# ENHANCED DATA HARVESTING FROM IN SITU, OCEAN-OBSERVING SYSTEMS

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## ABSTRACT

Responsive global-scale climate modeling and forecasting require comprehensive and timely data retrieval from observational networks. Satellite-based remote sensing has revolutionized oceanography, but the kinds of data that can be collected is limited. Most measurement buoys return at most a few thousand bytes of data per day. The harvest of data from *in situ* platforms must increase by orders of magnitude if scientists are ever to understand the complexities of the Earth's climate.

We report on the results of a NASA SBIR-funded effort to develop an advanced buoy platform and an enhanced data-transmission system, with the potential of returning at least 500 kilobytes/day of data from each buoy. The communications link is two way, allowing researchers to send commands to the remote system to alter its operation at any time. The ability to retrieve large amounts of data in real-enough time will change the way remote oceanographic data collection is done.

## 1.0 REMOTE SENSING & OPERATIONAL OCEANOGRAPHY

Satellite-based remote sensing has significantly extended climatological research capabilities and global models are showing success. Pioneering global climatology, however, has had little technological support for global-scale research: early ocean observing was restricted to buoys with data storage that limited the scope of investigation, particularly when data retrieval was delayed by months or years. Available (or practical) technology necessarily affected the questions that could be considered and, to be effective, large-scale models have had to wait for large-scale observing systems. Comprehensive and timely data retrieval from observational networks, both remote sensing and *in situ*, is necessary for responsive, global-scale climate modeling and forecasting.

Instruments on remote sensing satellites typically observe the entire surface area of the world's oceans every two days, mapping the ocean in several bands of the electromagnetic spectrum, a practical impossibility with standard shipboard oceanographic survey techniques. However, once a satellite is launched, it is virtually impossible to retrieve the instruments to perform maintenance or recalibration. *In situ* measurements are required on a continuous basis to provide reliable, verifiable data to compare with the on-orbit data. By comparing the satellite data to *in situ* data from the same location and time, satellite data can be adjusted to compensate for drifts in the on-orbit instrumentation. In this way one can perform a virtual recalibration of the instrumentation on a regular basis. Every instrument on every

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satellite must have this validation of their data, and the more *in situ* data are available, the more accurate and trustworthy the on-orbit data become.

Although satellites provide vast amounts of spatial and temporal information about the sea-surface layer, they typically do not provide information on sub-surface conditions. Nor can they give a complete picture of conditions at a particular site over time, except on long time scales, since they can only observe any particular site at most a few times per day. By contrast, *in situ* observations can provide information about the vertical distribution of temperatures, salinity, currents, organisms, and light through the water column. These are data central to global change research. A buoy moored in a single location for a long time period provides a complete picture of diurnal and interannual processes, albeit for a small sample area. They also can provide complementary information about nutrient distribution and other variables, such as the presence of suspended sediments that can affect ocean color. Therefore, *in situ* oceanographic platforms are required to make observations of not only ocean surface conditions as a calibration reference to satellite images, but also to provide additional observations that can support more direct estimates of primary productivity, biological processes, and carbon uptake and how these variables change with depth.

Changes in technology and the scale of ocean research have spawned a new concept in data collection: operational oceanography, the idea that large-scale programs of data collection operate independently from the users of the data. Until now, data users developed their own buoy programs at great expense and use of scarce internal resources. In operational oceanography, resources are shared and used more efficiently such that much more data can be collected and analyzed by more researchers. Expertise in observational technology then reposes not only in the scientific community, but with commercial and government agencies as well, all with a role to play in operational oceanography.

Programs such as CLIVAR, PIRATA, TOGA, WOCE, GOOS, and GCOS hope to expand observational networks with hundreds of additional buoys and enhance existing systems with additional sensors collecting vast data sets, but how is all that data to be retrieved? Most measurement buoys, using currently available satellite communications, can return only a few thousand bytes of data per day at most, and recovering complete observational data sets must wait for physical retrieval of the buoy. Numerical climate models, previously crude because of computer limitations, can now be much more detailed in temporal and spatial resolution, provided that enhanced computations are constrained by increasingly comprehensive data. Improved models will need continual updating of data for verification and assimilation, for example, to suppress chaotic tendencies and model the bifurcation dynamics present in the global system. The timely harvest of data from *in situ* platforms must be increased by orders of magnitude if scientists are ever to understand the complexities of the Earth's climatic systems.

