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A Sea-Air Interaction Deep-Ocean Buoy[1]

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ABSTRACT

A stable spar buoy, TRITON, has been developed as a platform for sea-air boundary-layer measurements in the deep ocean. The buoy has operated for 60 days on station in the tropical Atlantic and for seven days in the Gulf of Mexico. In 2-m seas, the horizontal, vertical, and angular displacements are less than 36 cm, 10 cm, and 1°, respectively. Over the 60-day period, the stable character of the buoy resulted in negligible wear on the anchor system, despite two tropical storms having winds of more than 20 m/sec. TRITON is equipped to record digital time series of air-sea temperature, current speed, current direction, humidity, wind speed, wind direction, rainfall, and wave heights.

1. *Introduction.* The mutual exchange of motion, heat, water, salt, gases, particulates, pollutants, and biological organisms between the ocean and the atmosphere occurs across the interface. Solar radiation, representing the ultimate source of energy for both the ocean and the atmosphere, is absorbed mainly at the earth's surface. Kinetic energy to drive atmospheric motions must be derived in a complicated cycle, starting with energy exchange at the surface. Latent heat in the form of water-vapor constitutes the greater part of this energy input. The transportation of heat across the ocean surface thereby becomes a vital link in the energy cycle of the system. Friction (in the form of drag) between the atmosphere and the ocean regains a small fraction of this energy to help drive the current systems of the globe.

Despite the significance of these exchanges across the sea-air interface, little success has been achieved by either oceanographers or meteorologists in the direct and simultaneous measurement of the quantities being transferred. Few measurements have been made in the open ocean under a range of oceanic and atmospheric states. Those that have been made (e.g., Garstang 1967) depend upon indirect computation of energy fluxes from air-sea property differences and from measurements of the magnitude of wind velocity. Techniques of measuring directly the stress, heat, and vapor flux are few and have yet to

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be applied to the ocean. Simultaneous measurements of momentum, heat, water-vapor flux, wave height, wave direction, and sea-surface wind velocity are so few in number that no significant study can be quoted.

Reasons for this dearth of data are not difficult to find. Adequate theoretical treatment of turbulent exchange in a single fluid under controlled laboratory conditions has emerged only recently (e.g., Malkus 1956). A completely general theoretical treatment that can be applied to environmental conditions is yet to appear. Simpler treatment, such as the exchange or bulk aerodynamic equations developed by Taylor (1918) and Rossby and Montgomery (1935) and later applied extensively by Jacobs (1951) and Budyko et al. (1954), depends upon restrictive assumptions. More precise formulations, such as those based upon the cross spectrum of two variables, have found only limited success when used on aircraft (Bunker 1955, Hsueh 1968). Other methods, which depend upon multiple levels of measurements, such as the logarithmic-plus-linear equations of Monin and Obukhov (1954), have been limited to near-shore measurements. Where theory appears adequate (cross spectrum), technology has failed. It is difficult to obtain a stable platform in the deep ocean. Even if stable platforms could be placed on a ship, the obstacle and heat source presented by the vessel prevent accurate ambient measurements. Towers represent stable platforms, but they are limited to the continental shelves or, if placed in slightly deeper water, they present major obstacles to both the ocean and the atmosphere.

Buoys of various types form a third category of platforms for boundary-layer measurements. These range from vehicles that follow closely the motion of the sea surface to those that remain at rest with respect to the sea surface. The former type has been used in wave studies by Longuet-Higgins et al. (1963). Brocks and Hasse (1963) have developed a gyro-stabilized mast, with pitch and roll eliminated by gyro-controlled servo motors. Heave (vertical motion) has not been eliminated, hence the mast rises and falls with an amplitude similar to that of the surface waves. Use of the Brocks and Hasse buoy is limited to relatively mild sea states. Other buoys, which neither follow the sea surface nor are stable (e.g., Deardorff 1962), have been employed to determine the flux of latent heat, sensible heat, and momentum. Taut line buoys used in relatively shallow water (less than 35 m) have been used by Kraus et al. (1966), and subsequently by Mollo-Christensen (1967). FLIP (Rudnick 1964) is an example of a large free-floating stable platform.

