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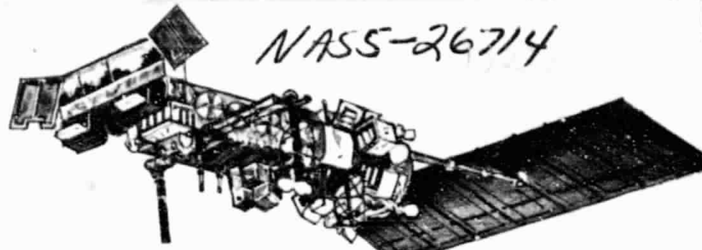

SATELLITE DATA RELAY AND PLATFORM LOCATING IN OCEANOGRAPHY

Report of the *In Situ* Ocean Science Working Group

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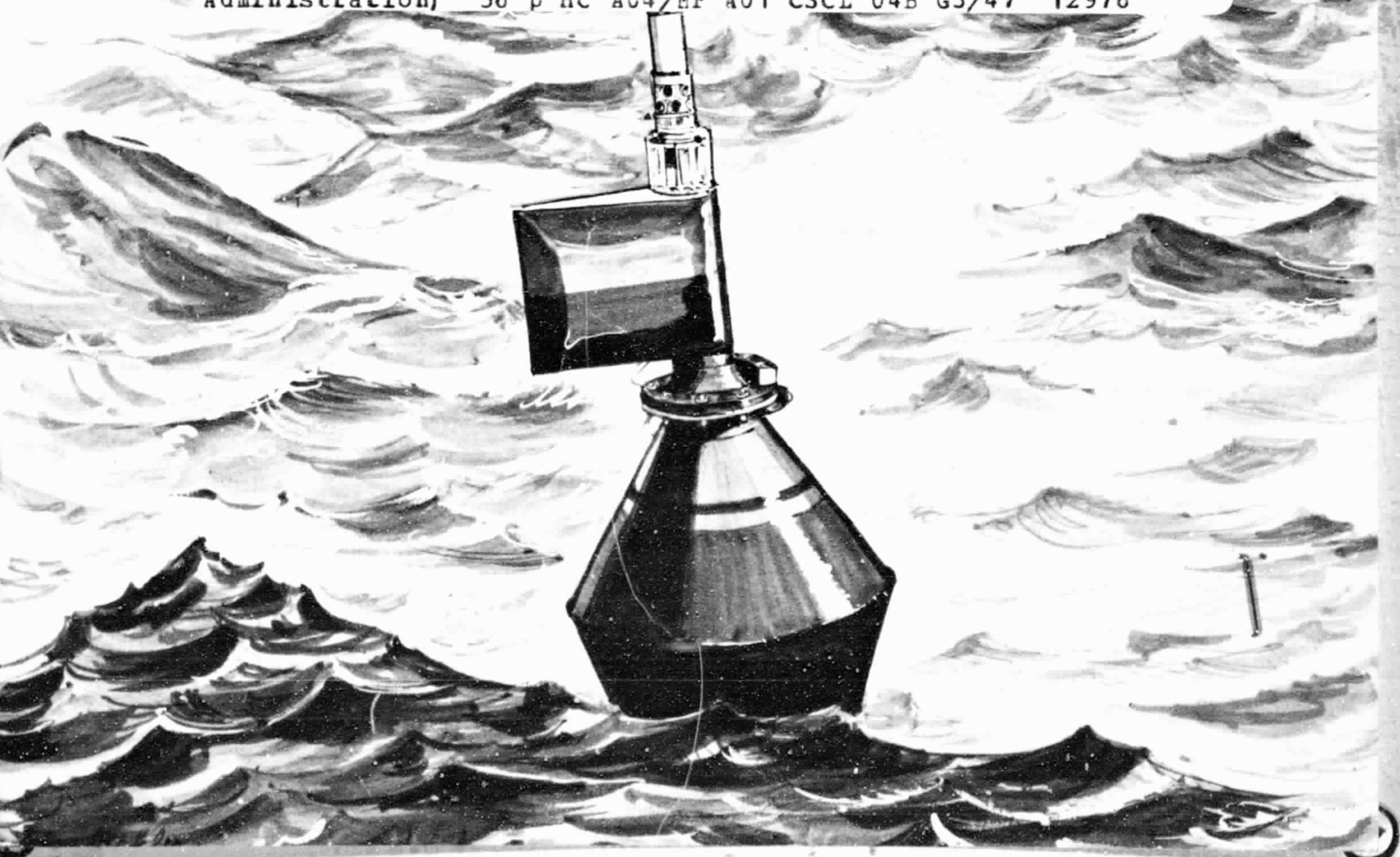

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COVER: Art work by Joanne Schinbeckler. The buoy was drawn from a photograph supplied by NOAA Data Buoy Center. The satellite pictured is the TIROS-N/NOAA A-G series of quasi-polar orbiting environmental satellites that carries the ARGOS system (see Section 4.1); the original sketch was supplied by NASA.

FRONTISPIECE: Sea-surface temperature image from a NOAA series satellite (right) and simultaneous tracks of current-following surface drifters (left). In the infrared image warm water is shaded dark. Data is from the Coastal Dynamics Experiment CODE (provided by K. Kelley, SIO).

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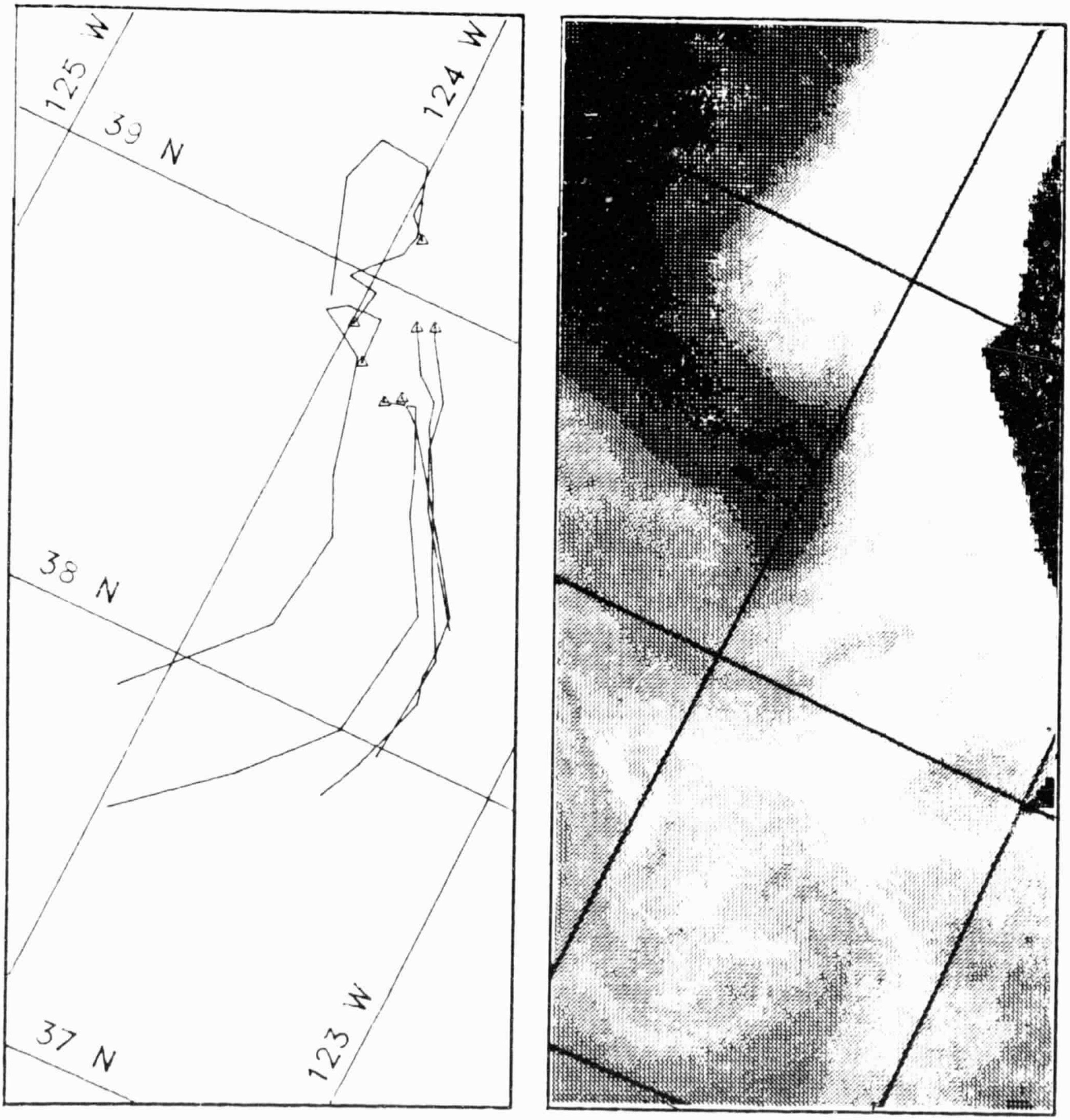

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FOREWORD

With Seasat, NASA demonstrated that satellites are capable of observing surface conditions for the global oceans, and that these observations can be used to address fundamental oceanographic problems. We recognize, however, that the solution of these problems requires complementary *in situ* observations of both surface and subsurface conditions, and that satellites are capable of locating instrument platforms and relaying the data ashore. With this in mind, NASA organized the *In Situ* Science Working Group of leading oceanographers to investigate future requirements for satellite collection of *in situ* data, as well as possible alternative methods for their location and collection. This report presents the results of their study. We express our gratitude to Russ Davis and the other members of this group for an imaginative and thoughtful report.

William Patzert, Manager

Physical Oceanography Programs

NASA Headquarters

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1. SUMMARY

This report concerns the uses of satellite data relay and platform locating capabilities in support of *in situ* ocean science. The purposes of the report are:

1) to summarize present and future uses of satellites to locate platforms and relay data from *in situ* sensors to shore,

2) to assess the adequacy of present satellite capabilities for these purposes, and

3) to recommend improvements of satellite and at-sea systems needed to maximize the utility of these capabilities.

The primary conclusions of the report are:

1) Scientific and economic trends in oceanography make satellite data relay and platform locating essential for continued progress in the field. Technical limitations of sensors and platform performance are being reduced, and as progress is made there will be a greater demand for data relay and locating.

2) Because of the high acquisition costs and intrinsic scientific value of ocean observations, data relay and locating services must not be interrupted for significant periods.

3) A system of the ARGOS type is better suited for use with most unmanned ocean instrumentation than is one involving geostationary satellites. High buoy transmitter and data processing costs for the present ARGOS system have limited the number of users and prevented full system utilization, but a dramatic increase in ARGOS use is anticipated in the coming decade.

4) ARGOS platform locating capability is adequate for most users, but utility would be greatly enhanced if less expensive buoy transmitters could be used when a lesser positioning accuracy is acceptable.

5) It is likely that in the near future the data relay capacity of the ARGOS system will be saturated in areas of intensive ocean exploration. There is a need for an expanded data relay capacity permitting a relatively small number of buoys to transmit large data volumes each day.

6) The improved ship navigation provided by the Global Positioning System (GPS) will facilitate marine operations and make possible the d[illegible] observation of currents from underway ships.

7) The need to transmit large data volumes, such as satellite images, to research vessels can probably be met by commercial systems such as MARISAT.

On the basis of these conclusions, the following recommendations are made:

1) Satellite deployment scheduling should take into account the high value and direct cost of the data lost by a protracted hiatus in platform locating and data relay services. This consideration, and the anticipated accelerating demand for ARGOS services, dictates continued availability, in the absence of premature satellite failure, of two ARGOS satellites. It also dictates maintenance of the TRANSIT navigation system or its replacement by GPS.

2) Support for development of the *in situ* ocean measurement technology necessary for full exploitation of satellite data relay and positioning capabilities should be continued.

3) The high accuracy navigation capability of GPS should be made available to the oceanographic community, although this need not be available in real time.

4) A technical study should be undertaken to determine how best to reduce the cost of buoy transmitters for those users who require platform locating but not the high locating accuracy provided by the present ARGOS system. Apparent options are relaxation of ARGOS transmitter certification specifications and/or mass production.

5) A technical study should be undertaken to determine how best to expand the data relay capacity of ARGOS. Support is needed for a relatively small number of buoys transmitting approximately 10,000 bit messages daily. An attractive option is the addition to ARGOS of a few high-speed data-only channels which could be accessed by buoy transmitters also capable of operating as conventional ARGOS beacons.

