Buoys as Platforms for Environmental Measurements

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The oceans and their contiguous water areas cover more than 70% of the earth's surface. Yet environmental conditions existing over, on, and under this vast area are sampled on a "hit-or-miss" basis. If the physical processes which govern these environmental conditions are to be properly understood, and if those conditions are to be extrapolated into predictions of future conditions, a system of observational platforms will be essential to measure and telemeter important parameters describing these areas. Buoys provide a feasible and cost-effective platform for pertinent environmental measurements. This paper describes types of buoys which are practical for environmental data gathering purposes, and indicates their capabilities and limitations. As a measure of buoys' relative effectiveness in fulfilling this function, a definitive statement of requirements for environmental data is also included, along with an initial comparative evaluation of each of the required parameters in relation to the composite national needs.

Introduction

THE oceans and their contiguous water areas cover almost three-quarters of the world's surface, but contain essentially none of the world's human population, excepting those hardy few who make their livelihood there or use the waters as a medium of transportation from one land area to another. Because of this vast size, the seas have a substantial influence on the physical environment of the world, both in the long-term and in the immediate view. But, because of their scarcity of inhabitants, environmental conditions are observed or monitored only on a "hit-or-miss" basis—by a few widely separated ocean stations manned by Coast Guard cutters, by a somewhat larger number of transient ships of opportunity, and by a handful of oceanographic ships dedicated to a random sampling of the existing conditions. Such monitoring of so vast an area can provide only agonizingly brief glimpses of this important environment.

Mathematical models of the world's environment now exist with sufficient accuracy and detail to represent existing conditions and to extrapolate to future conditions. These models are severely limited in accuracy and extent of extrapolation because of the lack of complete understanding of marine environmental physical processes, and because of the lack of "raw data pictures" of the environment from which extrapolations can be made. In other words, environmental understanding and prediction are information limited. There is not a sufficiently dense pattern of environmental observations over the oceans and contiguous water areas to provide an adequate knowledge of the initial state of the dynamic variables in order to be able to treat the prediction problem as a fluid dynamics problem, nor are there adequate time-series measurements at individual points for the adequate use of statistical capabilities. Here, as in other facets of life, there is truly an information gap.

This deficiency has been recognized for a number of years, among oceanographers as well as atmospheric scientists. As part of their quests for suitable marine observational systems, many federal agencies and academic groups have attempted development of automatic buoys as data sensing platforms. In general, these various individual programs have each concentrated on specific items of interest to the sponsors, have been inadequately funded, and have lacked a "total system" approach by concentrating largely on the buoy and sensing hardware and ignoring the important aspects of servicing and maintenance necessary to continue that hardware in long-term use. In 1966, the Ocean Engineering Panel of the Interagency Committee on Oceanography (ICO) recognized that the development, deployment, and operation of consolidated national, rather than individual agency, data buoy systems held considerable potential for the national interests, and requested that the United States Coast Guard manage an interagency-funded study to determine if national data buoy systems were feasible. In response to this request, the Coast Guard selected through competitive procedures, The Travelers Research Center Inc., Hartford, Conn., for a ten-month study of this concept. This feasibility study was completed in October 1967, and documented these important findings[1]: 1) significant national requirements exist for environmental information from the marine areas; 2) networks of automatic, unmanned buoys are feasible for acquisition of a majority of this required information; 3) compared with other feasible methods of acquiring this information, automatic buoys represent the most cost-effective approach to this capability†; 4) the national benefits derivable from buoy observation networks are estimated at several times the cost of providing that capability; 5) a representative system development plan could lead to deployment of networks of automatic data buoys in about seven years. Figure 1 illustrates the general concept on which this approach was based.

The President's National Council for Marine Resources and Engineering Development, established by the Marine Resources and Engineering Development Act of 1966 and commonly referred to as the Marine Sciences Council, accepted the findings of The Travelers Research Center feasibility study as justification for beginning the research, development, testing, and evaluation of National Data Buoy Systems, and designated the Coast Guard to act as the lead agency in this effort. In response to this designation, in January 1968, the Coast Guard established the National Data Buoy Development Project Office in Coast Guard Headquarters, Washington, to undertake this ambitious new program.

Presented as Paper 69-155 at the AIAA 7th Aerospace Sciences Meeting, New York, N.Y., January 20–22, 1969; submitted January 29, 1969; revision received April 16, 1969. The opinions or assertions contained herein are the private ones of the author and are not to be construed as official or reflecting the views of the Commandant or the Coast Guard at large.

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† As noted later in this paper, a "mix" of automatic buoys and other types of observational platforms may ultimately provide the best approach.

