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PROFILES IN SCIENCE

Dr. John W. Tukey

John W. Tukey, who for many years has been an ONR contractor, is Associate Executive Director, Research-Communications Principles Division of Bell Laboratories, and Professor of Statistics at Princeton University. His work includes development of a wide variety of new statistical techniques; applications of statistics and data analysis in many fields; techniques for making printed information more accessible; broad analysis and synthesis problems related to complex weapons systems; and other problems with mathematical or statistical aspects. Dr. Tukey has served as a member of the President's Science Advisory Committee and on a number of other advisory committees to the government, including the Science Information Council and the President's Air Quality Advisory Board. He has served on four presidential task forces concerned with pollution and the environment. He has served as president of the Institute of Mathematical Statistics, as vice-president of the American Statistical Association, and as a member of the Council of the National Academy of Sciences.

Measurements of Mid-Ocean Surface Conditions by Over-the-Horizon Radar

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Introduction

A pulse-doppler backscatter radar operating in the high frequency (3-30 MHz) band was used to measure ocean surface motions in the North Atlantic Ocean under a variety of environmental conditions. With the ionosphere as a part of the propagation path, data were collected at ranges from 600 to 2200 nautical miles. Environmental conditions included a relatively small hurricane, a large storm, and a relatively calm ocean. The doppler data were converted to wind vectors and compared with weather data taken at the same times and places. Preliminary results indicate that there is, in general, excellent agreement at all ranges and under all of the environmental conditions encountered. The agreement in wind strengths is fair to good, but at present reliability is mainly limited to the first hop data (600 to 1200 nautical miles) because of multiple propagation modes.

Improvements in this technique can be expected from refinement in some theoretical assumptions and in mode separation for the multiple hop case. This is a continuing project of the Naval Research Laboratory supported by the Office of Naval Research.

All techniques and methods for the prediction of weather and sea state, no matter how sophisticated or accurate they may be, suffer varying degrees of degradation from lack of inputs, especially in "real time." Generally, where large land areas exist, there are sufficient data available which, when coupled with climatology, can yield good weather preditions. However, for land areas adjacent to oceans the accuracy begins to fall off, and for mid-oceanic regions there is often no way to predict with any accuracy the magnitude of sea-state or direction of the surface winds due to lack of real time data inputs. At the present

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time, less that 10% of all data inputs to weather models come from ocean areas, which constitute 75% of the surface of the globe. For global analysis models, this is catastrophic, since it renders most of the predictions virtually useless.

With the increasing use of the world's oceans and the increasing importance of submarines in potential conflicts, the need for real-time knowledge of ocean conditions worldwide has increased proportionately. Despite this obvious need, weather service facilities directly concerned with the ocean have been curtailed. Both the Naval Weather Service and the Air Weather Service have suffered severe cutbacks in both personnel and hardware including ocean surveillance aircraft in the past two years. By the next year the U.S. Coast Guard will have lost most of its ocean-going weather ships in the North Atlantic Ocean. Reports from normal shipping in the oceans are spotty, are of questionable reliability, and concentrate on well-traveled shipping lanes. Satellites work very well except during storms, when cloud cover prevents observation of the ocean surface. The National Weather Service (NOAA), Naval Weather Service, and Air Weather Service all rely heavily on these sources of information.

Consequently, any single system which can reliably provide a substitute for the activities being phased out and, in addition, can provide real-time data under most environmental conditions from many remote and previously inaccessible areas of the world's oceans, should be considered as a possible candidate for future use by the whole weather community.

The primary object of the work reported here is to show the practicability of using a shore-based high frequency (HF) radar to provide in real time ocean surface parameters, such as sea state and surface wind speeds and directions, over a wide range of environmental conditions from remote ocean areas. An article describing work in a related field, "ONR's Remote Sensing Program," appeared in the October issue of *Naval Research Reviews*.

Other objectives include:

(a) refinement of both the theoretical and empirical ocean spectra models,
(b) establishment of criteria for accuracy, and
(c) preliminary specifications for a cost-effective workable system.

Background

The HF band (3-30 MHz) of electromagnetic energy has long been used for radio communications *via* both surface wave and skywave for over-the-horizon communications. Long range communications are possible *via* skywave because the ionosphere at approximately 50 miles above the earth's surface can reflect radio waves back down to the surface of the earth. Radars in this frequency band can use the over-the-horizon skywave path for long range observations.

Figure 1 shows typical over-the-horizon propagation geometry for remote observation of the ocean surface at large distances from the radar source. The curved lines represent the radar rays emanating from a radar located at zero height and zero range. The radar waves travel on straight lines to the ionosphere, which start at 100 kilometers, where they are bent and eventually reflected back toward the earth. On striking the rough earth's surface the waves are usually re-reflected in all directions. That portion of the energy which retraces its path back toward the radar is called backscatter and the radar is said to be operating in a monostatic (single station) mode when an appropriate receiver is used to collect the energy. One ground reflection is often referred to as a single hop.

The rest of the energy is called forward or side scatter and when picked up by an appropriate receiver, the radar is said to be operating in a bistatic (two station) mode. The forward scattered energy can again go up to the ionosphere and again be reflected back toward earth as before and other areas of the earth's surface can be examined by radar *via* second hop and higher hops. Around-the-world propagation of radar waves is regularly achieved in this manner.

The splitting of the rays into three discrete bundles in the figure is due to lobes in the antenna pattern.

Whatever the propagation path, the energy received from the earth's reflections can be examined for characteristics of the reflector (earth), or of the propagation path (ionosphere), or both.

It has been known for some years that land can be distinguished from the ocean in radar signals reflected from the earth's surface because wave motion on the sea surface can usually be determined by spectral analyses.

Resonant backscattering of high frequency (3-30 MHz) radio waves from the surface of the ocean has been studied both experimentally and theoretically by a number of investigators (1-8). The phenomenon is the result of coherent scattering of electromagnetic energy from that spatial component of the sea surface having a wavelength of one half the radio wavelength and traveling radially toward or away from the radio source.

Until recently most of the experimental work had been done using line-of-sight or groundwave propagation. The work of Mr. D. Crombie of the Institute for Telecommunications Sciences (1) goes back to the mid-1950's, when he recognized that the backscatter came from those ocean gravity wave trains having a resonant spacing (Bragg scatter). Recent

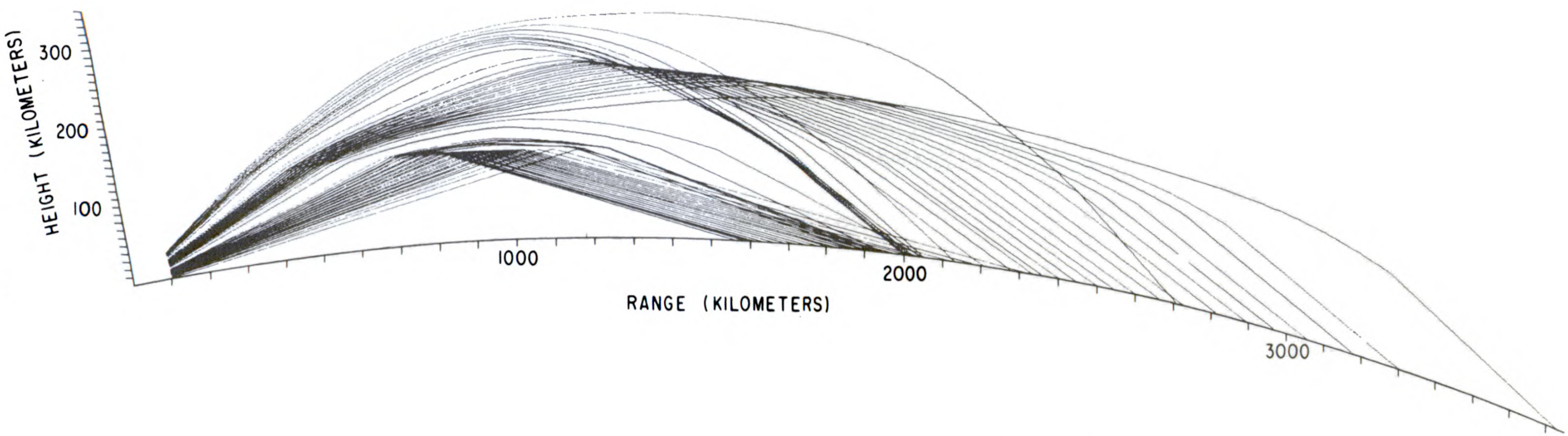

Figure 1 — Typical ray paths for over the horizon geometry. Antenna pattern and ionospheric structure are included.

improvements in hardware, in which both the dynamic range and frequency resolution were dramatically improved, now permits the use of the over-the-horizon (skywave) mode in making such distinctions and also in making precise measurements of the motions contained in the reflected signal. More recently it has been shown that, most of the time, the motion of the ionosphere can be readily distinguished from the movement of the ocean surface in the radar signal. Therefore it is now possible to use a pulse-doppler, coherent, monostatic HF radar to examine selected areas of the earth's surface and to determine such radar parameters as cross-section, doppler frequency, range and beamwidth. In 1972, scientists at the Naval Research Laboratory (2) were able to interpret radar data in terms of wind directions of the ocean surface. In this report the interpretation of the radar data will be further extended to wind speeds at the surface of the ocean. Since the radar can be shore based, it has definite advantages over mobile platforms such as ships and satellites in logistics, flexibility and in data processing.

Description of Work

The experimental work described here was performed at the Chesapeake Bay Division of the Naval Research Laboratory with a coherent pulse-doppler backscatter HF monostatic radar. Figure 2 is a photograph of the radar site.

The radar operates from approximately 13.5 to 27 MHz. The antenna is approximately 330 ft. long, 140 ft. high and is located on top of a ninety foot cliff overlooking the bay and can be used for observations over a substantial part of the North Atlantic Ocean.

The antenna can be steered in azimuth to cover from 107° to 047°, that is from the direction of Ireland in the North Atlantic to the coast of South Africa in the South Atlantic Ocean.

Some of the radar parameters used in the experimental measurements were:

repetition rate	= 22.5 pulses per second and 11 pulses per second
pulse length	= 500 microseconds and 800 microseconds (40 and 64 nautical miles)
frequency	= 15.6 MHz and 22.9 MHz
beamwidth	= 10° (at 15.6 MHz) and 8° (at 22.9 MHz)

These numbers yield, for 15.6 MHz at each fixed azimuth, a resolution cell (area of ocean surface) of approximately 40 nautical miles (nmi) deep (in range) and 90 nmi in width (azimuth) at 500 nmi. At 2000 nmi, the cell becomes 40 nmi deep and nearly 350 nmi wide.