This report first presents an overview of the major oceanographic applications of satellite data relay and locating . Section 3 contains a description of the ocean systems which make use of these capabilities and an estimate of the demands these systems will put on satellite systems.

It is found that a majority of demands over the coming decade can be met by present systems but that anticipated demand may exceed the capability of the present ARGOS system. Section 4 contains an assessment of the capabilities of ARGOS and suggestions for how it could be augmented. The final section contains an amplification of the recommendations summarized above.

2. APPLICATIONS

The course of oceanography over the last decade or two has been marked by a fundamental change in the way we view the ocean. Our concept has changed from one of a steady state ocean circulation perturbed by small scale waves to one of an ocean supporting a wide range of interacting phenomena occupying the full spectrum of time and space scales from seconds to decades and from centimeters to the size of ocean basins. This change in perception has been accompanied by a trend away from making occasional point observations from a single ship towards efforts to simultaneously observe the ocean over large regions for periods of years. Unfortunately, the expense of gathering observations has escalated dramatically, primarily because of the cost of the ship operations. The advent of remote sensing, data relay, and platform locating from satellites makes possible the more efficient and extensive observing systems needed to help solve the problems of modern oceanography.

Satellite remote sensing of the ocean is limited to observations which describe the ocean surface, not its interior. The remote sensing now of greatest utility to oceanographers is mapping of sea surface temperature and ocean color, satellite determination of the short wave radiative flux of heat through the ocean surface, and inference of surface winds from cloud motion. Additional benefit results from improved characterization of weather over the ocean. Developing methods for measuring winds over the ocean and sea level height from satellites promise to dramatically expand our ability to observe important ocean processes continuously over large regions. But as important as these surface signatures are, they represent two-dimensional views of the three-dimensional ocean and therefore can provide only a partial picture of oceanic phenomena. Further, remote observations of the ocean are indirect and not always as easily related to quantitative *in situ* observations as is needed. These considerations dictate a continuing requirement for *in situ* observations, both to interpret the descriptions gained from remote sensing and to observe phenomena which do not have strong surface signatures.

The marine environment imposes serious constraints on observational oceanography and makes satellite data relay and positioning of great value. Because the ocean is essentially

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opaque to electromagnetic radiation, remote sounding (such as is employed in observing the atmosphere) and long range underwater telemetry from observing systems are not possible. The oceans are vast, essentially unpopulated domains across which transportation by vessels steaming at ten knots and costing on the order of $10,000 per day is slow and expensive. The ocean is a hostile environment in which field operations are inefficient, maintenance of three mile long moorings is a major engineering task, and sensor survivability is limited.

Historically, oceanographers have mapped the ocean from slow-moving ships or have moored internally recording instruments and returned to recover or replace them. The emergence of satellite data relay and platform locating (uplinking) permits fundamentally different modes of operation which increase both the quantity and quality of some observations and permit new kinds of measurements. The remainder of this section discusses a number of scientific problems which can be addressed by uplinked *in situ* observations and some of the new operational modes made possible. In this discussion it is important to state that, even more so than with remote sensing, satellite data relay and locating is of value in diverse applications. Thus it is possible here only to give examples of some of the ways in which satellite data relay and platform locating will be used in oceanography; the list of examples is not comprehensive nor does it imply that omitted applications are less valuable than those included.

2.1 General Circulation Studies

A fundamental objective of oceanography is to observe, describe, and predict how the oceanic general circulation stores and transports heat, chemical species, and momentum. This question is central to understanding the ocean and its influence on the atmosphere, an interaction carried out primarily by latent and sensible heat fluxes. It is equally important in understanding the distribution of properties in the ocean, both naturally occurring quantities such as the nutrients supporting ocean life and those materials introduced by man.

One of the most important oceanographic discoveries of the last two decades is the seeming ubiquity of intense time-dependent currents (eddies and other low frequency phenomena). This variability makes observational description of the mean general circulation difficult since ocean eddies are frequently an order of magnitude more energetic than the mean flow. Eddies are also dynamically important as mechanisms influencing the mean flow, in transferring energy and momentum to smaller scales, and in directly transporting matter in the ocean.

One important example of the interaction of mean and transient components occurs near the Gulf Stream. This current is a source of warm and cold core "rings," which are often clearly evident in sea surface temperature imagery because they transport large bodies of water from one side of the Stream to the other. Further, observations (Niiler, 1980) and eddy-resolving models (Holland, 1978) indicate that eddies produced by the boundary current and its interior extension drive a significant part of the mean recirculation found to the south. Another example occurs along west coasts where equatorward winds generate upwelling currents which bring nutrient-rich water into the euphotic zone where it supports biological activity. While upwelling is a feature of the mean circulation, observations show that it is episodic and spatially variable and that vigorous eddy motions are responsible for distributing the upwelled water into the offshore coastal zone.

To understand the general circulation and the distribution of properties in the ocean, it is necessary to study both the mean state and the low frequency fluctuations. The sources and sinks of eddy energy must be identified and their transport quantified. One objective is to obtain worldwide maps of mean flow and eddy energy in several frequency bands from days to years at several depth levels. Such maps provide both valuable description and test eddy-resolving numerical general circulation models (Schmitz and Holland, 1982). Some maps of conditions at the surface (Wyrtki, *et. al.*, 1976) and at specific isotherm levels (Dantzler, 1977) exist, and progress is being made in extending this description to other ocean basins and depth levels. Because the quantity of data required is large, as is the cost of obtaining it, the method of approaching this mapping deserves special attention.

The North Atlantic is the best observed ocean from the point of low frequency variability. Still, there are only about two dozen sites at which suitably long time series have been obtained from moored instrumentation. It is unlikely that it will ever be feasible to deploy enough long-term moorings to map the mean flow and eddy variability in this basin, but it is feasible to use drifters to gain the needed data. Drifters provide the long records of velocity (and temperature if desired) needed to resolve low frequency phenomena and, since drifters migrate around the ocean, one instrument can sample many different locations. It appears that something like 100 to 200 drifters, which are tracked for 2 to 3 years, are sufficient to map one depth over much of the North Atlantic on a two-degree grid. An example of the measurement density achieved by drifters is given in Figure 1, which shows some 110 surface drifter trajectories compiled by Richardson (1983). Although these drifters were deployed mainly in the western mid-latitude North Atlantic, analysis of their motion provides a first order description of the surface circulation and eddy variability over much of the basin. The mean flow derived from these data is shown in Figure 2. Less complete, but equally important, descriptions of surface circulation in the North Pacific and the Southern Ocean were obtained from drifters deployed in the NORPAX and FGGE programs, respectively. Observations of currents at depth are less extensive than surface data but, by combining available long current meter records and subsurface float tracks, researchers are developing a picture of mean flow and eddy variability throughout the water column, particularly in the western North Atlantic.

2.2 Ocean-Atmosphere Interaction

The upper ocean, particularly the turbulent boundary layer nominally found in the upper 100 m, exhibits many phenomena involving large- and meso-scale currents and thermal variability. To oceanographers these phenomena are of interest on their own because they are the most direct manifestations of oceanic response to the atmospheric forcing, and because they influence the deep ocean. To meteorologists and climatologists, these phenomena are the most important aspects of the ocean since the ocean's influence upon the atmosphere is most direct through air-sea fluxes of heat.

Observations of ocean-atmosphere interaction are needed in a wide variety of oceanographic studies, from the general circulation scale to the meso-scale. One important class of experiment is upper ocean process studies, such as MILE (a list of experiments and programs

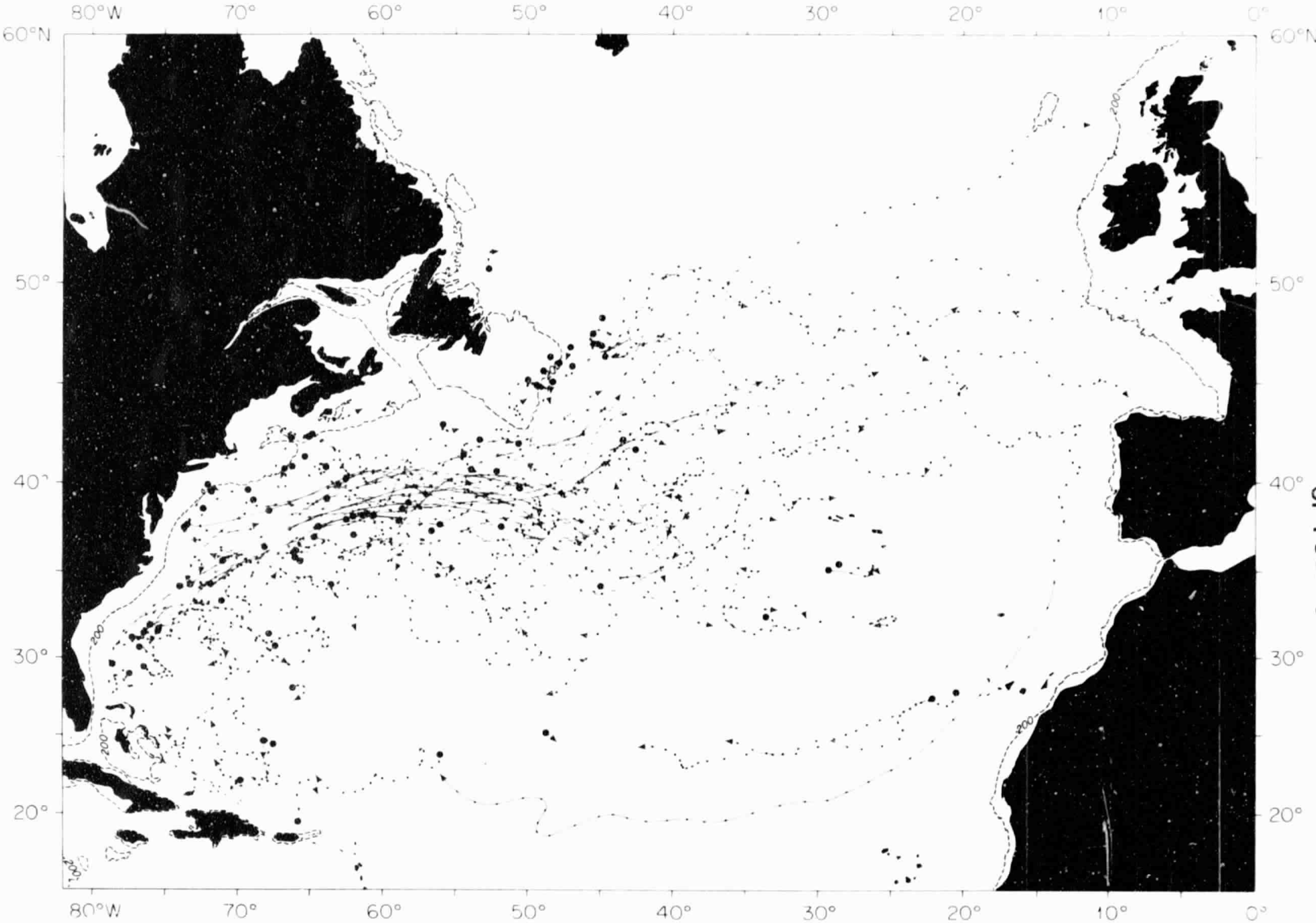

Fig. 1 Plot of 110 surface drifting buoy trajectories compiled by Richardson (1983).

