Application of Microwave Remote Sensing to Studies of Sea Ice

P. E. Gudmandsen

Phil. Trans. R. Soc. Lond. A 1983 **309**, 433-445
doi: 10.1098/rsta.1983.0053

Phil. Trans. R. Soc. Lond. A **309**, 433–445 (1983)
Printed in Great Britain

Application of microwave remote sensing to studies of sea ice

By P. E. Gudmandsen

Electromagnetics Institute, Technical University of Denmark 348,
DK-2800 *Lyngby, Denmark*

[Plate 1]

Monitoring of snow and ice is of importance for meteorological and climate research and applications, for hydrological purposes and for navigation and offshore activity in polar regions. For some of these applications long-term monitoring on a mesoscale and a synoptic scale is sufficient, whereas other applications require short-term observation on a mesoscale. This applies especially to forecasting of sea ice conditions, for instance. In the latter cases microwave remote sensing is the only technique that may deliver reliable and timely data irrespective of light, weather and cloud conditions. In the polar regions, this feature is of utmost importance.

All known microwave remote-sensing techniques have demonstrated their applicability in polar regions, in particular in connection with observations of sea ice. It has also been shown that a combination of simultaneously acquired data from different sensors may be of advantage in parameter retrieval.

This paper reviews the monitoring requirements and the microwave techniques available for this purpose with a view to snow and sea ice research and applications.

INTRODUCTION

Remote sensing from satellite is particularly useful in the polar regions which to a great extent are unexplored and inaccessible owing to severe environmental conditions. One important object for remote sensing is sea ice. In fact, vast areas of the world's oceans – approximately 10 % in the Northern Hemisphere and 13 % in the Southern Hemisphere – are covered by floating ice that is subject to large seasonal and annual variations in extent and composition. With the increased interest in the polar and sub-polar regions, largely driven by the exploration and exploitation of Earth resources on land and offshore, remote sensing becomes an important tool for surveillance and monitoring with a view to navigation and the safety of the operations.

Also it is understood that the polar regions are important parts of the Earth's heat engine and that the polar climate may have a strong influence on the climate of the Earth as a whole. Any climatic variation, which may occur for one reason or another, may have a large impact on the polar conditions and therefore be more easily observable than in other regions of the Earth. The annual variation of the extent of the sea ice may be an indicator of a climatic trend, for instance.

With such applications in mind, a series of investigations are being undertaken or planned to contribute to the understanding of the environment and to study the phenomena and mechanisms controlling the environmental conditions as expressed by the term air–sea–ice interaction. Remote sensing from aircraft and satellite plays an important role in these studies, which at the same time contribute to the understanding of the interaction between electromagnetic waves and the Earth's surface, i.e. the fundamentals of remote sensing. Many of the investigations are directed towards the development of methods of forecasting of the sea ice conditions, for instance to be based on satellite remote-sensing data as input to numerical models.

AIR–SEA–ICE INTERACTION

In the air–sea–ice system the sea ice plays an important role in a number of ways. Thus a sea ice cover insulates the ocean from the overlying generally much colder air. It reduces the heat flux from the ocean by a factor of about 100, which is of major importance for the air masses travelling over the ice. Also, owing to its high value of albedo, the ice cover insulates the ocean from solar heating, and being radiatively cool with respect to the atmospheric boundary layer it acts as a heat sink that cools the air and reduces the turbulence of the lower atmosphere. In addition, the ice is normally advected towards the open ocean where it melts and thereby cools the upper ocean. This is a major process for heat transport.

Conversely, the atmosphere has a strong influence on a sea ice canopy through the wind's creating two effects, motion of the ice and melting or forming of ice, depending on the relative temperature of the air masses involved. Also, the motion may create a convergence or divergence of the ice floes, thereby changing the ice concentration with a resulting change in the heat flux. In short, in the coupled system of air-sea interaction the sea ice cover will modify the weather system in an important way, one example being the suggested influence of the migration of storms along the edge of a sea ice cover.

In addition to the influence of sea ice on the cold water through melting, the ice floe motion creates a surface stress gradient that modifies the ocean mixed layer. It has been suggested that this modification is the cause of upwelling observed at the ice margin. Also, when the ice is being formed, the resulting brine will increase the salinity of the upper ocean and eventually create a transport of saline (and heavier) water to greater depths. Conversely, when melting, the sea ice is a supply of brackish water forming a surface layer that increases the stability of the ocean. Finally, an ocean current has an impact on an ice field through the resulting motion caused by subsurface drag. An important example is the East Greenland Current, which carries large quantities of sea ice from the Arctic Ocean to the southern tip of Greenland (60° N) influenced by the Coriolis force and to a greater extent by the weather system along its path.

Finally, it is observed that large ocean waves created by storms in the open sea adjacent to an ice field will break the ice canopy into floes, with an effect that diminishes as the waves are attenuated on their way into the ice field. Large waves may be felt at distances of 50 km from the ice margin and may create a divergence of floes into the open sea.

The above is an attempt of describing briefly the processes involved in the air–sea–ice interaction system. Obviously, there is a strong interaction between these processes, and the understanding of the effect may only be obtained through extensive measurements and observations in the field, associated with numerical modelling. An important example is the AIDJEX project (Arctic Ice Dynamics Joint Experiment), which was carried out through several years in the central Arctic Ocean, i.e. in the interior of a large ice field. This experiment demonstrated the capability of modelling the behaviour of the ice under these conditions (Untersteiner 1979). Another example is the NORSEX project (Norwegian Remote Sensing Experiment) carried out in the marginal ice zone north of Svalbard (NORSEX Group 1982). Both experiments are examples of undertakings involving remote sensing and in-situ measurements of atmospheric, oceanographic and ice processes. This will also be so with MIZEX (Marginal Ice Zone Experiment), a drifting experiment which will take place in the Fram Strait from about 80° N and southwards in the East Greenland Current (Johannessen *et al.* 1982). Numerical modelling will be applied to this situation of an open ice edge to arrive at a better understanding of the processes. During a conference at the Nato Advanced Study Institute, Maratea, Italy, in September 1981 the subject of air–sea–ice interaction was discussed in detail by a number of specialists (Untersteiner 1983).