Better ocean-observing systems are required for climate research, since the development of new models for climate change depend on more complete and more accurate data being collected in real-enough time. Present ocean observations are not designed for collecting the required data over all the ocean’s important regions and are generally time-limited, so can not provide the continual data required. Global warming studies require more, accurate, and long-term data to improve models to allow predictions and studies of effects on mankind (e.g., predict sea-level rise). The present state of technology makes implementation of a truly global ocean-observing system possible. Present deficiencies in technology require that improvements be made in surface buoys and data telemetry; the lack of satellite data telemetry with global coverage and adequate data capacity could quickly become the over-riding limiting factor.

## 2.0 ENHANCED DATA HARVESTING FROM OCEAN-OBSERVING SYSTEMS

A major impediment to timely ocean-observing contributions is the lack of an affordable communication infrastructure for retrieving observational data. Current data transmission services are not optimized for oceanographic data use and do not meet current and future needs. It is evident that what is necessary to support the oceanographic community at large is a standardized, end-to-end system solution that addresses the problems presented by high-volume, interactive, ocean-data collection.

Oceanographers, at present, are unable to use simple two-way radio telemetry on remote platforms because they typically lack a direct line of sight to the remote platforms. Available commercial satellite communication systems are limited by cost, data volume, or restricted to out-going messaging only. This forces many ocean research programs to deploy instruments utilizing minimal or no telemetry. These instruments must be recovered or visited on a regular basis at great expense for complete data sets to be retrieved. As the oceanographic community moves to longer and longer deployments, made necessary by the requirements of global change research programs, the risk of losing the instrumentation and the data increases to unacceptable levels. The rapid and reliable return of the data becomes increasingly important.

The limited capabilities of Argos and GOES have been heavily utilized by the oceanographic community to return data from long-term moorings. However, throughput is limited to a few thousand bytes of data per day, and a complete data set has to wait for physical retrieval of the buoy. The newly developed low-Earth orbiting (LEO) satellite services such as Orbcomm, Iridium, and Globalstar are designed for millions of users with very short messages, thus providing either very limited data rates or charging extravagantly for the volumes of data required for oceanography. The geosynchronous satellites, such as Inmarsat and Intelsat, are designed for real-time transmissions at much higher throughput than is needed and are, as a result, prohibitively expensive.

Although some applications demand real-time transmissions, most require only what we refer to as “real-enough time” data: data received on the same day in which it was collected, which is suitably timely for most purposes. Wavix has developed a data transmission system for our own moorings, which we plan to make available to the oceanographic community. The system offers the potential of returning at least 500 kilobytes of data per day from each buoy directly to the researcher. In addition, the communications link is two way, allowing the researcher to send commands to the remote system to alter, say, its data-handling protocols or observing schedules in response to events observed in the harvested data stream.

Two-way communication is a new possibility of particular interest to oceanographers. Commands can be sent to a remote buoy to recover from failures or to change experiment parameters in response to interesting phenomena. This type of interactivity will become more critical as expanding global climate change research creates new opportunities for research that will require greater flexibility in setting up and changing experiment parameters based on trends seen in the harvested data stream.

With the emergence of operational oceanography, a new generation of two-way satellite communications telemetry is required to provide the connection between the research laboratory, various modeling efforts, and environmental monitoring and management efforts. Such satellite telemetry will provide the link between the remote platforms and vessels which are observing the ocean and atmosphere.

Improved satellite communications for buoys means the potential exists to integrate comprehensive *in situ* data with satellite data into a truly global, ocean-observing system.

## 3.0 THE WAVIX BUOY

Wavix has developed a next-generation moored buoy system (Shaumeyer, 1999) with a modular design so that its suite of sensors and its data-gathering software can be easily reconfigured to support a variety of scientific experiments. Resulting from the partnership between Wavix and Woods Hole Oceanographic Institution, this design is a refinement of the platform WHOI designed for the GLOBEC (GLOBal ocean ECosystems dynamics) program.