With the exception of FLIP, all the buoys cited above are either specialized for a single task or suffer from one or more limiting constraints. In particular, none of these vehicles can serve as an adequate platform for the simultaneous measurement of quantities leading to the computation of the fluxes of water vapor, heat, and momentum, and of wave height and wave direction in deep water under a wide range of sea states.

The spar buoys have a number of desirable features, some of which are the following (i) The center of buoyancy can be placed far above the center of mass, resulting in a large torque to restore the buoy to its vertical position. (ii) The small cross section of the spar buoy does not allow significant moments for pitching movements due to waves. (iii) Similarly, the large moment of inertia around any horizontal axis further inhibits fast pitching motions. (iv) The small cross section at the interface and into the atmosphere represents a small obstacle to distort sea-surface and atmospheric characteristics. Such a small pertubation of the ocean surface and atmosphere can be avoided by judicious location of the instruments. (v) The spar buoy has a large heave stability; the small waterplane area and large submerged volume result in a long natural period of heaving motions.

FLIP, as the largest existing spar buoy, has the advantage of great stability, the capacity to carry a large payload of men, instruments, and power, and is able to survive in heavy seas. It has two distinct disadvantages. (i) It is costly to build, operate, and maintain. (ii) It is so large that it violates (iv) above, thereby losing one of the major attributes of a buoy.

In the design of TRITON, an optimum compromise was sought between the advantages and disadvantages cited above. As a major system to be used within the framework of a large oceanographic and meteorological experiment (Garstang and LaSeur 1968), TRITON was designed to carry sensors at more than one level in the atmosphere such that heat, water vapor, and momentum flux could be measured and computed accurately. Sensors at more than one level facilitate the computation of these fluxes by profile methods as well as by bulk aerodynamic methods. Simultaneous measurements of wave height, wave direction, sea-surface temperature, current speed, and current direction were incorporated. A method has been devised to obtain rainfall measurements on the buoy that are free from the effects of obstruction and motion that make such instruments on a ship almost valueless. Finally, the buoy has been designed to remain at anchor for a protracted period of time (at least 90 days) and to be left unattended for at least five days.

2. *Description.* (i) VEHICLE. TRITON is 34 m long overall and displaces almost six tons. In addition to the 10-m mast, the buoy consists of four tubular sections (Fig. 1): (a) two flooding tubes: cylinders 7 m and 6.5 m long by 0.61 m (24 in) in diameter, capable of being flooded and having fins attached on the lower flooding tube; (b) a pressure and buoyancy tube: a cylinder 7 m long by 0.61 m (24 in) diameter, containing compressed air (to blow the water from the two flooding tubes when retrieving the buoy) and having two 2-m-diameter spherical collars near the top, for buoyancy; and (c) a housing tube: a cylinder 5.5 m long by 0.56 m (22 in) diameter, containing the data-recording equipment and batteries and supporting an open tower and wave frame. The material is mainly grey steel. Some of the principal dimensions are summarized in Table I.