Although the absolute azimuthal resolution at this frequency is the 10° beamwidth, measurements can be taken with considerable overlap

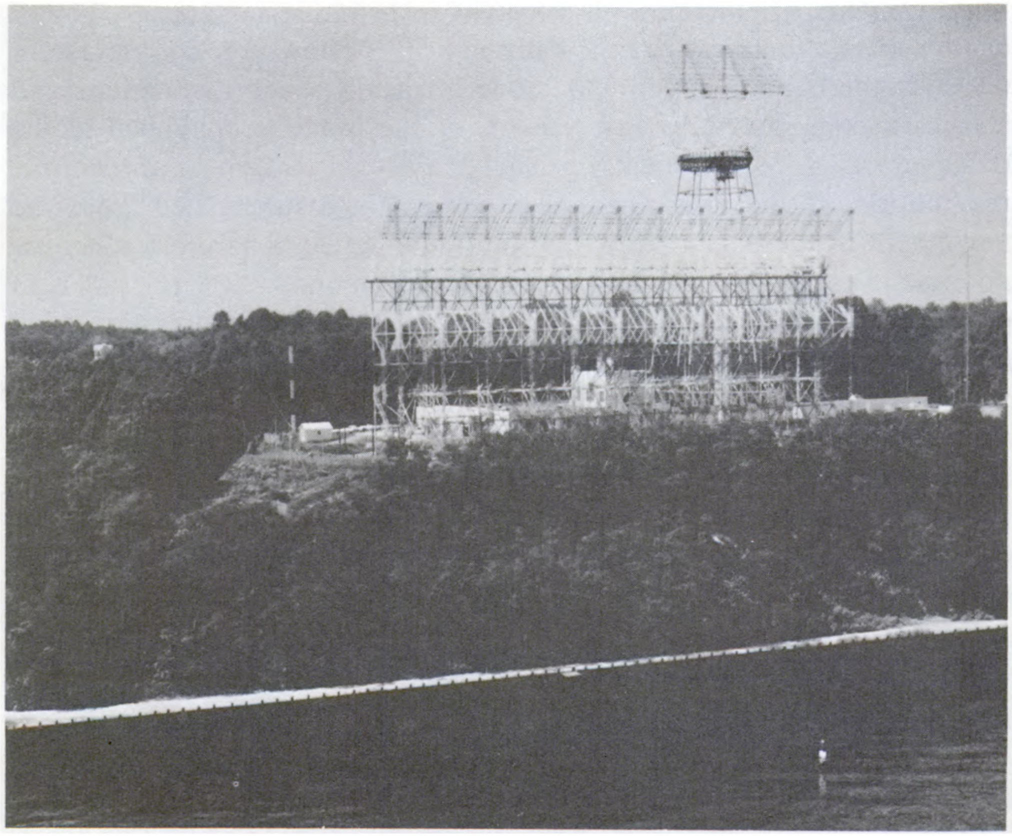

Figure 2 – Photograph of the Ionospheric Radar used in the experiment located at the Chesapeake Bay Division of the Naval Research Laboratory, Chesapeake Beach, MD.

in azimuth so that effectively higher accuracy can be obtained by noting the differences in adjacent azimuthal cells.

Similarly, although the minimum absolute range resolution is about 40 nmi, data processing has been done with range gates spaced every 10 nmi so that differences in adjacent range gates can be measured.

Over the horizon geometry required for the remote observation of the ocean surface at large distances from the HF source is used. Reflections or refractions severe enough to bend the radar rays back toward the earth's surface are most pronounced at the so-called ionospheric layers where the local electron densities reach maxima. The E layer is located near 100 km altitude and the F_1 and F_2 layers occur at approximately 180 km and 250 km altitudes respectively. Using E-layer propagation, data can be obtained from about 500 nmi out to 1200 nmi in range. Use of F-layer propagation can result in observations out to and beyond 2000 nmi range.

Calibration

Calibration is especially important in an over-the-horizon HF radar, because the radar measures a complicated slant range to the target rather than true range, and ionospheric layers tilts can cause appreciable azimuthal errors, while ionospheric motions can broaden the spectra of return signals.

The internal pulse calibration signal of this system can be used to determine the bandwidth, amplitude, and range simultaneously for any received signal. The range measured this way is the slant range. Azimuth is determined by the antenna direction. The bandwidth is the total bandwidth including ionospheric motions and motions on the earth's surface.

The bandwidth measurement is extremely important, because surface wind speed and sea state can be determined from ocean wave motion in the form of doppler spectra. Any spectrum broadening from ionospheric motions will introduce errors in this determination.

An external calibration technique can be used to resolve these errors. For this, land areas which exhibit zero doppler frequency (no relative motion) and a bandwidth comparable to that of the system calibration signal can be used. Especially useful are small isolated islands in the ocean whose geographical positions are already precisely determined. These islands will give an external range and azimuthal calibration as well as indicating the extent of the ionospheric motions. An example of this method of calibration is presented later in this paper. If suitable islands are not located at appropriate ranges and azimuths, beacons or transponders can be employed.

Display Format and Analysis

Figures 3-5 show some typical displays of amplitude in dB *versus* doppler frequency in Hz for a number of environmental conditions.

Figure 3 represents the signal obtained by a surface wave path resulting from vertically polarized electromagnetic waves transmitted over Chesapeake Bay. This mode can serve as a rough calibration for the over-the-horizon sky wave data. The Bragg spectrum lines indicating advance (A_1) and recede (R_1) resonant ocean waves are seen nearly symmetrically spaced around zero doppler at +0.47 Hz and −0.45 Hz. The advance line (A_1) is stronger than the recede line (R_1) indicating a stronger approach wave which means a wind blowing toward the radar. The system calibration signal (C) is located at 0.15 Hz. Peaks A_1 and A_2 indicate higher order terms due to multiple scatter. The peak at zero doppler (L) represents reflections from land in the area. Winds on this day were relatively calm. Stronger winds would broaden A_1 and R_1. Range is of the order of tens of miles.

Figure 4a represents the doppler signature obtained *via* sky wave looking in the direction of Newfoundland (054°). The peak at zero doppler is the ground reflection from Newfoundland, at 977 nmi slant

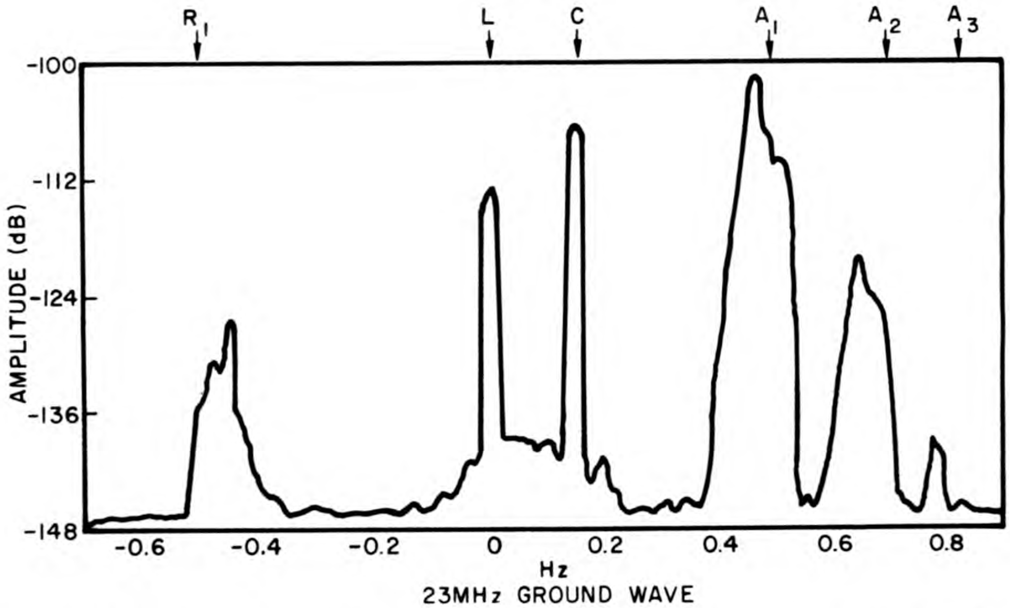

Figure 3 — Typical amplitude versus *doppler frequency plot of the processed data showing the calibration signal (C), a reflection from the land (L), the first order Bragg lines, advance (A_1) and recede (R_1) and higher order terms (A_2 and A_3).*

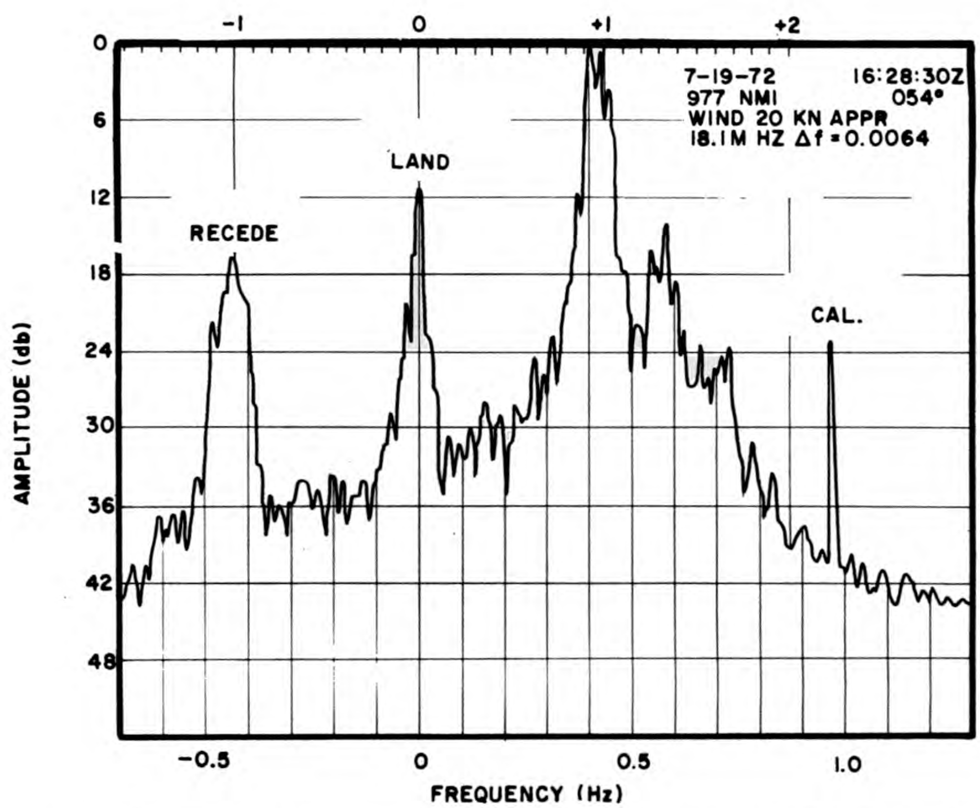

Figure 4a — Typical sky wave data of amplitude versus *doppler frequency. The first order Bragg lines are at ±0.42 Hz. The peak at zero doppler frequency is the result of reflections from Newfoundland. Calibration signal is near 1.0 Hz.*