National Data Buoy Systems

National Data Buoy Systems are networks of data buoys to measure those oceanographic and meteorological parameters which are required in the national interests. They include those networks which can best be operated by a single agency for the composite national benefit. They are referred to as systems because they must include all of the components—buoys, sensors, servicing ships, bases, data processing centers, communication nets, and trained personnel—necessary to maintain continuous and reliable data acquisition. The plural "systems" is intentionally used to indicate that different types of hardware may be necessary to satisfy the needs identified for the deep oceans, the continental shelf areas, the estuaries and Great Lakes, and the Arctic—all areas in which significant needs exist for environmental information.

The Coast Guard National Data Buoy Development Project Office is proceeding with the preliminary planning which will lead to a national capability to deploy National Data Buoy Systems. At the present time, the tentative approach envisions a three-pronged plan of action. First, a thorough assessment of the existing state-of-the-art in buoy and sensor technology is required. Although a number of different types of automatic buoys have been designed, and some even deployed, and a variety of types of oceanographic and meteorological sensors have been used on those buoys, no reliable information is truly available regarding the long-term performance of these components. Generally, if the buoy and sensors function for at least a short period and some scientific data are acquired, the operation is considered a success and longer-term experience or failure analyses are seldom if ever considered. Thus, very little engineering data are available on buoys and buoy-mounted sensors. The second prong will design and develop a limited prototype network of data buoys, probably consisting of 35 buoys and their required communications links. This phase of the plan must identify clearly the requirements which deep ocean and near shore data buoys must satisfy, i.e., specify clearly just which parameters are to be measured, over what range, with what accuracy, with what temporal and spatial sampling intensity, and how often. With this information as the performance specification, and a knowledge of current buoy technology, a "proof-of-principle" prototype network can be designed and deployed. At the same time, a third program of exploratory and advanced development will be sponsored to further buoy and sensor technology where deficiencies exist or become identified. In this way, important parameters for which no measurement capability now exists, or for which automatic measurement on buoys is not now possible, can have suitable sensors developed or adapted. The results of these three lines of attack will produce final designs and components which could lead to wide deployment of data buoy networks beginning about 1978.

I have purposely failed to mention or describe many of the important aspects of National Data Buoy Systems development in order to proceed more quickly to the subject of this paper. Obviously, there are many problems associated with the development of a capability to maintain automatic buoys in the hostile environment of the deep ocean on a year-round basis. Beyond the development of reliable hardware components, of adequate ships to handle and service such buoys, of proper laboratory facilities for calibration of large numbers of sensors, and of data handling equipment to process the masses of data which will be involved, there exist many nonengineering problems regarding the legal status of data buoys, the international role of such things in the world's oceans, and the ability of the national economy to fund an extensive deployment of these items. There are many more problems than answers at this early stage of the development cycle, and each could provide the basis for a separate paper. Suffice it to say that such problems are recognized, and are being addressed by the Coast Guard project office as its work proceeds.

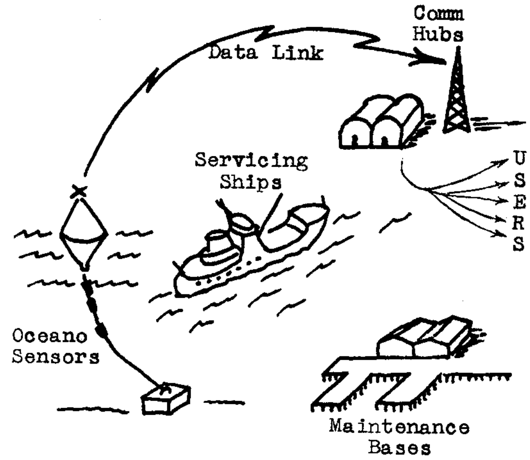

Fig. 1 Conceptual operational diagram national data buoy systems.

Environmental Data Requirements

One important product of the project work thus far has been the identification and statement of the composite national needs for environmental information in the marine areas. In its initial feasibility study, The Travelers Research Center determined the total national needs through an extensive series of questionnaires and interviews with experts in those government agencies which deal in some way with the marine environment, and with those in academic institutions working on government-sponsored, marine-oriented programs. In all, 97 agencies and academic institutions were questioned regarding their needs. This study documented 113 different things which were required to be measured in the deep oceans, on the continental shelfs, or in the estuaries and Great Lakes. Many of these environmental parameters were required on a scheduled, synoptic basis, for real-time use in predicting future conditions. Additional parameters were specified on a one-time or occasional basis, for research purposes. But all were considered necessary for basic understanding of the marine environment, and/or for present operational knowledge and future prediction.