Apart from the scientific interest in understanding the air–sea–ice interaction system there are practical applications to be derived from these experiments (and MIZEX in particular), i.e. the development of methods of forecasting the ice conditions with a view to navigation and offshore activity. In this context, the numerical model(s) will be modified to a format that they may be used solely with data that are relatively easily obtainable, i.e. synoptic weather and remote-sensing data. The subsequent sections in this paper will review the sea ice and ocean parameters that may be derived from satellite remote sensing and the remote-sensing techniques involved.

Sea ice and ocean parameters

Remote sensing may in most cases be characterized as observation by means of electromagnetic sensors of surface features, and the interpretation of remote sensing data relies to a great extent upon the differences in form and dielectric properties of the surfaces observed. In the context of sea ice and ocean observations, it is only with multi-year ice that some penetration into the material takes place and thereby reveals special characteristics. These facts are of importance for studies of the air–sea–ice system and for numerical modelling, where for instance some ocean parameters or phenomena will have to be derived from surface features associated with the phenomena.

Lists of pertinent parameters derivable from remote sensing are given in tables 1 and 2 for sea ice and ocean, respectively. These tables were generated during a workshop held in Copenhagen with the purpose of defining future satellite missions with microwave radiometers (Gudmandsen *et al.* 1983). For each parameter the tables state the observation requirements and the satellite instrument(s) likely to supply the parameter in question. The instruments are given in the order of likely importance by letter codes as follows: RA, radar altimeter; SAR, synthetic aperture radar; SCAT, scatterometer; PMR, passive microwave radiometer; VIR, visual and infrared radiometer. The observation requirements for accuracy and for resolution in space and time are based on considerations of their usefulness in basic research, climate research and operational or commercial applications. The frequency of data applications is given in terms of a code (from I to III) as stated. The figures quoted are arrived at on the basis of present knowledge and demonstrated capabilities, and on considerations of the scale of the geophysical variations in space and time. However, very little experience has been obtained with operational application of data and with numerical modelling for forecasting. Future studies in this direction may introduce modifications. In this context, it is worth mentioning that the requirements for time resolution can in most cases only be met with two or more properly phased satellites in orbit. With a near-polar orbiting satellite a frequent coverage is obtained at high latitudes (where sea ice observation is of importance) but with intervals of many days. Also, the frequency of observation is closely dependent upon the swath width of the instrument in question. One extreme is the radar altimeter, which by nature is a profiling instrument, and another is the passive microwave radiometer, which may have a swath width

TABLE 1. SEA ICE OBSERVATION REQUIREMENTS

	category†				observation requirement							
					accuracy		resolution					
							space		time			
parameter	basic	climate	opn/comm.	type of observation	desired	min.	desired	min.	desired	min.	code‡	proposed instrument
boundary	I	I	—	line position	5 km	20 km	5 km	20 km	1 d	3 d	A	PMR
	—	—	II	line position	500 m	5 km	500 m	2 km	1 d	1 d	B	SAR, RA
concentration	I	I	—	percentage area	2 %	5 %	25 km	25 km	1 d	3 d	A	PMR, SCAT
	—	—	I	percentage area	10 %	20 %	5 km	25 km	1 d	3 d	A	PMR
	—	—	II	percentage area	2 %	5 %	1 km	10 km	1 d	3 d	B	PMR, SAR
albedo	I	I	—	area average	0.02	0.04	25 km	100 km	3 d	2 weeks	A	VIR
motion	II	—	—	point displ.	100 m d^{-1}	1 km d^{-1}	5 km	100 km	1 d	7 d	A	SAR
	—	—	II	point displ.	50 m d^{-1}	1 km d^{-1}	1 km	10 km	6 h	7 d	B	SAR
ridging												
density	—	—	II	number/area	10 %	50 %	50 m	100 m	7 d	1 month	B	SAR, SCAT
orientation	—	—	II	orientation	10°	30°	n.a.	n.a.	7 d	1 month	B	SAR
height	—	—	II	height	1 m	1 m	n.a.	n.a.	1 d	1 month	C	SAR, SCAT
ice type	I	I	II	frac./area, by type	5 %	10 %	1 km	25 km	7 d	1 month	A	PMR, SCAT
leads												
fractional area	III	—	II	frac./area	10 %	50 %	50 m	100 m	1 d	3 d	B	SAR
orientation	III	—	II	orientation	10°	30°	n.a.	n.a.	1 d	3 d	B	SAR
floe position	—	—	II	point location	20 m	100 m	100 m	100 m	6 h	2 d	B	SAR
surface melting	—	II	—	frac./area	wet/dry	wet/dry	25 km	25 km	1 d	3 d	A	PMR
surface temperature	I	I	—	area average	1 K	3 K	25 km	100 km	1 d	3 d	A	PMR, VIR
ice thickness	III	III	—	area average	20 cm	1 m	25 km	100 km	7 d	1 month	D	inferred from ice type information
	—	—	III	area average	20 cm	1 m	50 m	1 km	1 d	3 d	D	

† Sampling key: I, continuous; II, frequent; III, occasional.

‡ Code: A, desired requirement can be met; B, substantial part of requirement can be met; C, measurement concept, capability not well determined; D, useful measurements, but limited.