The buoy features an advanced control and data system, described below, with flexible sensor interfacing that can accommodate a variety of scientific instrumentation. It was for this system that Wavix developed its two-way, high-bandwidth satellite-communications system known as WavSat, described in a later section.

### 3.1. THE BUOY STRUCTURE

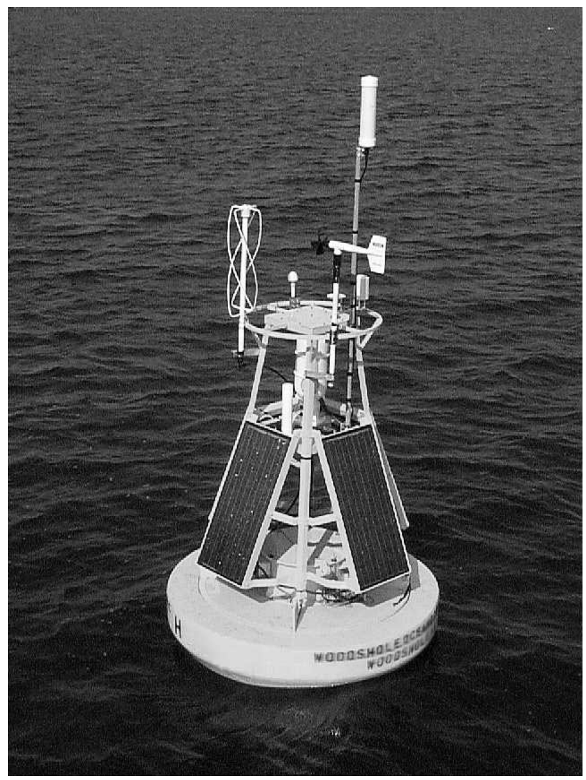

Figure 1. The Wavix buoy.

The buoy structure (Figure 1) is built of four components: the tower, the floatation collar, the electronics well (in the center of the flotation collar), and the base (not visible since it is below the water's surface). RF antennas for the satellite-communication system are visible at the top of the tower: the lower (and larger), helical transmit antenna and the upper (and smaller) receive antenna. The small knob to the right of the transmit antenna is the system's GPS antenna. The overall height of the structure is about 4 m, with the top of the tower about 3 m above the water line.

The tower is made from 6061-T6 aluminum for light weight. It is electrically isolated from the steel base by plastic shoulder washers, and is painted marine yellow with an epoxy finish. Mounted on the tower are the meteorology sensors, solar panels, antennas, and passive radar reflector, flashing light, and sound signal. The solar panels can be swung up to gain access to the electronics well in the center of the buoy.

The electronics well, constructed of welded, hot-dipped galvanized and painted steel, is 24” in diameter and about 45” deep to provide space for the batteries, solar panel regulators, power distribution system, the data system, and the WavSat mobile terminal. Waterproof bulkhead connectors around the top of the well connect external devices to internal electronics. Access to the buoy’s electronics well is through a waterproof hatch in its top. Inside the well, the electronics are mounted on aluminum trays which slide into place along guide rails, so that they are easily lifted out for maintenance.

The base is also constructed of welded, hot-dipped galvanized, and painted steel. The base provides the bulk of the stabilizing weight at the bottom of the structure. This creates a buoy that is stable only in the upright position in the water, even if the mooring breaks. (Other buoy designs are equally stable upside down and easily lost when they overturn and are unable to telemeter their location.) The base also provides a very stable platform for storage and transportation by ship to the deployment site.

The Surlyn-foam flotation collar provides the buoyancy. It is impregnated with a standard yellow pigment to indicate that it is a research buoy and not an aid to navigation. It survives being hit better than a steel buoy that would chip and then rust, and can be snugged up to the ship on recovery without damage to the buoy or ship. The foam also reduces buoy maintenance because it does not bio-foul as severely as steel buoys. To minimize the tilting motion of the buoy in the wave field, the lower portion of the foam is cut with two chines so the bottom of the floatation collar approximates a sphere. Waves therefore apply a minimum of tilting moment to the buoy and, combined with the elastic tether elements in the mooring, a more stable platform is obtained for scientific observations.

