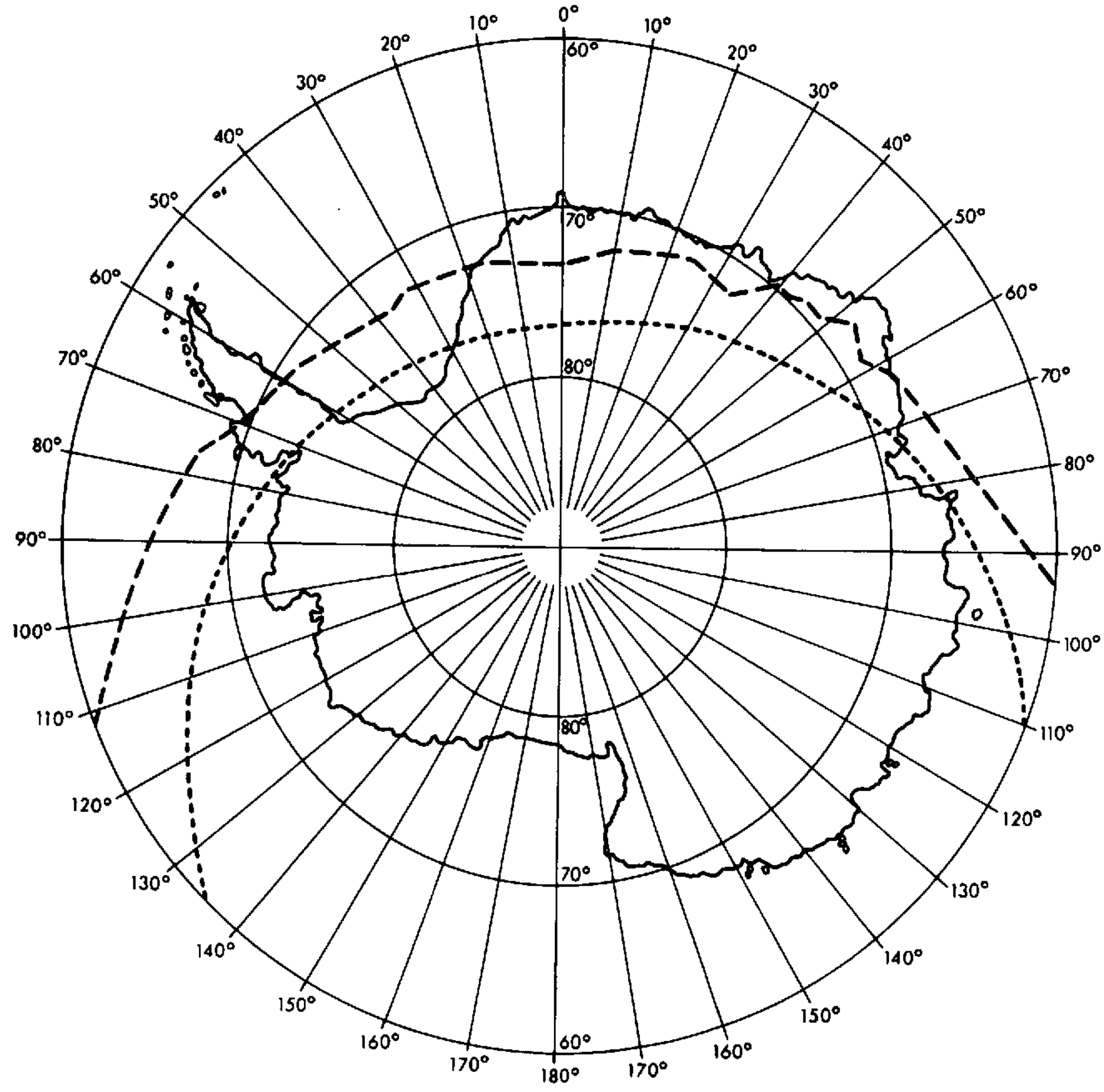
Before any large-scale operational use of Antarctic icebergs is implemented, there should be a comprehensive assessment of the potential societal and environmental impacts. A preliminary exploration of a variety of such factors reveals no obvious insurmountable obstacle for the concept. These factors include the international acceptability of exploitation of Antarctic ice, the en route environmental constraints, the acceptability of terminal operations, the demand for iceberg water and the integration of its delivery system with other established systems for furnishing fresh water, icebergs as reservoirs and recreation areas, and risk in iceberg water resource systems. The more avenues that are explored, the more promising the concepts seem to become. However, a more refined assessment can better be made when the potential operations become better defined and when specific terminal applications can be examined in detail.