TABLE 2. OCEAN OBSERVATION REQUIREMENTS AND SENSOR RECOMMENDATION

		observation requirement								
		accuracy		resolution						
				space		time				
parameter	type of observation	desired	min.	desired	min.	desired	min.	code†	comments	proposed instrument
wind speed										
global	area av.	10% or ± 2 m s^{-1}	10% or ± 2 m s^{-1}	50 km	100 km	6 h	72 h	A		SCAT (PMR),‡ PMR, RA, SAR
regional (coast, lake, storm, front)	area av.	10% or ± 2 m s^{-1}	10% or ± 2 m s^{-1}	10 km	50 km	6 h	72 h	C		
wind direction										
global	area av.	—	± 20°	50 km	100 km	6 h	72 h	A	—	SCAT (PMR)
regional	area av.	—	± 20°	10 km	50 km	6 h	12 h	C	—	—
sea surface temp.										
large-scale	area av.	0.2	0.5–1.0	200 km	300 km	20–40 d	—	B	2–6 GHz	PMR, VIR
mesoscale	area av.	0.5	0.5–1.0	5 km	10 km	3–4 d	—	B	wind corr.	VIR
small-scale	area av.	1.0	0.5–1.0	⩽ 1 km	1–4 km	hours	—	C	—	VIR
waves										
wind waves	area av.	⩽ 50 cm	1 m	5–10 km	100 km	6 h	—	A	—	RA (PMR)
swell	area av.	⩽ 50 cm	1 m	5–10 km	—	6 h	—	A	—	RA (PMR)
internal	line	—	detection	25 m	50–100 m	< 12 h	—	A	—	SAR
spectrum										
direction	line	20°	20°	25 m	50–100 m	< 12 h	—	A	—	SAR
dominant λ	line	*ca.* 50 m	50 m	25 m	50–100 m	12 h	—	A	—	SAR

† For codes, see table 1.

‡ PMR in parentheses implies that the radiometer data are used for atmospheric correction.

of 600 km and therefore may give a hemispherical coverage within 3 days, for instance. Thus operational applications for which processed and interpreted data for a certain area is available frequently and with short delay may not be feasible in the foreseeable future. However, by combining data from different sensors with different swath and perhaps frequency of operation a solution may be found. But this will require a detailed study of the feasibility and of the accuracy obtainable, particularly in forecasting.

One parameter, ice thickness, is important in ice dynamics and for navigation and offshore activity. However, there seems to be no possibility of obtaining this information from space except by a coarse estimate from the ice type classification (thin first-year ice, first-year ice, and multi-year ice) obtainable for instance by means of passive microwave radiometer data. There are in-situ methods of remote sensing available, and an airborne laser profilometer may determine the free board as a measure of the flow thickness.

Other parameters of importance for sea ice studies and forecasting are the surface air pressure and wind velocity. In fact the wind stress field over an ice field is a very important parameter – and for all numerical models of sea ice – which may only be derived from the surface atmospheric pressure field as deduced from data from meteorological stations and buoys.

Another parameter controlling the heat flux through sea ice is the snow cover, but so far there has been no method of estimation of this parameter from space. There may be some possibility of a rough estimate based on the passive microwave radiometer at high frequency (90 GHz and above) coupled to measurement of the air temperature, which approaches that of the snow.

Remote sensing instrumentation

Tables 1 and 2 concentrate mainly on microwave intrumentation, and visual and infrared radiometers are only included when the relevant parameter may be obtained with the required accuracy solely by this instrumentation. Thus sea surface temperature for small-scale and mesoscale applications may only be obtained by the infrared radiometer with its relatively fine spatial resolution, which cannot be obtained by the passive microwave radiometer, the other candidate instrument; likewise the albedo of ice fields can only be determined by means of a visual sensor.

However, the frequent cloud cover over large areas of the polar regions, especially during summer seasons, prevents the acquisition of timely data by visual and infrared techniques, whereas microwave sensors, which are largely insensitive to clouds, will be able to meet the requirements of frequent measurements of the Earth's surface. On the other hand, the very wide swath width of the VIR sensors gives a frequent coverage (at least once 1 day) so that this type of data at any rate may be considered complementary to microwave data.

Most of the sensors listed in tables 1 and 2 have been dealt with in other presentations of this Discussion Meeting. Therefore, in what follows I shall only address those problems that are specific for sea ice studies. One exception is the passive microwave radiometers, which will be dealt with in some more detail.

Most of the experience with the active microwave sensors, radar altimeter, scatterometer and SAR has been obtained by means of Seasat data. Owing to the low inclination (orbit to 72°) and the period of life (June–October 1978) of this satellite sea ice observation in the Northern Hemisphere is limited to the southern Beaufort Sea and to the East Greenland Current. Also, owing to the limited life time, a series of planned group operations in support of the satellite mission were not carried out. Consequently a great deal of the experience gained is based on previous knowledge of the areas in question.

Radar altimeter

The use of the radar altimeter in sea sea ice studies is based on the facts that backscatter from sea ice is much stronger than that from water and that the forms of the reflected signals are different. Owing to the roughness of a field of sea ice the return pulses rise slower but to a greater value than those from water and persist generally for a longer period. The altimeter data may therefore be used for detection of the ice–ocean boundary with an accuracy of 1–2 km at the satellite track because of its relatively narrow swath (M. Lefebvre, private communication). Thus the altimeter data may support those of the passive microwave radiometer, which give an accuracy of 10–15 km but over a very much wider area.

Also, because different ice types have different surface characteristics the altimeter data may be used for classification of sea ice based on the return signal characteristics. Again, it will be a profile information in support of the synoptic view obtained by the passive microwave radiometer – and the scatterometer.

The altimeter may prove useful for the observation of ocean waves near to the ice–ocean boundary (Tucker, this symposium) for use in the prediction of the break-up of an ice field, but this has still to be demonstrated. Unfortunately, the data are limited to a narrow area and the direction of the waves will have to be inferred from surface wind data.