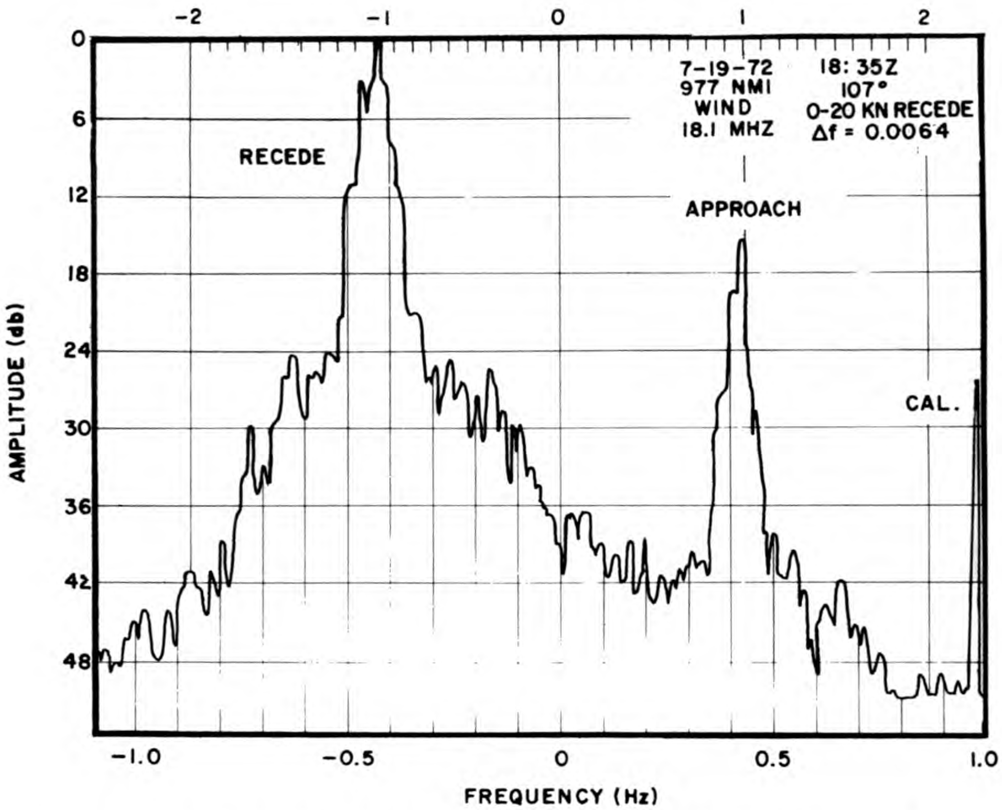

Figure 4b – Typical sky wave plot representing an area where no land is present. Winds were extremely calm. Calibration signal in near 1.0 Hz.

range. The reflections from the ocean surface are at ±0.4 Hz and the relative amplitudes of the advance wave at +0.4 Hz and recede wave at −0.4 Hz indicate the strongest component is toward the radar. The sea surface winds as given by weather maps were 10-20 knots blowing toward the radar. The calibration signal is at 1 Hz.

Figure 4b is a similar display at the same range but of 107° azimuth just north of Bermuda, where no land is located, and therefore no strong signal appears at zero doppler. The relative amplitudes of the advance wave (at +0.4 Hz) and the recede wave (at −0.4 Hz) indicate the strongest component is away from the radar. The surface winds from the weather maps were very calm, of the order of a few knots, blowing away from the radar.

Figure 5 shows a comparison of the spectra due to rough and moderately calm seas. In the upper half of the figure, the antenna was pointed at a region of the ocean 095° almost due east, where the winds were of the order of 30-40 knots and blowing away from the radar. The recede resonant wave peak is apparent at −0.5 Hz. The advance peak at +0.5 Hz is buried in the continuum.

The lower part of Figure 5 shows data taken at nearly the same time but at 059° azimuth, where the weather map indicated lower wind

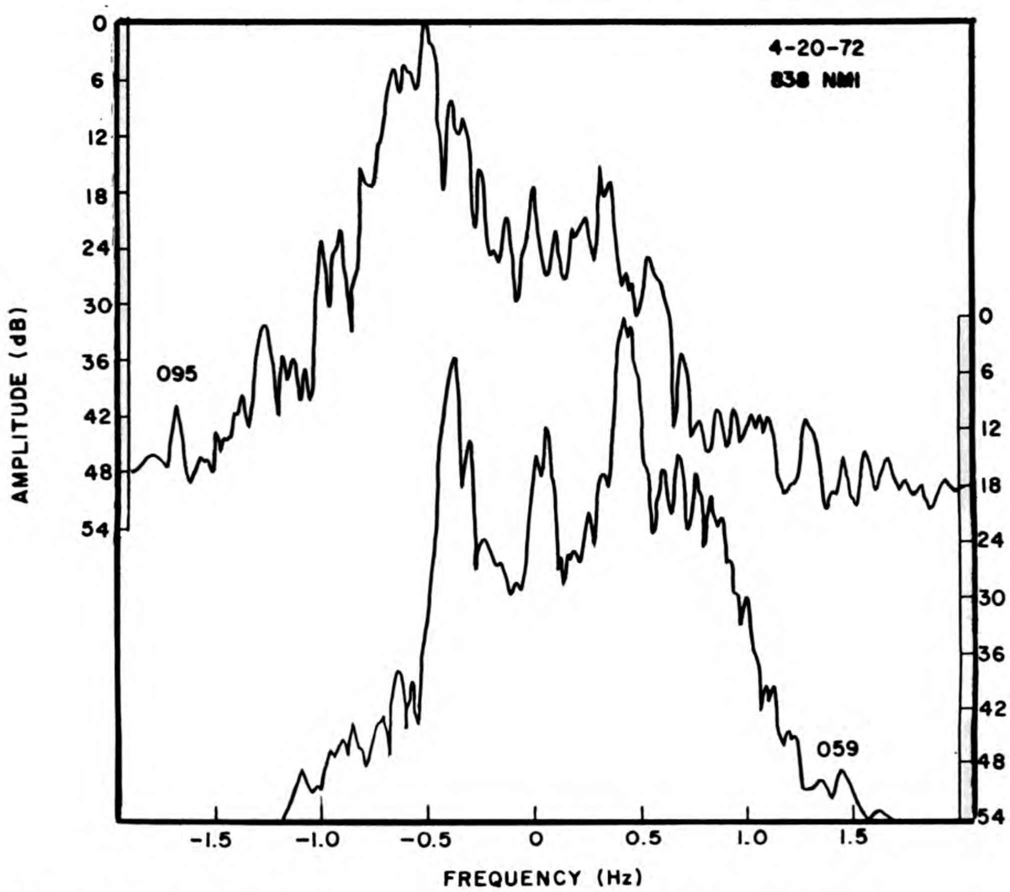

Figure 5 — Two amplitude versus *frequency plots at different azimuths. The upper plot shows a stormy area. The lower plot represents an area of fairly normal ocean conditions. Note the frequency spreading under stormy conditions.*

strength, 20 knots, and almost crosswind direction with respect to the radar. The land signature at zero doppler is apparent (Newfoundland). The major effect of higher winds is frequency spreading of the signals.

It should be pointed out that the data represent the average condition of the sea surface in an area roughly 40 by 175 nmi for each of these figures. Assuming that the sea surface roughness is the result of surface winds, these data can be interpreted in terms of these winds and compared with weather charts whose data were collected at approximately the same time as the radar data. Conversion to sea state can be made.

Experimental Results

The first attempt to correlate this kind of radar data with a corresponding weather map was done by Mr. A. Long, a British exchange scientist working temporarily at the Naval Research Laboratory, who superimposed radar data on a weather map as seen in Figure 6. It is obvious that the agreement with the wind direction is excellent.

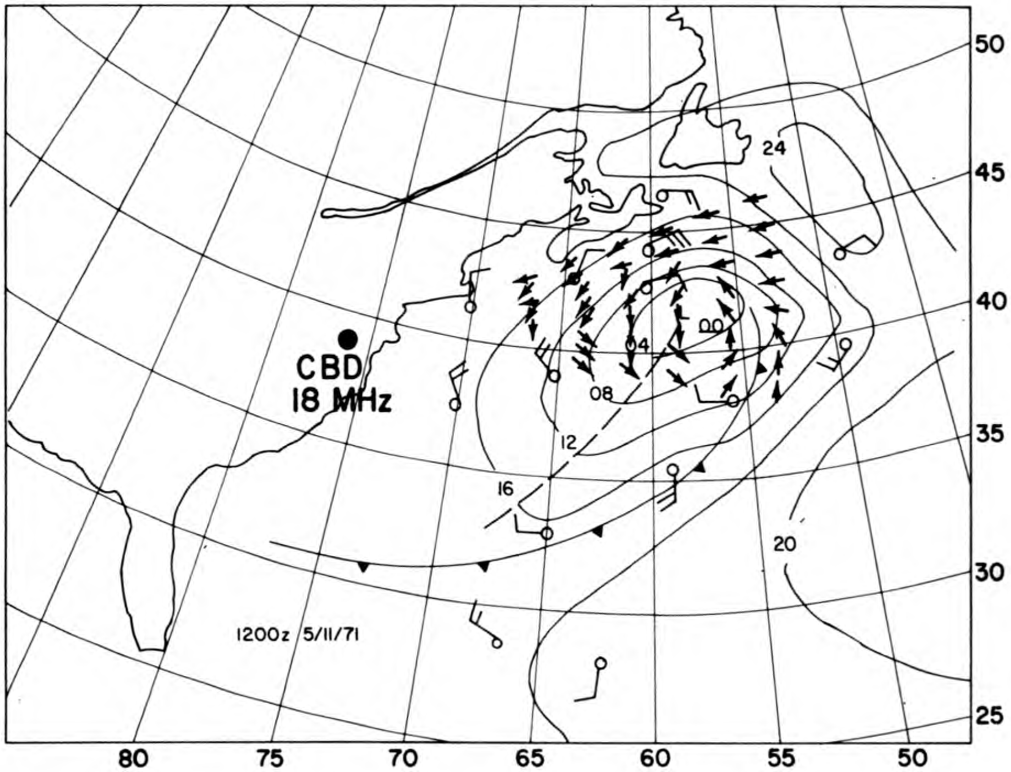

Figure 6 — Comparison of wind direction from a weather map with radar data. Weather map symbols have circular heads. Radar data is indicated by the arrowheads symbols. The agreement is excellent.

He used a directional sea spectrum theory developed by Pierson and Moskowitz (9) to derive an empirical relationship between the ratio of the amplitude of the Bragg lines and the angle of the local wind with respect to the radar beam. A cross wind would be indicated by equal amplitudes of approach and recede resonant lines. For a strictly radial wind, the ratio would have a maximum value. This value most probably will vary with the state of the sea as well as the transmitted frequency.

Figures 7-10 are maps comparing radar data with meteorological data including wind speed as well as direction. Figure 7 is a map of the North Atlantic on November 15, 1971 while Hurricane Ginger was present. No normal weather reports were available for the center of Ginger, but agreement between the radar results and normal weather reports is excellent for the peripheral winds as well as for the wind pattern in the rest of the covered area. Multiple propagation modes precluded wind strength determinations at second hop ranges, east of Ginger, although wind directions could be obtained. This is the first attempt to correlate wind speed as reported on the weather map with the wind speed as deduced from the radar data. The agreement is good.

Figure 8 is a similar plot taken for April 20, 1972 during a large storm. Because of its size, only part of the storm could be covered.