For this buoy, WHOI has developed a mooring (Paul, 1998) with highly compliant, elastomeric elements that can stretch more than 100% with very low tension, making the system suitable for coastal applications, although the design is stable for depths of more than 4000 meters. A new feature of the mooring system is the option to attach electronic sensors below the elastic elements, with the added ability to bring signals up to the buoy and send power from the buoy down to instruments. A coiled conductor, developed at WHOI, is spiraled around one of the elastic elements and provides electrical power to attached instruments, and carries telemetry and data back to the surface. Similar coil-cord assemblies have been tested at WHOI and have survived 6 million stretch cycles without failure.

### 3.2. THE BUOY DATA SYSTEM

The data system (Gaither, 1998) is an advanced workstation in a small, ocean-going package. Built around a high-performance PC/104 embedded system, it contains an 80486 microprocessor, 16 Mbytes of RAM, and enough solid-state, non-volatile storage to hold the operating system, system software, and at least one year's unprocessed time-series data, for each installed sensor, at hourly sample rates. Updates to the system clock and geospatial location data to accompany all measurements are provided by incorporating a GPS receiver system in the data system.

We have designed the data system so that it can be easily reconfigured with different instrumentation for different scientific missions. Sensors are interfaced through multiple serial ports, separately configured for either RS-232, RS-422, or RS485 operation. Analog data collection is performed using a PC/104 analog-to-digital converter board. It currently supports 16 channels of single-ended input or 8 channels of differential input, with input signals in either a 5V unipolar range or a bipolar +/-10V range.

The data system runs the Linux operating system, a Unix-like operating system that provides the multi-user, multi-programming process protection and network capabilities found in modern desktop workstations; full Unix security and password protection is naturally incorporated. Linux was a natural choice since it is the only operating system (and unique among Unix implementations) with native support for the AX.25 protocol, necessary for use with our communication satellites. Using Linux has provided us with a robust, flexible programming and operating environment for the buoy software. With a multi-tasking operating system, task scheduling such as collecting measurements in parallel from multiple sensors, and turning sensors on and off is easily implemented. Sampling, averaging, and transmission rates for individual sensors can be independently set.

Although the amount of data transmitted through the satellite link from the remote platform may be limited by choice or practical considerations, the rate of data collection by the buoy itself can be determined independently and is not subject to the same limit. The non-volatile memory that is part of the data system allows the buoy to collect data at much higher rates than can be transmitted. A typical configuration might be to set the sample rates to one-second intervals and then integrate over a 10-minute period to derive a single telemetered measurement every ten minutes, complete with measurement statistics. The buoy can be commanded at any time to alter its sampling program. In any case, the entire data set is stored on-board the buoy for later physical retrieval.

## 4.0 WAVSAT SATELLITE COMMUNICATONS

Wavix has developed a data transmission system (Shaumeyer, 1998; Shaumeyer, 2000) for its moored buoy, which it is making available to the community. WavSat Satellite Data-Communications is our proprietary communication system, comprising a constellation of two, low-Earth orbiting satellites, and an automated remote terminal integrated with the buoy's data system. Daily throughput of up to 500 Mbytes of data is possible, and the return link to the buoy allows complete system-control commands to be transmitted to the remote location. Coverage is global, and the average latency for data transmissions is approximately 1.5 hours, although it can be as much as six hours.

The connection between the researcher and the remote observing system has four elements: the WavSat satellite constellation, the mobile terminal, installed in the remote buoy and controlled by the buoy's data system, the shore-side groundstation, and the Data Center.

### 4.1. SATELLITE CONSTELLATION

The WavSat Satellite Constellation consists of two, low-Earth orbiting (LEO) minisatellites (masses near 100 kg) built and operated by Surrey Satellite Technology, Ltd. Wavix developed the system in cooperation with Volunteers in Technical Assistance and SatelLife, two non-profit organizations bringing technology and health assistance to the people of developing countries.

The WavSat system was specifically designed to support oceanographic research. The satellites operate in polar orbits at inclinations of 65 and 90 degrees, giving the system global coverage. On-board digital radios operate in the so called "Little LEO" UHF (uplink) and VHF (downlink) bands licensed for operation worldwide. Messages are sent between satellite and surface using packet (digital) radio technology; full-duplex operation is possible since uplink (to the satellite at 150 Mhz) and downlink (at 400 Mhz) are performed at different frequencies, with effective baud rates of 9600.

