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The current demand for large spatial arrays of seafloor instruments and deployment times of up to 12 months can be best fulilled by inexpensive, low-power data loggers with modern commercial magnetic disk drives for on-board mass storage. We recently designed, constructed, tested, and used 6 seafloor data loggers equipped with hydrophones for seismic refraction experiments on the Clipperton Fracture Zone and Australian-Antarctic Discordance. The instruments are based on Onset's Tattletale microcomputer, weigh only about 70 kg in air, and cost much less than existing instruments of comparable capability. They can be powered for up to one year, using expendables costing as little as $300 for shorter deployments, and record up to 4 Gbyte of data on disk drives using currently available hardware (10 Gbyte are available at this time), which with modest data compression would allow a sampling rate of 256 Hz over a year. Using modern clock crystals, timing can be corrected to 0.1 s/year or better.

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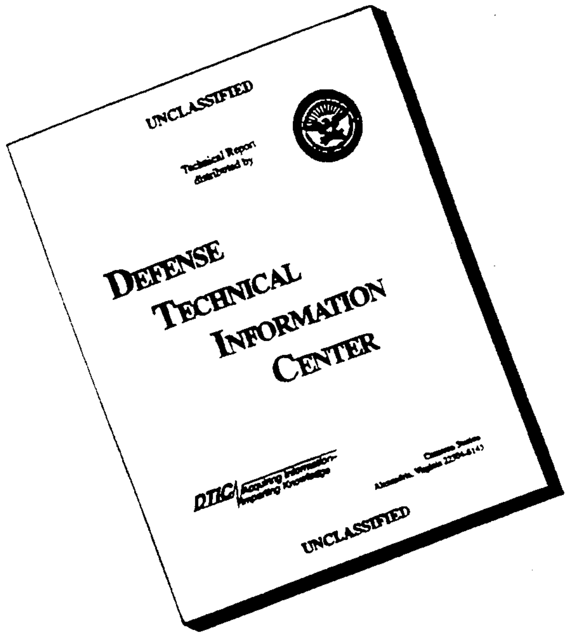

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FINAL REPORT: **Seafloor Data Loggers (Phase 1)**

UCSD 95-1313 (ONR N00014-95-1-1019)

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ORIGINAL ABSTRACT OF PROPOSED RESEARCH:

The current demand for large spatial arrays of seafloor instruments and deployment times of up to 12 months can be best fulfilled by inexpensive, low-power data loggers with modern commercial magnetic disk drives for on-board mass storage. We recently designed, constructed, tested, and used 6 seafloor data loggers equipped with hydrophones for seismic refraction experiments on the Clipperton Fracture Zone and Australian-Antarctic Discordance. The instruments are based on Onset's Tattletale microcomputer, weigh only about 70 kg in air, and cost much less than existing instruments of comparable capability. They can be powered for up to one year, using expendables costing as little as $300 for shorter deployments, and record up to 4 Gbyte of data on disk drives using currently available hardware (10 Gbyte are available at this time), which with modest data compression would allow a sampling rate of 256 Hz over a year. Using modern clock crystals timing can be corrected to 0.1 s/year or better.

This contract supported the construction of five of these instruments equipped with hydrophones at a per unit cost of $12500 for a demonstration project carried out 6 months from the date of funding, to be followed by a companion proposal to construct of 65 instruments capable of 1 to 2 years deployment in both deep and shallow water. The second proposal will include the development a trawl-resistant installation package for use in heavily fished areas of the continental shelf, as well as software and hardware that will allow rapid testing of the instruments and playback of data.

LONG-RANGE OBJECTIVES:

The instruments described would allow a world-wide array of continuously recording hydrophones to be maintained indefinitely.

1. Introduction

In during 1994, in response to a need to expand our seafloor hydrophone fleet for a survey of the Clipperton Fracture Zone, we developed a new instrument around Onset Computer's Tattletale 7, one of the most modern low-power computers commercially available at that time. The internal code name for this instrument was L-CHEAPO (Low-Cost Hardware for Earth Applications and Physical Oceanography). We built 6 such instruments and used them successfully both on the Clipperton experiment and on a later survey of the Australian Antarctic Discordance.

