HF RADAR OBSERVATIONS OF ARTIC
PACK-ICE BREAKUP

BELINDA J. LIPA, RANDY D. CRISSMAN and DONALD E. BARRICK

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HF Radar Observations of Arctic Pack-Ice Breakup

BELINDA J. LIPA, RANDY D. CRISSMAN, AND DONALD E. BARRICK, MEMBER, IEEE

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Abstract—**This paper describes the first reported high-resolution remote measurements of sea-ice velocities during the summer Arctic pack-ice breakup, made with a high-frequency (HF) radar system (CODAR, for Coastal Ocean Dynamics Applications Radar) located on Cross Island, Alaska. Each 36-min observation also gives the positions of the ice edge, the moving ice, and the open water, with an azimuthal and distance resolution of 5° and 1.2 km, respectively, to a range of 15 km. The statistical uncertainties in speed are typically 2–4 cm/s. The ice breakup was observed over a two-day period starting with low ice velocity and no open water and ending with ice and current velocities of approximately 40 cm/s. The position of the ice edge is verified by a simultaneous synthetic aperture radar (SAR) image. To compare the ice, current, and wind velocities, a uniform velocity model was fitted to the measurements of radial velocity. The speed of both ice and current under free drift conditions was found to lie between 2 and 5 percent of the wind speed and the direction within 20° of the wind direction.**

I. INTRODUCTION

SEA-ICE cover in the Arctic and its movement presently affects a broad range of man's activities. Its impact on weather and global climatology, as correlated with its seasonal advance and recession, is now beginning to be fully appreciated. Rapidly increasing commercial activities, such as oil and gas exploration and recovery, depend on timely knowledge of ice dynamics both for design of structures and safe operations. Military activities above and beneath the polar ice cap by several nations are planned based on its presence and movement. Finally, safe maritime transportation through open water areas is controlled by the moving ice edge from the Arctic shores of Canada, Alaska, and the USSR.

Our knowledge of the characteristics and dynamics of the ice covering this vast area of the planet is being obtained by remote observations of one type or another. Aircraft and satellite use of visual and infrared images provide information on ice coverage, when not limited by frequent clouds and fog. Passive microwave radiometric measurements from spacecraft have proven highly successful for monitoring ice coverage extent on large scales [1], [2]. Long-term temporal ice dynamics are observable with satellite active microwave synthetic aperture radars (SAR's), such as that on Seasat [3]. Microwave radar altimeters from space can measure ice topography from which ice thickness can be inferred [4]. Until now, no all-weather remote-sensing method has been demonstrated that can observe both ice cover and velocities/dynamics over smaller distance scales (<50 km) in real time; this information is critically important to oil/gas operations at an increasing number of locations in this region. We describe here a high-frequency (HF) radar system that promises to fulfill this need, and present results of the first measurements.

Over the last year, HF radar has been used by several groups to measure ice movement. The propagation of radar signals over the ice and the prediction of the radar cross section have been investigated theoretically [5], measurements of HF radar signal propagation over sea ice recorded [6], [7], and icebergs and pack ice observed [8]. Compact HF radars have been developed to map surface currents and other sea-surface parameters [9]. These devices, termed CODAR for Coastal Ocean Dynamics Applications Radar, are used in both coastal and offshore applications. During the summer of 1984, an experiment was carried out in Prudhoe Bay, Alaska, to record the velocity and position of tiny expendable transponders, either drifting on the sea or embedded in the ice pack [10]. One of the CODAR systems was the newer loop variety which is used operationally for the real-time measurement of ocean surface current velocity maps [11]. In addition to the transponder echo, the radar Doppler spectra contained Bragg echo from moving ocean waves one-half the radar wavelength and a strong echo near the carrier frequency due to moving ice. We present here the first analysis of this direct echo from ice and water waves to yield a true remote measurement of ice and water position and velocity during the ice breakup phase. Principles behind the system operation and the analysis methods are described and results are compared with wind observations and a simultaneous SAR image produced from an aircraft.