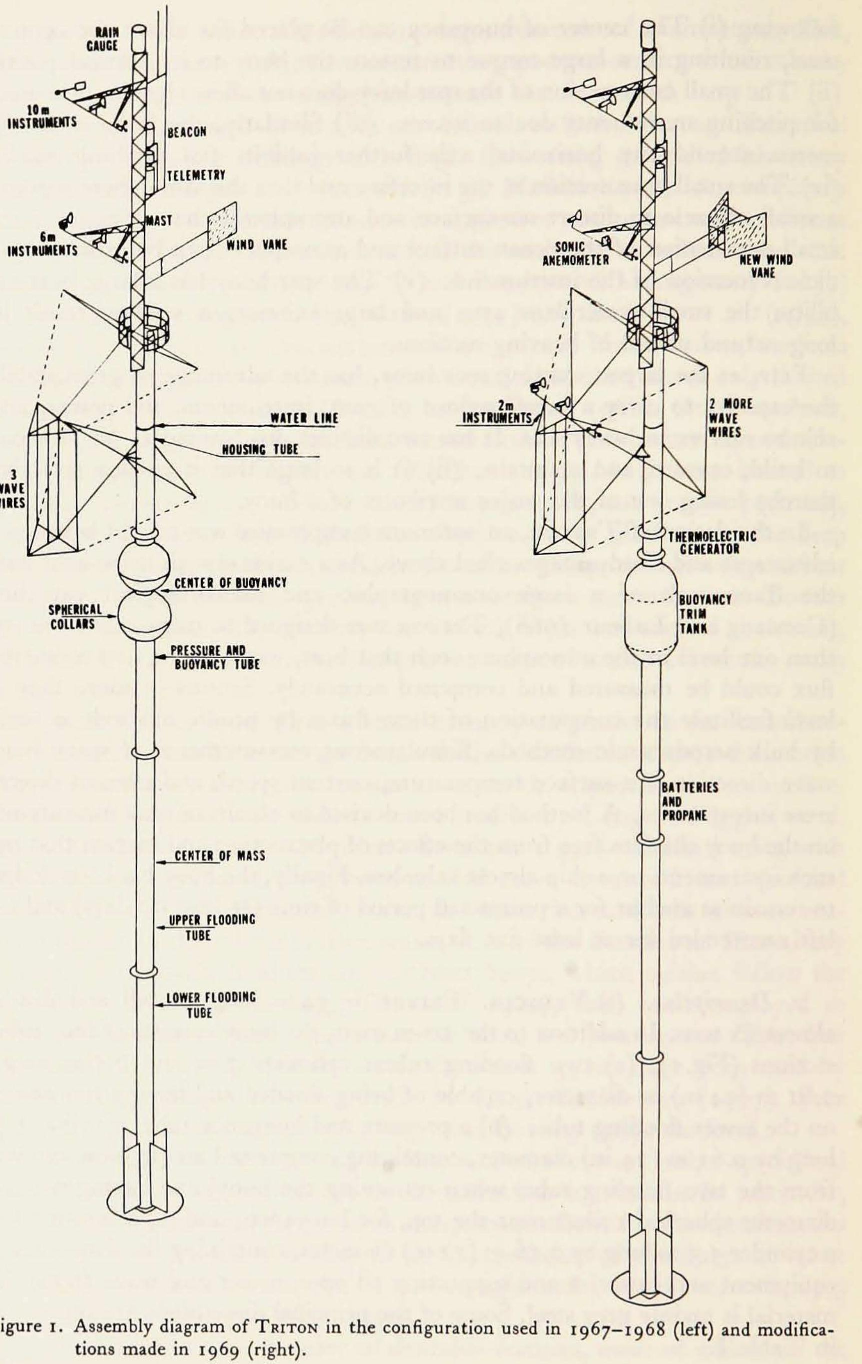

Figure 1. Assembly diagram of TRITON in the configuration used in 1967–1968 (left) and modifications made in 1969 (right).

Table I. Some dimensions of Triton.

	1967–1968	1969
Unflooded weight in air	5,700 kg	7,300 kg
Flooded weight in air	9,500 kg	12,200 kg
Center-of-mass (Below surface)	12.3 m	13.9 m
Center-of-buoyancy (Below surface)	4.4 m	5.0 m
Length below surface	24 m	27 m
Height above surface	10 m	10 m
Overall length	34 m	37 m

Each of the four cylinders is bulkheaded at both ends. Flooding is controlled by water valves on the bottom of each of the two flooding tubes and by air valves on the top end of the three lowest tubes. A rubber hose leads from each of the three air valves to a manifold (located on the platform). The manifold controls the flooding or blowing of the flooding tubes.

The buoy is transported over great distances to the site of assembly in sections; it is assembled in the water in a sheltered environment as near as possible to the station location. The lower damping plates are hinged at the centerline so that the two halves can be swung parallel to the main axis of the buoy to act as a stabilizer during towing. The four fins on the lower flooding tube, mounted parallel to the axis of the buoy (Fig. 1), damp the tendency for the buoy to rotate about the vertical axis.

When assembled, the buoy is towed to the station location (at a speed of five knots or less) in a horizontal position, with the mast retracted. On station, the damping plates are locked in a horizontal position by a swimmer, the anchor line is attached, the water valves are opened and the flooding tubes are allowed to fill with water, bringing the buoy into a vertical position. The uppermost section of the two flooding tubes is not filled completely.

By controlling the water and air valves, the buoy is ballasted so that the waterline is 2.7 m below the top of the housing tube. As shown in Fig. 2, an array of sensors and instruments is attached to a mast secured to the housing tube. The mast supports meteorological instruments at 6 m and 10 m above the waterline. A wind vane extends from the mast to orient the buoy such that the wave frame and the atmospheric sensors are in the upwind side. Various packages such as a rain gauge, radio direction-finding beacon, flashing xenon light, telemetry transceiver, compass, accelerometer, and inclinometer are mounted on the mast-vane structure.