This initial listing by TRC was only an idealized shopping list of environmental goodies to establish the fact that a composite need did exist for marine environmental information, and to gauge the potential extent of that need. The initial listing was also clearly recognized as being impractical, since a great deal of redundancy existed in it—parameters which are basically the same physical characteristic were called by different names by different people (transmissivity, clarity, and visibility, or sea state, roughness, wave spectrum, and swell spectrum). An immediate reduction was thereby possible, so that 69 more-or-less basic variables were identified. These formed the basis for the initial statement of system capability—the Tentative Operational Requirement in military parlance. One of the first steps taken by the Coast Guard project office was to substantiate more carefully this statement of requirements—to cycle back through the investigation process in order to harden the stated needs and to justify these needs on a basis more substantial than "it would be nice to have." The results of this analysis are displayed in Table 1, indicating the basic variables for which needs exist. In Table 1, each variable is described in terms of its usual units of measurement, range of values to be expected in the marine environment, accuracy with which each measurement is required, vertical layer in which it exists, and whether it is an operational or research requirement or both. For this description of requirements, the marine environment was classified

Table 1 Requirements for marine environmental information

Variable	Range and accuracy	Layers[a]	Use[b]
Air temperature	−80°–60° C ± 0.1° C	1,2,3	O,R
Atmospheric electricity	(Kv)	2,3	O
Atmospheric pressure	10–1100 mb ± 0.1 mb	1,2,3	O,R
Cloud base height	±100 ft	2	O
Cloud top height	±100 ft	1,2	O
Cloud type	(code)	1,2	R
Total cloud amount	0%–100% ± 10%	1,2	O,R
Cosmic radiation	···	1	O
Dew point	−80°–40° C ± 0.2° C	1,2,3	O,R
Ice crystal size	···	2,3	O
Ozone	···	1,2	O
Visibility	(naut miles)	3	O,R
Wind vector	0°–360° ± 2° 0–160 kts ± 0.5 kts	1,2,3	O,R
Gravity	0.95–1 × 10^6 mgal ± 2 mgal	3	O,R
Ice accumulation	(in. hr)	3	R
Ice breakup	···	3	R
Infrared surface radiation	0–2 ly/min ± 2%	3	R
Magnetic field declination	0°–180° ± 0.1°	3	O,R
Magnetic field inclination	0°–180° ± 0.1°	3	O,R
Magnetic field intensity	10^4–10^5 gamma ± 1 gamma	3	O,R
Precipitation rate	0–12 in./hr ± 0.01 in./hr	3	O,R
Insolation	0–2 ly/min ± 1%	3	O,R
Total radiation outward	0–2 ly/min ± 1%	3	R
Water level	−8–13 ft ± 0.2 ft	3	R
Wave direction	0–360° ± 5°	4	O,R
Wave height	0–100 ft ± 0.2 ft	4	O,R
Wave period	1–120 sec ± 1 sec	4	O,R
Ambient light	0–2 ly/min ± 1%	4,5	O,R
Ambient noise	−80–−20 db ± 3 db	4,5	O

Variable	Range and accuracy	Layers[a]	Use[b]
Carbon dioxide	1–12 × 10^{-4} atm ± 3%	4,5,6,7	R
Chlorophyl	(μg/lt)	4,5	R
Salinity	0–43 ppt ± 0.01 ppt	4,5,6,7	O,R
Current vector	0°–360° ± 1° 0–10 kts ± 0.03 kts	4,5,6,7	O,R
EH	(v)	7	R
Flux heat	···	4,5,6,7	R
Flux mass	···	4,5,6,7	R
Flux momentum	···	4,5,6,7	R
Inclination	0°–90° ± 1°	4	R
Nitrates	(mgal/liter)	4,5	R
Nutrients	···	4,5	O,R
Dissolved oxygen	0.5–9 mliter/liter ± 0.1 mliter/liter	4,5,6,7	R
pH	1–13 ± 0.2	4,5,6,7	R
Phosphates	(mgal/liter)	4,5,7	R
Tidal fluctuation	0–60 ft ± 0.01 ft	4	O,R
Plankton	···	4,5,7	R
Propagation loss	(db/kyd)	4,5	O
Silicates	···	4,5,6,7	R
Sound speed	4500–5800 fps ± 1 fps	4,5,6,7	O,R
Transparency	0–70%/m ± 2%	4,5	O,R
Turbidity	1–1000 pt/ml ± 1 pt/ml	4,5,6,7	R
Vertical current	···	4,5,6	R
Water pressure	0–10,000 psi ± ¼%	4,5,6,7	O,R
Water temperature	−5°–40° C ± 0.01° C	4,5,6,7	O,R
Biological growth	···	4,5,7	R
Bathymetry	16–36,000 ft ± 6 ft	7	O,R
Bottom photography	···	7	O
Bottom cores	···	7	O,R
Sediment deposit	±0.5 ft	7	O,R
Sediment load	···	7	R
Sediment movement	···	7	R
Sediment rate	···	7	R

[a] Vertical layers in which variable is required: layers 1—10,000- to 30,000-m altitude; 2—15- to 10,000-m altitude; 3—water surface to 15-m altitude; 4—water surface to 10-m depth; 5—10- to 500-m depth; 6—500-m depth to bottom; 7—bottom.
[b] Operational (O) or research (R) use of variable.

into seven vertical layers for convenience and separate analysis. These vertical layers are: 1) upper air, from 30,000 m down to 10,000-m altitude; 2) upper air, from 10,000 m down to 15 m above the air-sea interface (arbitrarily selected as representative of the top of a buoy mast); 3) surface, from 15 m above the sea-air interface down to the interface; 4) surface, from the air-sea interface down to 10-m depth (arbitrarily selected as representing the bottom of a buoy hull, or the lowest level at which a sensor might be attached directly to a buoy hull); 5) thermocline, from 10-m depth down to 500-m depth (taken as representative of the lower limit of the permanent thermocline); 6) lower ocean, from 500-m depth down to the bottom; 7) the bottom.