Scatterometer

The scatterometer acquires data which are a measure of the roughness of the surface within the resolution cell of the instrument expressed by the normalized backscatter cross section σ°. In Seasat the resolution cells have a side of approximately 50 km and the angle of incidence varies between 25° and 65° over the swath of 750 km. The resolution is therefore comparable with that of the passive microwave radiometer, and a comparison of data from the two sensors has been made by Fedor (1982) on a Seasat track in the Beaufort Sea extending from Banks Island to Point Barrow with multi-year and first-year ice and water present. A good correlation between the brightness temperature and σ° was observed, but detailed variations require continued research.

Owing to the very different backscatter coefficient of calm water and ice the return signal from ice may be 10–15 dB higher, so that the scatterometer may be useful for ice boundary delineation (Peteherych 1982). Also, there seems to be a seasonal effect, with σ° increasing when melt water ponds freeze, so that information may be obtained of such features. Finally, one would expect that directional scatterometer data could be useful for ridging data in areas with rather regular large-scale ice dynamics.

This application for sea ice studies requires further detailed studies and so far no results are available about the ice fields around the Antarctic, which went through their maximum extent during the Seasat period.

Application of scatterometer data for the open ocean is described by Guymer (this symposium) but it should be pointed out that, because of the large resolution cell, wind data may not be useful near to the ice–ocean boundary but will certainly serve as a complement to the wind calculated from the air pressure field.

Synthetic aperture radar

A synthetic aperture radar gives a synoptic image of an ice field with very fine spatial resolution. In Seasat synthetic aperture radar the data may be processed to a resolution of 25 m; the swath width is 100 km with an angle of incidence of about 20°.

A great number of Seasat orbits over the Beaufort Sea has been recorded, but only a few of them are processed digitally. From the East Greenland Current only two orbits were recorded and processed optically (spatial resolution about 100 m).

From the processed images it may be concluded that the main morphological features of sea ice can be clearly discerned, such as leads, polynyas, pressure ridges, shore-fast ice, multi-year floes, mixtures the multi-year and first-year floes and shore leads (Campbell 1983). There is an indication that this identification of sea ice type is due to a difference in the speckles (R. W. Larson, private communication). A statistical analysis involving third and fourth moments seems to reveal this feature, which is of importance for automatic analysis of synthetic aperture radar images.

The images from the Beaufort Sea so far processed and analysed were apparently acquired during calm conditions. However, the two orbits covering the East Greenland current were recorded under different weather conditions (Søndergaard 1979): one under relative calm conditions and the other under strong wind and large waves in the open sea (Denmark Strait). From the optically processed images it is not possible to distinguish sea ice from waves, while the ice boundary may be easily delineated during the preceding (3 days) passage. (An air-borne sea ice reconnaissance 6 days after the storm showed clearly the presence of sea ice.)

From seven sequential overlapping images it was ascertained that ice motion could be determined with an accuracy of ± 150 m when using ground control points located in each end of an image 1000 km long. With control points in only one end, the accuracy was only ± 500 m (Leberl *et al.* 1981), but by combining ground control points and satellite orbit data, a motion accuracy of the order of 50–100 m may be obtainable. For Landsat image processing a ground control point correlation technique has been developed so that two images may be registrated with a relative accuracy of 0.2–0.3 pixels (Hansen 1982). If this were also possible with radar images the 50 m accuracy would cetainly be feasible. However, with an angle of incidence of 20° or more, ground control points viewed from different aspect angles may be difficult to correlate, in particular in mountainous areas. At any rate, the accuracy attainable is much better than is possible today with drifting buoys and stations using present satellite navigation systems.

Satellite synthetic aperture radar images may also detect swell in an ice field as it has been observed by means of an airborne system (Overgaard 1980) and for satellites the interpretation is simpler owing to the high relative velocity, which results in an almost 'one-shot image'.

There is no doubt that spaceborne synthetic aperture radar will give a wealth of information useful for sea ice studies. It will provide unique data for detailed studies of ice models at different scales – site-specific, mesoscale and macroscale – under all weather conditions and during both day and night. However, considering the enormous amount of data – even after the initial compression of the radar data – some method of automatic (possible interactive) analysis will be needed if the data are going to be used even semi-operationally.

Passive microwave radiometers

A great deal of experience with passive microwave radiometer data for sea ice applications has been obtained from the electronically scanning microwave radiometer (ESMR) on Nimbus-5 (Wilheit 1972) and the scanning multichannel microwave radiometer (SMMR) system on Nimbus-7 (Gloersen & Barath 1977). ESMR operated on a single frequency, 19.35 GHz (1.55 cm wavelength), in a scan at right angles to the orbit, whereas SMMR operates on five frequencies, 6.6, 10.7, 18, 21 and 37 GHz, in a conical scan at vertical and horizontal polarization with an Earth incidence angle of about 50°.

Radiometers measure the ground's natural thermal emission in the microwave region, as expressed by Rayleigh–Jeans law. The intensity incident on a radiometer antenna is a measure of the brightness temperature of the area observed modified by the atmosphere, which causes an attenuation and an additional intensity contribution according to the atmosphere opacity and its temperature. Also, the radiated microwave intensity is weighted by the antenna pattern, the main lobe and the sidelobes. Furthermore, because an antenna creates a certain amount of cross-polarization and the emitted intensity in general is different at the two polarizations, a cross-polarized component will be added to the desired microwave signal. Thus although simple in principle – and also in equipment – microwave radiometer measurements become relatively complicated when corrections for the antenna pattern, the cross-polarization and the atmospheric effects have to be carried out to derive the brightness temperature from the raw data. This last effect is dependent on the content of atmospheric water vapour and liquid water, for which an estimate may be obtained for the SMMR, which has a channel tuned to near the water vapour absorption line (22.235 GHz).

Being a passive system, the field of view or 'footprint' is limited by diffraction, i.e. determined by the size of the antenna measured in wavelengths. For the ESMR the field of view is of the order of 35 km (actually varying over the swath), whereas the SMMR has a field of view ranging from about 30 to 150 km. Microwave radiometry may therefore only be useful for studying large-scale phenomena such as sea ice, for instance. This has been demonstrated by Gloersen *et al.* (1978), by Carsey (1982) and lately by Zwally *et al.* (1983).