At the top of the housing tube a hatch allows access to the compartment containing the digitizers, tape recorders, and batteries. The platform and railing extend around the hatch to facilitate servicing the electronics. Work is not possible on the platform when there is a probability of getting water in the electronics compartment. This criterion precludes work with the hatch open during rain or with wave heights over 4 m.

(ii) Anchoring System. A single slack line with 20% scope is used to anchor TRITON. From the buoy to the anchor we have used a length of chain, a swivel, a steel cable, another swivel, and finally braided nylon. Ten meters of chain weighing 230 kg (1.5 in) is attached to a bridle below the damping plates. The purpose of the chain is to provide ballast and lower the center of gravity of the buoy. A swivel is placed at the bottom of the chain; to this is attached a steel cable (1/4 in) impregnated with polyvinylchloride (Space Lay, Macwhyte Wire Rope Company). The length of steel cable used depends upon the depth of water. This particular cable, in addition to having suitable tensile strength, is capable of withstanding fishbite and corrosion. When anchored in 2600 m of water off Barbados, 1200 m of cable was used. Beyond the steel cable, braided rope (9/16 in) was used (2000 m in the Barbados experiment) with a swivel between the cable and nylon rope. This nylon rope was then shackled to 30 m of chain (5/8 in). The chain carried a 30-kg clump at the midpoint and 140-kg Danforth Anchor at the free end.

During the 1968 Barbados experiment, TRITON was anchored in 2600 m of water for 60 days. With the open trade-wind Atlantic extending eastward to the African coast, this location experiences the typical large swells of the tropical oceans; swells range between 1 m and 2 m with periods of six to eight seconds. On two occasions, incipient tropical disturbances with winds in excess of 20 m/sec passed over the station. Careful examination of the entire anchoring system at the end of the experiment showed no damage or signs of deterioration.

(iii) ATMOSPHERIC SENSORS. These sensors were chosen for use in a rugged environment, where they would operate for at least five days without servicing. Wind speed is measured by means of cup anemometers at 6 m and 10 m (total mast height) above the mean water surface. Six meters was originally chosen as the lowest level where the instruments could survive, but it was found recently that this level could be reduced to 2 m. The purpose of the two levels was to obtain valid hourly mean values rather than attempt to measure instantaneous gustiness. Matched pairs of thermistors are used to obtain the air temperature at 6 m and 10 m; the wet-bulb temperature is obtained at 6 m. The wind direction is measured at 10 m. Rainfall is measured at 10 m, using a 3.10-cm collector and modified tipping-bucket mechanism.

(iv) OCEANIC SENSORS. Three 3-m nichrome resistance wires are mounted on a triangular frame (4 m × 2.3 m × 1.6 m) located 3.6 m out from the buoy; these wires are used to measure wave height and direction. The wave height was recorded for each wire at a rate of four times per second. A pressure transducer 3 m below the mean sea surface measures an integrated pressure of the water column, leading to a measure of the sea state. The sea temperature at two meters below the mean sea surface is measured with a thermistor. The high stability of the buoy prevented us from measuring the sea-surface temperature without the use of a surface-following device for the sensor. Two

