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THE UHSLC *IN-SITU* SEA LEVEL NETWORK

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1. INTRODUCTION

In a 1973 paper, Klaus Wyrtki identified the potential of sea level observations for the interpretation of tropical Pacific ocean dynamics and climatic variations and the associated linkage to weather phenomena. This lead to the establishment of a network of gauges on oceanic islands that mapped the equatorial current system as well as the equatorial portion of the subtropical gyres of both hemispheres. Data from this network comprised the NORPAX data set, distributed by the University of Hawaii Sea Level Center (UHSLC), and became the basis of many of the early variability studies in the tropical Pacific Ocean (Mitchum and Wyrtki 1988).

During the 1980's, the University of Hawaii with the cooperation of the Pacific Tsunami Warning Center (PTWC) and the Atlantic Oceanographic and Meteorological Laboratories upgraded over 40 station in the Pacific with the installation of satellite platforms and redundant instrumentation (Kilonsky 1984). These upgraded sites enabled the University of Hawaii to provide real and near real-time data sets for the monitoring and analysis of oceanic events, and provided PTWC with invaluable information on tsunami generation and propagation. The success of the Pacific network spawned similar networks in the other tropical oceans, and the University of Hawaii currently operates 10 stations in the Indian Ocean and 5 in the Atlantic capable of satellite transmissions. Data from the UHSLC network are uploaded via the National Oceanic and Atmospheric Agency's Geostationary Operational Environmental Satellite (GOES) Data Collection System (DCS), Japan's Geostationary Meteorological Satellite (GMS) DCS, and the European Organization for the Exploitation of Meteorological Satellites METEOSAT DCS. These real-time data are transmitted from the downlink site to the UH Sea Level Center at the University of Hawaii via the Global Telecommunication System (GTS) of the World Meteorological Organization.

It is important to note the fundamental role that the UH stations play in the global sea level collection system. Data and data products were supplied under the Tropical Ocean Global Atmosphere (TOGA) and Integrated Global Ocean Services System (IGOSS) programs, and the data are also fundamental to the World Ocean Circulation Experiment (WOCE) and the Climate Variability and Predictability (CLIVAR) sea level efforts. None of these activities would be feasible without these UH stations as a major source of the input data.

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In the late 1990's, the UHSLC, in collaboration with the Pacific GPS Facility installed co-located, continuously operating Global Positioning System (CGPS) receivers at selected tide gauge (CGPS@TG) sites. To meet the challenges of measuring global sea level change and to support altimeter drift monitoring activities, other instrumentation has also been upgraded at the CGPS@TG stations. The remainder of this paper will detail the current configuration of the stations in the UHSLC network and present some discussion and recommendations for the design of future global sea level monitoring systems.

2. INSTRUMENTATION

The instruments used at an in-site sea level station can vary from the very simple, a tide staff, to the complex, pressure gauges, acoustic echo sounders, and reference level switches. All of these instruments have one goal in common. They are attempting to measure the difference between the level of the ocean and a fixed point on land. While individual measurements of sea level can vary dramatically in accuracy, even basic measurement, such as those made using a tide staff, can, if properly referenced, provide accurate long term records (Mitchum, 1997).

In an ideal situation, a sea level installation would produce the true water heights referred to a datum for the total period of the observations. However, even using the most accurate and stable of instruments such as acoustic echo sounders and reference lever switches, this is seldom possible. Thus while the UHSLC attempts to record observations that are of the highest possible accuracy, our main emphasis has been on collecting sufficient information to allow the observations to be corrected at the analysis stage. The UHSLC has done this by developing installations that utilize both fault tolerance and redundancy, and by transmitting the data in real-time. The standard UHSLC installation includes redundant stilling wells and float gauges, redundant reference level switches, weather proof enclosures, electric power sources, a tide staff, a microcomputer based data logger, and a programmable data collection platform that manages the logging and transmission of data from the various sensors. The UH sea level systems are fault-tolerant, that is, the total failure of any component in the system will not alter the ability of the system to observe and return data. Both the primary and secondary gauges are magnetic incremental shaft encoders. Stilling wells house the floats and are used to reduce the effect of surface waves. They have a conical base with a hole sized approximately 1% of the cross section area of the well at the apex of the cone. Besides the filtering provided by the stilling wells, we also employ digital filtering in the data logger. The sea level sensor is sampled every five seconds and averaged and logged every two minutes. The sea level sensor is also spot sampled every 15 minutes by a second microcomputer based data logger that has the storage capacity to save approximately one year of data.

For research in long time and space scales, sea level data must be related to a very stable datum or a fixed vertical reference point on land. In the UHSLC Network each station has its own local datum, defined by the zero of its tide staff, for the referencing of sea level heights. This datum is carefully measured by connecting the tide staff to permanent benchmarks using surveying methods that allow a maximum error of 0.005 meters. Visual staff readings and spot gauge data pairs are then used to statistically calculate the gauges zero reference level. At all the UHSLC installations the tide staff remains the primary tool for establishing the final sea level datum, however as a backup the UHSLC has designed an automated reference level switch. Though this instrument was initially developed to supplement the traditional method of using tide staff observations to link gauge observations to a fixed datum, it has over the years proven to be a precise technique, and because of the ability of the sites to telemeter data via satellites, information from this instrument has allowed the UHSLC to start assembling sea level information in near real time.