These papers are based on data from the single-frequency radiometer, ESMR, on Nimbus-5 and rely upon the observations that the emissivity of first-year ice has a temperature near 240 K (only varying by a small percentage), multi-year ice near 220 K and open (calm) water 140 K, at the frequency of 19.35 GHz. Also, it is found (assumed) that the atmospheric influence in the Arctic region may be accounted for by a constant-brightness temperature contribution. Based on the work leading to the paper by Gloersen *et al.* (1978), animated cine films have been produced that clearly show the large annual variability of the sea ice in the Northern Hemisphere.

Carsey (1982) analysed the summer–autumn microwave variation of the Arctic pack ice in the period 1973–6 and, assuming that at the time of minimum ice extent (end of summer) there was no first-year ice, multi-year ice emissivity and ice concentration could be determined. It was found that the emissivity showed regional variations in accordance with knowledge of the ice composition in the Arctic Ocean. Zwally *et al.* (1983) analysed data for the same period, 1973–6, in the southern ocean and determined the ice extent through the period, assuming that only first-year ice was present; they found that the maximum ice area around the Antarctic decreased during the period by the order of 10%. Also, Cavalieri & Parkinson (1981) demonstrated the large-scale air–sea–ice interaction by relating the advance and retreat of the ice–ocean boundary to the mean surface air pressure.

Early results from the SMMR on Nimbus-7 and the parameter-retrieval algorithms developed were presented by Gloersen *et al.* (1981 *a*, *b*), but it is only after extensive further development of algorithms and calibration procedures that the results from the first SMMR observations could be presented (Gloersen *et al.* 1983). In addition to other global data (sea surface temperatures, near-surface winds, atmospheric water vapour, cloud liquid water and rainfall rates), results from the polar regions comprise sea ice concentration, multi-year ice fraction and radiating temperatures. The results are presented as polar maps and the distribution of first-year and multi-year sea ice seems to be in accord with historical experience and localized observations from underflights. It has been demonstrated (NORSEX Group 1982) that the ice–ocean boundary can be located to within 10 km, that temporal and spatial changes in ice concentration can be observed at a 25 km scale (Cavalieri *et al.* 1982 *b*), and that the spatial distribution of the multi-year ice fraction can be monitored (Cavalieri *et al.* 1982 *a*). A distinct patch of multi-year ice about 100 km in extent was tracked over a 24 day period as it drifted into the Fram Strait and the East Greenland Current from north of Svalbard (NORSEX Group 1982).

These results look very promising for large-scale sea ice studies as a contribution to the understanding of the air–sea–ice interaction process. However, further developments are necessary to improve the accuracy of parameter retrieval, in particular in the marginal ice zone. Here the temperature is near the melting point of the ice, so it is important to include temperature variations in the sea ice emissivities. If this is done (from ice buoy temperature data, for instance) the accuracy of the sea ice concentration may be better than 5 % (NORSEX Group 1982). Another improvement may result from including the snow cover.

The development of general parameter retrieval algorithms stems from the desire of being able to process satellite data routinely. It is to be expected, however, that by proper regional

---

DESCRIPTION OF PLATE 1

FIGURE 1. Example of brightness temperatures determined by means of the passive microwave radiometer system (SMMR) on NIMBUS-7 at the frequencies 6.6, 10.7, 18, 21 and 37 GHz, vertical polarization. The figures represent a mosaic of data from seven orbits recorded on 13 March 1979, based on the so-called cell-tapes, i.e. digital brightness temperature data in standardized Earth-located cells. These images of Greenland consist of 128 × 128 picture elements covering an area of approximately 3000 km × 3000 km. Black indicates that data were not available on that day but gaps will be filled if data for the following recording day – 2 days later – were included.

Based on these data and those from the horizontal polarization an unsupervised classification has been made into five categories of clouds and sea ice, as shown in the lower right image. The ice classification is rather coarse distinguishing only between 'west ice', i.e. sea ice in Baffin Bay and Davis Strait, and 'east ice', i.e. ice in the East Greenland Current and the Greenland Sea. The west ice is predominantly first-year ice whereas the east ice is a mixture of first-year ice and multi-year ice, the latter transported by the East Greenland Current southwards through the Fram Strait (between Greenland and Svalbard, which is seen in the upper right corner). A great deal of the ice east of Greenland is first-year ice and the large advective fan extending into the Greenland Sea is a mixture of the two types of ice. It is also seen that it is apparently difficult to distinguish between light clouds and low-concentration sea ice, labelled drift ice, whereas the heavy clouds of a frontal system southwest of Greenland stand out clearly.

At all five frequencies a pattern of brightness temperatures is noted on the Greenland ice cap. This has been attributed to the snow pack on the ice with variations in snow crystal size, which is dependent upon accumulation and temperature. In fact a principal component analysis based on this multi-frequency data has shown patterns approximating existing contour maps of accumulation rate and annual mean temperature.

This figure is part of a study carried out at the Electromagnetics Institute, Technical University of Denmark, to explore the capabilities of using satellite microwave radiometer data for Arctic research and surveillance.