The low cost and power requirements of this new instrument drew the attention of the Naval Oceanographic Office (NAVOCEANO), who were looking for an instrument capable of one-year deployment sampling continuously at 250 Hz. Under support of this ONR/NAVOCEANO contract we have refined the design of the instrument, incorporating the newer, cheaper Tattletale 8, a 16-bit analog to digital converter (ADC), a better clock crystal which will allow time correction to better than 0.1 seconds per year, and hardware modifications and data compression to achieve a total of 40 Gbytes of data after decompression using twin 10 Gbyte disk drives. Using Lithium DD batteries this instrument has a one-year capability. The new instruments are:

1) Inexpensive (cheap): On the initial development cycle the first seven L-CHEAPOs were built for about $11,000 each all up (hardware, flotation, hydrophone sensors, software contract, some salaries, and overhead), although many components were scavenged from existing inventory. Even with further hardware and software development, full costing of parts, and better clock crystals, the price of the NAVOCEANO instruments, determined by dividing the award amount by the number of instruments, came to around $28,000 per instrument. This estimate includes labor, overhead, and sensors. However, the accelerated delivery schedule (see below) makes it difficult to estimate a realistic per-instrument cost based on this contract.

2) Low power: The L-CHEAPO consumes less than 300 mW while sampling at 250 Hz. This means, for example, that the instrument will run for 1 year on only 7.2 kg of lithium DD cells. Additional batteries are needed for mass storage, and is a function of sample rate. 250 Hz data over one year would require

another 3.6 kg of batteries. Short deployments would require very much less. However, power consumption estimates have not yet stabilized for this instrument, as current development efforts are lowering consumption in a number of ways.

3) High capacity: An essential part of the initial development was the creation of the hardware and software to mount SCSI (Small Computer Systems Interface) mass storage devices onto the Tattletale (an option not yet offered by Onset). Disk drives are our device of choice; drives of up to 9 Gbyte capacity are available at this time (at less than $2000 each), and bigger, cheaper, faster and less power hungry drives are being released continuously. During the Clipperton and AAD experiments a variety of drives up to 2.4 Gbyte capacity were used. The development of the NAVOCEANO instrument called for the inclusion of a second disk drive and data compression, quadrupling the capacity to 18 Gbytes using twin 4.5 Gbyte drives.

4) Easy to use: Although fully configurable, once powered the L-CHEAPO will start recording after an elapsed hour if nothing more is done. The instrument is small enough to be deployed and recovered by hand, without the use of cranes or winches. The checkout procedure is simple, obviating the need for highly qualified engineers at sea.

5) Rapidly turned around: The pressure cases are small, easy to handle aluminum cylinders. It takes about 30 minutes to open the pressure case, swap the disk drive and batteries, restart the instrument and close it up again.

Although the 5 instruments were built expressly for NAVOCEANO to their specifications, the experience gained from building these instruments has been used in a broader spectrum of cooperative research. Specifically:

a) We are collaborating with Monterey Bay Aquarium Research Institute (MBARI) and have equiped two seafloor seismometer/tiltmeters with the L-CHEAPO data logger, with the possibility of constructing 5 instruments for them in the future (Stakes *et al.*, 1995).

b) We have made several deployments of 5 L-CHEAPO hydrophones for the marine mammal research program at Cornell University to monitor whale vocalizations and acoustic noise levels, with the possibility of constructing instruments for them in the future (these instruments sample at 1000 Hz).

c) We are lending our own suite of L-CHEAPO hydrophones to McNutt and Caress in April 1996 to conduct an airgun seismic survey in the South Pacific.

d) Two NSF submissions (Tectonic controls on the evolution of a spreading center, Blackman/Phipps Morgan; Measurement of ground deformation at a fast-spreading ridge crest, Tolstoy/Fornari) are based on the new instruments.

e) The L-CHEAPO logger is used in a program to map continental shelf structure for the petroleum industry using electromagnetic sensors. A proprietary survey of this type was conducted in the Mediterranean Sea in October 1995.

2. The Data Logger

The prototype L-CHEAPO was built around the Tattletale 7 data logger with an improved clock crystal and a SCSI interface for mass storage devices. We relied on the 12 bit analog to digital converter (ADC) built into the Tattletale. Under NAVOCEANO support we have improved the clock even more, replaced the Tattletale 7 with the Tattletale 8, added data compression and a second disk drive to quadruple mass storage capacity, and added a 16-bit ADC for increased dynamic range.