RADAR DATA COLLECTION PERIOD FROM 1635 Z TO 1655 Z
WEATHER DATA TAKEN FROM SURFACE CHART MARKED 1800 Z

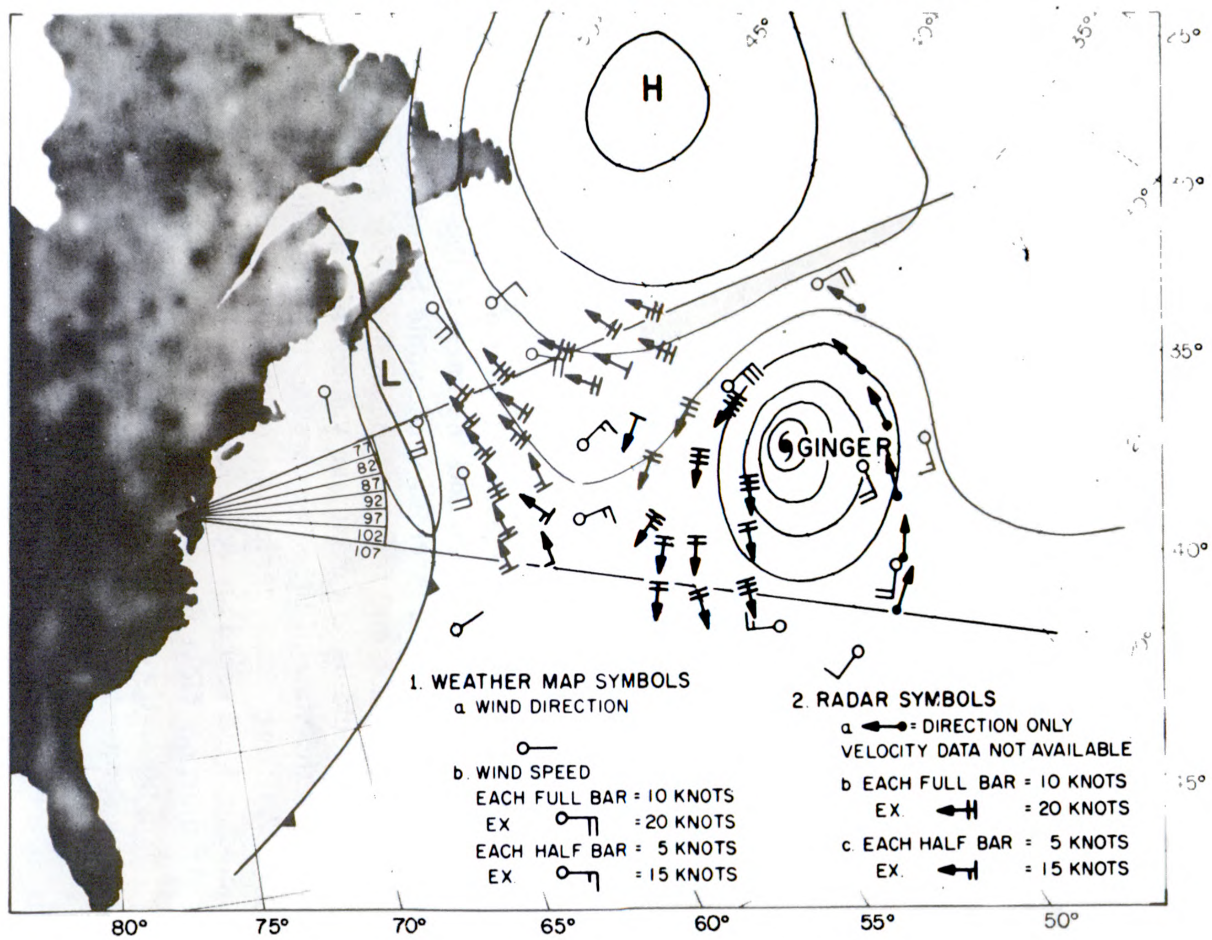

Figure 7 — Comparison of weather and radar data over the North Atlantic in the presence of Hurricane Ginger, 9/15/71.

1. WEATHER MAP SYMBOLS

a. WIND DIRECTION

b. WIND SPEED

EACH FULL BAR = 10 KNOTS

EX. = 20 KNOTS

EACH HALF BAR = 5 KNOTS

EX. = 15 KNOTS

2. RADAR SYMBOLS

a. = DIRECTION ONLY VELOCITY DATA NOT AVAILABLE

b. EACH FULL BAR = 10 KNOTS

EX. = 20 KNOTS

c. EACH HALF BAR = 5 KNOTS

EX. = 15 KNOTS

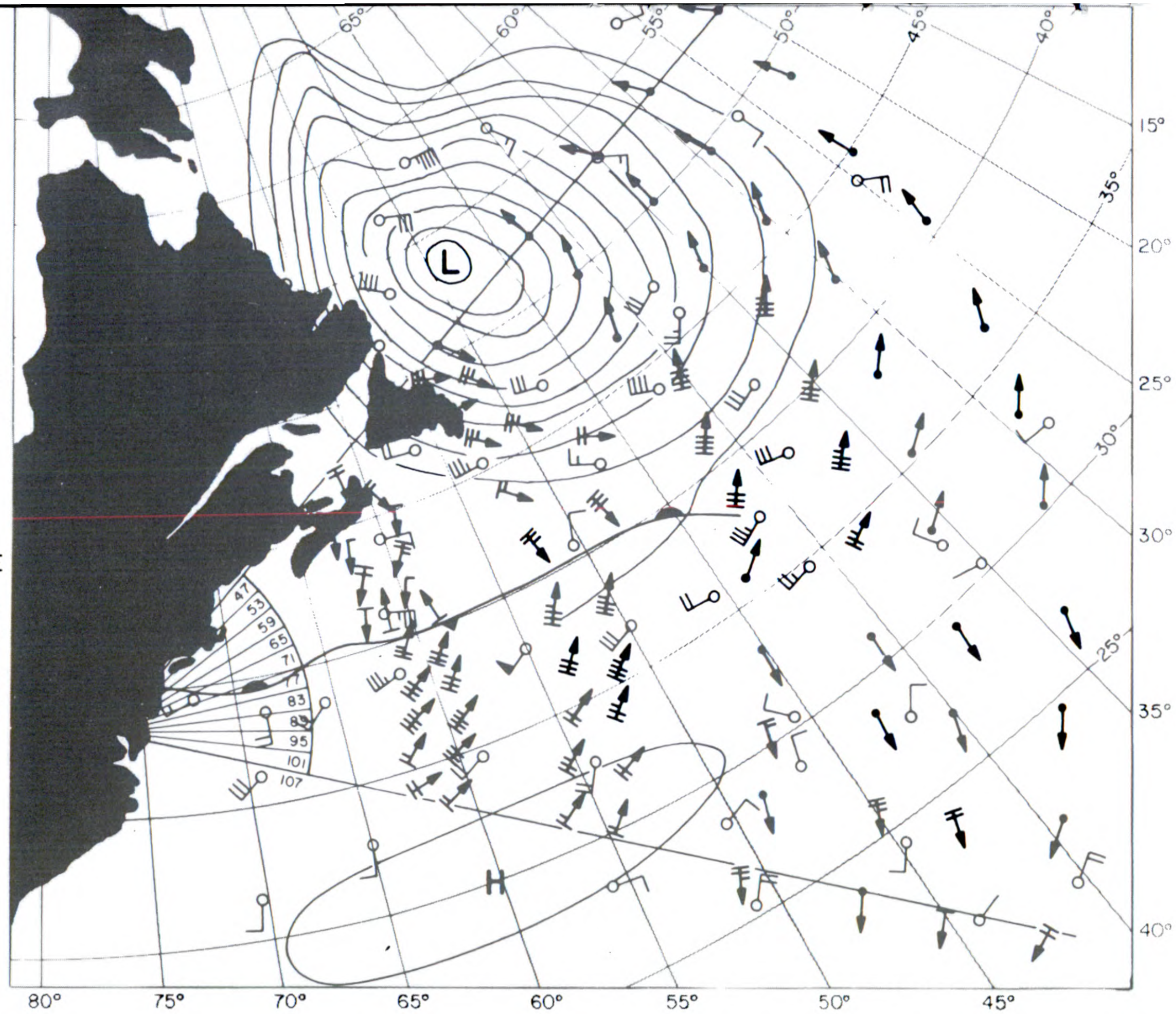

Figure 8 — Comparison of weather and radar data over the North Atlantic while a large storm was in progress, 4/20/72.

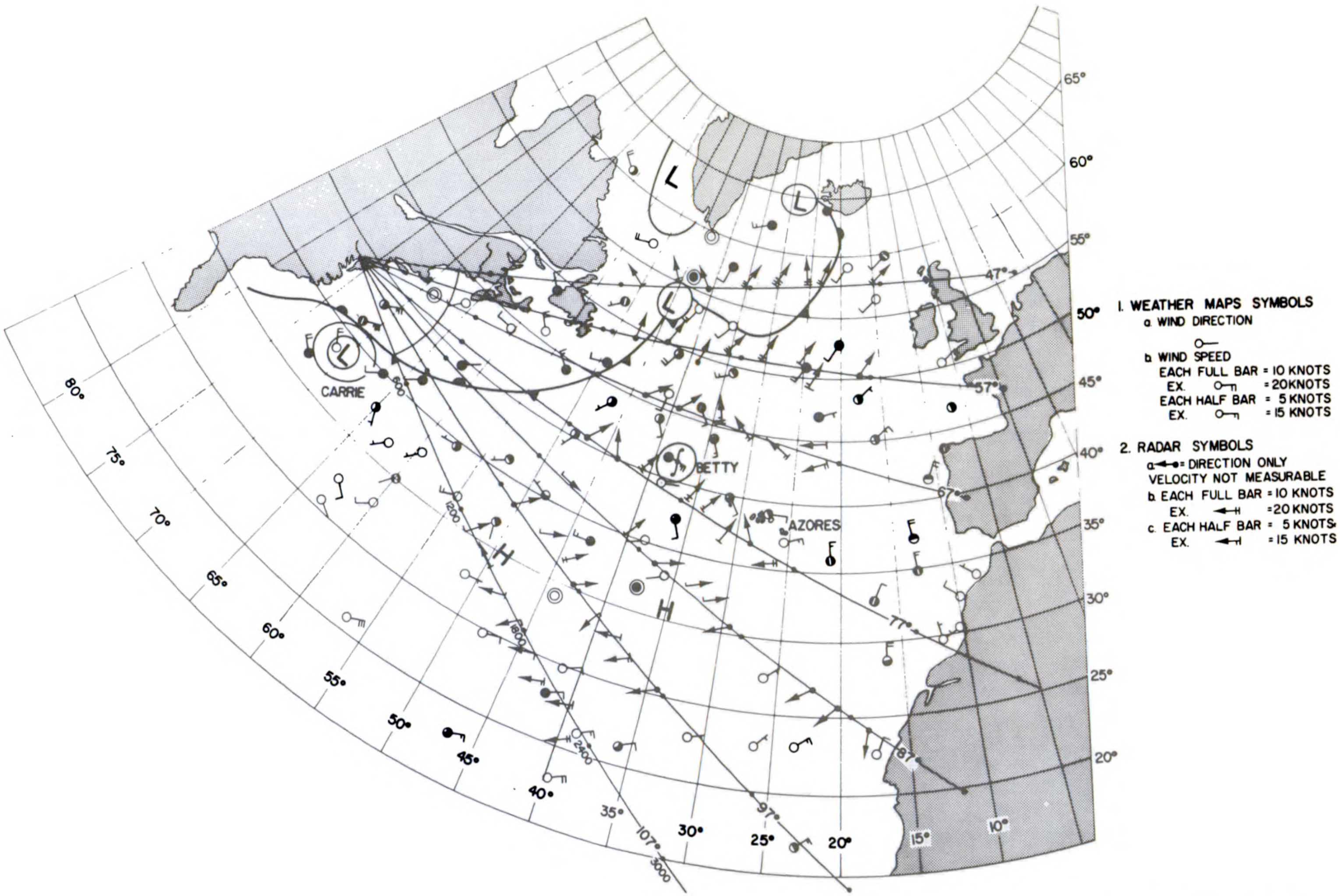

Figure 9 – Comparison of weather data and a few radar data during a calm period over a large expanse of the North Atlantic.