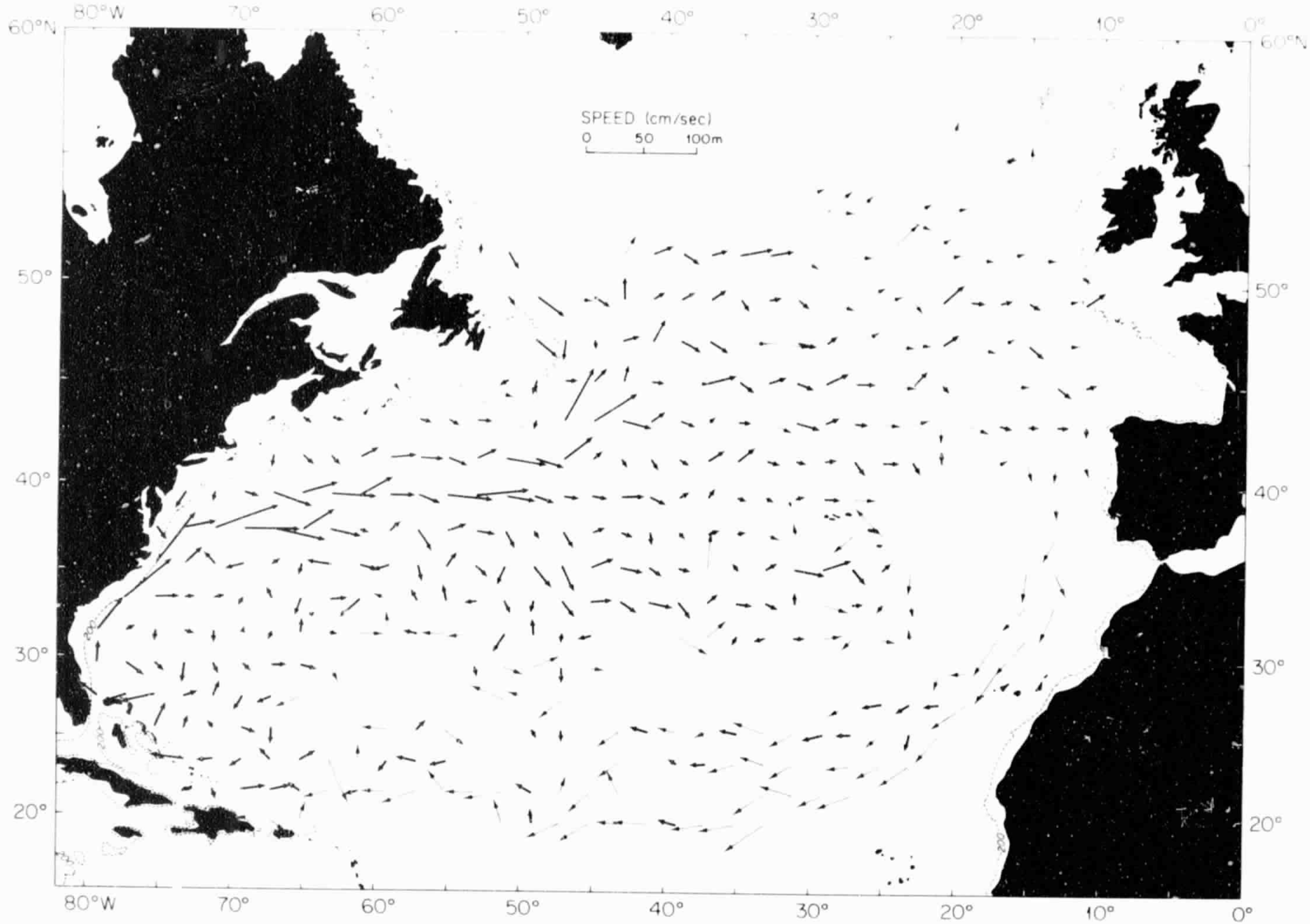

Fig. 2. Mean velocity computed from the data in Figure 1 (Richardson, 1983). The arrow length is proportional to speed.

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known by acronyms is given in Appendix A), JASIN and STREX, in which the upper ocean is closely observed over scales of the order 100 km and several weeks. Of primary interest are the physical mechanisms by which heat and momentum are transferred to, and stored within, the ocean. An important objective of such studies is development and validation of process models from which relatively broad-scale ocean response can be predicted from knowledge of atmospheric forcing. New process studies might be directed toward the mechanisms of deep water formation in high latitudes or toward modification of the ocean boundary layer and generation of geostrophic currents under strong atmospheric forcing, such as hurricanes or polar air-mass outbreaks.

Another class of experiments addresses the regional or large-scale heat budget in places where ocean thermal variability is believed to influence short-term climate (or long-period weather) in the atmosphere. Examples of such studies are the NORPAX examinations of thermal anomalies in the mid-latitude Pacific and the EPOCS, NORPAX and TROPIC HEAT observations of variability in the equatorial Pacific. Historically, such regional studies have been hindered by a lack of methods to observe air-sea fluxes and heat advecting currents over scales of 1000 km and years.

In addition to ocean velocity, essential elements of upper ocean dynamics are the storage of heat and the air-sea fluxes of momentum, water vapor, and heat. Over the next decade, remote sensing can be expected to contribute to upper ocean explorations, notably in description of surface winds, sea surface height (*i.e.* geostrophic surface currents), and radiative heat flux. Nevertheless, many critical variables will remain inaccessible from space, and *in situ* capabilities to observe them will be needed. Upper ocean velocity, temperature and heat storage, and salinity variability can be observed from moorings, drifters, or ships-of-opportunity. Air-sea fluxes of momentum, heat and water vapor can be monitored using bulk formulae and relatively simple *in situ* measurements of wind, air temperature and humidity, and sea surface temperature, all of which are observable from ships and buoys. *In situ* radiation measurements are more difficult, but remote observations of the short-wave flux are promising, and in the tropics (equatorward of 30°) variability of the net infrared flux is small enough that it need not be monitored for many purposes.

2.3 Regional Studies

Different regions of the ocean exhibit unique phenomena and physical processes. Examination of these areas, and their unique local dynamics, is often accomplished in regional field experiments having objectives of both describing the local circulation and examining the dynamical mechanisms. The observational approach is similar to general circulation studies, but it involves more concentrated observational arrays in place for periods of many months. These arrays are intended to describe structures over tens or hundreds of kilometers and their relation to other oceanic and atmospheric events. Examples of phenomena requiring this kind of approach are the meso-scale eddies (e.g., MODE, POLYMODE and Gulf Stream ring studies), coastal processes (e.g., CUEA and CODE), equatorial processes (e.g., INDEX, SEQUAL and PEQUOD), and upper ocean response to atmospheric forcing (e.g., MILE, JASIN and STREX).

The list of inadequately described regional processes is endless but it may be worth mentioning a few entries on the observational agenda. Western boundary currents have unique nonlinear dynamics which have not been well characterized, in part because of the difficulty of mooring instruments in these intense currents. Warm and cold core rings generated in these currents are interesting both from the standpoint of dynamics and as large laboratories in which to study biological response to changing physical environments. Studies of these rings are focused on "moving targets" and greatly benefit from drifter-based instrumentation and timely relay of *in situ* observations. Study of the interaction of ocean currents with sea floor topography and coastline irregularities requires detailed mapping of velocity fields and benefits from drifter-based flow visualization. Tropical regions are associated with unique phenomena such as trapped equatorial waves, large thermal anomalies (as El Niño), equatorial upwelling, undercurrents, and apparent oceanic influence on large-scale atmospheric variability; the spatial coverage required for such studies dictates use of some drifter-based instrumentation and relayed data.

The 1982-83 El Niño Southern Oscillation (ENSO) episode was associated with record-breaking tempestuous weather at many distant locations around the Pacific. Satellite data relay systems will form an integral portion of the monitoring network now being established to record the onset of future ENSO events which occur irregularly every three to seven years. In the onset phase of an ENSO event, sea level decreases in the western Pacific and begins to rise in the eastern Pacific and the upper ocean currents along the equator in the central Pacific reverse direction from westward to eastward. These changes are easily observed with instrumentation placed on islands and on moorings. Real-time data transmission via satellite provides an opportunity to predict the onset and subsequent intensity of the event and its effects.

Because they address geographically localized phenomena, regional studies need moored observations with well defined array geometries. They also benefit from the dense spatial coverage feasible only from drifter observations, relayed *in situ* data which can be used to adapt measurement strategy, and the velocity mapping provided by current-following drifters. There is also a particular efficiency in using drifting instrumentation in regional studies. After the drifters have described the local structures, the array migrates into the general circulation and begins providing information on the largest oceanic scales at no cost beyond provision of drifter longevity. For all these reasons it is certain that satellite data relay and drifter locating will continue to be important elements in regional ocean studies.

2.4 Unique Observational Modes

Satellite technology has provided oceanographers with new data sources from remote sensing systems, vastly improved positioning of both ships and unmanned buoys, and a capability to relay data from *in situ* instruments to shore and from shore to ships at sea. These capabilities not only improve the accuracy and utility of conventional observational methods, but they also permit fundamentally new modes of operation which deserve special mention.

Before introduction of the TRANSIT satellite navigation system, the lack of accurate navigation on a worldwide basis was a major limitation to oceanography. TRANSIT now provides accurate (± 200m) ship positions several times per day anywhere on the globe. This has greatly improved the efficiency of at-sea operations, has made possible more elaborate observational programs by increasing the precision with which observations can be positioned, and has made possible direct observation of currents over the time periods between navigational fixes. Introduction of the Global Positioning System (GPS) will provide another quantum step in maritime navigation, improving on the accuracy of TRANSIT and allowing continuous ship location. In addition to other benefits, this will permit nearly continuous monitoring of upper ocean currents from underway ships using acoustic velocity profilers or other shipboard instrumentation.

System ARGOS allows unmanned surface buoys with low power transmitters to be located and to relay *in situ* observations to shore. This makes possible ocean velocity measurements using current-following drifters and permits deployment of other instrumentation from drifting buoys without the expense and operational difficulty of deep-ocean moorings. Beyond these direct benefits, the ability to relay *in situ* data to shore and to relay large quantities of timely data from shore to ships at sea permits new and improved operational methods which deserve special mention.

Historically, analysis of oceanographic observations has been completed long after the data were taken. As attention is directed to phenomena occurring over long time scales, and to instrument systems capable of describing these phenomena without frequent and expensive tending from ships, this approach must be modified. The lifetime of subsurface current-following drifters is now several years, and moorings are frequently deployed for more than a year. As instrument longevity is increased, data gathering becomes more cost effective, but the pace of scientific inquiry does not permit a leisurely wait for results to become available. As instrument longevity is further increased, the complete utilization of observations and proper planning of subsequent sampling will require that analysis proceed in parallel with data gathering. In this vein, analysis of still active SOFAR floats is now underway and the results are being used to plan new deployments.

As observational arrays become more elaborate, seeking to relate more oceanographic variables at more sites, they become more severely degraded by instrument failure. At the same time, the luxury of redundant instrumentation or of deployments frequent enough that failures will be minimal becomes unacceptably expensive. Thus it is becoming essential that observing arrays report at least the health of each instrument so that key instruments that fail can be replaced. It is now common for deep ocean moorings to include ARGOS transmitters which signal loss of the mooring and permit its replacement or recovery. If the data of interest are relayed, then it becomes possible to take advantage of the logistic efficiencies of instruments which are deployed from ships-of-opportunity or aircraft and are not recovered; this seemingly extravagant loss of instrumentation becomes quite cost effective as the expense of using research vessels escalates.

As the questions addressed by oceanographic observation become more specific and sophisticated, it becomes more difficult to design the right observing array without having knowledge of the existing conditions. The recent history of oceanography is filled with examples of experiments seeking to describe some special event which did not occur at the time and location of the observations. With relayed data it becomes practical to place long-term arrays capable of detecting the phenomena of interest and to use the data from that array to schedule and site more elaborate observational studies. This approach is employed now when eddies are seeded with surface drifters which are used to position shipboard observations of eddy evolution. The same approach could be employed with subsurface eddies if autonomous SOFAR listening stations telemetered data through satellites.

In a similar way, timely transmission of data, particularly from remote sensing systems, to ships at sea makes possible the use of sampling arrays tailored to current conditions. It is common practice in studies of the upper ocean for ships to receive satellite surface temperature and color imagery from shore stations where some processing has been applied. In complex field programs, involving various aircraft and ships, data are also exchanged between the different vehicles and with shore stations where preliminary analysis and integration of the various data is most practical. Such data exchange makes possible efficient adaptive sampling strategies without which observational goals could not be achieved. As an example, rapid data exchange permits exploration of the relationship of small scale features, such as internal waves, fronts, or fine structure, to larger scale features if these features can be located from timely data relayed through satellite links.

2.5 Operational Modes

The applications of satellite data relay and locating discussed above are scientifically oriented. There are also many operational uses of such capabilities, and consideration of both types of uses might well lead to a better system for each.

The largest operational need for marine observations is in support of weather forecasting for civilian and military users. The majority of these data are now obtained from routine shipboard weather observations which are encoded and transmitted in radio messages. Such data differ from scientific observations in that timely receipt by operational users is essential. A significant fraction of ship reports are not included in the operational data base, presumably because they are lost in the radio network or are not received quickly enough for distribution, and data quality is degraded by encoding and transmission errors. Utility of these observations could be enhanced if they were taken and relayed at near-synoptic times and were received in a standard format which did not require special translation before insertion into models. All of these considerations indicate that the quality and quantity of weather observations available to forecasters could be substantially improved by timely satellite data relay.