Across this digital-radio link the packet-level transport layer is provided by the AX.25 Link-Layer Protocol, long used by radio amateurs. AX.25 packets perform a similar function to IP packets in the TCP/IP suite of protocols, with the major difference being that source and destination addresses in AX.25 packets are radio callsigns. File uploads are performed in AX.25 connected mode, in which packets are acknowledged and the communication channel is guaranteed to be error free. The applicationlevel layer is the PACSAT suite of protocols, which define high-level mechanisms for transferring files to and from the satellite with identifiable headers, as well as commands and responses for requesting directory listings from the satellite and other operations.

The satellites operate in a store-and-forward mode, much like an electronic bulletin board. Data files are uploaded from the buoy to the satellite, where they are stored in the file system. At a later time in the satellite's orbit (or possibly during the same orbit), our groundstation downloads available files. In a similar fashion the groundstation can uplink files addressed to the remote buoy, which the buoy will then download and process them as appropriate.

## 4.2. REMOTE TERMINAL

The WavSat remote terminal, an independently packaged version of our original buoy radio, is an autonomous, fully automatic, two-way digital radio. It contains its own compact computer system (similar to the buoy data system, described above), providing a good compromise between size, power consumption, and performance. The terminal incorporates its own modem and RF circuitry for use with the WavSat satellites. In operation the radio uses two omni-directional, quadrifilar antennas: the uplink antenna is about 1 m tall and 20 cm in diameter; the downlink antenna is 0.5 m tall with a 10-cm diameter.

A configurable serial port is the digital interface to the terminal for sending data and receiving commands. A data stream fed to the terminal is collected, compressed, packetized, and spooled internally for uplink to a passing satellite. Satellite-tracking software running on the terminal determines when the radio is to establish a data link for upload, and initiates that process. Simultaneously, any command files that are addressed to the remote terminal are downlinked from the satellite, unpacked into a standard format, and passed back out the serial interface to the host system.

## 4.3. GROUNDSTATIONS & DATA CENTER

In operation, the WavSat groundstations operate much like remote terminals. The major practical difference is that groundstations download large amounts of data being sent from many different sources, and uplink relatively fewer command files to various remote systems. The groundstations also operate as Internet gateways so that all data can be sent to the Wavix Data Center as soon as it has been downloaded from the satellite, and so that commands from the researcher's home location to the remote terminal can be relayed by the Data Center.

The Data Center is the single network location from which all remote data are distributed, and through which all commands pass on their way to remote terminals. Relayed by the groundstations, data are processed and immediately made available across an Internet connection. Since the operation is automated, data formats and retrieval protocols are flexible. For the command link, the Data Center creates virtual internet nodes for each remote terminal so that commands are sent to it as simply as electronic mail, using standard Internet-style (RFC 822 compliant) addressing, e.g., *thermometer-1@mybuoy-4.wavix.net*.

## 5.0 THE FUTURE

Instruments on-board satellites require *in situ* data for validation and calibration that can be provided by sophisticated buoys stationed in the world's oceans. Buoys can also contribute continuous time series data between satellite observations at strategic locations, and can be used to measure sub-surface properties. These capabilities expand the usefulness of satellite data by providing more complete measurements of dynamic processes and by measuring ancillary properties for a more comprehensive understanding of these processes.

The ability to retrieve large amounts of data within hours of its being collected, coupled with the ability to send commands to the data platform, will enrich real-time assimilative computer models using remote-sensing data and has the potential of changing the way remote experimentation is done in the oceanography community, and enhance the utility of ocean-observing systems. Oceanographic research programs are typically designed around the limits on how much data can be retrieved. Removing that barrier should allow more and better sensors and more dense data rates such that researchers can look at ocean processes in much greater detail. Such telemetry capability is required as we move toward a Global Ocean Observing System that will return data for scientific studies, weather forecasting, satellite ground-truth observations, resource management, and a host of other uses. These programs cannot wait for instrumentation to be recovered for data, but must continuously have data in near-real time to be of benefit.

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