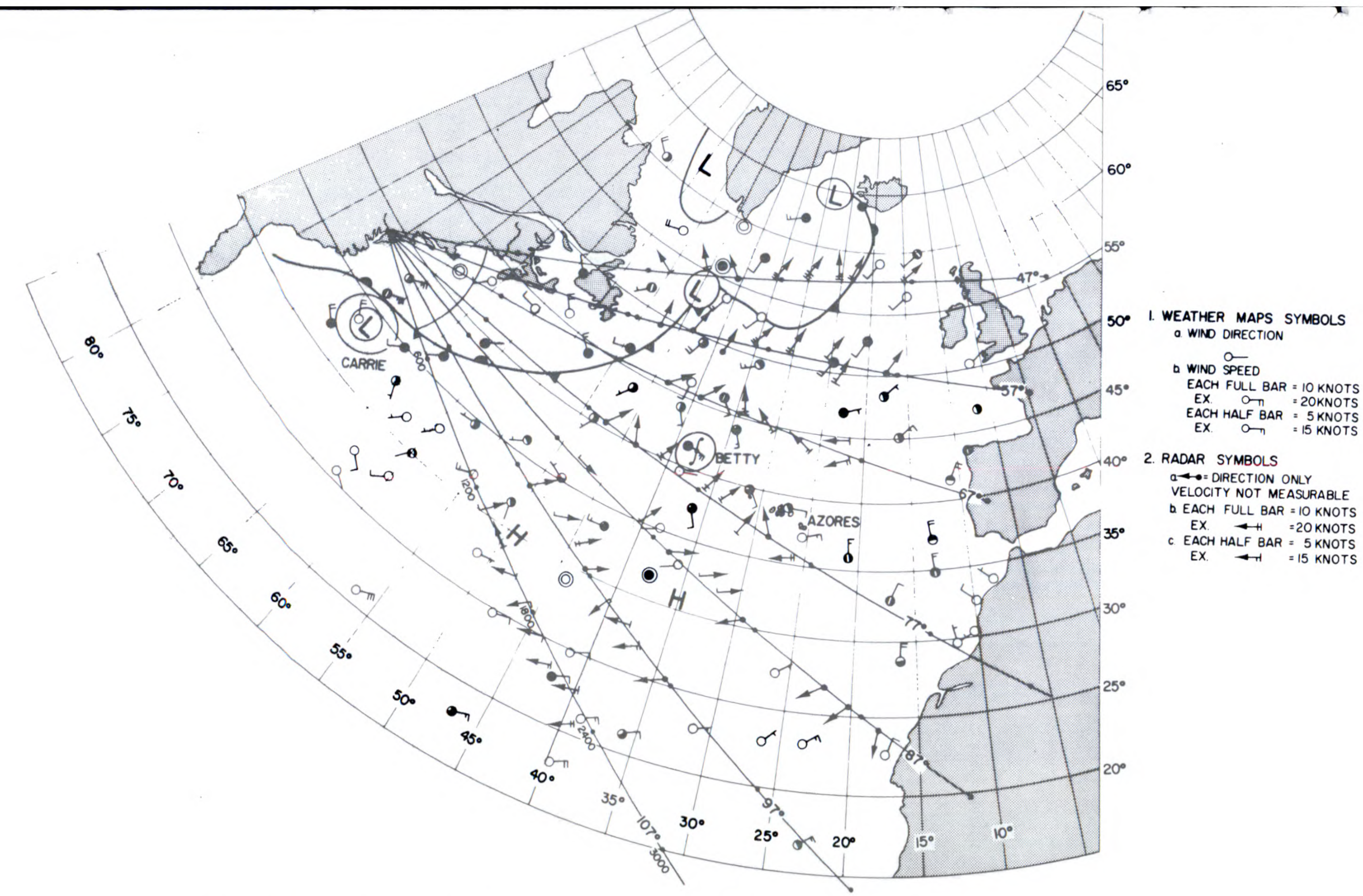

Figure 10 – Comparison of weather data and radar data over the North Atlantic in the presence of tropical storm (formerly hurricane) Betty.

Note that there is a front along the 40th parallel with opposing winds only a few hundred miles apart. Again, in comparing radar data with normal weather reports, the wind directions are in good agreement, while the wind speeds are quite credible. Multiple propagation modes prevented the determination of wind speeds for the second hop case, *i.e.*, east of 35° W, although the directions were obtained.

In order to get a preliminary check on the validity of the assumptions and the scale used to determine the wind strength, the data shown in Figure 9 were taken on July 19, 1972 during very calm conditions. Only a few data points were plotted to indicate the calm area east of the radar and compare it with the somewhat more turbulent conditions to the north. Agreement was excellent, and it appears that, at least for this case, wind speeds differing from 5-10 knots can be resolved.

According to Hasselman (10) and Barrick (11), increasing sea surface roughness will increase the amplitudes of the side bands around the first order Bragg lines of the ocean wave spectra. Conceptually, differences in areas under the spectral plots can be used as a measure of this roughness and of the speed of the local wind.

The data collected to date indicate that this is an acceptable approach but that there is some variation with frequency. There are insufficient data at this time to indicate the form of this variation or to indicate the degree of accuracy inherent in this method. Data taken simultaneously at several different frequencies would be useful in determining the practicality of this approach.

Figure 10 is another weather radar map of the North Atlantic for August 31, 1972 covering "Hurricane Betty," which was some 1800 miles from the radar. However, Betty which had been a hurricane for the several preceding days, had been downgraded to a tropical storm with maximum winds of about 30 knots and no longer was a major influence in the ocean. An examination of the map shows that there are no strong weather systems in the North Atlantic, and indeed the radar returns bore this out. Over much of the ocean the winds are fairly calm, so that the wind directions shown may not mean much. In general, the radar data show good accord with the weather map data. In the ranges from 1200 to about 1600 nmi many of the radar data yield only wave direction, because unstable ionospheric motions mask the ocean surface motions at certain azimuths. However, from 1600 to 2500 nmi the data were excellent for determination of both wave direction and velocity, as can be seen from the figure.

Because radar coverage was excellent for both first and second hops, it was decided to test the practicality of establishing known land masses as external calibration points, in range, azimuth, and in assessing spectral spreading due to ionospheric motions. The land return can be compared with the internal calibration signal, which is a close replica of the transmitted waveform, to determine any broadening due to ionospheric motions.

The Azores are located at true ranges from 2088 to 2406 nmi from the radar and are confined in azimuth to a narrow beam from 73.6° to 75.9° or 2.3°, much narrower than the illuminating beam of 8°. Figure 11 shows the geometry. In range the islands can be separated into three

Figure 11 – Map showing the radar coverage of the Azores from 2000 nautical miles to 2500 nautical miles range from the radar, with radar beam at 077° azimuth.

groups dominated by the islands of Flores, Pico and Sao Miguel respectively.

Figure 12 is a montage of 24 doppler-amplitude plots with range as a parameter taken at 077° azimuth, *i.e.*, pointing at the Azores. When land is present, it appears at zero doppler frequency. As before, R and A indicate the recede and advance components respectively of the ocean waves. Along the abscissa is the doppler frequency with the markers at zero and ± 0.5 Hz from the carrier. Slant ranges are given to the right of each trace and start at 2070 nmi. Data were taken at 20 nmi increments of range. Indications of zero doppler signal are first seen at a slant range of 2130 nmi corresponding to Flores, and have disappeared by 2230 nmi. A second zero doppler signal begins at 2270 nmi corresponding to a group of islands including Pico and persists out to about 2390 nmi. The third zero doppler signal begins at 2410 nmi corresponding to Sao Miguel and vanishes at 2510 nmi.

As a check on the accuracy, the distance between Flores and Pico given by chart is 138 nmi and by radar is 140 nmi. The distance between Pico and Sao Miguel given by chart is 149 nmi and 140 nmi by the radar. These values are within the absolute resolution of the radar, whose accuracy is limited to ± 20 nmi for this case. Figure 13 is a range-doppler plot of the Azores region. The three land groups can be clearly distinguished from the ocean wave reflectors.

This then provides accurate, absolute calibration points for the radar system for signals of interest at ranges in the first hop through 2500 nmi and at azimuths around 077°. Under most conditions, the two calibration areas (Newfoundland and the Azores) will be sufficient for all of the one hop coverage in the antenna beam (047°-107° azimuths).

As previously mentioned, the 31 August data produced several additional calibration areas which will not be discussed in detail, but which should be mentioned so that an insight can be gained as to the potential inherent in this technique.

Examination of the data so far has yielded identifiable areas such as Ireland, the Irish Sea, England, the North Sea, Germany, the Adriatic and Mediterranean Seas, the French and Spanish coasts, the Atlas Mountains in Africa, and perhaps some features in the Sahara Desert.

Further studies will have to be made to assess the usefulness of such data, but for the moment it appears that whenever radar coverage extends out as far as 6000 nmi, there will be adequately known terrain highlights to yield accurate range and azimuthal measurements.

Conclusions

These experimental results indicate that use of the over-the-horizon technique holds great promise for immediately shoring up the eroding