Large areas of the ocean are infrequently traveled and, consequently, weather observations from these areas are too few to be of use. During the Global Weather Experiment an array of 300 drifting buoys was deployed in the southern hemisphere. Their surface weather observations were satellite relayed and included in the operational data base. This made possible analysis of previously unobserved regions and resulted in significantly improved performance of numerical weather forecasting models (Guymer and Le Marshall, 1981). The potential for improving surface analyses in other data-sparse regions using inexpensive drifters has been demonstrated (Ocean Data Systems, 1981), and a recent study (Phillips, 1981) suggests that such surface observations can also be used to improve satellite temperature sounding inversions in cloudy regions.

In a similar way, there are civilian and military requirements for subsurface temperature observations from which analyses of upper-ocean thermal structure are prepared. Like weather observations, expendable bathythermograph observations are encoded and transmitted in radio messages from U.S. Navy ships and other participating vessels. The encoding process is more complex and errors are more frequently introduced. The requirement for timeliness is less severe, since ocean thermal structure nominally evolves on a scale of days rather than hours. It would appear that satellite relay would again be of value, but it may not be possible to utilize a civilian system because of security considerations.

There are numerous other operational activities, both ongoing and planned, which make direct use of satellite uplinked data. For example, the U.S. Coast Guard uses satellite tracking of transmitters placed on icebergs to gather data for ice movement forecasts critically important to maritime safety. In a similar way, satellite-tracked current-following buoys are used in forecasting the movement of oil slicks in support of beach protection and clean-up activities. A somewhat more elaborate operational use of satellite relayed observations is a proposed moored array in the eastern tropical Pacific relaying daily measurements of upper ocean currents and temperatures which would signal the onset of El Niño. This phenomenon, a recurrent intrusion of anomalously warm water eastward or southward past the Galapagos Islands into the coastal zone of South America, has a strong adverse effect on the productive fisheries there. The proposed satellite-uplinked equatorial array would provide sufficient warning of El Niño for fisheries management to prevent overfishing. A major factor in the high worldwide price of fish meal in the 1970's was overfishing during the 1972 El Niño.

There also are ancillary benefits to operational activities of satellite-uplinking. Relayed data from scientific programs directly supplements the environmental data base available for operational use. Studies by U.S. Navy and GARP researchers have shown that all weather data which are timely and are incorporated into analysis and forecast models will lead to improved products. Additionally, weather and ocean temperature analyses employ climatological norms and dynamical relations so that they are indirect but significant beneficiaries of all the various oceanographic uses of uplinked *in situ* data discussed above.

Finally, it should be noted that there are various operational uses of satellite data relay and locating which do not involve environmental data. One important use is for emergency communication links for ships. Even with the relatively high cost of ARGOS transmitters, the benefits of a high-reliability data link and associated locating capability are widely recognized and, in fact, during a transatlantic race in 1981 over 100 sailboats were tracked *via* ARGOS. Similar uses among the research, commercial, and military fleets might become widespread if future satellite systems were made easily available to such users. The automatic locating capability provided by a system like ARGOS might well be of value in the national enforcement of fishing regulations.

2.6 Conclusions

From the foregoing it is evident that there is a diverse collection of ways in which satellite data relay and platform location is essential in oceanography and other ocean related endeavors. In functional terms the capabilities of most importance are (1) collection of *in situ* observations from unmanned instrument platforms or ships-of-opportunity, (2) positioning of unmanned platforms, (3) navigation and velocity determination of research vessels, and (4) transmission of large data volumes to ships at sea.

The trends which indicate an increasing utilization of satellite data relay and platform locating have been discussed. With this increased utilization it becomes essential that there be a commitment to maintaining satellite capabilities. Ocean instruments and operations are too expensive to permit dependence on satellite systems with uncertain lifetimes. In this respect it is of concern that the TRANSIT navigation system is degrading without a guaranteed replacement and that the ARGOS system may be limited to a single operational satellite with the associated possibility that all service could be discontinued by a single system failure.

3. OCEAN TECHNOLOGY

The requirements for satellite data relay and locating are determined by the oceanographic technology which employs those capabilities. In this section a number of instrument types are discussed in terms of (1) the improvements in ocean technology required before satellite capabilities can be fully utilized in applications such as those above, (2) the special requirements placed on future satellite systems by such instruments, and (3) the probable number of such instruments which will be employed in the near future.

It will be noted in the following discussion that oceanographic utilization of satellite data relay and locating capabilities is in its infancy. Much of the technology discussed either is in development or is being rapidly improved. This is a reflection of the fact that the potential for satellite uplinking is largely untapped. As oceanography moves forward from "brass and mahogany" the demands on satellite systems will increase, but it is difficult to predict how rapidly. In the same way, as the user costs of satellite services decrease and systems become more flexible, new uses will follow.

3.1 Current-Following Surface Drifters

Satellite locating makes possible the worldwide use of surface drifters to observe currents in the upper ocean. In addition to benefits derived from the quasi-Lagrangian nature of such observations, a major advantage of surface drifters is the economy and simplicity of their deployment from research vessels, aircraft or ships-of-opportunity. This makes possible deployment of the spatially dense arrays needed to explore spatial structures, and the extensive arrays needed to obtain representative sampling of large-scale phenomena.

A major limitation to the utility of current-following surface drifters is uncertainty in how well their motion represents current velocity. Wind, surface waves, and sheared currents act on the surface buoy to cause the drag producing drogue element to slip through the water. Improvement of drifter performance is both a difficult and a critical engineering problem in which much progress has been made. But at present, an ability to predict current-following performance under the range of oceanic conditions does not exist. The development of self-contained acoustic Doppler current profilers may permit *in situ* verification of drifter performance through direct measurements of drogue slippage. There appears to be no fundamental technical roadblock in the pursuit of accurate current followers but continued support is required. Field experimentation is required to evaluate candidate buoy designs and to validate models developed to predict their performance.

Potential advantages of surface current-following drifters are that they cost less to fabricate and deploy than current meters and that they need not be recovered. The present high cost of certified ARGOS transmitters permits effective use of drifters only if they provide data over lifetimes of the order of one year; such drifters are expensive to fabricate and are too large to be easily deployed from ships-of-opportunity or any but the largest aircraft. Consequently, use of satellite-tracked drifters has been largely restricted to limited descriptions of the general circulation. Reduction in buoy transmitter costs would make economical the use of smaller, less expensive, and more easily deployed drifters with shorter lifetimes. This would permit massive deployments in regional studies of spatially complex processes and an accelerated examination of the general circulation. This, in turn, would accelerate usage and presumably permit reductions in user costs. Thus the effect of transmitter cost reduction is exponential!

The majority of uses for satellite-tracked surface current-followers are directed toward phenomena with scales of the order of tens of kilometers and several days. Thus the frequency of positioning from the ARGOS system (from 2 to 6 times daily, depending on latitude and the number of operational satellites) and location accuracy (± 1 km) is generally more than adequate. The associated uncertainty of average velocity over several hours is generally less than the spatial and temporal variability of upper ocean currents. Thus any system improvement of accuracy or positioning frequency would be less valuable than one which made economically feasible the use of larger numbers of current-following drifters. In fact, some performance degradation could be accepted by many if there were an associated decrease of user costs.

The ARGOS system is currently supporting about 300 platforms at any one time, a significant function being current-following drifters. This is much less than the system capacity. If user costs (including transmitter purchase and data processing fees) were reduced. utilization would increase and questions of system capacity might become important. However, with the present user costs it is unlikely that within a decade the total demand for locating drifting buoys will exceed 500 platforms, the majority being current-following buoys with limited instrumentation. It is, however, plausible that during large field programs there would be as many as 150 current-following drifters within the field-of-view of an ARGOS satellite, and this may approach the system limit.

3.2 Subsurface Current-Following Drifters

Development of neutrally buoyant floats, which can be acoustically tracked at long range (Rossby, Voorhis and Webb, 1975), has made possible mapping of subsurface velocity fields on the meso-scale and the statistical examination of the subsurface general circulation. Such floats are not subject to the slippage errors affecting surface drifters. They are tracked at ranges of the order of 2000 km through acoustic ranging in the SOFAR channel and have demonstrated lifetimes of several years. To date they have been employed primarily in the North Atlantic, where a combination of permanent land-based listening stations and moored listening stations has been used for tracking.

The primary limitation to the widespread use of SOFAR floats is the lack of a worldwide network of land-based listening stations and the expense of deploying and maintaining moored listening stations. Support of moored listening stations is manpower- and ship time-intensive, and consequently expensive, particularly if floats are tracked over wide areas in inaccessible regions. Development of listening stations which relay data through satellites will lead to greatly expanded, and more cost effective, use of SOFAR floats. This would eliminate the need to retrieve data from listening station recorders and to maintain a regular cycle of maintenance. Satellite locating would permit the use of drifting or lightly moored listening stations which might be deployed from ships-of-opportunity or aircraft.

It is unlikely that in the near future more than a dozen satellite-linked listening stations will be deployed at any one time. Thus they will not represent a large fraction of ocean platforms. But each station might need to relay the order of 10,000 bits of data per day, some from auxiliary environmental sensors. In order to track buoys over a significant fraction of an ocean basin it would be necessary for approximately 5 stations to be within the instantaneous field-of-view of an ARGOS satellite. This will represent a significant fraction of the oceanographic demand for data relay capacity and apparently exceeds the capability of the ARGOS system. This demand could be met by the combined use of GOES data relay and ARGOS positioning; the penalty of carrying two independent systems is very undesirable but not insurmountable.

A novel, but as yet unproven, concept for subsurface current followers is the "pop-up" buoy which occasionally pops to the surface, is located by satellite, and then submerges for further current following. This approach eliminates the need for listening stations and might make possible inexpensive and easily deployed buoys which could be used in large numbers. It is, however, limited to applications such as description of the general circulation, where continuous tracking is not required. The approach is entirely dependent on development of inexpensive buoys, and thus on reduction of satellite transmitter costs.

3.3 Instrumented Upper Ocean Drifters

A number of logistic advantages have been mentioned for instrumented surface drifting buoys if satellite data relay and platform locating are available. This is particularly true for sampling upper ocean temperature, heat storage, salinity variability, and the air-sea fluxes which are so central to ocean-atmosphere interaction studies. The ocean technology for making such measurements is similar to that employed on moorings but deserves some comment here.

Drifters can support vertical arrays of thermistors and/or conductivity sensors for upper ocean observations. There remain problems of longevity for these chains and, although some recent success has been achieved in the STREX program, more careful engineering is needed before such instrumentation becomes routine. Unattended measurement of conductivity is less satisfactory than temperature but, fortunately, temperature is more useful; under most circumstances temperature variability has the greater influence on dynamically important density changes and is, itself, the variable of greatest interest with respect to oceanic influence of the atmosphere.

Of critical importance in ocean-atmosphere interaction studies are the air-sea fluxes of momentum, heat, and water. In the majority of studies the non-radiative fluxes are best monitored from wind, air and water temperature, and humidity measurements used in conjunction with bulk formulae. Careful experimentation is needed to determine how these measurements can best be made from buoys, but there are many promising avenues and considerable experience to build upon. *In situ* measurement of incident short-wave radiation is possible although there are difficulties with long-term measurements from buoys. Inference of shortwave flux from satellite measurements may be preferable. Net longwave radiation flux is difficult to observe, either *in situ* or remotely, and development of suitable technology is required before measurement of all parts of the heat flux is possible.

Technological progress toward routine observations of the upper ocean requires continued support yet the future is promising. However, it must be recognized that the requirements for a satisfactory current-following surface drifter may be incompatible with many kinds of sensors, particularly meteorological sensors. Practical use of such buoys is dependent on the existence of an ARGOS type system providing positioning and relay of limited data volumes; it would be impractical for such buoys to carry both a GOES and an ARGOS transmitter.

It is unlikely that the number of well instrumented upper ocean buoys in place at any time in the next decade will exceed 100, since their unit cost is substantial. The specific instruments and sampling rates used on such buoys will vary with the application but might, for example, provide four to six daily observations of wind velocity, air temperature and humidity, two bands of radiation, ocean temperature at a dozen levels, and a few levels of ocean currents. For most purposes 10 to 12 bit precision will suffice so that a typical buoy might relay on the order of 1000 bits daily. Since many of these platforms would be associated with intensive regional studies, it is likely that there might be as many as 20 within the field-of-view of an ARGOS satellite.