In the UHSLC field program we have continued to develop and test new instrumentation and techniques for measuring and referencing sea level data. Personnel at the center have recently designed and manufactured a second generation self-contained data logging system that is based on an a Persistor CF-1 Single Board Computer (SBC), using a Motorola processor. The data logger runs the PicoDOS operating system, which is similar to MS-DOS, and communicates with the sea level gauges using a SDI-12 interface. The sea level gauges used with this data logger are AQUATRAK acoustic echo sounders. These gauges are the same as those used by U.S. National Ocean Service (NOS) in their sea level installations and when used in conjunction with the reference level switches provide very accurate individual measurements. This new data logger, the AQUATRAK gauges, and the reference level switches serve as the basis for the newly designed CGPS@TG absolute sea level stations.

As in the standard installation, the UHSLC absolute sea level stations utilize both fault tolerance and redundancy to produce the highest possible quality data return. They include two stilling wells with acoustic echo sounders, two reference level switches, weather proof enclosures, fault tolerant electric power sources, a tide staff, the second generation data logger, and an upgraded programmable data collection platform that manages the logging and transmission of data from the various sensors through geostationary satellites. The absolute stations are also equipped with a co-located dual frequency geodetic GPS and a specially designed meteorological sensor package. While these packages measure only minimal meteorological parameters; pressure, temperature, and relative humidity, in support of water vapor measurement calculations, the pressure measurements are also very useful for correcting sea level for the isostatic effects of atmospheric pressure.

3. SEA LEVEL MONITORING SYSTEMS, DISCUSSION AND RECOMMENDATIONS

In 1982, the University of Hawaii first uploaded data from a sea level station using a satellite. Now most of the island stations are linked to the UHSLC using satellite transmitters. Though we understood the implications for improving ocean monitoring, the decision to establish such links was also motivated by a desire to improve the rate of data return from these remote sites and to facilitate maintenance planning by having immediate feedback on the status of the stations. Since the implementation of this strategy in 1982, the percentage of data loss has been reduced from over 6% to less than 2%; that is, we average a better than 98% data return. By quality controlling the data in near real-time, problems with data acquisition or data flow can be assessed and corrected in a timely fashion.

Near real-time data from tide gauges have been shown to contribute significantly to the calibration of altimeters (Cheney et al. 1994; Murphy, et al. 1996; and Mitchum 1994 & 1997). Values from the tide gauge values were used to identify a gradual rise in the data from the TOPEX/Poseidon system. An analysis subsequently showed the rise to be caused by an error in the software used to compute the altimeter range. Given the cost of the satellite, it is clear from this study that a select set of near real-time sea level gauges, mostly from island sites, can provide a relatively low cost calibration to altimeter missions.

While information from tide gauges is important for regional studies, such as those of tides, storm surges, and tsunami, sea level is also very useful for monitoring and predicting the climate system on seasonal to decadal time scales. The UHSLC *in-situ* sea level network is physically constrained to land-based stations and was designed to take optimal advantage of island groups in the oceans. Studies have shown that the spatial scales of the low-frequency sea level variations required only one gauge in each island group and at intervals not less than 1000 km along continental coasts (Roach et al., 1989). Thus, near real-time observations from network gauges provide an excellent basic capability for ongoing monitoring of the ocean circulation (Johnston and Merrifield, 2000), and can be used in the analysis of interannual, decadal, and longer term variability relating to ENSO events (Merrifield et al., 1999), monsoons and other ocean wide fluctuations, and the determination of global sea level rise. The length of the records, compared with other measurements, such as, XBT and TAO buoy records, also make such sea level data extremely important for these types of monitoring and predictability studies, and give near real-time sea level observations added importance for model initialization, validation and assimilation, and supplemented by accurate altimetry measurements, for mapping sea level variability.

The specific spatial design of a global sea level network is beyond the scope of this paper. There are, however, several working groups under the GLOSS (UNESCO 1997) and the CLIVAR programs which are studying the requirements for a core network of gauges, and seek to identify sites for long-term trend monitoring and for calibration of altimeters and the support of ocean circulation studies. Given our current experience in the collection and distribution of sea level products, we can make the following recommendations to these working groups.

As much of the variation pertinent to the ocean's climate variation signal consists of low frequency and large spatial-scale variations, emphasis should be placed on those stations that have long enough data sets, approximately 20 years, to allow detection of sea level signals on the interannual and longer time scales. Emphasis should also be placed on maintaining those stations capable of monitoring the global ocean circulation, mostly on islands and at straits and choke points.

For altimetry calibration and mapping purposes and for model calibration and data assimilation, gauges should deliver their data in real-time via satellite. Again for use with altimetry to enable the calculation of absolute currents,GPS and meteorological sensor packages should be collocated at selected tide gauge sites. As there are no immediate plans to fly multiple altimeters in an operational mode, a set of *in-situ* stations should also be maintained as a backup that can produce near real-time sea level information for monitoring on a global scale.

Finally, one or several centers should be identified to collect, quality control, and distribute near real-time *in-situ* sea level data. The Internet has revolutionized data exchange methods, and any such center should use it to expedite the exchange of sea level data and to facilitate the production of useful products. These centers should also be actively involved in research utilizing *in-situ* data. There is more incentive to collect and quality control the sea level information when it is being used actively for research. For example, the UH Sea Level Center currently has ongoing research in the following areas of interest: tropical ocean dynamics, calibration of altimetry data with *in-situ* sea level data, climate variations on interannual and decadal time scales, the impacts of climatic events on fisheries, and the development of new cost-effective methods for data collection and station maintenance including GPS leveling instrumentation.

4. CONCLUSION

In conclusion, the UH Sea Level Center is currently providing near real-time sea level products for monitoring and studying the ocean's variability and for calibrating and validating satellite altimeter products. With the development of new geodetic techniques based on very long baseline interferometric measurements and the Global Positioning System, the network will provide the capability to establish a global reference frame to link sea level measurements and obtain absolute measurements of global sea level rise for the first time.

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