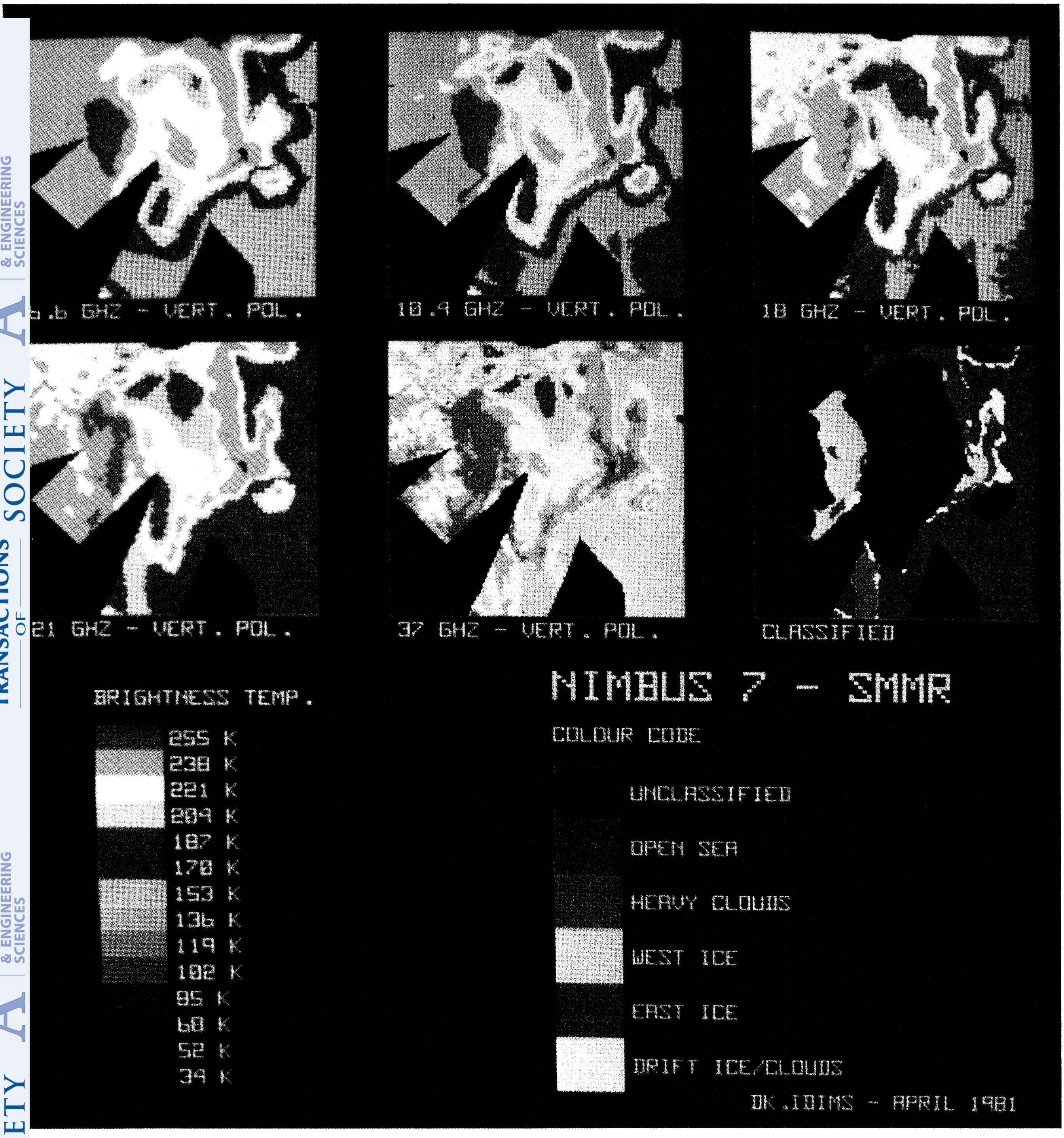

FIGURE 1. For description see opposite.

tuning of the algorithm better retrievals may be obtained. In fact the 5% accuracy quoted above was obtained in this way. Also, statistical analysis procedures, as employed successfully with the multispectral Landsat data, may prove very useful, but an appreciable increase in computer time may rule this out except for regional studies. For ice studies, data from other satellites (active microwaves and visual–infrared) may prove useful for tuning of retrieval algorithms in an interactive process; also it may be necessary to account for seasonal and regional variations.

As outlined previously, data from the adjacent open ocean are also of interest in these studies. An analysis of the retrieval of sea surface temperature and near-surface winds from SMMR data shows that by temporal and spatial smoothing of the data ($\frac{1}{2}$ month and 200 km) a standard deviation of about 1.5 K (compared with climatological data, FGGE and WMO) and 2 m s^{-1} results. However, data are only reliable at distances of 600 km from coastlines owing to antenna sidelobe interference, and the usefulness of this information for studies of the marginal ice zone is subject to further research.

FUTURE SATELLITE MISSIONS WITH MICROWAVES

The only microwave sensor instrument in operation today is the scanning multichannel Microwave radiometer on Nimbus-7, which was launched in November 1978. It has by far exceeded its projected lifetime and there seems to be no important sign of fatigue. Global data have been acquired since the launch and a huge data base is awaiting detailed geophysical interpretation, which certainly will take place when well calibrated and corrected data become available. The data are incorporated in the plans for MIZEX, where there will be great possibility for conferring with ground control and underflight measurements (Johannessen *et al.* 1982).

In 1984 a satellite of the U.S. Air Force Meteorological Satellite Program will be launched with a microwave radiometer system under the name of special sensor microwave/imager (SSM/I). It is a seven-channel, four-frequency conically scanning radiometer with two channels (dual polarization) at 19, 37 and 85 GHz and a single channel at 22 GHz. The fields of view of this instrument will be comparable with those of the SMMR, and it is hoped that the data may be available to non-military agencies so that the success of the SMMR may be continued. In particular, the high frequency of 85 GHz may prove very useful because of the better spatial resolution, but also because there is hope that it may supply data on snow cover.

A follow-on to Seasat will be seen first with the launch of the European Remote Sensing satellite, ERS-1, in 1987. With the promising results with Seasat data there are good reasons to expect that the active microwave instrument (synthetic aperture radar and wind scatterometer) and the radar altimeter will supply data of great value to ocean and ice studies as concluded by the EARSeL/E.S.A. Workshop on microwave ocean and ice. However, in view of the great amount of data to be acquired from this satellite, great emphasis will have to be placed on data processing.