LIVE IMAGERY

The principal advantages of live (real-time) imagery obtained with earth readout stations in Antarctica are that it would be possible to collect complete imagery from every orbital pass over Antarctica and it could be made available for immediate use. This would eliminate the storage capacity limitations and reliability problems of space-borne video recorders. Also, the information could be made available soon enough to be of tactical value in the control of harvesting operations.

There are a number of ways that live readout might be provided in Antarctica. Synchronous satellite relay could make live readout possible almost anywhere on earth. This could require the development and operation of the relay satellites and considerable modification to current ERTS designs, but it may be the ultimate solution. An earlier solution that could be made compatible with current ERTS configurations would be to provide a readout station on board a ship that could be moved to provide the service wherever it was needed. Or earth stations could be installed at suitable locations such as McMurdo station for year-round operation. The latter is sketched as a reference case. The readout coverage from a 10-m-diameter antenna centered at 510 m above sea level near McMurdo is illustrated in Fig. 19. The coverage contours are for an ERTS satellite at a nominal orbital altitude of 930 km (500 n mi) over Antarctica. The inside contour is at 5 deg angle of elevation and the outside contour represents the approximate physical line-of-sight horizon from the antenna site. The operational coverage that could be achieved would probably lie between these two contours and somewhat closer to the outer one. It appears that this site alone could provide live readout for most of Antarctica except for coastal and drift-ice areas in the sector of eastern Antarctica between the Weddell Sea and the Amery Ice Shelf. It could provide excellent coverage for readout of stored data because it could follow *every* orbital pass for a relatively long time. Therefore, it could obtain stored readout with very small delays from many areas that it could not reach for live readout.

An alternative to live readout for alleviating the deficiencies of the initial experimental ERTS system relative to Antarctic imagery would be to greatly increase the capacity and flexibility of the recording system. This might require improving the earth station network for readout of stored data in addition to increasing the recording capability in the satellite. A site at McMurdo may be an attractive augmentation that would permit much live readout as well as transmission of most of the stored data on every orbital pass.



- - - - - - -Coverage at 5 deg elevation

— — —Line-of-sight coverage

Fig. 19—Potential earth station coverage from McMurdo

The initial investment required to install a readout station near McMurdo is estimated to be comparable to the Fairbanks, Alaska installation--about $500,000. A crew of 35 has proved satisfactory to provide four operating shifts of eight men each. If a "quick look" facility is to be provided, an initial investment of about $100,000 would be added. It is estimated that about $1.5 million per year will be required to cover the annual operating expenses and to recover the initial investment costs during its useful life. If the filtered imagery is to be transmitted to potential users by synchronous satellite relay, it may not increase greatly the costs of the McMurdo station if a suitable site is selected that is within a satisfactory look angle to the relay satellite, but the communication relay costs must be added as a part of the total user costs.

THERMAL AND MICRO WAVELENGTHS

A thermal wavelength band (10.4 to 12.6 micrometers) is planned for inclusion in ERTS-B. With imagery from this band it may be possible to measure small surface temperature differences day or night. Such a capability may greatly aid in distinguishing icebergs from sea ice and may even permit height determinations of icebergs by temperature differences. Approximately the same ground resolution would be desirable at thermal wavelengths as is provided with the other wavelength bands. Also, approximately the same cloud-cover limitations will apply. Because most of the cloud cover in Antarctica consists of particles that are large compared to these wavelengths, the cloud cover is not expected to provide significantly greater openings at thermal than at the shorter wavelengths. The thermal band is used to record the one-way thermal emission from the surface, and the cloud cover attenuates or darkens this emission. At the shorter wavelength bands, the observations are of scattered sunlight and the brightness of the cloud-scattered sunlight degrades any contrast that might otherwise filter through the cloud cover. However, the distinction between the ways in which the bands obtain imagery is not expected to make any great operational difference in the effects of cloud cover. On the other hand, the many more observation opportunities available with the thermal band (every pass, independent of solar illumination) will permit obtaining two to six times as many glimpses through cloud openings and will enable monitoring throughout the year.