The crystal supplied on the Tattletale is inadequate for all but the most approximate timing duties. However, provision is made for an external timebase and on our prototype instruments timing was performed by a 4 MHz "Vectron" temperature compensated crystal oscillator with drift rates are 3 to 30 millisecond per day (1 to 10 seconds per year). Repeat deployments of the same clocks indicate that most timing error is due to miscalibration of the oscillator (or linear drift), and since the clocks are timed against shipboard standards before and after deployment, we can correct for miscalibration and expect an accuracy on the order of a few milliseconds per day, which is adequate for electromagnetic experiments, tiltmeters, and all but the longest seismic experiments. The accuracy afforded by recalibration was adequate for the OBS seismic tomography experiment published by Burnett *et al.* (1989). However, the nonlinear component of drift will produce uncertainties of up to 1 second in year-long deployments, and NAVOCEANO's specification was correction to 0.1 s over one year. The Seascan clocks currently used in the TILT-OBS offer excellent performance (on a recent 68 day deployment of these instruments the average drift rate was 0.2 ms per day), but the price of these clocks with the extra pressure case they would require would easily exceed the entire price of the instruments as proposed. However, Seascan Inc. has produced, partly to our specification, a more compact and inexpensive oscillator with a quoted accuracy of 4 milliseconds per day (1.5 seconds per year). Given that oscillators generally operate much better than specification in the isothermal seafloor environment, and that most of the error is linear drift, we are confident that these will achieve the Navy requirement of clock accuracies correctable to 0.1 s per year (a prototype oscillator has been under test for nearly 3 months to verify this). A great many repeat tests of about a dozen of these oscillators produce typical drift rates of 1 ms per day, well within specification.

Although an IDE disk drive is available for the Tattletale 7, it is not available on the more inexpensive Tattletale 8, and in any case this interface limits the capacity, choice and power economy in available disk drives. It also exempts the use of other storage devices such as DAT tapes or optical WORMS. To use the largest disk drives, desirable for collecting continuous time series, a SCSI interface was built for the Tattletales and driver software written. Data are recorded in a 2 or 4 Mbyte PCMCIA RAM memory module before writing to disk, allowing several hours' data collection, depending upon sample rate, before the power hungry mass storage device is switched on. So far we have successfully operated the L-CHEAPO using 230, 450, 2400, 1000, and 4400 Mbyte drives.

The Tattletale has an integrated 12 bit A/D converter. Although 16 bit ADCs are preferred in most seafloor applications, the short initial development cycle forced us to use the 12 bit ADC in the prototype and sample the hydrophone at two different gains to preserve dynamic range. This compromise doubled the mass storage requirements but provided a simple and immediate solution to our urgent need for new instruments. However, for the current instrument we have developed hardware and software to add a 16-bit ADC to the Tattletale 8.

Total possible recording time depends on the sampling rate. Continuous recording is required for simplicity, reliability and flexibility. Trigger algorithms for seismology applications are complicated and have been suspect in the past. It is clear that continuous recording represents the safest strategy. Of course, ultimately a triggering algorithm must be used to sort out data from noise, but in the laboratory mistakes are less harmful, human intervention is possible, and the algorithm can be modified to suit conditions. The sampling rate is adjustable; currently between 1 and 1000 Hz. We have also implemented a simple data compression algorithm used by the IGPP IDA program which will effect a 50% or more (maximum is 75%) reduction in mass storage requirements. Using one of the 4 Gbyte disk drives readily available at this time, sampling at 64 Hz with no data compression, we can record 1 channel of data for a complete year. Use of two 4 Gbyte or one 9 Gbyte disk drives and data compression extends the sampling rate to 250 Hz for the Navy requirement. Data volume not only has an impact on disk size, but also total power consumption, since less data needs to be written to the power-hungry disk drive.

The bandwidth is limited at the high end by the sample rate, with a maximum Nyquist of 1000 Hz in the current instrument, and at the low end by the sensor. The Hi-Tech brand hydrophone we are currently using has a low frequency -3 dB corner of 0.05 Hz (the high frequency is 7.5 kHz) and a low frequency roll-off of -12 dB/octave below 0.05 Hz. Given that the natural noise spectrum on the seafloor climbs steeply below 0.02 Hz, the usable bandwidth is probably out to several hundred seconds period or longer. We have also used the instruments with the Cox/Webb differential pressure gauge (Cox *et al.*, 1984) to enhance the response at very low frequencies.