II. EXPERIMENTAL CONFIGURATION

The CODAR system was deployed on Cross Island, located about 20 km from the mainland as shown in Fig. 1. Fig. 2 shows the CODAR receiving antenna which is also used as a transmitter, and the portable building used to house the radar system shown in Fig. 3. The transmit frequency used was 25.4 MHz; 16-μs pulses were transmitted and the received echo sampled every 8 μs. The CODAR antenna consists of two crossed loops and a monopole; amplitude and phase mismatches between the elements are eliminated in the software [11]. The normal CODAR range of 50 km over open water is reduced to about 15 km by the presence of ice. Data were

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B. J. Lipa is with Ocean Surface Research, Inc., Woodside, CA 94062.

R. D. Crissman was with Gulf Oil Exploration & Production Co., Houston, TX. He is now with Codar Technology, Inc., Longmont, CO.

D. E. Barrick is with Ocean Surface Research, Boulder, CO 80303.

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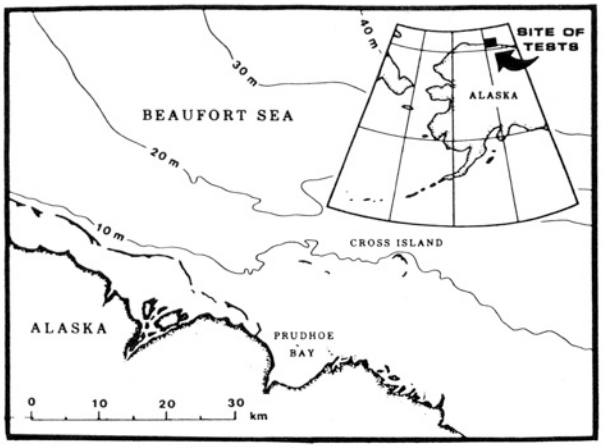


Fig. 1. The experimental location. The CODAR loop system was located on the southwestern tip of Cross Island.

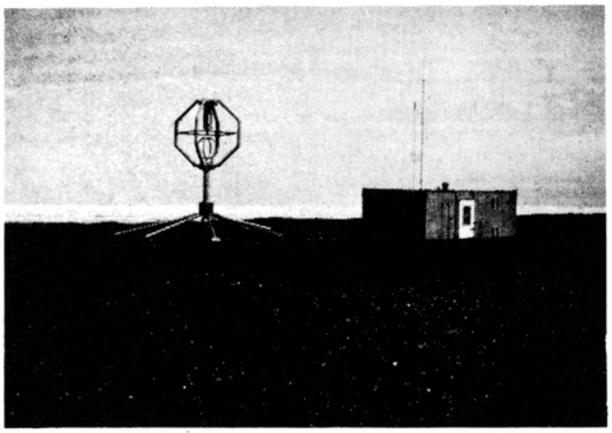


Fig. 2. The CODAR receiving antenna operating at Cross Island. In the background is the portable building used to house the radar system.

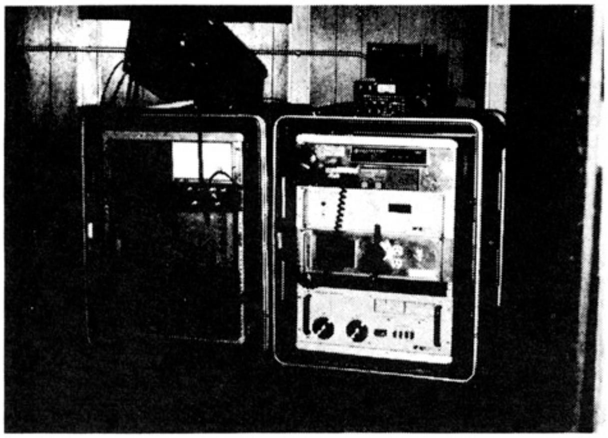


Fig. 3. The radar system. Two hardware racks contain the transmitter, receiver, computer, and tape drive. Above are the terminals for real-time display.

taken from July 16 to July 18, 1984, to map the crucial ice breakup phase. During this time, an SAR image was available to check the CODAR results for ice position. Wind velocity for comparison with radar results is obtained from a weather station operated on Cross Island by Gulf Oil; these data were transmitted by satellite to a ground station in Boulder, Colorado.