3.4 Deep Ocean Instrumentation

Surface drifters can be used to support instruments for measuring velocity, temperature and other properties in the deep ocean if satellite data relay and positioning are available. The advantages of easy deployment and the lack of a need to recover instrumentation are also provided by light moorings, which continue to provide data even if the mooring fails and the instruments drift freely.

Current meters, conventional or acoustic profiling, and deep ocean temperature and conductivity sensors could be supported below drifting buoys and linked through a telemetry line to a buoy-mounted satellite transmitter. Other instrumentation, such as the hydrophones of SOFAR listening stations, could be attached to the same "data bus" as required by individual programs. In addition to sensors, the technology required includes a flexible and reliable telemetry cable, telemetry controller, and buoy transmitter. The advantage of such a general purpose telemetry system is a combination of logistic economy and data availability for directing opportunistic measurements or scheduling instrument replacement. As the instrumentation payload becomes more valuable, these advantages decrease, but the cost of the ship operations required for deployment and recovery of heavy deep ocean moorings makes such "expendable" buoys cost effective in many circumstances.

It is estimated that during the next decade the number of buoys relaying deep ocean observations will be small compared with upper ocean buoys, primarily because they will involve more sophisticated and expensive instrumentation. The data relay requirements will probably be comparable to instrumented surface drifters, averaging 1000 bits per day per buoy.

3.5 Research Ships

Even as satellite uplinking of *in situ* observations becomes more widespread, dedicated research vessels will continue to be the primary platforms for many ocean measurements and for servicing unmanned instruments. Most ship operations depend on accurate navigation, and the direct observation of currents from ships depends critically on accurate navigation. The present TRANSIT system is sufficiently accurate for most purposes, but during the periods between fixes (typically several hours) ship position becomes uncertain by several miles and direct current observations are impossible. The introduction of the Global Positioning System (GPS) promises a significant improvement in marine navigation, permitting continuous positioning, but the accuracy which will be available is not yet known.

For most operational purposes (instrument deployment and recovery, hydrographic measurements, bottom sampling, *etc.*) continuous positioning with absolute accuracy of 200 m is adequate. Shipborne current observations, such as those made by a profiling Doppler acoustic velocimeter, impose more stringent demands on relative positioning accuracy. A current velocity uncertainty of 2 cm/sec is acceptable for sampling upper ocean currents on the meso-scale. Velocity variability from surface waves prevents present instruments from detecting this signal level in less than about 500 sec. Thus velocity measurements are limited by navigation unless ship displacement over 500 sec can be measured to 10 m. This would make possible continuous profiling of upper ocean currents with 2 cm/sec precision and 2 km resolution from underway ships anywhere in the world. It should be noted that even if accurate navigation were available only some time after the observations were collected, much of the scientific value of shipborne velocity data could be recovered in post-processing.

Availability at sea of timely observations from satellite remote sensors and other systems can significantly expand ship capabilities. This requires, however, transmission of significant data volumes. As an example, a single AVHRR (Advanced Very High Resolution Radiometer) surface temperature map of a 300 km square with 10 bit resolution requires a 1 million bit message. At present this kind of data transmission is carried out using the ATS (Advanced Technology Satellite) system and is most successful. This is an "experimental" system and there are no plans for its continuation. The commercial MARISAT service provided by Communications Satellite Corporation is capable of meeting this demand using digital transmission over a telephone channel permitting data rates up to 2400 bits per second. The cost of relaying a million bit message is presently less than $70 but a significant investment is required for ship installations which are substantially more complex and less reliable than those required for ATS.

3.6 Ships-of-Opportunity

As attention is turned toward low frequency phenomena, particularly those of importance to climate variability, it becomes more important to gather numerous observations over wide expanses of ocean. One approach toward such meteorological and upper ocean observations is the use of ships-of-opportunity, *i.e.* commercial or fishing vessels which serve as instrument platforms while carrying out their normal functions. This approach is routinely employed for gathering marine weather and subsurface temperature observations which are encoded and reported by radio message. An increasing number of oceanographic programs, most notably the NORPAX Anomaly Dynamics Study, are utilizing paid observers on commercial vessels to collect subsurface temperature observations using expendable bathythermographs (XBTs).

As ship costs increase and scientific programs demand even more numerous *in situ* observations, the use of ships-of-opportunity will likely increase for both operational and research uses. In fact, major scientific observational programs may well be carried out primarily from such platforms. Because such observations must be made on a noninterference basis by relatively untrained personnel, it is essential that the observing system be self-contained and require a minimum of manual operation. It is also important that data transmission and distribution involve a minimum of manual manipulation to avoid error introduction. This argues for satellite relay of data collected by onboard instrumentation packages which integrate data from various meteorological and oceanographic sensors. Additionally, satellite relay makes scientific observations available for operational uses requiring timely data receipt, and it allows the shore-based scientist to shape his sampling strategy and to schedule maintenance of onboard equipment on the basis of data examination.

Hardware is available to automate the recording, onboard processing, encoding, and transmission of XBT profiles. There are currently 50 to 100 ships gathering 2 to 5 XBT profiles daily for civilian oceanographic programs, and many more naval vessels which forward XBT data for operational purposes. After onboard processing, a profile can be relayed in 300 bit messages. Thus it is reasonable to assume that in this decade there will be 100 ships-of-opportunity seeking to relay daily from 300 to 1500 bits of XBT data for scientific use. A majority of users will probably employ GOES data relay, since ship positioning is not required and the data stream will generally include weather observations which are of operational value if distributed in a timely manner.

3.7 Operational Uses

The use of ships-of-opportunity for gathering routine weather observations for operational use will continue. It is recognized that the utility of these data would be enhanced if they were received more rapidly than is possible using the present technique of manual encoding and radio transmission. Technology for automating data collection and relay is available but its use is not yet widespread, presumably because of economic constraints. It is anticipated that use of GOES to relay ship weather observations will increase but not so fast as to significantly increase the total quantity of data relayed by that system.

The technology for using drifting and moored buoys to obtain surface weather observations from data-sparse ocean regions is well developed. Buoy-mounted atmospheric profilers are being developed to increase coverage of the lower atmosphere over that available from satellite profilers. Operational constraints on antenna size and transmitter power, plus the need to position drifting buoys, make the ARGOS system attractive for buoy use.

The primary disadvantage of using ARGOS to relay operational weather reports is the delay between data transmission and distribution by System ARGOS. If data are received and distributed by local real-time receiving stations (Local User Terminals), the timeliness of ARGOS data is quite satisfactory. This was demonstrated in a NOAA Data Buoy Center experiment in which data from drifting buoys deployed in the Gulf of Alaska during STREX were received by a Local User Terminal in Edmonton, Alberta. The results, shown in Figure 3, demonstrate that ARGOS data received at the Local User Terminal were much more timely

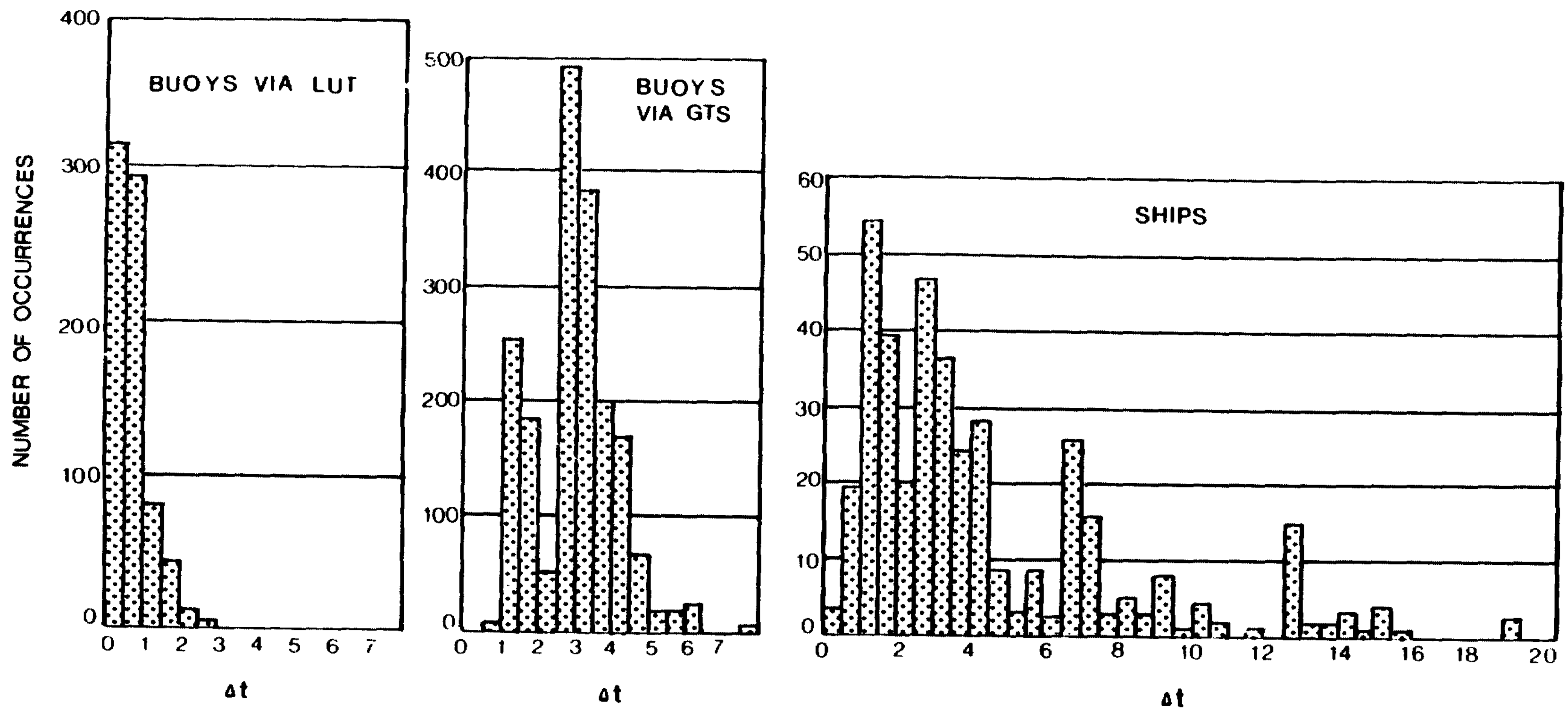

Fig. 3. Histograms showing the number of data messages available for analysis within the time, Δt hours, following the observation. Local User Terminals (LUT) receive ARGOS data directly. The receipt time delay is greater if data is received by System ARGOS and distributed over the Global Telecommunications System (GTS). Both satellite methods outperform routine ship reports relayed in ship-to-shore radio messages.

than either ship reports relayed by radio message or data received by System ARGOS and distributed over the Global Telecommunications System (GTS).

A significant fraction of the ARGOS data received at the Local User Terminal was available for operational weather analyses and forecasts during STREX. Table 1 shows the percentage of data available for each of the four National Meteorological Center (NMC) analysis cycles. Clearly, satellite relay is a vast improvement over routine ship reporting and, even without Local User Terminals, a large fraction of data is available for most analyses.

The ARGOS polar-orbiting satellite system provides buoy data at times primarily determined by buoy location on the globe. Data volume variations with time were examined in STREX to determine the fraction of data available within time intervals centered on the synoptic analysis times. Figure 4 shows the observation times of the drifting buoys during a 2-month period. A significant data gap at about 09Z and 21Z shows the satellite orbit effect. A 3-hour shift (45° in longitude) either way would have placed the data gaps directly at two of the synoptic periods and would have considerably degraded the utility of the buoy data for those times. This highlights the need for careful planning of the deployment of operational weather buoy arrays.

NOAA is currently studying how best to relay weather reports from buoys using GOES, ARGOS or a combination of the two. Until the trade-off between buoy system cost, receiving station cost, and data timeliness is known, it is difficult to assess the demands which operational weather buoys will place on data relay systems. It is unlikely that in the next decade this demand will be large in comparison to the total system use.

The operational need for subsurface temperature observations from civilian vessels is apparently not sufficient to support an observing network beyond that employed for scientific purposes. The lack of security in a civilian satellite relay system precludes military use for critical tasks.