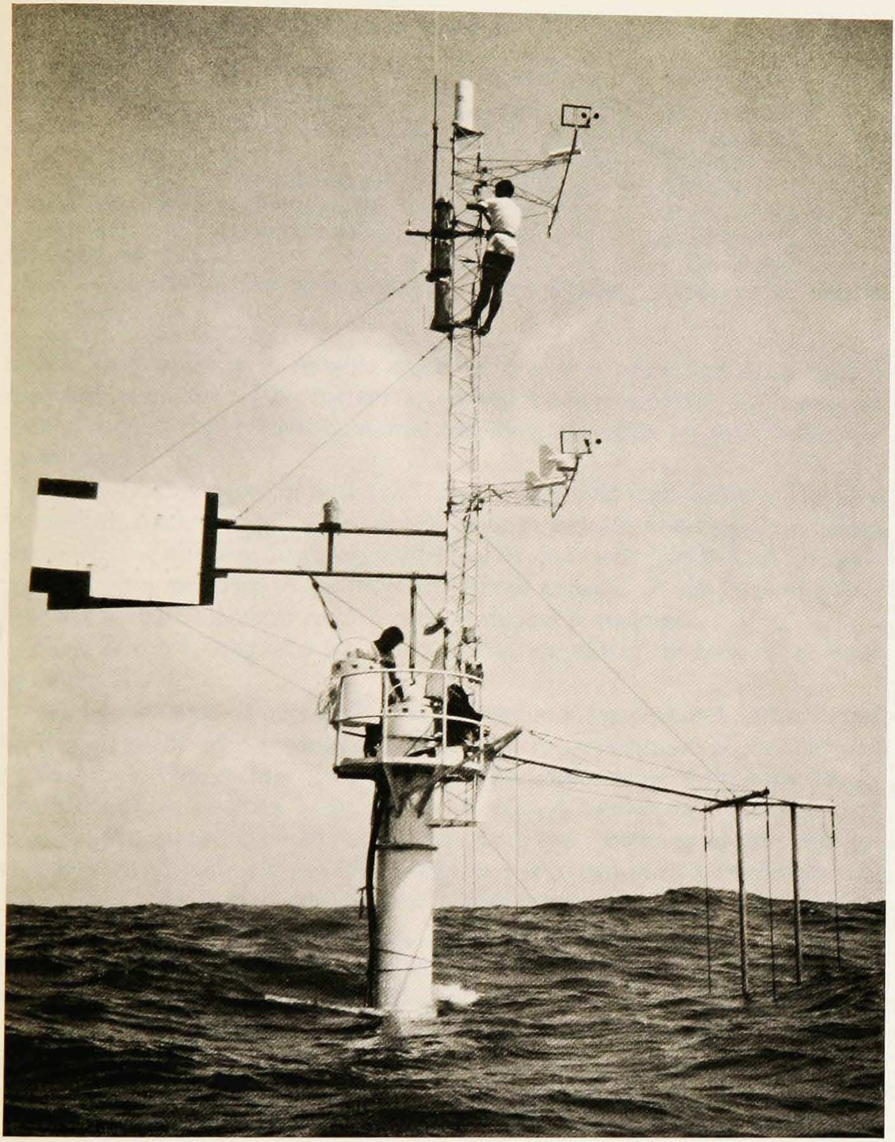

Figure 2. TRITON with the recorder hatch open and tubs removed to change tapes. The tubs are opened and serviced on the buoy, weather permitting.

Table II. Manufacturers of sensors used on TRITON.

Instrument	Manufacturer	Instrument	Manufacturer
Anemometers	Geodyne Corporation	Accelerometers	Systron-Donner Corporation
Compass	Geodyne Corporation	Inclinometers	Edcliff Instruments
Water-temperature thermistor	Fenwal/Geodyne	Rain gauge	MRI, Inc.
Wave-pressure guage	M. B. Electronics	Wind Vane	R. M. Young, Inc.
Thermistors	Fenwal/Geodyne	Wave wires	Bisset-Berman Corporation
Vane-aspirated thermistor shields	Climet Instrument, Inc.	Current meter	Geodyne Corporation

meters was chosen as a suitable depth to keep the sensor immersed during moderate sea states. The current speed and current direction are measured with a current meter having internal recording capability at 30 m below the sea surface.

(v) VEHICLE-BEHAVIOR SENSORS. Two orthogonal inclinometers are used to monitor pitch and roll. Two accelerometers measure the surge and heave. Recently, the third orthogonal accelerometer has been installed. A compass provides buoy orientation readings. A second compass in the current meter provides measurements to resolve current-direction readings.

None of the sensors used has failed. Manufacturers of the sensors are listed in Table II.

(vi) RECORDERS. The signals from the sensors are digitized and recorded on two magnetic tape recorders. Each recorder carries 400 m of two-channel (3/8 in) tape. One recorder is used to record measurements of the wave height (from the three resistive wave wires) as well as measurements of the buoy motion. The second recorder is used to record the remainder of the measurements. Each of the recorders and its digitizer is contained in a watertight tub. Two other tubs contain the batteries used to power these systems and the telemetry. A telemetry transmitter, requiring interrogation, can be used to monitor the operation of one digitizer. The recorders are serviced by removing the tubs through the hatch (Fig. 2).