CONCLUSIONS

In this brief review of microwave remote sensing in ice studies, emphasis has been placed on satellite observations. However, the work reported was based on a number of extensive investigations with equivalent aircraft instruments supported by ground control measurements. From the experience gained in this way in many areas of the polar regions and under various conditions it has proved possible to work out processing algorithms to make a useful parameter retrieval for sea ice research, for instance. A great deal of knowledge about interpretation of microwave information and images was likewise obtained.

To obtain more experience in this direction and better retrieval accuracy, more field investigations are needed, however, and a large-scale programme like MIZEX may prove very important in this respect. It is a programme involving many research disciplines, which will require exchange of data between scientists to achieve their goals; in this connection it is interesting to note the different attitudes to remote sensing by the people concerned. The geophysicist tends to look to remote sensing as a 'research tool' whereas the remote-sensing scientist considers his discipline as still being in a research and development phase.

Nevertheless there is already one operational application of satellite microwave remote-sensing data, previously from ESMR and now from SMMR. The data are used in almost real time for sea ice mapping and forecasting in both polar regions, taking advantage of the fact that they are insensitive to clouds and light conditions.

The European remote sensing satellite, ERS-1, has been announced as a semi-operational satellite, but judging from the experience gained by several groups in reaching the present level of understanding and utility of microwave remote-sensing data it can be stated that a great amount of interest and work is needed to reach this goal. It is not just a question of establishing a system for processing and quick dissemination of data: it is an equally large task to develop the parameter retrieval algorithms and the necessary processing facilities with sufficient throughput. In this context it is worth noting that whereas most investigations have been concerned with only one type of instrument, there seems to be a tendency to explore the symbiosis of several instruments.

REFERENCES

Campbell, W. J. 1983 Presented at the EARSeL/E.S.A. Workshop 'Microwave ocean and ice' Igls, April 1982 (ed. W. J. Campbell & P. Gudmandsen). (In preparation.)

Carsey, F. D. 1982 *J. geophys. Res.* **87**, 5809–5835.

Cavalieri, D. J. & Parkinson, C. L. 1981 *Mon. Weath. Rev.* **109**, 2323–2336.

Cavalieri, D. J., Gloersen, P. & Campbell, W. J. 1982*a* (Submitted for publication.)

Cavalieri, D. J., Martin, S. & Gloersen, P. 1982*b* (Submitted for publication.)

Fedor, L. 1982 Presented at the EARSeL/E.S.A. Workshop 'Microwave ocean and ice', Igls, April 1982 (ed. W. J. Campbell & P. Gudmandsen). (In preparation.)

Gloersen, P. & Barath, F. 1977 *IEEE J. ocean. Engng* **OE-2**, 172–178.

Gloersen, P., Campbell, W. J. and Cavalieri, D. 1981*a* In *Oceanography from space* (ed. J. R. F. Gower), pp. 777–783. New York: Plenum Press.

Gloersen, P., Cavalieri, D. & Campbell, W. J. 1981*b* In *Oceanography from space* (ed. J. R. F. Gower), pp. 823 829. New York: Plenum Press.

Gloersen, P., Cavalier, D. J., Chang, A. T. C., Wilheit, T. T., Campbell, W. J., Johannessen, O. M., Künzi, K. F., Ross, D. B., Staelin, D., Windsor, E. P. L., Barath, F. T., Gudmandsen, P., Langham, E. & Ramseier, R. O. 1983 (Submitted for publication.)

Gloersen, P., Zwally, H. J., Chang, A. T. C., Hall, D. K., Campbell, W. J. & Ramseier, R. O. 1978 *Bound-layer Met.* **13**, 339–359.

Gudmandsen, P., Skou, N. & Wolff, B. (eds) 1983 *Microwave radiometer requirements, a workshop report*. Electromagnetics Institute, Technical University of Denmark. (In preparation.)

Hansen, P. 1982 *Image-to-image registration on a subpixel level using cross correlation.* (49 pages.) Report no. R264, Electromagnetics Institute, Technical University of Denmark.

Johannessen, O. M., Campbell, W. J., Dunbar, M., Dyer, I., Hasselmann, K., Hibler, W. D. III & Wadhams, P. (eds). 1982 MIZEX. A plan for a summer Marginal Ice Zone Experiment in the Fram Strait/Greenland Sea. Unpublished manuscript.

Leberl, F., Roggam, J., Elachi, C. & Campbell, W. J. 1981 (Submitted for publication.)

NORSEX Group, NORSEX 1 1982 *The Norwegian Remote Sensing Experiment in the marginal ice zone*. Geophysical Institute, University of Bergen. (Submitted for publication.)

Overgaard, S. 1980 *Multiyear sea ice investigation in the East Greenland Current.* (69 pages.) Report no. R228, Electromagnetics Institute, Technical University of Denmark.

Peteherych, S. 1982 Presented at the EARSeL/E.S.A. Workshop 'Microwave ocean and ice', Igls, April 1982 (ed. W. J. Campbell & P. Gudmandsen). (In preparation.)

Søndergaard, F. 1979 In *Proceedings of the workshop on SEASAT/SAR Processor* (ESA SP-154), pp. 69–75.

Untersteiner, N. 1979 *Polar Rec.* **19**, 363–367.

Untersteiner, N. (ed.) 1983 *Air–sea–ice interaction.* NATO Advanced Study Institute. (In preparation.)

Wilheit, T. T. 1972 In *NIMBUS-5 user's guide* (ed. R. R. Sabatini), pp. 59–105. Greenbelt, Maryland: N.A.S.A. Goddard Space Flight Center.

Zwally, H. J., Comiso, J. E., Parkinson, C., Carsey, C. L., Campbell, W. J. & Gloersen, P. 1983 *Antarctic sea ice cover 1973–1976 from satellite passive microwave observations.* Washington, D.C.: N.A.S.A. (Submitted for publication.)