Microwaves could penetrate cloud cover, and the reflections from the top and bottom of ice have been used to measure ice-shelf thicknesses by ranging techniques from aircraft. However, these techniques are not yet feasible from ERTS and the angular resolution achievable at these ranges and wavelengths would not be very useful for observing most individual icebergs. However, synthetic aperture radar techniques could be used from aircraft or satellites to provide high-resolution surface mapping independent of cloud cover or solar illumination. Although these techniques may not soon be available on operational ERTS type of satellites, they could be employed with aircraft to greatly reduce the flight effort required with sensors that are obstructed by cloud cover.

SEA-ICE BEHAVIOR AND ICEBERG EVOLUTION

In order to plan the operational harvesting of icebergs it is important to understand sea-ice behavior and iceberg evolution. Much of this knowledge could be obtained by monitoring and following iceberg processes over several yearly cycles of seasons in the areas of interest. Since this should be done prior to operational harvesting, the cost of obtaining the information should be treated as research cost to be recovered during the years of harvesting operations. It does not seem important to have a "quick-look" capability for this type of information. However, in order to achieve usefully complete coverage through the prevailing cloud cover, it would be desirable to obtain imagery on nearly every pass opportunity. The very limited sampling of part of western Antarctica that was accomplished with ERTS-1 will be useful for correlation with more comprehensive data that might be obtained in the next few years. Comprehensive satellite imagery should be buttressed with ground truth information that might be obtained from a test program to acquire, harness, insulate, and tow real (though small) icebergs in Antarctica. Only then would it be possible to design and invest in operational systems with the necessary confidence.

TACTICAL HARVESTING INFORMATION

Tactical information for aid in acquiring icebergs and controlling the harvesting operations should be timely, and timeliness could be achieved with live readout and a "quick-look" capability. Each operational harvesting expedition could include this capability as an integral part of its facilities. Alternatively, it could be accomplished at a common central station, e.g., McMurdo, and the useful processed information could be forwarded to the harvesting expeditions by satellite relay. In either case, the costs of obtaining the information would be an operational expense that legitimately should be charged to the harvesting operations.

CLAIMING AND MONITORING SERVICE

When there is the possibility of independent harvesting operations competing for icebergs, a claiming procedure that will permit efficient planning and harvesting will be needed. This might be accomplished by practices established in other situations, e.g., staking claims perhaps a year or two in advance, or stationing a man on board so that the ice "ship" is not abandoned. However, a more attractive way of claiming might be to coordinate and monitor the claiming with ERTS imagery. This method could be used to coordinate the claiming early enough to permit efficient planning for harvest without excessive claiming effort or resource waste. The claiming service would be a legitimate operational harvesting expense, and the charge could be determined by the quantity or value of icebergs claimed.

ENTITLEMENTS TO ANTARCTIC ICEBERG RESOURCES

The Antarctic icebergs are a continuous yield resource. They simply melt and return to sea water without a direct benefit to mankind if they are not harvested and used in the process. They are part of the international waters and should be available to anyone as an extension of the freedom-of-the-seas doctrine. Furthermore, it would seem desirable to avoid the tradition practiced for water entitlements in parts of the world in which indefinite claims are established by the first to perfect their rights, so that future new needs may be denied if the resources are not adequate.

It is suggested that the claiming and monitoring service with satellite imagery be extended to include auction of the icebergs, with any surplus revenues used to increase the harvest and equalize the costs. The auction and claiming could be once a year, sufficiently in advance of the harvesting season to permit adequate planning and preparation for the operations. This method of granting entitlement to icebergs should secure the greatest economic benefits from this resource, and it would not deny anyone future access.

ECONOMIC POTENTIALS FOR ERTS

About $1.5 million per year is estimated to be necessary to maintain a continuous ERTS readout and "quick-look" station in Antarctica. This would permit using the full capabilities of ERTS-1 and ERTS-B on every orbital pass to provide a wealth of information about Antarctica in general, in addition to that of primary value for the harvesting of icebergs. Also, a station near McMurdo would be able to read out any stored information on every ERTS orbit. This might permit greatly increased world-wide use of the image storage capability of ERTS by relieving readout constraints.

The estimated revenue requirement to procure and place an operational ERTS into orbit and control its operation will probably be between $5 and $10 million annually. However, the Antarctic harvesting of icebergs should only be assessed its fair share of this revenue requirement.