Mechanical clocks are used to start the digitizers and recorders at fixed intervals. During the 1968 Barbados experiment, the wave digitizer was programmed to start every two hours and to record 16,506 words of wave and buoy motion data in about 11 minutes. The other digitizer was programmed to start every five minutes and to record the data from each sensor in turn eight times within a 32-second interval, and then to record 32 seconds of wave-pressure data. With this data-recording rate, the buoy can operate about 5.5 days before the tapes must be changed. The 24 7.5 volt dry-cell batteries last about 45 days. It is possible to operate the system at faster or slower data rates, but this will affect the life of the batteries and the servicing intervals. A block diagram of the system is shown in Fig. 3.

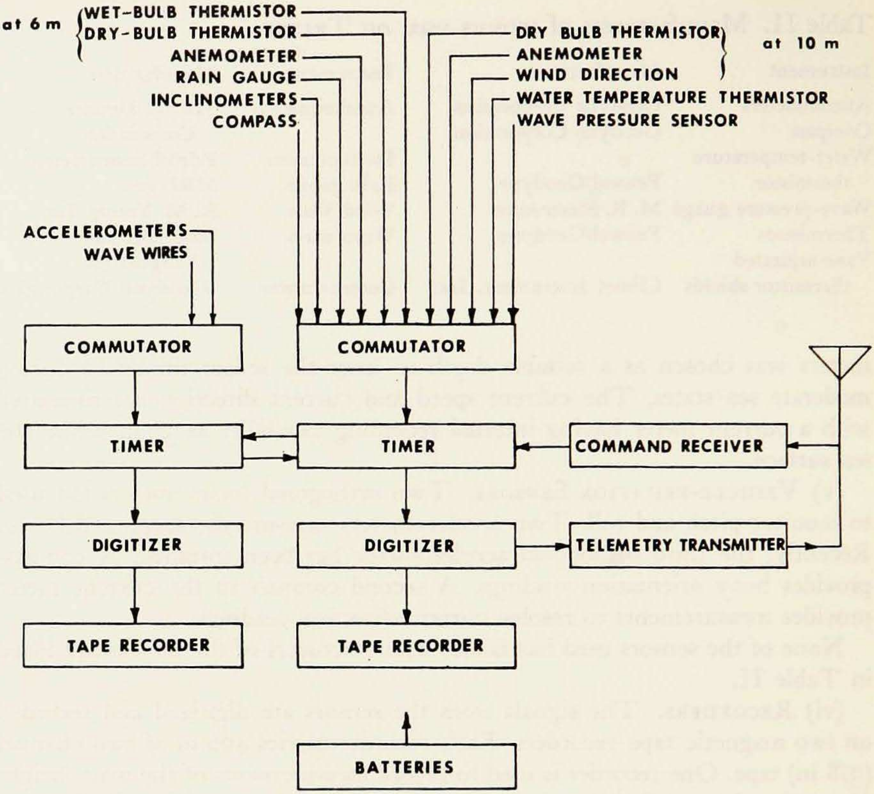

Figure 3. Block diagram of the electronic system of TRITON in the configuration used in 1967–68.

3. *Performance*. In October 1967, TRITON was operated for a week near Stage I, a tower operated by the U. S. Naval Mine Defense Laboratory at Panama City, Florida. The water at this location was about 30 m deep. This site was chosen so that 16-mm cameras could be used to record the buoy motion. TRITON was also operated from late June through the end of August 1968 at Barbados, as described above.

At Panama City, in 1-m seas, the motions of the buoy had a period of six seconds, with a vertical heaving motion of 6 cm, a horizontal surging motion of about 6 cm, and pitching motions of less than 0.3°. At the same location, with 4-m seas and gusts of wind to 20 m/sec, the heaving motions were about 17 cm with surging motions up to 71 cm and the pitching motions up to 2.5°. The small heaving motion and the large surging and pitching motions were due to the shallow depth of the water. No large swell is found at this location, since the shallow water extends for many kilometers. The bottom of the buoy was only 5 m from the ocean floor and moved little; this allowed the rest of the buoy to pivot around, causing the pitching and surging observed.