III. Signal Analysis

CODAR measures the Doppler spectra of received signals as a function of range; an averaged spectrum is obtained every 1.2-km range over a 36-min time period. An example is shown in Fig. 4. These spectra show three types of signals: first-order Bragg echo from moving ocean waves, which occurs surrounding the Bragg frequencies (±0.51 Hz for CODAR); backscattered echo from the surface of moving ice, which surrounds the carrier frequency at zero Doppler; and signal from transponders deployed on the ice at greater distances [10]. The strength of the backscattered signals decays with distance until it disappears below the noise floor at approximately 15 km.

The analysis of CODAR sea echo to give surface current velocity maps is covered in detail in [11]. Minor modifications to this analysis produce simultaneous maps of the ice velocity field. We give here a brief description of the modified analysis procedure.

The signals from the three CODAR antennas are combined in the software to effect the rotation of a broad beam (shaped as $\cos^4(\psi/2)$ for azimuth angle ψ from the boresight). This allows the measurement of five independent Fourier angular coefficients of the narrow-beam radar cross section, which are given as a function of the radian frequency Doppler shift ω by

$$b_n(\omega)=\int_{-\pi}^{\pi}\sigma(\omega,\ \phi)tf_n(\phi)\ d\phi \tag{1}$$

for $n=-2, -1, 0, 1, 2$, where $\sigma(\omega, \phi)$ is the narrow-beam radar cross section at azimuth angle ϕ and the trigonometric functions $tf_n(\cdot)$ are defined by

$$\begin{aligned} tf_n(\phi)&=\cos\ n\phi, \qquad n\geq 0\\ &=\sin\ (-n\phi), \qquad n<0. \end{aligned} \tag{2}$$

For first-order Bragg scatter, $\sigma(\omega, \phi)$ is the sum of two impulse functions in frequency [12]. In the presence of a surface current velocity $v_c(\phi)$ radial to the radar, this can be written

$$\sigma(\omega,\ \phi)=K_1\delta(\omega-\omega_B-2k_0v_C(\phi))+K_2\delta(\omega+\omega_B-2k_0v_C(\phi)) \tag{3}$$

where ω_B is the Bragg frequency $\sqrt{2gk_0}$ with k_0 the radar wavenumber, and g the gravitational acceleration. Ice provides a hard target for radar reflection; for a radial velocity $v_i(\phi)$, the radar cross section is therefore given by

$$\sigma(\omega,\ \phi)=K_3\delta(\omega-2k_0v_i(\phi)). \tag{4}$$

The proportionality factors K_1, K_2, and K_3 in (3) and (4) are not relevant to the derivation of the velocities.

We now make the assumption that the ice echo at a given Doppler frequency arises from at most two azimuth angles, this covers most situations of practical importance [10]. With the substitution of (3) or (4), (1) then reduces to

$$b_n(\omega)=A_1tf_n(\phi_1)+A_2tf_n(\phi_2) \tag{5}$$

which expresses the five radar Fourier coefficients at each Doppler point as a function of four unknowns (the two angles

ϕ_1 and ϕ_2 and the two amplitude factors A_1 and A_2). These unknowns are then determined by least-squares fitting to the data. This calculation gives the angle producing the return at a given velocity. The distinct separation of ice and water-wave echoes in the Doppler spectrum (see Fig. 4) is used to determine whether the echo at a particular frequency is produced by moving ice or water. Inversion of this angle–velocity relationship then gives the velocity as a function of angle, i.e., the desired velocity map. Statistical uncertainties in the velocities follow automatically from the standard least-squares formulation.

IV. Observation of Ice Breakup

Fig. 5 illustrates the radial velocities measured by CODAR as the ice breaks up, from July 16 to July 18, 1984 (local time). At the beginning of the period there is no Bragg echo, and hence no evidence of open water. Ice motion of low velocity occurs in a roughly northerly direction. Open water, with corresponding Bragg scatter, was observed starting July 17 and the velocities of both ice and currents increased in magnitude and veered towards the east over the remaining time period. The statistical uncertainties in the radial velocities of both ice and water are typically 2–4 cm/s.

In general, the moving ice and water were observed in the same locations with approximately the same velocities. It thus appears that the ice and water were moving together in response to the wind field. This information can be used effectively to define an ice edge.