Table 1 displays the vertical layers in which each of the basic variables exist. This over-all listing of information represents the most comprehensive, accurate statement of marine environmental requirements known to exist today. It contains 61 basic variables for which either operational or research (or both) requirements exist in the marine environment.

Relative Value of Parameters

The classification of the required environmental variables into vertical layers was accomplished for several reasons. First, of course, the method of sensing and relaying measurements from the different layers may be different. Measurement of a temperature in the two surface layers may be retrieved from probes mounted directly on a buoy body, for example, while temperature measurements from layers above or below the surface layers must be obtained from probes separate from a buoy, and relayed back to the buoy by some means. A second intent was to assist in relating the comparative worth of the various measurements at different levels. Thus, is a temperature measurement in the upper air (layer 1, for example) as important a piece of information as an air temperature measurement within 15 m of the sea surface? The cost in achieving these two measurements will certainly not be the same!

In order to determine the comparative value of the many required variables, the Coast Guard project office devised a process of expert judgment as an aid in determining the most cost-effective system capability level. Four government agencies were selected as representative of the four primary areas of benefit from marine environmental information—the United States Navy (National Security), the Environmental Sciences Services Administration (over-all knowledge of the environment), the Bureau of Commercial Fisheries (living resources in the waters), and the operational Coast Guard (maritime commerce and transportation safety). Each agency was asked to evaluate each of the required variables in each appropriate vertical layer, and further, to evaluate each vertical layer in relation to the missions for which that agency is responsible. Table 2 indicates the criteria which these agencies were asked to use. Thus, a basic variable which an agency considered to be essential to the performance of that agency's missions was evaluated as "5." Minor gradations in this evaluation were permitted by also assigning a "4" to this category. A comparative evaluation score for each variable was then obtained by multiplying the rating of that variable by the evaluation of the layer in which it is located, and summing the scores thus obtained for all four agencies. The evaluation scores thus ranged conveniently from 0 to 100, with 0 indicating that no agency considered that variable in that layer as desirable, and 100 indicated that all four agencies rated that variable as a "must" parameter in a "must" layer. The results of this evaluation procedure are displayed in Table 3 for the operational variables. Those variables which are presently judged to be capable of measurement from an automatic buoy are also indicated for reference purposes.

The information presented in Tables 1 and 3 appears to be unique in the field of environmental sciences. Here are presented a composite listing of those fundamental items of interest to meteorologists and oceanographers dealing with the marine environment, along with an expert judgment of their relative worth for national beneficial use. The exact values, units, and scores shown here are, of course, open to wide review and controversy, and criticism. The mere fact that the Coast Guard project office has been willing to make and advertise such a listing is, in itself, a major step in advancing the state-of-the-art in the marine environment. Constructive criticism of these listings is welcome, and solicited, since these factors will be used as one of several bases for system design of a marine environmental observation system.

Observational Platforms

The subject of this paper deals with the capability of buoys for environmental observation, and thus far, this approach to data acquisition has been referred to almost exclusively. Of course, there are other means of measuring most, if not all, of the variables which are required from the marine environment. Orbiting and stationary satellites, horizontal sounding balloons, ships of opportunity, aircraft, submersibles, and oceanographic ships are all capable of providing this same information to a greater or lesser extent than buoys. In the final analysis, it is highly probable that the most effective over-all observational system will include a "mix" of these various platforms. The Coast Guard project office recognizes this mix of capabilities, and is including this probability in the present planning. One man's system is usually another man's subsystem! But, to date, all studies and analyses of the concept have indicated that networks of automatic, unmanned buoys will certainly be a part of this over-all mix of observing platforms, and that development of that capability is justified as soon as practicable. Development of buoy systems is the task undertaken by the Coast Guard.

Buoys as Observational Platforms

"Buoy" is a rather ill-defined word, insofar as dictionaries are concerned. A home dictionary defines it merely as a float, especially in connection with an aid to navigation. And, indeed, buoys have had a long history as aids to maritime navigation.[2] The Coast Guard alone maintains approximately 23,000 NAVAID buoys at the present time, ranging from rather simple, river-type channel markers to more sophisticated, lighted sound buoys off shore.

Table 2 Criteria for estimating relative values of variables and layers

Value	Criterion
5,4[a]	Must have to satisfy agency missions
3,2[a]	Important to satisfy agency missions
1	Useful to satisfy agency missions
0	Of no value to satisfy agency missions

[a] Two values assigned to permit indication of minor gradations in value.