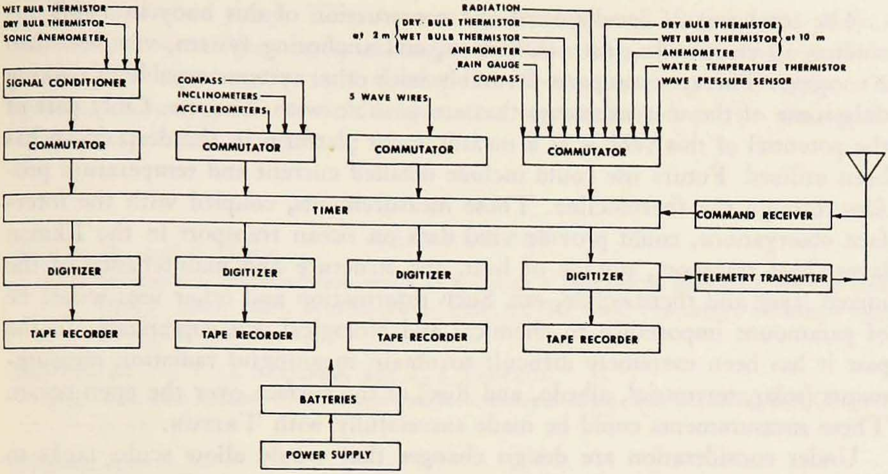

Figure 4. Block diagram of the electronic systems of TRITON to be used in 1969.

At Barbados, the dominant period of buoy motion was about 12 seconds; the theoretical undamped period of heaving for this buoy is 12.5 seconds. In 1-m to 2-m seas, motions of 35 cm for surging and 10 cm for heaving were observed. Pitching motions were less than 1°.

4. *Future Developments and Concluding Remarks.* Since the performance of the buoy, particularly its stability, has proved satisfactory, more sophisticated measurements are planned. In cooperation with Battelle Northwest Laboratories, a three-component sonic anemometer will be added at the 6-m level; a high-precision rapid-response thermistor is used in conjunction with the sonic anemometer. The water-vapor content as well as the fluctuations in water-vapor content can be computed from the sonic and temperature measurements. Using cross-spectrum techniques, the instantaneous fluxes of momentum, heat, and water vapor can be computed and compared with the values computed by means of the profile or bulk aerodynamic equations. Because power requirements with such additions are higher than can be supplied by the present dry-cell system, it will be necessary to incorporate a thermo-electric power supply, using the catalytic combustion of propane (Rubinstein 1967). Two additional cylindrical sections will be added as shown in Fig. 1. The lowermost of the two new sections will contain the cadmium storage batteries and the propane storage tank.

A digital clock will be used as a central programmer and timer for all digitizers. A third digitizer and tape recorder will be added for the sonic anemometer and a fourth for the buoy motions. Two additional wave wires will also be added to eliminate all ambiguity in the directional spectra. A block diagram of the system is shown in Fig. 4.

The total cost of development and construction of this buoy in 1968, including all electronics, instrumentation, and anchoring system, was less than $100,000. This cost compares favorably with other systems capable of making only some of the measurements that are possible with TRITON. Only part of the potential of this vehicle as a measurement platform in the deep ocean has been utilized. Future use could include detailed current and temperature profiles through the thermocline. These measurements, coupled with the interface observations, could provide vital data on ocean transport in the Ekman layer, heat transport, storage of heat, the structure and maintenance of the mixed layer and thermocline, etc. Such information and other uses would be of paramount importance to chemical and biological oceanographers. In the past it has been extremely difficult to obtain meaningful radiation measurements (solar, terrestrial, albedo, and flux) at the surface over the open ocean. These measurements could be made successfully with TRITON.

Under consideration are design changes that would allow scuba tanks to be used to blow the water from the flooding tubes and allow the present pressurized section to be filled with styrofoam. Such a modification could make the buoy unsinkable, short of actually breaking up. The stable characteristics of the buoy apparently result in much-reduced strain and wear upon the anchor system. It is possible that the characteristics of the TRITON buoy make it well suited for long-term anchoring. While it would be unwise to advocate at this point a program of proliferation of such deep-ocean platforms, it appears that, for carefully controlled experiments that are seeking to establish the fundamentals of processes at the sea-air interface, buoys of the TRITON class provide an extremely useful tool.

Time series of computed values of momentum, latent heat, and sensible heat fluxes and wave spectra will be presented in a separate paper.