V. Comparison with Other Observations

CODAR observations of the ice breakup were consistent with the following general overview of ice conditions and movement derived from visual observations and satellite images. On July 15 and early on July 16, west–southwest winds lodged the ice between the mainland and barrier islands against the southern shore of Cross Island and the pack ice north of Cross Island. The area around Cross Island was totally ice covered, although several open water areas had formed along the coast in response to melting caused by river outflows and air temperatures above freezing. On July 16, 1984, northwesterly winds began transporting the ice south of Cross Island along the coast. These winds also transported ice into the area south of Cross Island from the west.

Detailed comparisons were made with the following concurrent observations.

A. SAR Image

In Fig. 6, the radial current and ice velocity vectors measured by CODAR are superimposed on an SAR image taken within 4 h. This verifies the ice edge observed by CODAR—the region within 10 km northeast of Cross Island is dominated by locked-in ice, and the region of open water and floating ice to the south and southwest corresponds to the current and ice vectors observed by CODAR.

TABLE I
Comparison of Current, Ice, and Wind Velocities

Time		Percentage of Wind Speed	
		Current	Ice
7/16	20:49	—	4.0 percent
7/17	00:49	—	1.8 percent
	04:49	—	1.2 percent
	08:49	2.5 percent	1.7 percent
7/18	14:39	2.8 percent	2.8 percent
	18:30	4.6 percent	4.1 percent
	20:30	4.1 percent	4.8 percent
	22:30	4.4 percent	4.7 percent