Table 3 Relative values of required operational variables

Layer 1:	
Air temperature	36
Atmospheric pressure	43
Cosmic radiation	18
Cloud top height	35
Total cloud amount	37
Dew point	36
Ozone content	28
Wind vector	33
	266
Layer 2:	
[a] Air temperature	49
Atmospheric electricity	5
[a] Atmospheric pressure	59
Cloud base height	53
Cloud top height	43
Total cloud amount	61
[a] Dew point	46
Ozone content	10
[a] Wind vector	45
	371
Layer 3:	
[a]Air temperature	83
[a]Atmospheric electricity	10
[a]Atmospheric pressure	81
[a]Dew point	76
[a]Visibility	52
[a]Wind vector	83
Gravity	45
Mag. field declin.	40
Mag. field inclin.	40
Mag. field intensity	40
[a]Precipitation rate	59
[a]Insolation	61
	670
Layer 7:	
[a]Salinity	41
[a]Current vector	39
[a]Sound speed	17
[a]Water pressure	51
[a]Water temperature	45
[b]Bathymetry	38
[b]Bottom photos	11
[b]Bottom cores	38
[b]Sediment deposit	22
	302
Layer 4:	
[a]Wave direction	80
[a]Wave height	80
[a]Wave period	80
[a]Ambient light	30
[a]Ambient noise	25
[a]Salinity	100
[a]Current vector	95
Nutrients	30
Tidal fluctuation	55
Propagation loss	15
[a]Sound speed	50
[a]Transparency	50
[a]Water pressure	95
[a]Water temperature	100
	885
Layer 5:	
[a]Ambient light	30
[a]Ambient noise	25
[a]Salinity	100
[a]Current vector	85
Nutrients	30
Propagation loss	15
[a]Sound speed	40
[a]Transparency	55
[a]Water pressure	95
[a]Water temperature	100
	575
Layer 6:	
[a]Salinity	45
[a]Current vector	36
[a]Sound speed	29
[a]Water pressure	51
[a]Water temperature	49
	210

[a] Anticipated as measurable from automatic ocean data buoys.
[b] Anticipated as measurable from servicing ships tending buoys: total relative value of all variables, 3279; total relative value of atmospheric variables, 1307 (39.9%); total relative value of oceanographic variables, 1972 (60.1%); total relative value of all variables measurable from data buoy and servicing ships, 2431 (74.3%).

Thus, automatic buoys are by no means new; only the application to environmental data acquisition is relatively new. The initial TRC feasibility study, which formed the basis for the present Coast Guard effort to develop ocean data buoys, identified 50 different buoy developments which had been at least partially undertaken by government or academic groups for data acquisition purposes.

Buoy design may be classified into three types for convenience and over-all discussion—stable buoys, surface-following buoys, and a general grouping of intermediate designs which fit neither of the first two descriptions completely. A stable buoy is one which remains essentially motionless in the presence of wave and wind forces imposed by nature and is generally of the long, thin "spar" shape. The classic example of this type of buoyant platform is the FLIP (Floating Instrumented Platform) developed by the Office of Naval Research and the Scripps Institution of Oceanography. This buoy is 355 ft in over-all length, with 300 ft normally submerged, weighs 600 tons, and includes laboratory and hotel spaces for five people. Because of the relatively small area of this buoy at the waterplane, ($12\frac{1}{2}$ ft in diameter) and its relatively large mass, this buoy experiences about four centimeters of vertical movement, and 0.2° of roll in 4- to 5-ft waves, providing a highly stable platform for a variety of observations.[3] A second, similar approach to a stable buoy is the seastation proposed by the British Seastation Telecommunications Ltd. This spar buoy is designed to be 455 ft in length, with a crew of 16, and a helicopter landing pad for refurbishment purposes.

Stable spar buoys do not have to be as large as these two examples. As a matter of fact, many older NAVAID buoys were actually wooden logs, 30–60 ft in length and 1–2 ft in diameter, weighted and anchored from one end to float upright as a navigational marker. Each of these buoys has a period of resonance for vertical motion (heave) and for roll and pitch. Very large spar buoys, such as the FLIP and the British Seastation noted above, have long periods of resonance—long in relation to the natural periods of the waves to which they are exposed. Smaller spar buoys will normally have resonant periods of heave or roll, or both, which fall within the periods of natural wave spectrum of forcing functions, from approximately three to 25 sec/cycle. Thus, in certain natural wave conditions smaller spars may exhibit resonant motion, and become decidely unstable platforms. Various means to damp these undesirable motions have been attempted on several types of smaller spar buoys, but the best solution is large size.