After weighing the pros and cons of glass versus aluminum pressure cases we chose aluminum. The large capacity of 17" glass spheres are not needed for the new instrument, which easily fits inside a 6" diameter Al cylinder. Although inexpensive and resistant to corrosion, glass balls are very prone to damage on opening and closing, and great care has to be taken when servicing such instruments at sea. They are cumbersome to handle. In contrast, the small aluminum cylinders we chose for the L-CHEAPO are easily carried and opened by one person. Our experience is that corrosion is minimal if only plastics are used in contact with the pressure case, and zinc cathodic protection can be employed. Although aluminum cylinders require added buoyancy, a new 13" flotation ball manufactured by Billings is ideal for this application. A frame containing 2 of these balls costs and weighs less than a 17" ball and provides adequate flotation for short deployments, with two 2-ball frames supplying flotation for the extra batteries of a 1-year deployment. MBARI has housed the recording system in a 17" glass sphere along with auxiliary electronics and batteries.

We use the acoustic release system developed over the last six years by the Cox/Constable/Webb group at Scripps. This release has proved very reliable, and at around $1000 in parts this is the most inexpensive unit we are aware of. It relies on a timed and coded series of pings, with reset windows designed to allow reflections and multiples to decay between pings. We have used this release with complete success on both ridges and deep seafloor in well over a hundred deployments. The release mechanism is usually a single weight held by a stainless steel burn wire, although systems supplying mechanical advantage have been used as well. Burn wires have been a standard release for many years, being inexpensive and reliable.

The ease and speed of opening the Al pressure case obviates the need for a through-the-pressure-case data transfer system. Even at full SCSI speeds, data transfer rates are still low enough that it would take several hours to copy a Gbyte capacity disk to tape. This is hardly fast enough to keep up with instrument recoveries, and in any case does not allow for changing batteries.

For the initial application, the moored system was most easily constructed and provided most insurance against getting stuck on the seafloor. Other applications need a bottom-mounted package, and such a system is being developed for the petroleum-sponsored magnetotelluric recorder. The Navy also has interest in a 'trawl-resistant' installation for use on the continental shelf.

The data logger is housed in one of the small cylinders; the other cylinder contains the acoustic command/release/navigation board. This is partly to keep the pressure case size and weight down, and partly because the release unit only needs servicing about once every cruise at most.

2:1. Deployment and Recovery

Deployment is simply a matter of dropping the device overboard, and a moored configuration can be deployed and recovered by hand. Bottom-mounted configurations will benefit from a light crane and release hook. Surveying can be accomplished by acoustic navigation using the acoustic transponders, proceeding in the traditional manner of moving the ship around the array while ranging on the instruments. Instrument locations can be determined to better than 10 m using this method now that P-code (or differential) GPS navigation for the SIO ships is available.

Recovery will be by means of acoustic release. Strobe lights, which allow recovery to continue in darkness, and radios (which are of increasingly limited use given the accuracy of GPS positioning and the reliability of our release) can be mounted on the flotation frame. Table 1 summarizes the characteristics of the new instrument

2:2. Testing

Considerable testing has been accomplished during the initial deployment phase and the development of the NAVOCEANO instruments. The first test of 5 moored systems and 2 bottom-mounted systems occurred in August 1995. Repeated deployments of 4 bottom-mounted systems occurred in October 1995 as part of a parallel project to collect electromagnetic data for a petroleum industry sponsor. Five systems were deployed off Hawaii in February 1996 as part of the Cornell marine mammal program. One instrument was deployed in Monterey Bay as part of MBARI's borehole seismometer program. One instrument is currently on the seafloor in the southern Pacific Ocean as part of an 8-month deployment of a seismometer array.