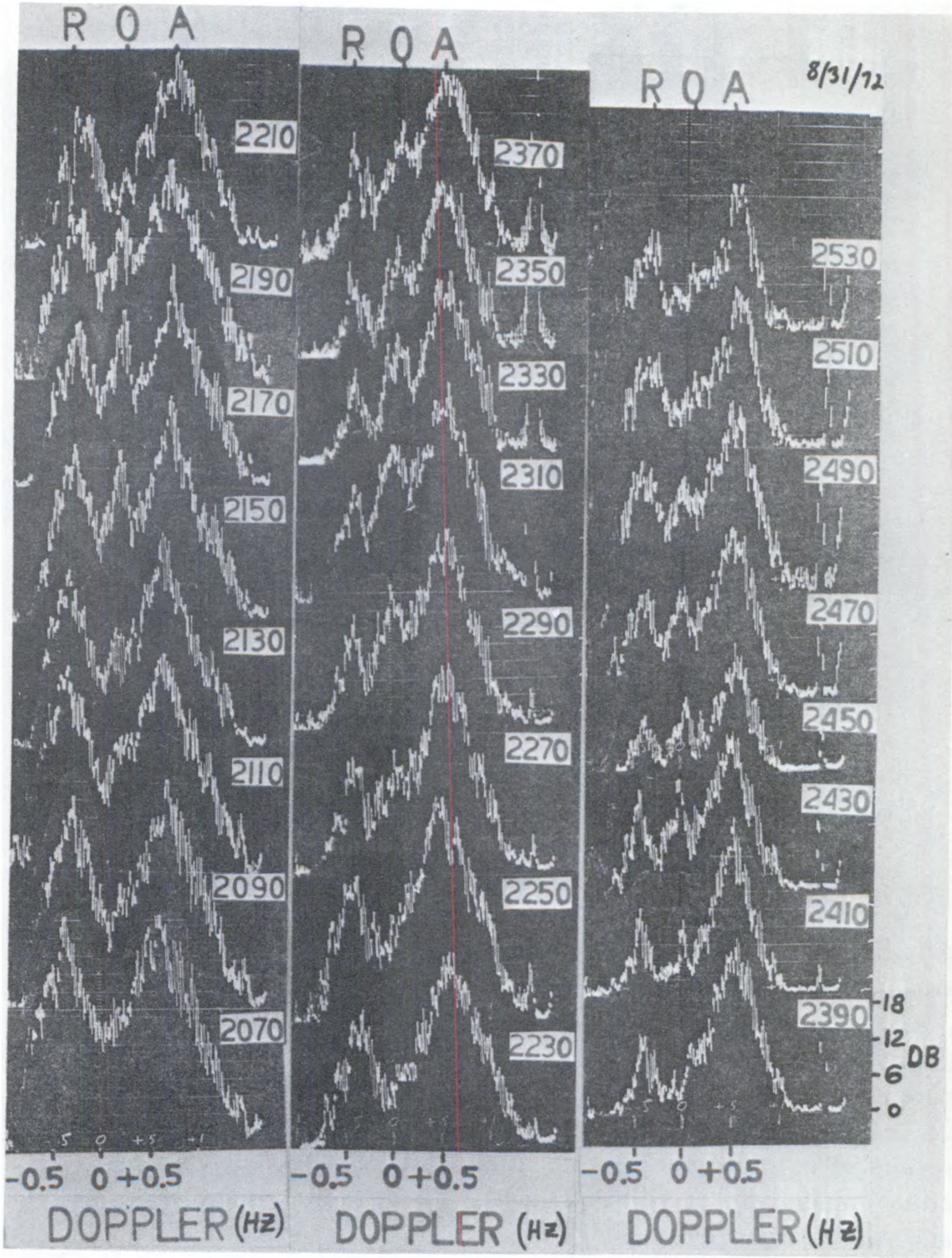

Figure 12 — Montage of amplitude—doppler data taken at azimuth 077° and with 20 nautical mile range intervals of the area outlined in Figure 12. Signals appearing at zero doppler indicate Azore island groups.

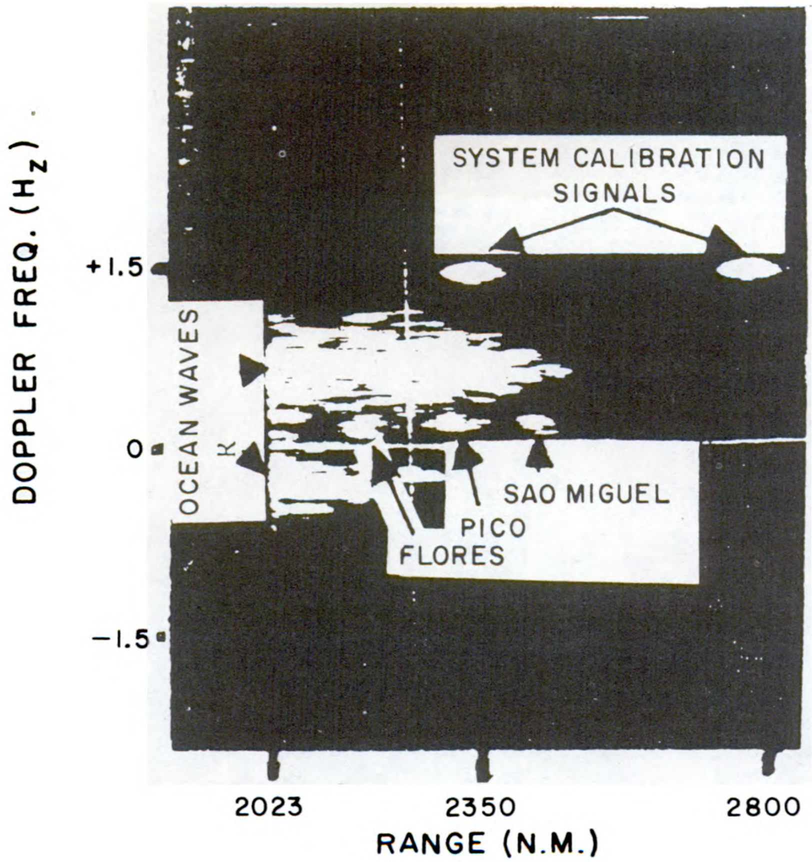

Figure 13 — Range—doppler plot showing the ocean wave signal and the three group of Azore Islands near zero doppler. System calibration signals are at +1.5 Hz and 2350 and 2800 nautical miles.

data base for the weather services as well as providing data from ocean areas which have never been adequately covered.

The technique for extracting wind direction appears to be on solid ground. The wind speed and sea state determinations, although apparently satisfactory, need more work. Accuracy of the data appears comparable to that of other sources, but confirmation must await the results of more stringent verification tests. Such verification tests are either under way or being planned with both Naval Weather Service and Air Weather Service.

The following remain as worthwhile activities for future effort:

(a) Refine application of existing theories to use the continuum around the Bragg lines for sea state determination.
(b) Attempt mode separation so that wind speed can be extracted from the second hop data.
(c) Make simultaneous measurements with two widely separated frequencies.

(d) Vary radar parameters to obtain specifications for the minimum systems required for such observations.

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NRL Research Aims at Sensing Severe Sea Storms

Naval Research Laboratory (NRL) atmospheric scientists are engaged in the development and evaluation of a portable sea storm analyzer that is expected to enhance present methods of detecting and locating storms at sea.

The Navy, as well as commercial mariners and shippers, need to detect and locate storm activity in remote ocean regions to facilitate efficient and safe Fleet and commercial operations.

Presently, storms at sea are located by such techniques as direct observations, meteorological analysis, satellite photography and detection of distant lightning.

However, NRL scientists state that the immediate weather prognosis that emerges from any of the combinations of these techniques is inadequate, and during wartime reduced communications would further degrade such storm forecasts.

The NRL portable analyzer would furnish real-time information about the presence and locations of storms at sea from a single land or sea location.

In explaining the research, the scientists reported that lightning strokes within storms are broadband radiators of the electromagnetic energy which is known as atmospherics. They say appreciable electromagnetic radiation has been measured at frequencies as low as a few hertz to as high as several hundred megahertz.

Within this broad spectrum, the scientists added, the 3-30 kilohertz (kHz) very-low frequency (VLF) range is attractive for a long-range detection system because the energy propagates in the waveguide composed of the earth and ionosphere.

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Plasma Physics at the Naval Research Laboratory

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Now in its second decade as a distinct organization in the Research Department, the Plasma Physics Division (formerly the Plasma Physics Branch of the Radiation Division) has distinguished itself in the fields of electron beam technology, high-temperature physics, and numerical simulation. Its principal programs are directed toward high-altitude nuclear effects on radar, x-ray and microwave generation, and controlled thermonuclear fusion. The Division is involved in a variety of interdisciplinary programs and has ties with other agencies and institutions.

History of the Division

The Plasma Physics Division, like the discipline of plasma physics, is a relative newcomer compared to other divisions at NRL. The Division was established in early 1966 under the direction of Dr. Alan C. Kolb, whose scientific interests and research style have done much toward establishing its direction. The Division's major areas of interest are the generation and study of hot dense plasmas (of relevance to controlled thermonuclear fusion); pulsed power technology; high-current relativistic electron beams; and the development and use of lasers in plasma studies. Originally the main forte of the Division was in experimental physics. More recently a major effort in theoretical and computational plasma physics has been developed.

Because the Division was initally small and narrow in scope, joint programs in plasma studies were established with Cornell University and the University of Maryland. These collaborative efforts, still in existence, provided access to experts in various disciplines, enlarged our base in the scientific community, and expanded our capability to respond rapidly to diverse problems. With the growth of the Division, the need for these programs has diminished, but they are maintained at reduced levels and still represent models of mutually beneficial cooperation between academic and governmental research groups.

By 1970 the Division had gained a position of leadership in a number of areas of experimental plasma physics and technology. One of its

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principal achievements was the construction of a large theta-pinch plasma experiment, known as PHAROS. PHAROS used a 2-megajoule capacitor bank to magnetically compress and heat a dense plasma to temperatures of 20 million degrees for periods of more than 10 microseconds. These results represented the closest approach to conditions necessary for controlled fusion at the time and were not surpassed until 1972. In terms of the characteristic Lawson number used to measure fusion conditions (the product of the density and confinement time), the PHAROS experiment reached a Lawson value of 10^{12} seconds per cubic centimeter, a factor of 100 smaller than that required for ignition.

A second major contribution of the Division during its early years was the design and construction of the first low-impedance, high-voltage electron beam accelerator, GAMBLE I. This accelerator, still in active use, can produce up to 20 kilojoules of 1-MeV electrons in a 50-nanosecond pulse. It was constructed as a part of the research effort for the Defense Atomic Support Agency (DASA), now know as the Defense Nuclear Agency (DNA).

During these initial years, the Division support came principally from DASA, the Advanced Research Projects Agency (ARPA), and the Office of Naval Research (ONR). As a result of the deployment of the Soviet antiballistic missile system and the United States' decision to deploy the Safeguard System, DASA placed major requirements on the Division—initially in the area of the vulnerability of missiles and reentry vehicles to high-altitude nuclear bursts and eventually to the complete phenomenology of high-altitude nuclear bursts. The increased emphasis in this area led to a significant change in the Division's character. In the absence of opportunities to gather data on high-altitude explosions by field testing, emphasis was placed on the development of a theoretical, computational capability within the Division.

Following Dr. Kolb's departure from NRL in 1970, the Division underwent major administrative changes and realigned its resources to address the priority requirements of DASA. Concurrently, much of the laser effort was transferred to the newly established Optical Sciences Division. Upon completion of the reorganization, the Plasma Physics Division emerged with groups organized around three principal disciplines: (a) pulsed power technology and relativistic electron beams as applied to radiation sources with possible application to controlled thermonuclear fusion; (b) high-temperature plasma physics oriented towards the study of laser-matter interaction, reaction rates of ionized gases, and the development of short-wavelength lasers; and (c) computational and theoretical plasma physics with main application to high-altitude nuclear effects phenomenology, upper ionospheric modeling, and plasma dynamics. The Division, comprised of approximately 150 personnel, is the largest group of its kind in the United States; and in the area of plasma physics it is the largest computational group in the world.

Some of the major highlights of the past few years were the construction of the largest operational low-impedance electron beam generator, GAMBLE II (1-MeV, 1-MA, 50-nsec pulse); completion of the largest electron beam plasma heating experiment; development of a unique class of exploding wire plasma sources, which have yielded up to 5×10^{11} fusion-produced neutrons from deuterated polyethylene (CD_2) wire; development of a vacuum-ultraviolet laser with emission at 1600 and 1161 angstroms; development of the first three-dimensional (3D) magnetohydrodynamic (MHD) reactive flow computer code to describe high-altitude nuclear explosions, the first 2D computer code capable of describing the full set of Maxwell equations and allowing for relativistic motion of particles; a major breakthrough in numerical techniques through the use of the Boris-Book "flux corrected transport" algorithms allowing for accurate computer modeling of fluid motion with very large gradients (shocks); the first successful modeling of self-consistent anomalous transport with fluid equations; the development of a code calculating infrared and visible emissions from nuclear events at arbitrary locations; the discovery of the spontaneous generation of magnetic fields in laser-matter interactions; nonlinear analysis of the "modified two-stream" and "beam-cyclotron" instabilities, crucial to an understanding of the interaction of expanding weapon debris with background air; modeling of salt fingers (submarine saline anomalies) and submarine wakes; studies of turbulent flows in compressible media; and application of plasma turbulence concepts to the formation of the earth's bow shock and Type 3 solar flares.