A surface-following buoy is essentially the opposite of the stable spar design—a large waterplane area with a shallow draft. Under contract with the Office of Naval Research, the Convair Division of General Dynamics has developed the 40-ft discus buoy as an automatic deep ocean data platform.[4] A Coast Guard version of this has been in use as an aid to navigation, replacing a lightship off Sandy Hook, N.J. since June 1967. This buoy measures 40 ft in diameter at the waterline, is $7\frac{1}{2}$ ft thick in the buoyancy body, and displaces 100 tons when ballasted properly for deep ocean deployment. In this version, a 3-ft diameter superstructure provides a visual reference, supports visual, audible and radio NAVAIDS, and provides access to the buoy interior. The 40-ft discus design was developed to meet severe design criteria—survivability in 150-knot winds, 60-ft waves, 10-knot current, all acting together with a 5-in. coating of ice on the superstructure. To date, two ocean data buoys, in addition to the lightship replacement buoy, have been fabricated; and one withstood the full brunt of Hurricane Betsy in 1967 off Florida without damage or significant failure. Smaller versions of this discus-hull form have also been designed and fabricated.

As its generalized name implies, surface-following buoys tend to ride on the surface of the water, and conform to the wave contours imposed on them—much as a cork bobbing in a basin of water. Obviously, with a buoy of the size of the 40-ft discus, small waves (waves smaller than the diameter of the buoy) will have little effect on the buoy's motion. For long waves, however, this type of design will conform to the slope of passing waves—at least in theory—and provide an analog of the wave surface.

A third classification of buoys includes those designs falling between the two extremes of spar and surface-following types. A typical example of this intermediate category is the NOMAD buoy, developed over the past 20 years by the U.S. Navy and the Weather Bureau.[5] This boat-hull shaped buoy is approximately 10 × 20 ft in horizontal dimensions, and approximately 9 ft deep. As with the other types of buoys, meteorological sensors are mounted on superstructure portions of the NOMAD buoy, while subsurface sensors are attached to the mooring line beneath the buoy.

Thus, there are many types of buoys and buoy designs which have been developed. Each has specific advantages for ocean use, and most have specific disadvantages for continued use at sea. The most common disadvantage is the lack of proper servicability; most are extremely difficult to handle and refurbish at sea. In any network of automatic data buoys required to be in continuous use on a year-round basis, the maintenance procedure becomes quite important. Within several years of operation, the operating and maintenance costs soon outweigh the initial development and procurement costs. Hence, careful attention to servicability in the initial design will provide important cost savings in the over-all life cycle of the system. In addition, as the Coast Guard has amply experienced in the operation of its NAVAID buoys, simple and quick installation and repair procedures are essential for reliable long-term performance—all components must be as "sailor-proof" as possible. Once again, careful attention in the initial design will pay off handsomely in the long run.

Meterological Sensors for Buoy Use

Typically, atmospheric sensors for use on buoys are adaptions of similar sensors used at shore observation stations. After all, there is little need to "reinvent the wheel" when temperature, pressure, and wind vector instruments have already been in widespread use ashore. In several cases, however, measurements must be made by automatic mechanical sensors on buoys when such measurements are made by human observers or by devices requiring periodic human adjustment ashore. In these instances, specialized sensors have been developed or will be required for buoy mounting.

Where possible, of course, atmospheric measurements will be made by sensors mounted directly on the buoy body or antenna mast, and these values can be relayed directly to encoding and telemetry components by hardwire connections. Many atmospheric measurements are required at altitudes above the top of the buoy superstructure—those measurements commonly made by human observation or by RAWINSONDEs ashore. A comparable means of upper-air observation must be achieved for automatic use from buoys.

Three general approaches to upper-air measurements from automatic data buoys seem feasible: balloon-supported radiosondes with relative position-fixing capability; rocket-deployed parachute-suspended radiosondes with relative position-fixing capability; remote-sensing infrared and microwave instruments mounted on the buoys. Automatic devices for inflating and releasing weather balloons do not appear feasible at the present time, although the use of smaller 100-mg balloons may change this opinion in the future. The use of rockets to deploy parachute-mounted radiosondes is entirely feasible on an automatic basis. This capability has been demonstrated from automatic buoys, using production military rockets (2.75-in. diam) capable of achieving altitudes of approximately 22,500 ft. The addition of a LORAN-C or OMEGA receiver to determine relative position changes during descent has also been shown to be feasible. In this manner, temperature, pressure, relative humidity, and wind vector profiles within the lower 20,000 ft of altitude are feasible for automatic measurement.

Considerable interest and effort has also been placed on the development of remote infrared and microwave sensing of surface and atmospheric variables from aircraft and satellites. Reversing these devices to look upward, rather than at the earth's surface, may be feasible, both using passive and active devices; and these techniques may be adaptable to automatic buoy use.

Very briefly, the following sections review potential approaches to measurement of operational atmospheric variables by sensors mounted on automatic buoys, along with some of the problems associated with each of these approaches. These operational variables are discussed in the order that they are listed in Table 1.