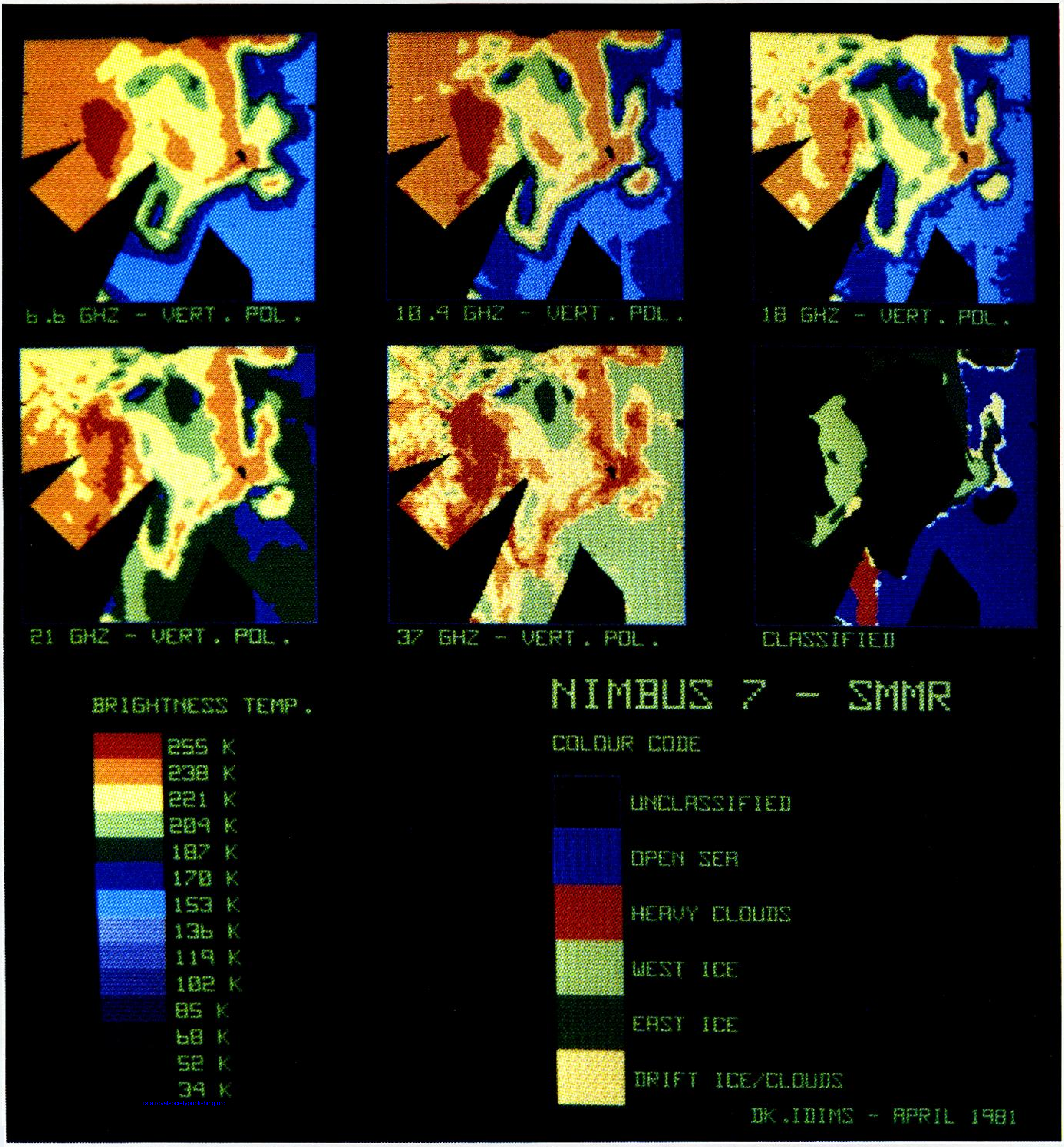

Figure 1. Example of brightness temperatures determined by means of the passive microwave radiometer system (SMMR) on NIMBUS-7 at the frequencies 6.6, 10.7, 18, 21 and 37 GHz, vertical polarization. The figures represent a mosaic of data from seven orbits recorded on 13 March 1979, based on the so-called cell-tapes, i.e. digital brightness temperature data in standardized Earth-located cells. These images of Greenland consist of 128 × 128 picture elements covering an area of approximately 3000 km × 3000 km. Black indicates that data were not available on that day but gaps will be filled if data for the following recording day – 2 days later – were included.

Based on these data and those from the horizontal polarization an unsupervised classification has been made into five categories of clouds and sea ice, as shown in the lower right image. The ice classification is rather coarse distinguishing only between 'west ice', i.e. sea ice in Baffin Bay and Davis Strait, and 'east ice', i.e. ice in the East Greenland Current and the Greenland Sea. The west ice is predominantly first-year ice whereas the east ice is a mixture of first-year ice and multi-year ice, the latter transported by the East Greenland Current southwards through the Fram Strait (between Greenland and Svalbard, which is seen in the upper right corner). A great deal of the ice east of Greenland is first-year ice and the large advective fan extending into the Greenland Sea is a mixture of the two types of ice. It is also seen that it is apparently difficult to distinguish between light clouds and low-concentration sea ice, labelled drift ice, whereas the heavy clouds of a frontal system southwest of Greenland stand out clearly.

At all five frequencies a pattern of brightness temperatures is noted on the Greenland ice cap. This has been attributed to the snow pack on the ice with variations in snow crystal size, which is dependent upon accumulation and temperature. In fact a principal component analysis based on this multi-frequency data has shown patterns approximating existing contour maps of accumulation rate and annual mean temperature.

This figure is part of a study carried out at the Electromagnetics Institute, Technical University of Denmark, to explore the capabilities of using satellite microwave radiometer data for Arctic research and surveillance.