As implemented, the ARGOS system is intended solely for environmental purposes. The safety advantages associated with having ships report position and short operational messages

NMC Analysis Cycle	Limited Fine Mesh	Operational	Optimal Interpolation	Final
Time after synoptic observation, hours	2:00	3:45	4:30	9:30
Buoys via LUT	98	100	100	100
Buoys via GTS	24	79	91	99
Ships (all circuits)	29	57	66	88

Table 1. Percent of data available for various NMC analyses during STREX experiment.

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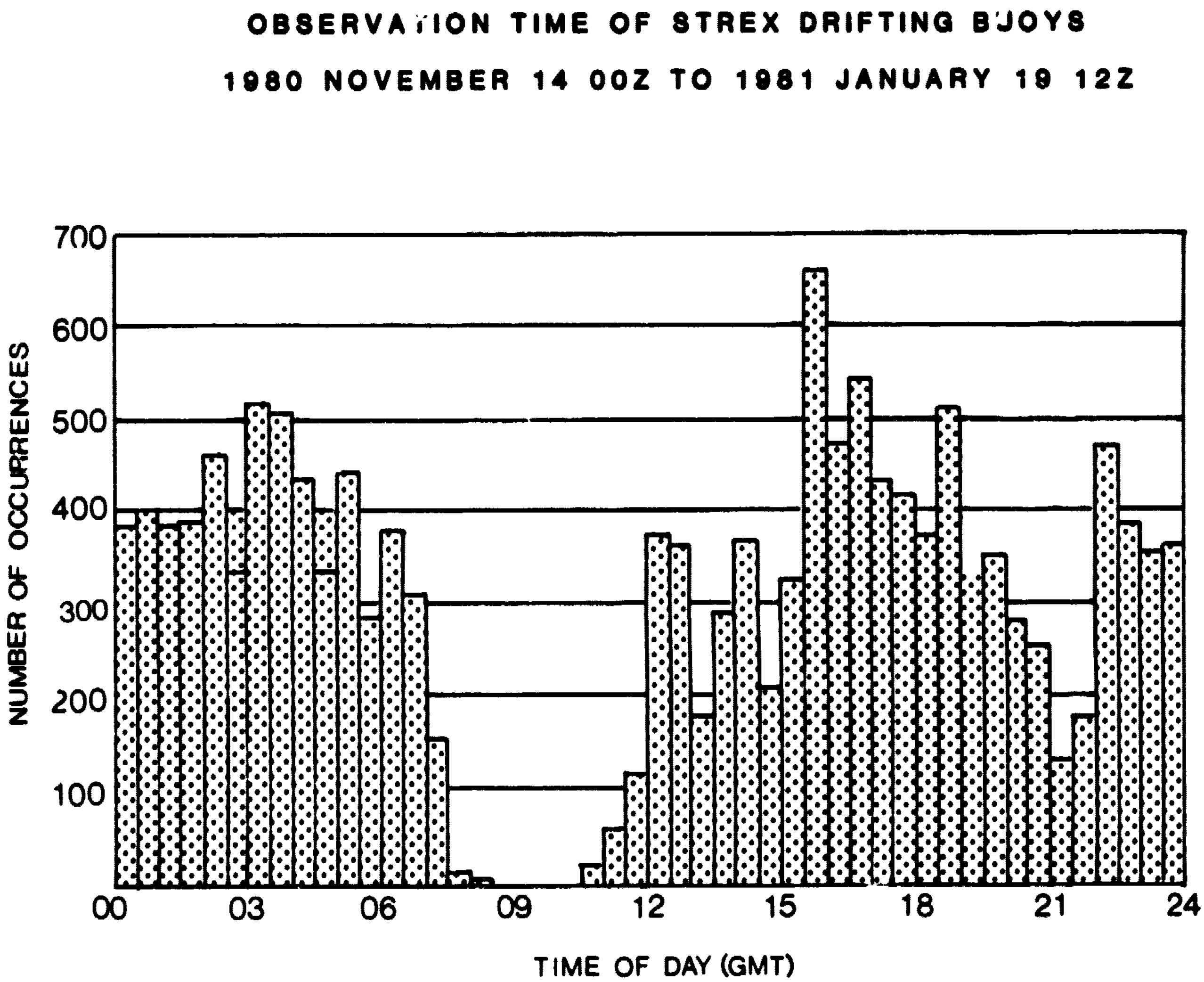

Fig. 4. Data volume variations of buoy reports from the STREX area for the indicated time period.

through a high-reliability satellite link are obvious. Similarly, there are other operational maritime uses for satellite positioning and data relay such as enforcement of fishing treaties, law enforcement, and search-and-rescue. Since a major factor in using ARGOS is the cost which is presently supported by a small user community, it seems desirable to open its use (and that of follow-on systems) to a large class of operational users. This would have both direct value to oceanographers who would enjoy improved safety and indirect value in lowering user costs and thereby permitting new scientific uses.

3.8 Conclusions

The foregoing provides an approximate picture of the systems which make use of satellite data relay and platform location. These may be roughly categorized as (1) unmanned platforms, primarily surface drifting buoys, requiring location and limited data relay (100 bits daily); (2) unmanned instrumented platforms requiring location and moderate data relay (1000 bits daily); (3) unmanned moored or drifting platforms which transmit large data volumes (10,000 bits daily) and may require location; (4) ship systems which require continuous navigation with 200 m accuracy for operational purposes and 10 m accuracy to permit useful direct current measurement; and (5) ship programs which require reception from shore of large data volumes (1 million bits daily).

Much development of ocean instrumentation is required in the area of unmanned platforms. Current-following drifters must be made more accurate and less expensive; meteorological sensors must be made more reliable and long-lived; methods of sending data from submerged ocean instruments to satellite relay transmitters must be improved; and automated systems, such as remote SOFAR listening stations, must be improved. These are problems requiring considerable work but there is every reason to anticipate success.

The positioning requirements of unmanned platforms, including current-following drifters, are well met by the ARGOS system (± 1 km, a few times daily). The primary cause of the present underutilization of ARGOS locating is user cost. Availability of inexpensive transmitters would dramatically increase the use of current-following drifters and greatly enhance knowledge of ocean currents. There is demand for lower cost transmitters even if they lead to degraded positioning accuracy.

While the ARGOS capacity for data relay is larger than the present demand, the demand is rapidly increasing as ocean systems are developed to exploit this capability. It is difficult to forecast demand, but we have estimated that within the decade there will be periods of intensive ocean observation during which an area comparable to the field-of-view of an ARGOS satellite will include (1) 150 buoys transmitting minimal data messages of up to 100 bits daily, (2) 30 instrumented buoys transmitting 1000 bits daily, and (3) 5 heavily instrumented buoys relaying 10,000 bits daily. To this will be added an impossible-to-estimate demand for ARGOS services in support of operational needs. A majority of ship-of-opportunity needs will be met by GOES without imposing a significant demand on that system.

The likely accuracy of the degraded civilian GPS system (hundreds of meters) will be adequate for most ship operational uses but the full system capability is needed for direct measurement of currents from ships. If the implementation of GPS is delayed, there will be a period of unsatisfactory marine navigation due to degradation of the TRANSIT system.

Data relay to ships *via* ATS is presently quite adequate. The significant equipment and operational costs of commercial data relay make it desirable to maintain availability of ATS to the oceanographic community for as long as possible. However, the MARISAT system appears capable of meeting future demands, if at a substantial cost.

The above conclusions indicate that a system of the ARGOS type is required to locate and relay data from unmanned buoys. Although the system is currently far from saturation, there is a real danger that expanded demand will saturate the system. The capacity of ARGOS to meet these future demands is considered in the following section.

4. ARGOS CAPABILITY

Because the ARGOS system is well suited to locating and relaying data from unmanned ocean buoys, it will support a large share of the oceanographic users in the next decade. The present utilization of the system is far less than its capacity, but the projections of §3 indicate a rapidly expanding demand over the coming decade. Such a dramatically growing response to satellite systems is not unique to ARGOS; utilization of the commercial MARISAT system grew by a factor of more than 10 during its first five years of operation.

The *In Situ* Ocean Science Working Group requested the Goddard Space Flight Center to estimate the capability of ARGOS to support demands for platform locating and data relay and to recommend possible improvements where required. In particular, we sought to determine if ARGOS could support the peak demand envisioned in the Conclusions of §3. A brief description of ARGOS, its ability to support positioning of inexpensive transmitters, and its ability to meet anticipated demand for data relay are considered below. Since GOES provides an important supplement to the data relay capabilities of ARGOS, a brief description of that system is included.

4.1 ARGOS System Description

System ARGOS receives and processes Data Collection Platform (DCP) signals for data relay and platform location. It is carried by the TIROS-N/NOAA A-G series of quasi-polar orbiting environmental satellites. From a typical altitude of 850 km the satellite has a field of view at the earth surface of approximately 5000 km diameter and an overpass lasts for approximately 11 minutes. Successive satellite groundtracks are separated by 25° of longitude at the equator so that a DCP is generally within the field of view on from four to twelve overpasses per day, depending on its latitude.

Typical ARGOS transmitters require 10 to 15 watts of power during transmission and employ simple omnidirectional antennas between 20 and 50 cm long. Each DCP transmits independently without need of interrogation or clock synchronization between the various

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DCPs. The relatively low power, simple antenna, and absence of the receiver required for interrogation are the operational characteristics which make ARGOS so attractive for unmanned buoys.

Each DCP transmits on a regular cycle of between 40 and 60 seconds so that as many as 16 transmissions from any DCP might be received during a single overpass. Each DCP transmission consists of a 280 ms preamble containing a unique code identifying the DCP and various other overhead data. Each transmission also includes a data record of from 32 to 256 bits sent at 400 bits per second and lasting from 80 to 640 ms. The maximum transmission length is thus 0.92 second.

All DCPs transmit with a carrier frequency of 401.65 MHz ± 1.2 kHz. The frequency of the signals received at the satellite depends on the offset (stagger) of the transmitted carrier from the nominal 401.65 MHz, transmitter instabilities of the order 10 to 100 Hz, and the Doppler frequency shift caused by the relative motion between satellite and transmitter. The Doppler shift depends on buoy-satellite kinematics and has a maximum value of approximately 9 kHz. Specifically, the Doppler shift is

$$\Delta f = \left(\frac{v}{c}\right) f_o \cos(\alpha) = \cos(\alpha) \times 9 \text{ kHz}$$

where f_o is the carrier frequency, v is the satellite speed, c is the speed of light, and α is the angle between the satellite track and the vector from the satellite to the transmitter.

Because the DCPs are not synchronized, their emissions are essentially random in time, making it possible for more than one to arrive at the satellite at one time. If two signals arrive simultaneously, and if their frequencies differ by less than the required separation, they will interfere and one or both may be lost. However, the separation of frequencies induced by Doppler shift coupled with the frequency stagger between different transmitters may permit reception of several simultaneous signals.

Each ARGOS receiver processes up to four simultaneous signals by means of four separate phase-locked-loops (Data Recovery Units or DRUs) which lock onto signals following assignment by a search unit which performs a continuous frequency sweep within the receiver passband of approximately 24 kHz.

DCP location is deduced from the Doppler shift of several transmissions from a given transmitter. In principle, location can be determined from three transmissions, even if the exact carrier frequency is not known; in practice five are used to improve accuracy. There is an across-track ambiguity in location determined from a single overpass, but this is readily removed using data from successive passes.

4.2 GOES System Description

The Geostationary Operational Environmental Satellite (GOES) Data Collection System relays environmental data from Data Collection Platforms (DCP)s via a system of U.S. satellites. The system includes GOES East and GOES West spacecraft which cover an area from eastern Australia across the Americas to western Europe and Africa between approximately 77 degrees north and south latitude. A third geostationary satellite is in orbit over the equator midway between GOES East and GOES West as a backup in the event either of them fails. This standby satellite is normally used during periods of eclipse to prevent loss of data through either the East or West spacecraft.

The GOES Data Collection System supports two operational modes, interrogate and self-timed, and an experimental random reporting mode. In the interrogate mode the platform must be polled through the satellite before the DCP can transmit its data. In the self-timed mode a specific time slot on a spacecraft channel is assigned to a DCP which is then internally programmed to transmit only during the assigned time slot. Typical message length for a self-timed DCP is 30 to 35 seconds. In the random reporting mode the DCP transmits whenever a preset threshold of a critical measurement parameter is reached. In oder to insure a high probability of a random message being received, the random messages are short (2 to 4 seconds) and are repeated in a random manner one or more times.

The GOES data transmission rate for all operational modes is 100 bits per second. Maximum message length is four and one half minutes. All messages are checked for parity errors and transmission quality. There is no processing of data into engineering units.