5. *Acknowledgments*. The electronic systems were designed and manufactured by the Geodyne Corporation, and we would like to acknowledge the efforts of the project engineer Mr. George Dumas. Much of the construction of the vehicle was done by Dan Clark, Inc. and we would like to acknowledge the help of Mr. Clark in the design. A large part of the detailed work on TRITON was carried out by graduate students in oceanography at the Florida State University. Their dedicated efforts led to the successful execution of the field program, and we extend to them our grateful appreciation. The cost of the vehicle and of much of the electronics and instrumentation was supported by a grant (No. WGB-90) from the Sea-Air Interaction Laboratory of ESSA. A subsequent ESSA grant (No. E22-148-68 (G)) supported the field program. Florida State University provided funds for the wave system, current meter, and associated electronics. This support is gratefully acknowledged. Computations at the Florida State University Computing Center were supported under a grant from the National Science Foundation [No. GJ 367].

Note added in proof. TRITON was operated for 90 days in the tropical Atlantic, from 1 May 1969 through 30 July 1969. Heavy seas on about 21 May dislodged a valve and flooded the thermoelectric power supply. The system, excluding the sonic anemometer, operated on batteries during the remainder of the period.

REFERENCES

BROCKS, K., and L. HASSE
1963. Fluctuation measurements made at sea with a gyroscopic stabilized floating mast. Intern. Assoc. Met. Atmos. Phys. Proc. IUGG Gen. Assembly, Berkeley, 1963. Publ. IAMAP 13; 117.

BUDYKO, M. T., T. G. BERLIAND, and L. I. ZUBENOK
1954. The heat balance of the earth's surface. Izvestia Acad. Sci. U.S.S.R., Ser. Geograf., 3; 17.

BUNKER, A. F.
1955. Turbulence and shearing stresses measured over the North Atlantic by an airplane acceleration technique. J. Meteorol., *12*: 445–455.

DEARDORFF, J.W.
1962. An experimental ocean buoy for air-sea transfer studies. Final Report NSF G9715, Dept. Meteorol. Climatol., Univ. Washington; 79 pp.

GARSTANG, M.
1967. Sensible and latent heat exchange in low latitude synoptic scale systems. Tellus, 19 (3): 492–508.

GARSTANG, M., and N. E. LASEUR
1968. The 1968 Barbados Experiment. Bull. Amer. meteorol. Soc., *49*: 627–635.

HSUEH, Y.
1968. Mesoscale turbulence spectra over the Indian Ocean. J. atmos. Sci., *25*: 1052–1057.

JACOBS, W. C.
1951. The energy exchange between the sea and atmosphere and some of its consequences. Bull. Scripps Inst. Oceanogr., *6*: 27–122.

KRAUS, E. B., J. CHING, and R. ELSBERRY
1966. Aruba Expedition 1965 – Observations and analysis. Woods Hole Oceanogr. Inst., Ref. 66–70.

LONGUET-HIGGINS, M. S., D. E. Cartwright, and N. D. SMITH
1963. Observations of the directional spectrum of sea waves using the motions of a floating buoy, *In*, Ocean Wave Spectra. Prentice-Hall, N.Y. 357 pp.

MALKUS, W. R. V.
1956. Outline of a theory of turbulent shear flow. J. fluid Mech., *1*: 521–539.

MOLLO-CHRISTENSEN, E.
1967. Air-sea interaction studies in Buzzards Bay, Massachusetts. Progr. Rep., Dept. Meteorol., Mass. Inst. Tech.; 19 pp.

MONIN, A. S., and A. M. OBUKNOV
1954. Basic regularity in turbulent mixing in the surface layer of the atmosphere. U.S.S.R. Acad. Sci., Works of Geophys. Inst., *24*: 151.

Rossby, C. G., and R. B. Montgomery

1935. The layer of frictional influence in wind and ocean currents. Pap. phys. Oceanogr. Meteorol., *3*; 101 pp.

Rubinstein, M. A.

1967. State of the art of direct energy conversion power supply for buoys. Trans. 2nd Intern. Buoy Techn. Symp., Washington, D.C. 213 pp.

Rudnik, Philip

1964. FLIP: An oceanographic buoy. Science, *146*: 1268.

Taylor, G. L.

1918. Phenomena connected with turbulence in the lower atmosphere. Proc. roy. Soc. London, (A) *94*: 137–155.