Present Division Programs

A major goal of the Division is to perform experimental studies leading to the understanding of various processes in a hot, dense plasma. The High Temperature Physics Branch carries out the fundamental work in this area, and its principal tool is optical diagnostics. More explicitly, it has pioneered in the use of laser scattering for determining plasma temperature and density, and in the spectroscopic observation of line emissions from various atoms for determining such properties as electron and ion temperatures. Wherever practical, nonoptical techniques are also utilized, such as probes for measuring changes in plasma pressure and in electric fields. However, there are basic difficulties in performing such perturbing diagnostics in the laboratory plasmas (involving densities about 10^{16} particles/cm^3 and temperatures above 100,000 degrees).

In the past, most of the experimental programs involved plasma produced by theta pinches. With a change in requirements, these programs have practically vanished. The current principal interest of the High Temperature Physics Branch centers around a joint laser-matter interaction program involving the Plasma Physics, Nuclear Sciences, and Optical Sciences Divisions. The principal mission of this program is to perform experiments which will enhance our understanding of laser-produced plasmas and of the interaction of electromagnetic waves with matter. This program will provide the scientific community with the necessary foundations to determine the viability of such schemes as laser-induced controlled thermonuclear fusion, as well as the use of lasers for the production of x-rays. The experimental facility in this effort is on a par with the best in the world. It is centered around a 1.06-micron neodymium laser that delivers 100 joules on target with a pulse width of less than 1 nanosecond. The targets are suspended in a 27-port chamber which allows extensive diagnostics, such as measurements of the x-ray and neutron emissions, spontaneously generated magnetic fields, and laser scattering.

A second major experimental effort is centered around the Triton electron beam plasma heating facility. Developments in high-current relativistic electron beams during the past 5 years have made it relatively easy to produce tens of kilojoules in times of the order of 50 nanoseconds. The efficiency of existing facilities in converting stored capacitor bank energy to electron beam energy is of the order of 30 to 50 percent. These beams can be bent, pinched, expanded, and otherwise manipulated to suit the application. A few of these applications include generation of microwaves, excitation of gas lasers, collective acceleration of heavy ions, heating magnetically confined plasmas, and electron-beam-induced fusion of small deutrium pellets (*i.e.*, in much the same way as laser-pellet schemes).

The Triton facility consists of a 1.3-megavolt, 130-kiloampere, electron beam generator firing into a 4-meter long linear theta-pinch plasma. It employs sophisticated diagnostic tools, such as ruby laser scattering, CO_2 laser scattering, spectrographs, x-ray detectors, and probes. The experimental work has been designed to study the detailed dynamic behavior and interaction of the high-current relativistic beam with a preionized, preheated plasma. Its principal objective is to identify and understand the various complex processes which take place. The experimental setup has recently become operational, and initial results have been obtained. An important outcome of this experiment will be a knowledge of the feasibility of using relativistic electron beams for preheating a large volume of plasma to moderate temperatures.

In addition to the Triton experiment, which is unique in its degree of diagnostic sophistication and support, the Sol Experiment, which consists of a 600-kilovolt, 7-ohm electron-beam generator, is used for performing preliminary studies on the interaction of an electron beam with a gas or plasma in different configurations. The simplicity of this experiment allows one to perform experiments with little preparation and to observe interesting gross physical phenomena conveniently.

An electron-beam generator identical to the Sol generator is being used for the generation of microwaves at frequencies of 7.8 GHz and higher. These microwaves are produced by the passage of relativistic high-current electron beams through a rippled magnetic field structure. A recent experiment has led to the observation of maser-like radiation at 7.8 GHz at powers of 20 megawatts for durations of 50 nanoseconds. The wattages thus far achieved may have far-reaching implications in the area of high-power microwave generation.

In the area of electron-beam-induced thermonuclear fusion, experiments are being performed on GAMBLE I and GAMBLE II. In these experiments the high-current electron beams are focused or channeled into very small areas of the order of a few millimeter to submillimeter cross sections.

In a related development, about 2 years ago, initial work at NRL was done in which an exploding wire load (instead of an electron beam) was used on GAMBLE II. The large current produced by GAMBLE II creates a high-temperature, high-density Z-pinch plasma from the wire. When CD_2 wires are used, this plasma is a prolific neutron source. Several other groups have since followed NRL's lead in this field, although the best results are still from GAMBLE II, primarily because of its unique pulse rise-time characteristics.

A third major area of experimental work in the Division is centered around a new concept for the production of a large volume of a hot and dense plasma, at a temperature of 10^7 degrees, a density of 10^{19} particles per cubic centimeter, and volumes of the order of a few liters. This concept is currently one of the most promising approaches to controlled thermonucler fusion. The device being developed to examine this concept is named LINUS.

On the theoretical side, the Division's effort is directed mainly toward complementing experiments and understanding plasma and fluid phenomena in the atmosphere and the ocean. The problems under investigation are highly diverse, embracing controlled thermonuclear fusion, nuclear weapons effects, ionospheric communications, and geophysics. In order to be able to predict or describe such phenomena in a meaningful way, many disciplines have to be made to converse. The principal ones are:

1. Plasma physics, which describes the microscopic behavior of collisionless plasmas in which collective effects dominate the transport characteristics and yield results which may bear no similarity to "classical" results

2. Magnetohydrodynamic and fluid dynamics theory in which the phenomena are described in macroscopic terms
3. Atomic and molecular physics, which is essential for providing a self-consistent picture of the physical environment
4. Numerical techniques, which allow for computational descriptions of complex phenomena.

As the mathematical description of these physical phenomena is usually too complex to be handled analytically, a major part of the effort is concerned with computer solutions, or as they are commonly called, computer experiments. During the last 3 years, the theoretical effort has evolved a methodology which allows individual researchers, or teams, to proceed in parallel towards the solution of a single problem, with each group developing modules which fit into a final computer code that describes the whole phenomenon. Every phase in the development of the model is checked for its physical validity before one proceeds to the next step. This approach has shortened the development time for large-scale codes and has facilitiated improvements to the code even after it became operational. The benefits emerging from such an approach are enormous, as it provides the most efficient way of utilizing the skills of specialized individuals.

The theoretical work can be divided roughly into eight categories or programs: low-altitude nuclear effects (LANE); high-altitude nuclear effects (HANE); ionospheric modeling; laser-plasma interactions; atomic chemistry; electron beams; LINUS; and internal waves in stratified fluids. Of these, ionospheric modeling is supported by ARPA and NAVAIR, LINUS by ONR, internal waves by ARPA, and the others by DNA.

The radiation that destroys incoming missiles also blacks out defensive radar. Hence, both fluid and radiative effects must be correctly treated in the LANE program. The NRL program has successfully achieved this in producing the first 2D LANE code with multiburst capability, the beginning of a series of 2D and 3D codes. The problems of interest concern the physics of turbulent processes at the edges of the "mushroom cloud."

In HANE (until recently the principal program in the Plasma Dynamics Branch), radiation quickly escapes, simplifying part of the problem, but the fluid processes involved in coupling debris and air plasmas are complex. The NRL work has produced TIGHT, an early time 2D code that describes the debris-air coupling in terms of atomic chemistry; and MRHYDE, also 2D, which treats later times when temperatures are lower and the chemistry is primarily molecular. The latter was the first HANE code capable of treating multibursts. A new 2D early time code that combines a description of plasma, radiation, and chemistry effects is being written. It provides roughly an order of magnitude improvement in running time over codes written outside NRL, because of the higher resolution made possible by the flux-corrected transport algorithms developed in the Division.

Theoreticians in the Plasma Dynamics Branch have shown that consideration of anomalous resistivity elicited by plasma effects is critical in an understanding of the coupling problems. Past work, motivated by the coupling problem, has given rise to analytic models of collisionless shocks and plasma turbulence. Ongoing research concerns the basic physics of high-Mach-number flows and shocks needed in calculating debris-air coupling.

The goal of the recently begun ionospheric program is eventually to produce a 3D model of the entire ionosphere, from the D layer (60 to 80 km) out to 1000 kilometers. This will be used to predict the propagation of radio and other wavelengths in the normal ionosphere and in the perturbing presence of nuclear weapons or solar flares. A 1D code already exists for altitudes above 150 kilometers and for middle latitudes. The physics becomes challenging at lower altitudes, in the auroral regions and at the equatorial electrojet. Important theoretical contributions have already been made in understanding the nonthermal features of the aurora, the interaction between barium clouds and their images in the lower ionosphere, and electron deposition in the polar regions.

Laser-plasma interactions (a joint program with the Nuclear Physics and Optical Sciences Divisions) are of concern in the design of high-intensity x-ray devices. A 2D fluid code is running which includes all the atomic and spectroscopic physics needed to describe the behavior of high-Z materials (*e.g.*, Al, W) bombarded by a 50-kilojoule laser. Several theorists are also working on understanding the exploding wire, an alternative source of x-rays.

The chemistry packages in the codes described above supply the ionization/recombination rates of highly stripped ions, an unfamiliar and little-studied state of matter. The chemistry group also tabulates electron impact excitation cross sections for atomic species found in atmospheric and laboratory plasmas, and it studies the physics of charge exchange processes, *e.g.*, proton deposition in the auroral problem.

A strong effort directed at support of the microwave experiments has been rewarded with a theory in excellent agreement with observation. Further studies of the recently observed "maser cyclotron" radiation are under way. Another team is working on a theory of the interactions (observed in numerical simulation work) between a relativistic electron beam and the back current it induces in a plasma.

The theoretical work on LINUS has concentrated on the implosion dynamics and the physics of the various dissipative processes (thermal conduction, compressibility, flux leakage) in a 1D (radial variation only) cylindrical liner. Recent studies have shown that hydrodynamic instabilities of the Rayleigh-Taylor type that tend to disrupt the liner can be suppressed by rotation. Other problems under investigation are the nonlinear stability of the liner, the dynamics of the flying cusp, and end and cusp loss processes. A 2D (r-θ) code is being written.

Studies of internal waves in stratified media provide data related to submarine operations. The physical problems are those involved in predicting the rise and spread (through diffusion) of a turbulent wake which differs from the surrounding ocean in salinity and temperature.

Conclusions

In a fairly short time the Plasma Physics Division has shown that it can deal with many complex and important technical problems at the state-of-the-art of plasma physics. It has simultaneously attracted a large group of young and very capable professionals. The program of the Division will continue to emphasize the solution of major experimental and theoretical problems, particularly in the areas of plasma generation, pulsed electrical power, and computational studies. The work is characterized by close collaboration among the various experimental and theoretical groups inside the Division and with groups outside the Division and outside the Laboratory.

(Continued from Page 21)

A prototype atmospherics analyzer has been in operation at NRL for over two years in a joint effort project with German, Japanese and Argentine scientists to check the efficiency of the technique.