Each GOES spacecraft has 233 channels in the range 401.7-402.1 MHz. Of these, 200 are domestic and 33 are international. The international channels are common with the European METEOSAT and the Japanese GMS spacecraft, thus allowing platforms to move from one area of the world to another without losing data.

Currently, small moored buoys use a GOES DCP with a 10 watt transmitter and a 3 to 5 dB gain logarithmic spiral antenna, which is a cone one meter high on a base plate 0.43 meter in diameter. The antennas can be purchased for three elevation angles to the GOES spacecraft: 20 degrees, 40 degrees, and zenith. Larger buoys will use a GOES DCP with a 40 watt transmitter. While GOES transmitters require three to ten times the power required for ARGOS transmitters, the average power to transmit a particular message is typically less. While the ARGOS message is repeated frequently during the day, the GOES message need be sent only once. An ARGOS transmitter sending maximum length records uses about 3 watt-hours per day. A GOES transmitter drawing 50 watts during transmission can send a 10,000 bit message twice with this energy.

The user may build or purchase a station to receive and readout the GOES data directly from the spacecraft, independent of the GOES ground system. Most users, however, receive their data via a dial-in telephone line to the Central Data Distribution Facility in the World Weather Building at Camp Springs, MD. The user pays the cost of the telephone. There is no charge for the data.

The GOES Data Collection System is operated and funded entirely by the U.S. although many non-U.S. organizations use the system. International agreements limit its use to the relay of environmental data with a minimum of data collection platform housekeeping information. It is available for use by any organization which complies with the requirements established by the National Environmental Satellite, Data, and Information Service of NOAA. Currently, there is no charge to the user.

4.3 ARGOS Locating

The accuracy of ARGOS locating is primarily dependent on knowledge of the satellite orbit and on the medium term stability of transmitter frequency, that is, the change in frequency during one overpass of approximately 11 minutes. The Detailed ARGOS Technical Document (ARGOS, 1978) indicates location error increases approximately linearly at a rate of about 0.5 km per Hz change in carrier frequency over 10 minutes. The present ARGOS specifications, to which commercially available transmitters conform, limits this medium term drift to 2 Hz per ten minutes, so that approximately 1 km of the present systems error may : ascribed to transmitter medium term frequency drift.

ARGOS employs various transmitters at known locations to improve knowledge of satellite orbits. In mid-latitude tests of location accuracy, when users compare ARGOS fixes to the known location of their transmitter, it is found that the standard deviation of the error is of the order 1 km. These are probably optimistic tests because the test sites are near ARGOS calibration transmitters so that orbit determination is better than at a typical mid-ocean site. Nevertheless, it is clear that the ARGOS system provides very accurate locating.

Discussions with transmitter manufacturers suggest that the two specifications which impact most on transmitter complexity are the medium term frequency stability and the requirement that the spurious transmissions be suppressed 40 dB within 20 kHz of the carrier and 30 dB outside this range.

It seems that the medium term stability requirement for ARGOS transmitters is essential for maximum performance. However, the requirement also may contribute to transmitter cost and thus prohibit widespread oceanographic use of inexpensive current-following drifters which need not be located with 1 km accuracy.

The ARGOS specification for spurious emission is presumably intended to insure that one DCP does not interfere with another that does not share its frequency. It seems, however, that a 40 dB requirement may be much more than is needed and might be relaxed in the interest of maximizing system utility.

We recommend that ways to increase ARGOS locating utility through use of less expensive transmitters be studied. Possibilities are

1) making ARGOS transmitter certification specifications more flexible to permit degraded performance where it reduces user costs;
2) exploring ways in which mass production could be used to reduce unit costs.

4.4 ARGOS Data Relay Capacity

In §3 we have concluded that there is demand for relay of substantial data messages, up to something like 10,000 bits daily, through System ARGOS. It is also likely that future intensive ocean experiments may involve demand for data relay from 200 platforms simultaneously within the field of view of an ARGOS satellite. Because of the random access nature of the ARGOS system, as the number or length of transmissions made during an overpass increases, so does the fraction of messages lost through interference, and eventually the system becomes saturated.

Although a single transmission from an ARGOS DCP is limited to 256 data bits, there are two mechanisms by which a platform may send large data volumes, namely the use of multiple identification codes and commutation of data records. The combination of these two techniques provides ARGOS with considerable flexibility to deal with a wide range of data message lengths.

A 256 bit ARGOS transmission lasts 0.92 second, so that a single platform can send, during one repetition cycle of 40 to 60 seconds, a 10,240 bit message if it is distributed through 40 sequential transmissions. Each transmission must contain a different DCP identification code, thus appearing to System ARGOS to be from a different platform. While this is less efficient than a single long transmission would be (30% of the total transmission is preamble), it provides ARGOS with the flexibility to accommodate a wide class of users.

ARGOS relays each of the sequential data records received from each DCP during each overpass. Thus by distributing a data message over several sequential transmissions it is possible to send messages longer than 256 bits using a single buoy identification code and transmissions of 0.92 second. While the order of ten transmissions might be sent during an overpass, this provides no redundancy of transmission and is, therefore, highly susceptible to data loss from interference. One commercial vendor achieves satisfactory results relaying 1024 bit messages in four commutated transmissions.

ARGOS is presently structured to allocate 4098 different identification codes, which comfortably exceeds the number of platforms expected in the next decade. This number of DCPs probably could be accommodated if they were uniformly distributed over the globe. The practical system capacity is limited by the data loss resulting from interference between transmissions when many DCPs are simultaneously within the satellite field of view.

In §3 we have estimated that during a future intensive field experiment the 5000 km diameter field-of-view of an ARGOS satellite might include the following mix of buoys:

(A) 75 current-following drifters transmitting 32 bit messages

(B) 75 current-following drifters transmitting 64 bit messages

(C) 30 instrumented buoys relaying 512 bit messages every 12 hours

(D) 5 high-volume buoys relaying 5120 bit messages every 12 hours

A reasonable message structure would be to commute the 512 and 5120 bit messages over four sequential transmissions and to employ 5 identification codes for each high-volume buoy. This would result in 101 seconds of buoy transmission during each 40 to 60 second transmission cycle. If the transmissions were perfectly synchronized and the frequencies of simultaneous transmissions were always well separated, this could be handled by the four DRUs in an ARGOS satellite. But in practice data will be lost because only four signals can be received at one time and because simultaneous transmissions will interfere.

A quantitative estimate of the data lost by interference among a reasonable mix of buoy types is provided by the ARGOS performance simulations reported by ORI (1982). The collection of DCPs used in that study was

Buoy Type	Number	Bits per Burst	Bursts per Message	Burst Interval	Bits per Message
A	40	32	1	60 sec	32
B	40	96	1	60	96
C	6	192	4	60	768
D	1 or 3	256	40	12	10240

Each D-type buoy employs five separate identification codes. The DCP mix employed in the simulation differs from the projection of §3, involving a larger fraction of high-volume buoys, between 40% and 80% of the total data throughput, and between 45% and 55% of the total transmission time per burst cycle. The difference is, perhaps, less than the uncertainty of the projections and does not affect the conclusions concerning system saturation so long as it is noted that the projected demand is larger than that used in the simulations by a factor of 1.5 to 2.

The simulations involved a number of realizations of buoy location, overpass geometry, transmission timing, and transmitter frequency stagger. Type A and C buoys were placed randomly with uniform distribution over an "operating region" subtending 45° of longitude and running from the equator to 60°N, corresponding roughly to the size of the North Atlantic. Type B platforms, meant to represent drifters and non-oceanographic users, were distributed randomly over a region four times the area of the operating region. For single high-volume buoy simulations the type D buoy was at the center of the operating area; the three D-type buoys were placed in a 750 km triangle at the operating region's center. DCP transmission times were randomly distributed and transmission frequencies were selected to have a Gaussian distribution with 670 Hz standard deviation.

Signals were considered receivable if the satellite was more than 10° above the buoy's horizon and a DRU was available for processing. The simulation determined the degree of interference resulting from simultaneous transmissions. An interfering transmission increases the probability of bit errors in the received signal, just as if the signal-to-noise ratio were reduced. The increase in error rate depends on the frequency separation of the simultaneous transmissions and their relative signal strengths. The minimum ARGOS bit-error-rate (BER), corresponding to no interference and typical signal-to-noise ratio, is approximately $2x10^{-5}$.

In the simulation each transmission was examined to determine the BER associated with interference from simultaneous transmissions. If the BER exceeded the maximum allowed, then the entire transmission was considered lost. The "fraction of data received" is the average number of individual transmissions in a message received at least once in four successive over-passes divided by the number of such transmissions in a message. If, on average, 2 of the 40 transmissions making up a high-volume buoy message are not received on any of four successive overpasses then the "fraction of data received" is 38/40.

The simulation results, described in Figures 5 through 7, are presented as the average "fraction of data received" *vs.* the allowable bit-error-rate. Figure 5 shows that almost all messages from minimal drifters of type A are received at quite low error rates. Type C instrumented buoys, which because of message commutation repeat individual transmissions less frequently, are subject to greater data loss from interference. Nevertheless, Figure 6 shows that over 95% of the type C buoy transmissions are received with error rates less than 10^{-3} even when there are three high-volume buoys in operation. From Figure 7 it is seen that a single high-volume buoy wiil be received successfully with high probability, but the mutual interference between three such buoys leads to significant data loss. Type D buoys are most subject to interference because each transmission is repeated only every eighth burst cycle.

It will be noted from Figure 7 that even under the worst simulated situation, 90% of the high-volume buoy's messages are received with a bit-error-rate of 10^{-2} or less. The interference which leads to this BER is considerably less than that required to cause the ARGOS DRU to lose lock with the signal. Thus it is possible that, using ingenious error correcting coding of the data, the desired data throughput could be achieved.

While the primary reason for having two operational ARGOS satellites is to guard against complete loss of service in the event of satellite failure, the problem of saturation is much reduced when two systems are operational. With only one ARGOS satellite in operation, the

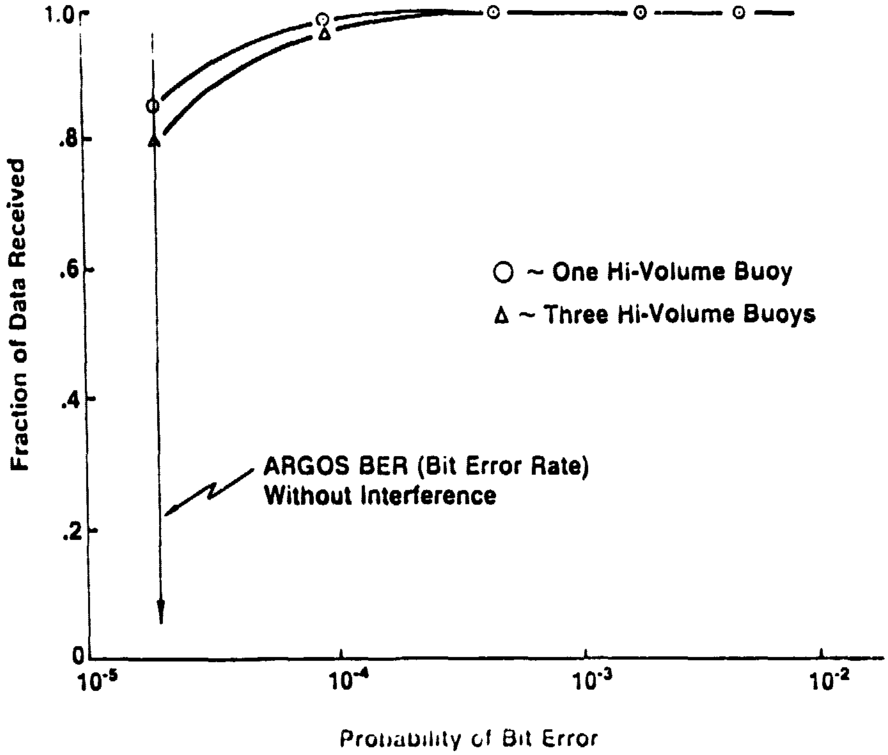

Fig. 5. Fraction of data received at least once in four successive overpasses with less than the indicated probability of bit error (bit-error-rate) for type A buoys transmitting minimal 32 bit messages. From ORI (1982).