2:3. Sensors

We have incorporated crystal hydrophones and a post-amp board in the 5 L-CHEAPOs, as many (though clearly not all) ocean-bottom seismometer applications can be performed using the L-CHEAPO as an ocean-bottom hydrophone. OBHs have been found to record P-wave arrivals extremely well (*e.g.* Rowlett

Table 1: Instrument Specifications

Processor	Onset Tattletale 8 (Motorola 68332)
Digitizer	Crystal 16-bit ADC
Number of Channels	1–16, selectable
Sample Rate	1 – 1000 Hz, selectable
Memory	256 kbyte processor RAM
	256 kbyte flash EMPROM
	1 to 4 Mbyte PCMCIA RAMcard
Disk Interface	SCSI with power switching to 2 drives
Disk	Dual 9 Gbyte
Data compression	50%
Clock Drift	<0.5 second per year correctable to < 0.1 s
Batteries	14 V (nom.) for digital and ±6 V (nom.) for analog
	36 Lithium Oxyhalide DD give 8 month's operation (250 Hz)
Pressure case	18 cm O.D. 7075-T6 Aluminum, variable length
Flotation	2–4 (depends on batteries) 33 cm glass spheres
Instrument Power	300 mW at 250 Hz sampling
Disk Power	200 mW (time averaged for 250 Hz sampling)
Weight	70 kg in air (depends on batteries)
	-14 kg in water
Anchor	20 – 30 kg scrap
Acoustics	Custom
Frequencies	10–15.5 kHz in 0.5 kHz steps
Commands	Time base code for commands:
	Disable, Enable, Release
Release	Stainless steel burnwire
Hydrophone Response	Flat between 0.05 Hz and Nyquist/2
	-12 dB/octave below 0.05 Hz to 0.005 Hz

and Forsyth, 1979). The cost factor, in particular, becomes important when instruments are lost (as they inevitably are; loss rates between 1 and 5% are characteristic), as the low capital and labor costs involved make replacement easier. Low cost also allows the deployment of arrays large enough to guarantee redundancy of data, again making the loss of an occasional instrument more bearable.

3. Accelerated Delivery Schedule

Although our contract clearly stated that the instruments would be ready for operation 6 months from funding (which occurred 6/1/95), we agreed to attempt an accelerated delivery schedule in an effort to accommodate NAVOCEANO's desires. The accelerated schedule resulted in severe compromises in both cost and performance of the instruments. Although the additional money required to obtain pressure case material in a shorter time was provided by NAVOCEANO, a large number of component parts and circuit boards were purchased with a surcharge for accelerated delivery. This typically doubled the cost of the dozen or so circuit board runs that the instrument required. We were forced to order parts and run circuit boards before design parameters, such as power consumption, had stabilized. This resulted in a number of re-orders. Incredibly, and in spite of this, seven new instruments were in the water for a test deployment on the 13th August, only 6 weeks after funding. All but one of these instruments worked and collected data, although the power consumption was higher than anticipated. Because the lead time on machining and anodizing the pressure cases meant that a pressure case length had already been chosen at that time, the endurance of the instruments delivered to the Navy was less than the specified year. This problem would not have occurred in a six month development cycle, as the pressure case can easily be made long enough to accommodate the requisite number of batteries. NAVOCEANO took delivery of the instruments several weeks early, a little less than 3 months after the contract start date.

As a result of early delivery, there were several 'bugs' in both the hardware and software of the instruments provided to NAVOCEANO, as well as the problem of the short pressure case. Furthermore, power requirements had not been reduced by several changes made subsequent to delivery. Many of these bugs were fixed within weeks of delivery, and one of the PI's deployed 4 instruments repeatedly in October as part of a highly successful electromagnetic survey. The dual disk drive capability was not implemented in software, nor was data compression (subsequently implemented). Most, if not all, of the problems with the original delivery reported by NAVOCEANO are associated with known, and since fixed, bugs, and we currently have the NAVOCEANO instruments in our possession for upgrading and testing. This included replacement of the hand-wired postamplifier board with a printed circuit version.

4. Summary

Although delivered before development was completed, after minor bug fixes and updated software, along with a lengthened pressure case, the L-CHEAPO-95 instrument meets all of NAVOCEANO's specifications. In particular, the new Seascan crystal oscillator easily meets the rather stringent clock specification of 0.1 s/year (after simple drift correction). Although we expect that further work on the hardware and software will reduce power consumption somewhat, large improvements will not occur without replacing the Tattletale 8 with a custom CPU/memory/real time clock board. Although this would represent a significant development project (approximately 3-man months), it is by no means beyond the scope of phase 2.

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