The analyzer performs an analog spectral analysis of received impulses through the use of three sharply tuned amplifiers at frequencies of 5, 7 and 9 kilohertz.

The azimuthal angle of received signals is derived within the analyzer by conventional direction-finding circuitry. Differences between arrival times together with the amplitude ratios of the three signals provide an estimate of distance.

Each result is displayed on a calibrated oscilloscope grid as a dot of light, the height of which represents the azimuthal angle and the horizontal position of which gives an estimate of distance. A time-exposure photograph of the screen shows "clusters" of dots which can be associated with storm regions.

Analysis of the film, says the scientists, has shown that it is possible to locate sea storms by their technique but difficulties arise because of the wide intensity range of impulses and because of overlap between impulse clusters.

Consequently, a system has been added to record the characteristics of individual VLF impulses on magnetic tape. Analyses of these recordings have shown that improved accuracy and resolution are possible. Work is continuing on the project.

On the Naval Research Reserve

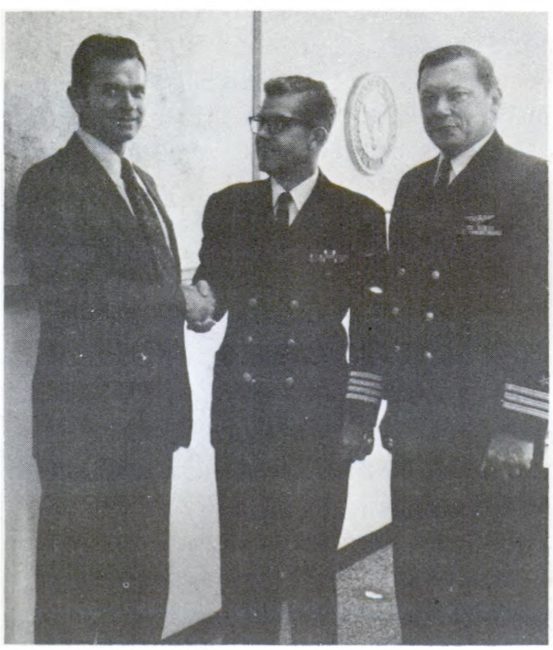
The Metroplex and the World's Largest Airport

Naval Reserve Research Company 8-12, Dallas, Texas hosted a three-day seminar on 17-19 August 1973 at the world's largest airport—the new Dallas-Fort Worth Regional Airport. Thirty-five reservists participated in intensive briefings and presentations about the Metroplex, the airport, the computer controlled baggage and people mover transit systems (AIRTRANS), and SURTRAN, the surface transportation system for the airport. Included in the briefings were the Council of Government's role in supporting the nation's most dynamic Metroplex and details on the Research and Development that went into planning this undertaking.

To top off the multimedia presentations, the officers (representing eight units from Dallas, Fort Worth, Houston, Austin, College Station, and ONR Chicago) boarded SURTRAN buses for a tour of the airport which is larger than Manhattan Island.

The Texas Research Reserve Units regularly schedule three three-day seminars a year to provide some ACDUTRA for those CAT-D officers unable to get two-weeks with pay. The College Station unit sponsors a seminar in January, the Houston unit in May, and Dallas in August.

New Reserve Coordinator



CAPT C. H. Bird, Jr., USN, Assistant Chief for Administration and Research Reserve (center) welcomes the new Research Reserve Coordinator from the Branch Office in Chicago looks on. Mr. Gerdon reported to the Office of Naval Research on 24 September. He is a Commander in the Naval Reserve Research Program and actively participates with NRRC 5-8, Washington, D.C. He and his family reside in Springfield, Virginia.

Research Notes

NRL Scientists Aid FAA in Ocean Surface Studies

Scientists at the Naval Research Laboratory (NRL) have been applying the NRL developed technique of Sea Photo Analysis to assist the Federal Aviation Administration (FAA) in its communication research program.

The FAA is studying multipath effects in communication between satellites and aircraft flying over the ocean.

The techniques of Sea Photo Analysis have been used to obtain the ground truth descriptors of the ocean surface necessary in attempting to correlate multipath effects with the roughness of the scattering surface.

Denzil Stilwell and Roger Pilon, NRL chief investigators, said that Sea Photo Analysis utilizes photographic and laser techniques to obtain the spectrum of the ocean surface. The wave pattern is recorded in an aerial photograph, which is optically transformed into its Fourier components using a laser. The transform is then used to deduce such descriptors as root-mean-square wave height and slope, wind speed and wind direction.

The type of analysis used in this study is generally applicable only to the relatively short wave lengths present in a sea—the roughness generated by the local wind—by the clarity of the earth's atmosphere, the stability of airborne platforms and the photographic process. Therefore, the FAA has been obtaining supplementary data on long wavelength ocean swell through hindcasts by the Naval Oceanographic Office.

Project Hydrox II Men Breathe H_2-O_2 in Navy Test

An experimental series involving a total of 26 manned dry chamber dives has recently been completed by the Research and Development Division of Michel Lecler Inc. as part of a U.S. program to study the effects of breathing hydrogen-oxygen mixtures under pressure. This research was jointly funded by the Office of Naval Research and the Naval Bureau of Medicine and Surgery. Mr. Peter Edel, Director of Research for the Research and Development Division of Michel Lecler Inc. (who was in charge of preliminary experiments with this breathing mixture in Project Hydrox I), is also the principal investigator for this project and was in charge of operations during the experimental dives made in this series.

A team of scientists from the Naval Submarine Medical Research Laboratory at Groton, Connecticut were present for approximately one-third of the tests to work with Mr. Edel to provide data which will aid in the evaluation of hydrogen-oxygen breathing mixtures for possible future use in deep diving operations. The Naval Submarine Medical Research Laboratory's participation in this experimental series included pulmonary studies, biochemical estimates, behavioral scientific observations of performance, speech studies, and the use of a doppler system, which detects the presence of bubbles in the blood stream.

The experiments were conducted at the hyperbaric chamber complex recently completed at Michel Lecler's Research and Development Division in Harvey, Louisiana, which has special control systems specifically designed for safe handling of hydrogen-oxygen mixtures. This system permits the operator to select from up to 17 different gas mixtures from the control console, and allow as many as 4 subjects to breathe different gas mixtures in the chamber simultaneously.

From the standpoint of economy, amount of equipment and personnel required on the job and simplicity of operations, there is no substitute for air. Such a mixture is safe and appropriate for diving operations. Unfortunately, the narcotic properties of nitrogen at elevated pressures make this gas mixture inadvisable for practical dives below 200 feet, and helium-oxygen mixtures are currently being used in routine commercial and military diving operations below this depth. Experimentally, helium-oxygen has been used to a simulated depth of 1,500 FSW (feet sea water) in a dry chamber by the Royal Naval Physiology Laboratory in England, and slightly in excess of 2,000 FSW at the Comex Laboratory in Marseille, France. In addition, the U.S. Navy holds the world record for a simulated dive to 1,600 FSW in a water-filled chamber using the facilities of Taylor Diving Company in Belle Chasse, Louisiana.

However, exposure to very high pressures with helium-oxygen breathing mixtures are characteristically accompanied by impairment due to the high pressure nervous syndrome (HPNS) or "helium tremors." Although reducing the rate of compression and/or the addition of other inerts (such as nitrogen) into the breathing mixture may permit increased depth capabilities, comparison of the effects observed during simulated dives suggests that the practical depth limit for working dives is being rapidly approached, or may have even been exceeded with helium-oxygen mixtures. Even if this problem could be overcome in the future, the breathing resistance of this mixture at extreme pressures would ultimately limit the use of this gas at some, as yet, unattained depth. The lowered density of hydrogen (as compared to helium) would lead one to expect a reduction in breathing resistance, and hence, a greater ultimate depth capability with respect to this problem.

In the past, investigators have been discouraged from working with "hydrox" because of its explosive and flammable properties over a broad range of hydrogen-oxygen ratios. However, work done by the Bureau of Mines and Dorr of Ocean Systems has demonstrated that oxygen percentages as high as 3 or 4 percent in hydrogen are completely safe with respect to flammability and explosive hazards. A mixture of 97%H_2-3%O_2 could be utilized at depths as shallow as 200 FSW (feet sea water) where the oxygen partial pressure in the mixture is mathematically equal to the oxygen partial pressure in the air at sea level.

Although very little data exist with respect to manned exposures with hydrogen-oxygen breathing mixtures under pressure, a vast amount of experience is available with helium-oxygen and nitrogen-oxygen mixtures in manned exposures to elevated pressures. Project Hydrox II took advantage of these existing data to make a comparative study of these three oxygen diluents under identical conditions. Each of the four test subjects made two dives to 200 FSW for 120 minutes on each of the three following breathing mixtures: 97%H_2-3%O_2, 97%He-3%O_2, 97%N_2-3%O_2. In all cases, the decompression tables for these dives were calculated by Mr. Edel to insure uniformity of method. Various tests performed by the volunteer diver-subjects under identical conditions with

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the three above mentioned gas mixtures will serve to provide a basis for evaluating hydrogen-oxygen in comparison with the present standard diving mixtures.

Work on this project is continuing at this time to analyze the data stemming from these experiments. Although it will be several months before this work will be completed and conclusions may be drawn from this experimental series, a preliminary evaluation of the data indicates that the hydrogen mixture moves into the divers' lungs approximately 1-1/2 times faster than the helium mixture and twice as fast as air according to James H. Dougherty of the Naval Submarine Medical Research.

Even though helium-oxygen is much less dense than air at surface pressures, in very deep dives the breathing resistance with He-O_2 mixtures may place severe restrictions upon the useful work which may be performed by the diver. These tentative findings suggest that, as far as breathing resistance alone is concerned, a diver may be able to achieve greater productivity at a given depth with hydrogen-oxygen than with helium-oxygen mixtures currently in use for deep diving operations. Another interpretation from these findings is that a given work output from the diver may be sustained at much higher pressures with hydrogen-oxygen mixtures than with helium-oxygen.

Although a great deal of valuable information is expected to result from Project Hydrox II, more experiments will be required before the potential role of hydrogen-oxygen as a deep diving breathing mixture may be fully assessed. For example, the effects of HPNS are not readily discernible until depths of at least 800 or 1000 feet are reached. Experiments at that level (and beyond) may be required to ascertain whether or not the HPNS or "helium tremors" are likewise produced by hydrogen-oxygen mixtures and, if so, to what magnitude.

It is not expected that hydrogen will "replace" helium as an oxygen diluent for deep diving anymore than helium "replaces" air. However, if Hydrox II and future experiments confirm the mathematical predictions made concerning this breathing mixture, this may provide us with another tool to use in deep diving operations which possibly may enable us to make deeper probes into the hydrosphere, unencumbered by protective shells.

NAVAL RESEARCH REVIEWS publishes highlights of research conducted by Navy laboratories and contractors and describes important Naval experimental facilities. Manuscripts submitted for publication, correspondence concerning prospective articles, and changes of address, should be directed to Code 109, Office of Naval Research, Arlington, Va. 22217. Requests for subscriptions should be directed to the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. Subscription price: $4.50 per year in the U.S. and Canada; $5.65 per year, foreign; $0.45 per individual copy. The issuance of this periodical approved in accordance with Dept. of the Navy publications and printing regulations.

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Cover Caption

Photograph taken from a satellite of the spiral arms of a hurricane over the ocean. See page 1.

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