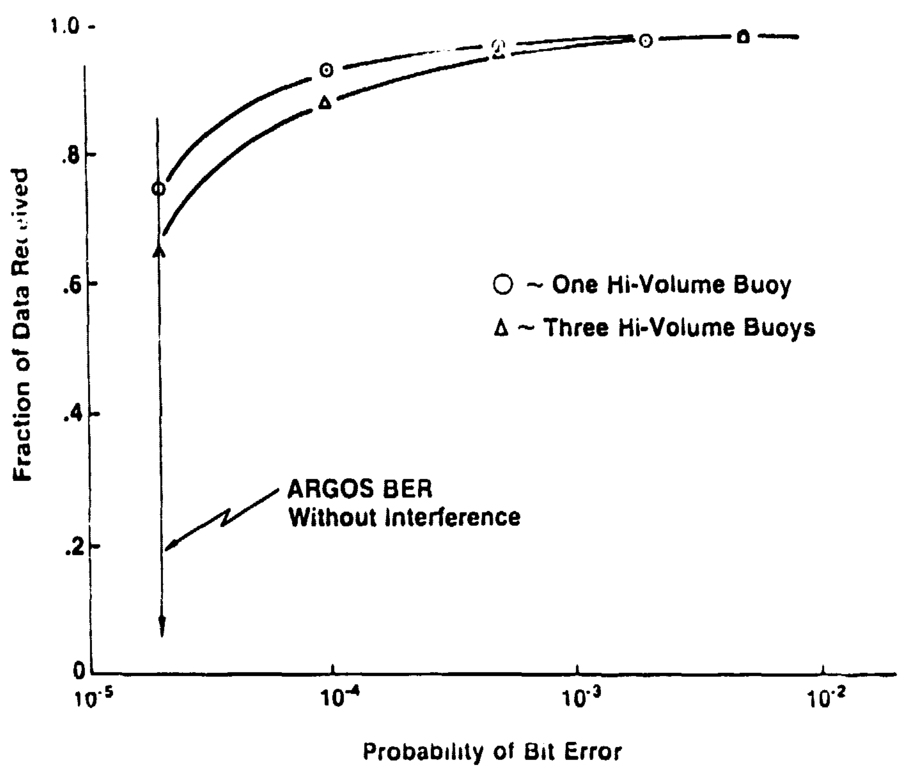

Fig. 6. Fraction of data received versus bit-error-rate for type C buoys transmitting 768 bit messages.

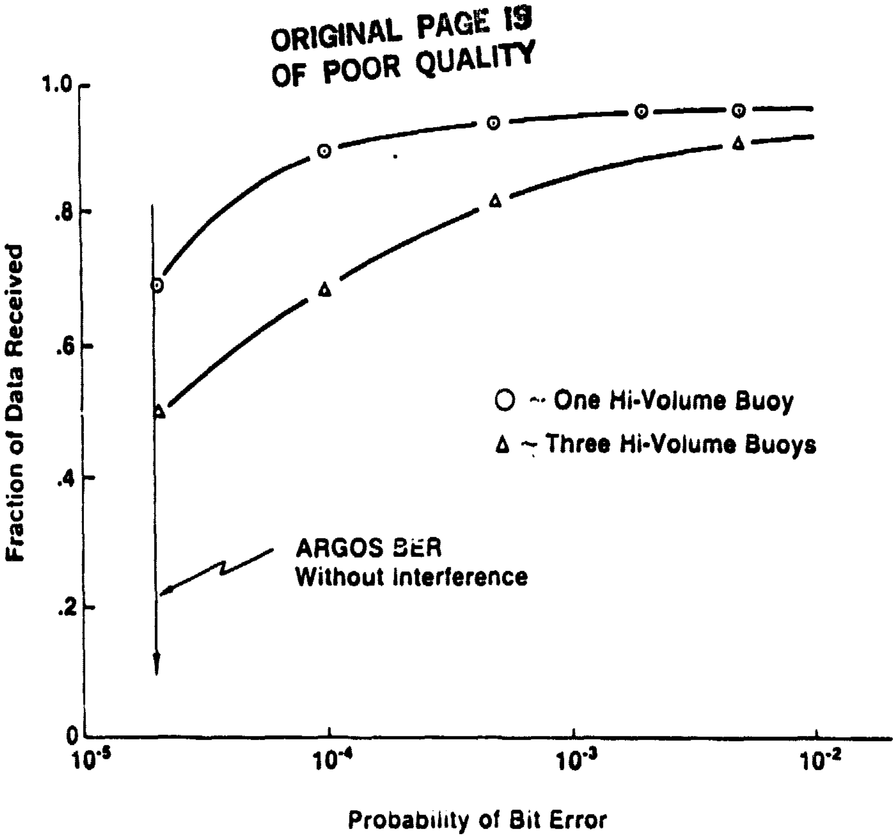

Fig. 7. Fraction of data received versus bit-error-rate for type D buoys transmitting 10240 bit messages.

simulation results represent the data throughput achievable in a 12 hour period. In order to approach the daily data volume projected in §3 it would be necessary to update the DCP messages every 12 hours. However, if there are two satellites in operation, users have the option of increasing data volume by changing messages every 6 hours or increasing the fraction of data received by recovering some lost transmissions during the four successive overpasses of the second satellite. If F_1 is the fraction of data received in four overpasses, then the fraction of data received using two satellites will be

$$F_2 = 1-(1-F_1)^2$$

In a similar way, if there are two satellites in operation it would be possible to have current-following drifters, which represent a majority of the total transmission time, transmit for periods of about 9 hours and then remain silent for the next 9 hours. This would reduce the number of DCPs seen by the satellite at any one time and yet provide location data every 12 to 18 hours; if one satellite fails, then data is provided approximately every day.

The simulation results show clearly that the data relay demands projected in §3, which exceed the simulated demand, will saturate the ARGOS system with one operational satellite. If two satellites are operating, all drifters operate with a 50% duty cycle, and all data messages are updated every 6 hours, the projected demand is approximately equivalent to that used in the simulations. In this case there is a significant quantity of data lost to interference and the system must be regarded as marginal.

Ashcraft and Marini (1981) recently studied the capacity of ARGOS to locate DCPs transmitting minimal data messages. This study included an examination of the effect of increasing the number of ARGOS DRUs above the present four. Their results indicate that this would not significantly increase capacity unless the system bandwidth were also increased. There are two ways in which this might be done:

1) increase the allowable transmitter frequency stagger and the search bandwidth of DRUs with the present ARGOS characteristics
2) add a high-speed data-only channel for large data volume users.

Both options could be implemented with minimal operational impact if there is spectrum space available. The second-channel option would be most attractive from an operational viewpoint if the same transmitter could be used to access the data-only channel and the conventional platform locating channel.

From the simulation results it is clear that if demand increases as anticipated, then the ARGOS system will be saturated within a decade. While GOES can accommodate some demand, the associated technical difficulties of power and antenna make this unsatisfactory in many cases. For this reason we recommend that ways of expanding ARGOS data relay capacity be studied. It appears that this will require an increase of the system bandwidth.

5. SUMMARY AND RECOMMENDATIONS

In §2 a number of applications of satellite data relay and platform locating were presented. This discussion demonstrated that these satellite services now play an important role in oceanography and that their importance is increasing. Oceanographers are now purchasing and developing equipment which will make greater use of satellite data relay and location, and consequently increase their dependence on these services. This fact dictates:

> **Recommendation 1.** Satellite scheduling should take into account the high scientific value and direct cost of ocean data which would be lost by a hiatus of satellite services. Of particular concern are (1) the fact that degradation of the TRANSIT navigation system without implementation of GPS will severely compromise many commercial and scientific ship operations, and (2) the fact that if only one ARGOS satellite is scheduled to be operational, then a single premature failure would lead to the irretrievable loss of a large volume of valuable ocean data. Because oceanography has come to rely heavily on satellite navigation and ARGOS, these services should be supported. We strongly recommend (1) maintenance of TRANSIT or rapid implementation of GPS, and (2) scheduling to provide two operational ARGOS satellites in the absence of a premature failure.

In §3 a number of ocean systems making use of satellite data relay and platform locating were described. This discussion provided several examples of ocean technology recently developed to exploit the availability of satellite services and demonstrated that such development is leading to new and exciting ocean technology. Because of changing economic constraints on oceanography--in particular, increasing ship operation costs--and the increasingly sophisticated questions being asked of observational oceanographers, it is essential that such development be continued. Thus,

> **Recommendation 2.** Support for development of *in situ* ocean measurement technology necessary for the full exploitation of satellite systems should be continued.

One of the specific technologies recently developed is the direct measurement of upper ocean currents from underway ships using profiling acoustic velocimeters. In order for these systems to provide absolute currents it is necessary to determine ship motion over periods of the order 10 minutes with an accuracy of 10m. While this is possible in some locations using LORAN-C, only GPS can provide such accuracy on a global basis. Thus,

> **Recommendation 3.** The high accuracy capability of GPS should be made available to the oceanographic community. Until there is an operational need for real-time current observations, there will be no major disadvantage to providing this high accuracy capability only during post-observation data processing.

A large fraction of the ocean systems using satellite data relay and platform locating are unmanned buoys. The ARGOS system provides both functions with a single system; the ARGOS system is very well designed for ocean users. In §3.1 it was noted that the present ARGOS locating accuracy exceeds the requirements for many ocean current observations using drifters; our ability to describe currents would be enhanced if the cost of buoy transmitters were reduced, permitting more numerous observations, even if this necessitated degraded accuracy. It was also noted in §3 that the demand for data relay is increasing and that projected demand to relay data volumes of the order 10,000 bits per day from a few high-volume buoys may saturate ARGOS capacity.

Section 4 addressed the capabilities of the ARGOS system. It was suggested that the high cost of commercial buoy transmitters may be due, in part, to overly severe ARGOS certification specifications. The relatively low volume of production certainly contributes to cost. Thus,

> **Recommendation 4.** A technical study should be undertaken to determine how best to provide low cost ARGOS transmitters, even if they are not capable of providing the high location accuracy of present transmitters. This may be possible through a combination of encouraging mass production and relaxing transmitter certification requirements.

It was founo in §4 that projected demand for data relay will severely saturate a single satellite ARGOS system and significantly degrade a two satellite system. Thus,

> **Recommendation 5.** A technical study should be undertaken to determine how best to increase the data relay capacity of ARGOS, particularly its ability to support a small fraction of users relaying large data volumes. It appears that increased capacity will require an increased ARGOS bandwidth. The spectrum space available for ARGOS transmitters of the present type could be increased or a separate high-speed data-only channel might be added. If the data-only channel is added, it should be accessible to transmitters which can, through frequency change, also be located.

APPENDIX A

GLOSSARY OF TERMS

ARGOS	present satellite data relay and platform locating system
ATS	Advanced Technology Satellite - experimental satellite used now for data relay to ships
AVHRR	Advanced Very High Resolution Radiometer - provides infrared images of the ocean surface
BER	bit-error-rate
CODE	Coastal Dynamics Experiment - a study of coastal circulation
CUEA	Coastal Upwelling Ecosystems Analysis - a study of coastal upwelling
DCP	Data Collection Platform
DRU	Data Recovery Unit
El Niño	see ENSO
ENSO	El Niño Southern Oscillation - large scale climate event centered in the tropical Pacific
EPOCS	Equatorial Pacific Ocean Climate Studies
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Programme
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GTS	Global Telecommunications System
INDEX	Indian Ocean Experiment - a study of Indian Ocean circulation
JASIN	Joint Air-Sea Interaction Experiment - an international GARP experiment
LUT	Local User Terminal - local real-time receiving station
MARISAT	maritime communications satellite: Communications Satellite Corp.

MILE	Mixed Layer Experiment - an upper ocean process study
MODE	Mid-Ocean Dynamics Experiment - a study of mesoscale ocean dynamics
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NORPAX	North Pacific Experiment - a study of climate variability in the North Pacific
PEQUOD	Pacific Equatorial Ocean Dynamics - a study of equatorial processes
POLYMODE	a joint US-USSR experiment on mid-ocean dynamics
SEQUAL	Seasonal Equatorial Ocean Dynamics - a study of equatorial processes
Ships-of-Opportunity	commercial or fishing vessels which serve as instrument platforms
SOFAR	long-range acoustic propagation in the oceanic sound channel
STREX	Storm Response Experiment - an air-sea study near Ocean Weather Station P
TIROS	Television and Infrared Observation Satellite
TRANSIT	present satellite navigation system
TROPIC HEAT	a study of climatic variability in the Pacific
XBT	expendable bathythermograph - instrument used to collect subsurface temperatures

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