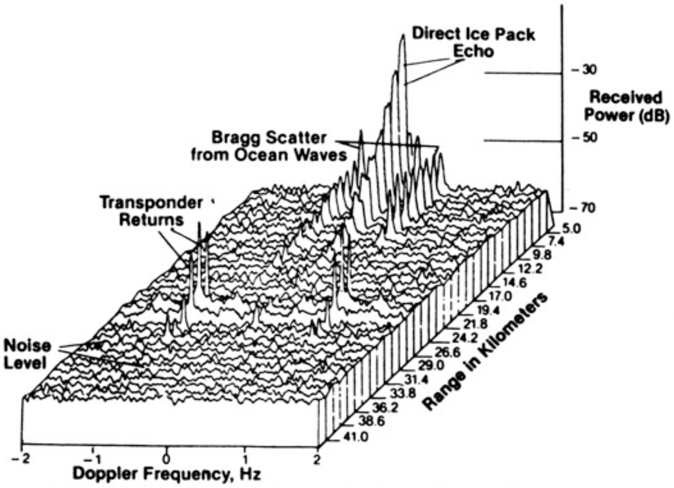


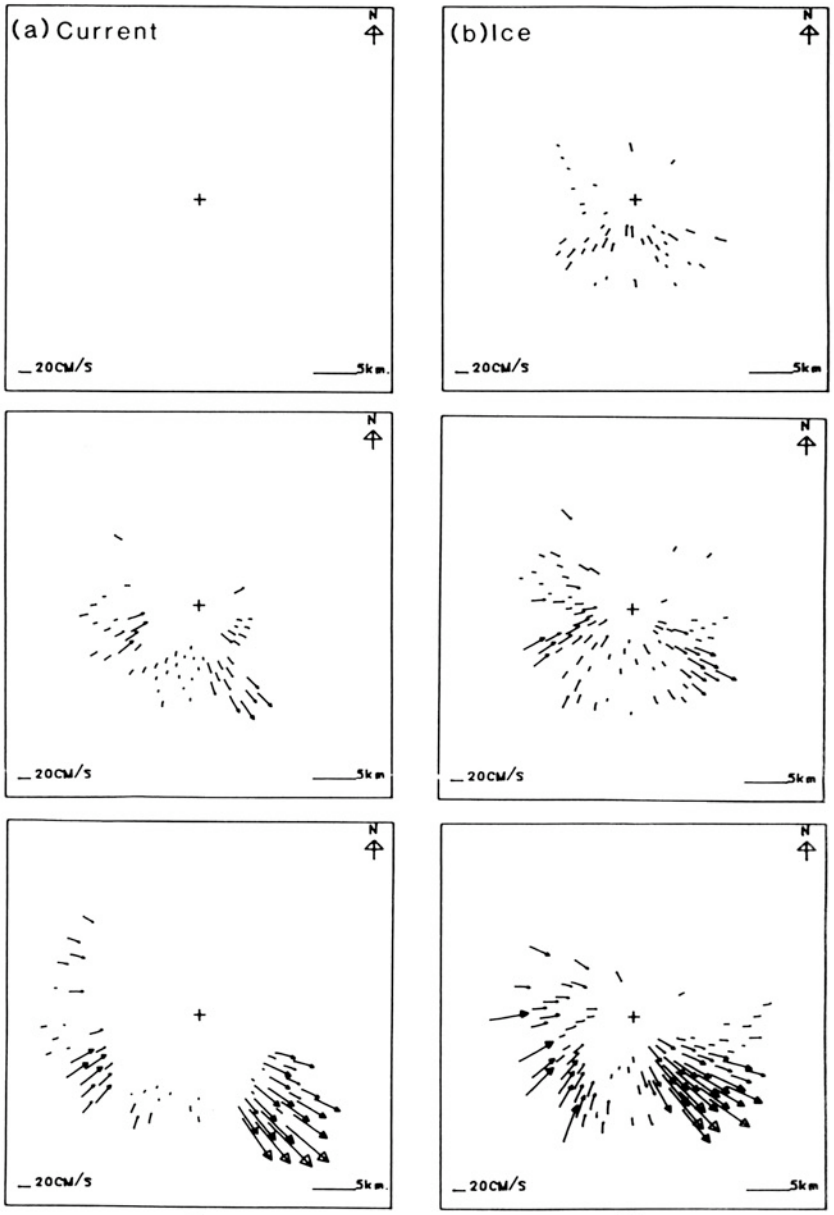
Fig. 4. CODAR Doppler spectra as a function of range. In the closer ranges, Bragg scatter from moving ocean waves and direct ice echo are evident; this decreases with range until it passes beneath the noise floor. The transponder echo is seen in the more distant range cells.

B. Wind Measurements

To make a comparison with the measured wind velocity, we require a measure of total velocity to be made from the radial components measured from the single CODAR site. To do this, we used a uniform velocity model with speed V and direction ν between ranges 4 and 8 km for both ice and water. In terms of this model, the radial velocity at azimuth ϕ is given by

$$v(\phi) = V \cos(\phi - \nu). \tag{6}$$

The model parameters V, ν were then determined by least-squares fitting to the measured radial data. This was done separately for ice and water, and results compared with wind speed and direction in Fig. 7. Both speed and direction of motion are clearly highly correlated; during the period of free ice drift after July 17, the ice and current appear to move at the same velocity. The speed is from 2 to 5 percent of the wind speed (Table I) while the direction is within 20° of the wind direction. The uniform velocity model assumed is extremely crude; a detailed study of the interaction of ice, water, and wind requires dual-site CODAR observations of radial velocity from which the total velocity can be calculated without the assumption of a model.



(a) (b)

Fig. 5. Radial velocity maps measured by CODAR during ice breakup. (a) Current velocities. (b) Ice velocities. The length of the arrow is proportional to the speed. Only ice velocity is observed until July 17, 8:49, confirming that there is no open water before breakup to produce sea echo. Local time (1984) from top to bottom: July 17 00:49, July 18 14:39, July 18 22:30.