1) Air temperature measurements present no particular problem in the surface layer. A platinum resistance probe appears to be the most practical type presently available, and measurements at 5, 10, and 15 m above the air-sea interface should provide sufficient information. These probes need to be mounted somewhat away from the buoy body to minimize the buoy's effect on the measurements. For upper-air temperatures, the typical radiosonde represents the best available measurement. Further solid-state miniaturization of the radiosonde with some increase in accuracy and telemetry capability are probable.

2) Atmospheric electricity measurement requires determination of the voltage developed between a point in the air above the air-sea interface and the water's surface. The normal potential gradient in fair weather is on the order of 100 v/m of height. This value may increase to 10,000 v/m with the approach of a thunderstorm. It is expected that a probe mounted at a standard height on the buoy mast will be required, with a high-impedance voltage-measuring circuit to measure the potential to ground (the water). No means of measuring this parameter above the buoy's mast is presently known.

3) Atmospheric pressure measurement can be obtained in the surface layer by a precision aneroid or diaphragm barometer. Measurement at only one level within the surface layer is expected. Above the surface layer, the standard radiosonde measurement is available, with improved accuracy of measurement and telemetry.

4) Cloud base height does not appear practicable from an automatic buoy within the present state-of-the-art. An optical ceilometer, using visible light, laser beam, or microwave beam may be feasible.

5) Cloud top height does not appear practicable from an automatic buoy, within the foreseeable future. This parameter is better measured by meteorological satellites.

6) Total cloud amount could conceivably be achieved by averaging the percentage of time a cloud base height detector indicated the presence of clouds directly overhead, over periods of several hours. At the present time, this is not considered a satisfactory substitute for the usual human subjective measurement of cloud cover in tenths. This parameter is far better measured from meteorological satellites.

7) Cosmic radiation measurement requires the detection and counting of ionized atomic nuclei, possibly using a scintillation or Geiger-Muller counter. Such instruments have been used in satellites; but, to date, have not been adapted for automatic buoy use. While the technology presently exists, there are no current state-of-the-art sensors for cosmic radiation measurement from buoys.

8) Dew point measurements currently used on ocean data buoys require the detection of dew formed on cooled surfaces by optical methods. Direct measurement of the surface temperature at which dew is first formed provides the required information. A major problem on automatic buoys involves the continued cleanliness of the cooled surface, especially in the presence of salt-laden air, since salt deposits will quickly destroy the sensitivity of this procedure. Dew point measurements at heights of 5, 10, and 15 m above the air-sea interface are feasible. Dew point measurements, in the form of relative humidity measurements, are achievable above the buoy body by radiosondes.

9) Ice crystal size measurement has been stated as an operational requirement, but no known automatic method of measurement exists; and, in fact, no common approach to measurement or unit of measurement is presently accepted.

10) Ozone measurement requires the detection and quantification of the triatomic form of oxygen, concentrated principally around 25,000-m altitude. Its measurement can be used to trace horizontal and vertical air motions at various heights. No currently available detector is known for automatic buoy use, although a remote ultraviolet sensor may be feasible. Measurement of ozone from meteorological satellites may be more practical.

11) Horizontal visibility in the surface atmospheric layer may be measured by back-scatter detectors using visible light pulses. It appears quite feasible to utilize the navigational light on an ocean data buoy for the light source, measuring the magnitude of the pulses returned from particles and droplets suspended in the air surrounding the buoy. Although this principle normally samples the return from within 50 m of the detector, it will provide the equivalent meteorological range of visibility.

12) Wind vector measurement can be achieved in the surface layer through use of conventional rotating cup or propeller anemometers, or by hot wire, acoustic, or drag force devices. The primary difficulty exists in measuring wind direction, since the buoy orientation is not fixed. Thus, a compass—usually magnetic but conceivably a gyro type—must be added to determine the buoy orientation. Two sources of direction error are thus involved. Wind vector measurements above the surface layer may be obtained by measuring the relative location of a radiosonde, rising or falling near an automatic buoy. The radiosonde will be equipped with a LORAN-C or OMEGA receiver in the radiosonde package and will relay the measurement to the buoy. Although absolute positioning accuracy of these electronic navaids are not sufficient for this purpose, the relative accuracy can provide $\pm 2°$ in azimuth and 2 knots in speed.

13) Gravity measurements from an automatic buoy do not appear feasible, unless an extremely stable buoy could be developed. Current state-of-the-art meters are large in volume and weight, and achieving the required degree of accuracy appears highly unlikely.

14) Magnetic field declination is the angular difference between the horizontal component of the earth's magnetic field and true north at definite points on the earth's surface. Although it is quite possible to mount both a true-north-seeking gyro compass and a magnetic compass on an automatic buoy, and measure the difference between the two indications, it is doubtful that the required 0.1° accuracy can be obtained. Accuracies of $\pm 2°$ appear feasible, but these accuracies are not scientifically meaningful.

15) Magnetic field inclination requires measurement of the vertical angle between the total magnetic field vector and the horizontal component at the earth's surface. This parameter does not appear feasible from an automatic buoy, unless a highly stable design can be achieved.