The total cost of delivering iceberg water to the final user or distributor is estimated to be about $24 per $k{\cdot}m^3$.(2) This is only a small fraction of the cost of desalting sea water or of long distance interbasin transfer. Therefore it is not expected that iceberg water will suffer serious competition from these other sources even if the price is raised considerably. However, the demand for iceberg water for agricultural uses is expected to be very elastic about this point, and to supply the agricultural demands it will be necessary in most cases to reach the scale that will permit the attractive prices that have been estimated for iceberg water. Therefore, it is felt that the iceberg harvesting systems may only be able to afford an additional assessment of a few percent of the delivery price for the water before the demand might be seriously affected, i.e., large volume demand might fall rapidly with increasing assessments above about \$1 per $k{\cdot}m^3$ for ERTS aid.

If 10 percent of the annual yield of Antarctic icebergs were harvested, an assessment of \$0.10 per $k{\cdot}m^3$ would produce an annual revenue of about \$10 million, which should be adequate to compensate for the share of ERTS operating costs. However, since early harvesting operations may commence at only 1 percent of the annual yield and some research and development costs should be assumed by the iceberg harvesting operations, it would seem appropriate to begin assessing iceberg harvesting operations at a rate between \$0.1 and \$1.0 per $k{\cdot}m^3$.

In order to obtain as much useful imagery with optical sensors on board high-altitude aircraft as might be obtained with full use of ERTS, at least 10 aircraft passes would be required for each ERTS pass to achieve a comparable coverage. The most suitable aircraft for such a task would require at least 1,000 hours of imaging flight every 24 hours in order to duplicate the ERTS coverage. Although a feasible basing and operational plan has not been conceived, an operating fleet of more than 120 aircraft and 400 flight crews would be required to maintain such operations over an extended period of time. This would be a prodigious and costly operation compared to that required with ERTS (at least 10 to 100 times as great an effort). Even with a likely requirement for coverage of only portions of the Antarctic, the task of doing it with optical sensors on board aircraft seems much larger than full coverage by satellite.

If satisfactory coverage could be obtained with synthetic aperture radar on board aircraft, it may be possible to do so for limited operations at costs comparable with the full use of ERTS. The capabilities and costs of both techniques need test and evaluation in order to select the appropriate operational role of each.

The costs of not having the equivalent of ERTS imagery for harvesting of icebergs in the Antarctic are also difficult to assess. Small bootleg operations would be possible without paying an ERTS toll. However, it should be very difficult to achieve dependable competitive operations or obtain user commitments with any operation that would try to harvest without coordination through an ERTS information system established for this purpose.

IV. AUTHOR-IDENTIFIED SIGNIFICANT RESULTS

This investigation shows that ERTS systems offer unique capabilities vital to the success of Antarctic iceberg harvesting operations. The potential contributions of ERTS to the research, planning, and harvesting operations are major factors in the promise of the use of Antarctic icebergs to relieve a growing global thirst for fresh water and for the abatement of thermal pollution. ERTS offers enough orbital overpass opportunities to penetrate the prevailing (~80 percent) cloud cover and provide a comprehensive, high-resolution coverage and continuous monitoring of Antarctic surface features. It will be possible to determine the sea-ice behavior and its potential influence on the harvesting of icebergs. Also, it will be possible to monitor iceberg locations, characteristics, and evolution. Much mapping, other resource, and research information about the Antarctic will also be available in the concerted use of ERTS for surveying Antarctic iceberg resources.

Facilities for live readout of Antarctic imagery appear desirable to acquire enough looks for adequate timely coverage through cloud-cover openings. The thermal wavelength bands will offer better year-round opportunities for coverage than the bands used in ERTS-1, and they are not dependent on solar illumination. With these modifications to the initial ERTS-1 performance, it should be possible after a few years of observations supplemented with appropriate ground truth data to characterize the sea-ice behavior and iceberg evolution adequately to design equipment and plan for efficient iceberg harvesting operations. Such a modified ERTS system could also provide a unique and invaluable service in iceberg harvesting operations. The tactical control information and the methods of claiming and entitlement that are suggested promise efficient harmonious operations in harvesting Antarctic icebergs for world-wide benefit. The iceberg harvesting operations could easily bear the costs of the ERTS services that will be essential to the success of economical large-scale use of the continuous Antarctic iceberg yield that is otherwise wasted as it melts and returns to sea water.

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