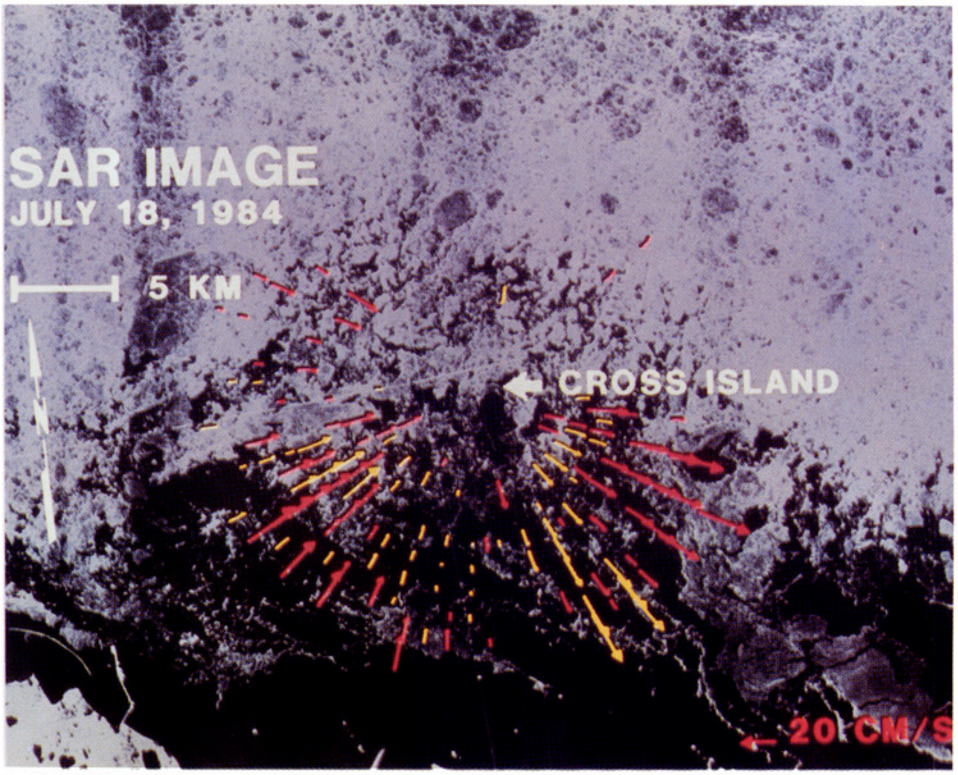


Fig. 6. Superposition of CODAR velocity vectors on a SAR image. Current vectors are yellow; ice vectors are red. Local time: July 18, 1984, SAR—10:00, CODAR—14:39.

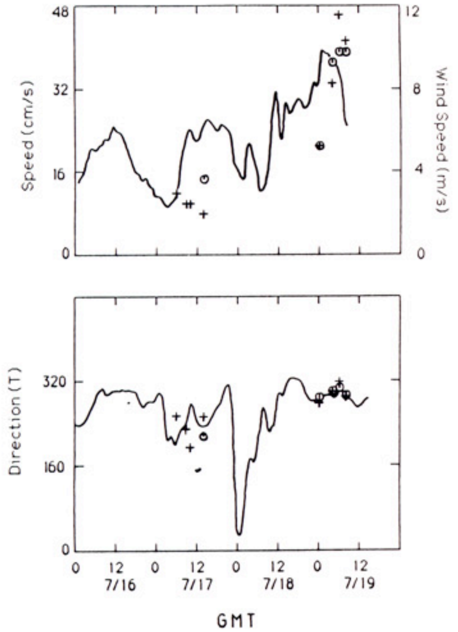


Fig. 7. Comparison of wind, ice, and current velocities as a function of Greenwich mean time: −Wind; ⊕Currents; +Ice.

VI. CONCLUSIONS

We report the first remote fine-scale measurements of water and ice velocity and position during Arctic summertime pack-ice breakup. These measurements are verified by coincident aircraft imagery and correlate well with simultaneously measured wind velocities. The results presented here show that CODAR can detect the position of the ice edge and measure its advance or retreat and that water and ice motion can be mapped to distances of at least 15 km from the interrogating site. The observations of radial velocity were made with a single radar site; for a detailed analysis of ice and water motion, dual-site observations are required to give the total velocity vectors. Having confirmed the feasibility of ice position and velocity measurements with HF radar, we intend to make dual-site observations in the near future. It is clear that HF radar can be used in many applications from the coast, islands, or man-made platforms in the Arctic for real-time monitoring of water and ice movement.

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Belinda J. Lipa, for photograph and biography please see this issue, p. 245.

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Randy D. Crissman received the Master's degree in civil engineering, with specialization in water resources and hydrodynamics, from the State University of New York, Buffalo.

From 1982 to 1985 he was employed by Gulf Oil Exploration and Production Company, Houston, TX, where he directed the evaluation of CODAR for detecting and measuring ice movement. He is currently Vice President, Radar Systems Division, of Codar Technology, Inc., Longmont, CO. He provides marketing and project management support for CODAR operations and projects.

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Donald E. Barrick (M'62), for photograph and biography please see this issue, p. 146.