16) Magnetic field intensity measurements do not appear feasible in an automatic buoy, because of buoy movement and the induced field of the buoy body itself. Here, again, the high degree of accuracy required for this measurement apparently precludes automatic buoy measurement.

17) Precipitation rate measurements can be obtained by periodic measurement of the height of liquid accumulated in a rain gauge. This approach requires all precipitation to be in liquid form, so that snow or freezing rain will have to be melted. Location of the rain gauge funnel will have to be at least 15 m above the surface to prevent the entry of spray. Analyses of rain samples collected on automatic buoys from this height have indicated no significant salt content.

18) Insolation measurements are feasible from automatic buoys, using conventional pyroheliometers or photo-sensitive devices, although the required accuracy of $\pm 1\%$ appears beyond the present state-of-the-art. As in the case of other optically-sensitive surfaces, contamination presents a significant problem for long periods of unattended operation. Salt spray, dust, and bird guano affect the long-term sensitivity and accuracy of these devices.

The above brief discussions of those operational atmospheric variables required to be measured in the marine environment were made in the over-all context of automatic (or unmanned) buoys only. If buoys were sufficiently large to contain and sustain a crew, many of the measurements which are unfeasible from an automatic buoy could be achieved from a manned buoy. Manned buoys, such as the FLIP and the British sea-station, are entirely feasible. They are also quite costly to operate, when the servicing ships, rotational crews, and frequent replenishment are considered. Unmanned buoys, probably in conjunction with satellites which provide complementary measurements and relay telemetry, provide a far more cost-effective observational system than comparable networks of manned buoys.

Limitations of Buoys as Atmospheric Observation Platforms

By their very presence in remote locations over the earth's surface, buoys will provide valuable observational platforms for atmospheric variables as well as the more obvious oceanographic variables. But buoys also possess some inherent limitations regarding their use as observational platforms. They are, by no means, the ultimate and sole answer to the present information gap over the ocean areas of the world. First, buoys represent discrete points of measurement information, spread over extensive areas otherwise devoid of observational data. This grid of such measurement points imposes certain filters on the phenomena which can be measured and described—spatial and temporal filters which will limit the detail of cyclic variations which can be detected. For example, assuming simultaneous measurements from a grid of buoys separated by 500 miles in the deep ocean areas, phenomena with wave-lengths less than 1000 miles will probably not be well defined. Periodic measurements in time will similarly limit the periods of cyclic phenomena which can be identified. This characteristic is not unique to buoys, of course, for it is present in any grid of discrete observing points. Buoys present a problem in this regard only because of their relatively large cost of operation.

Because buoys are floating objects, they impose problems of platform motion which are not typically encountered with observations ashore. Buoy motion can create noise to mask out certain bands of frequencies or wave numbers of atmospheric variables by making difficult the resolution of any phenomena falling within these bands of motion noise. This noise may be imposed both by the physical rolling and heaving motions of the buoy itself, created by wave actions encountered by the buoy, and by the lateral motion of the buoy within the "watch circle" constrained by its mooring line. Among atmospheric variables, this effect is most pronounced for wind vector measurements in the surface layer, although the accuracies of other variable measurements are also somewhat limited.

The design of buoy hull selected for an observation platform also has an effect on atmospheric measurements. The stable spar will have the least platform motion, imposing the least motion noise on wind vector and other sensors. However, because the spar shape remains relatively motionless, the heights of those sensors mounted on the buoy superstructure change constantly as waves rise and fall on the buoy. Thus, for example, a temperature sensor mounted 5 m above the buoy waterline will be periodically submerged by waves of 5 m or more in height. Proper averaging over long observation periods, or long sensor time constants, can compensate for this factor. If accurate location of variable measurements relative to the water surface is important, the stable spar platform is a poor choice. On the other hand, the surface-following hull design will maintain sensor heights relative to wave surface, but imposes significant roll and heave motion as the buoy follows passing wave contours. Thus, intelligent choice of hull design can often compensate for buoy motion limitations and be matched to the measurement requirements. The dynamics of the buoy platforms must be considered in system design.

Conclusion

Buoys provide valuable platforms for atmospheric and oceanographic observations in the marine environment. Significant requirements exist for information from ocean areas, and no systems presently are available to provide this information on a continuous and reliable basis. Hence, the early development of this capability is justified. The Coast Guard has undertaken the lead role in this development effort.

Buoys are capable of most required surface observations, but possess limited capability in the upper-air region. Extending this capability upward through the use of rocket-deployed RADIOSONDEs, or through the use of infrared or microwave remote sensors appears feasible. A total system approach to data buoy development is necessary, both to insure that adequate support and maintenance facilities are provided along with the basic buoys and sensing instrumentation, and to insure that buoy motion characteristics are matched as nearly as possible to the observational requirements. This development project forms an ambitious and stimulating challenge to those of us who have been assigned the task.

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