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Woods Hole Oceanographic Institution

Real-Time Tomography Mooring

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James Lynch, Daniel Frye, Kenneth Peal, Stephen Liberatore,
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Technical Report

Funding was provided by the Office of Naval Technology
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ABSTRACT

A real-time tomography system has been developed which combines ocean acoustic tomography with satellite-based time keeping and satellite telemetry. The basis of the system is the acoustic tomography transceiver and its associated acoustic navigation grid. To this basic system, a link to the surface has been added to provide a pathway for telemetry of the tomographic data to shore and a downlink for satellite-derived time which is used to correct the transceiver's clock. The surface buoy contains a GPS receiver, clock comparator, system controller and multiple ID Argos transmitters. Processed tomography signals, transceiver location data, time, time drift and surface buoy engineering data are transmitted to satellite using a total of 32 data buffers transmitted every eight minutes. The report describes the real-time tomography system in detail, with particular emphasis on the modifications implemented to convert the standard tomography instrument to a real-time oceanographic tool.

Key words: Acoustic tomography, real-time, telemetry

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REAL-TIME TOMOGRAPHY MOORING

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1. INTRODUCTION

1.1 Ocean Acoustic Tomography

Ocean acoustic tomography was first proposed by Munk and Wunsch in 1978 [1], and was first demonstrated in the ocean in 1981 [2]. We are now entering the second decade of tomography's existence as an oceanographic measurement technique, a decade in which we hope to see tomography go from being an experimental novelty to a first rate oceanographic tool. For those interested in the details of tomography as a technique, we refer to the initial paper by Munk and Wunsch [1], which while slightly dated, is still an excellent overview of the technique, and also to a more recent review by Worcester, Corunelle, and Spindel [3], which covers tomography's status from 1987-1990, i.e., almost to the present. The latter paper contains an excellent reference list, which can further guide the interested reader to the (now quite extensive) literature on tomography.

For the purposes of this report, it will suffice to say that acoustic tomography in its basic form is a technique that uses the time of flight of acoustic pulses between sources (usually moored) and receivers to create fully 3-D maps of the ocean sound speed, temperature, and (given two-way transmissions) current fields. To make these maps, one must resolve and identify the various acoustic multipaths (eigenrays) which connect sources and receivers and clock their arrival times to very high accuracy. Tomography also requires very precise mooring (actually, source/receiver) positioning accuracy, as each 1.5m of distance error between the moorings corresponds to 1 msec of travel time error. Typical oceanographic feature signals are of the order of 10-50 msec, so unaccounted-for mooring tilts of a few tens of meters can mimic large-scale oceanographic features. The first decade of tomography was, to a large part, spent learning how to deal with these experimental measurement issues, which demand higher levels of instrument performance and ocean acoustic expertise than any other oceanographic measurement.

As previously mentioned, the second decade of tomography is being geared towards exploitation of the technique, rather than technique development. Small, less expensive, commercially available instruments such as the transceiver manufactured by Webb Research of Falmouth, MA, are envisioned probing sizable fractions of ocean basins with mesoscale resolution over decadal periods. Larger systems, based on the experience gained from the Heard Island transmissions [4], could be used to monitor global ocean warming over multi-megameter scales and decadal periods. Assimilation of tomographic data into numerical models for forecasting and model development offers another exciting use of tomography – indeed the oceanography of the future appears to be a synthesis of measurement and modeling techniques, optimized to produce the most information for the least expense and effort.

1.2. Real-Time Tomography

If one wishes to monitor the ocean and incorporate daily information into predictive numerical models, then data must be available in near real-time. Real-time information also allows one to rescue and redeploy faulty instruments in the ocean and to think about the data while it is being collected rather than waiting a year or two for the recovery of internal recording devices. Obtaining real-time ocean acoustic tomography information is not a trivial exercise, mainly due to the large telemetry bandwidth needed to get the data ashore and the very limited power available to moored instruments. The total bit rate attainable and the energy required to send a bit are absolutely critical parameters to any proposed telemetry system. Cost, reliability, and durability are other key factors. To date, a number of possible solutions to the problem of telemetering acoustic tomography data in real time have been proffered.

A brief overview of these proposed systems, their strengths and their weaknesses follows. The first, and perhaps oldest concept for real-time tomography is to use moored sources transmitting to the Navy's SOSUS (Sound Surveillance System) receivers. This technique was considered from the inception of tomography, and was first implemented by Spiesberger [5] and later implemented in real-time by an SIO and APL/UW collaboration [6]. This technique has several advantages. By using existing receivers and inexpensive receiver modifications, it has the advantage of comparatively low cost. The bandwidth of the channel is also very large (effectively infinite for our purposes), so that the data rate required is not a problem. The system also has many receivers, creating many acoustic paths for one source.

A second scheme for implementing real-time tomography is to connect the tomographic systems to existing submarine telephone cables, which are outdated for telephonic purposes, but are potentially very useful for oceanography. This concept would allow very high data transmission bandwidths, many deep ocean locations, transceivers near the SOFAR axis (the ideal spot for tomography), and two-way transmissions for reciprocal tomography. The disadvantages are extremely high installation and maintenance costs (a cable-laying ship is needed), the cost of renting or buying the cable system, and the geographic positions of the cables, which are not optimal for oceanography.

In an effort to retain the submarine cable telemetry concept, but ameliorate some of the difficulties noted above, work on tying oceanographic sensor output into the phone cables via inductive modems is being pursued by WHOI investigators. This avoids the difficulty of direct electrical attachment of the sensor output to the phone cable. Moreover, high baud rates are attainable by the modem. Long lifetimes (~five years) could be expected for the bottom receiver/inductor, so that maintenance is reduced. The disadvantages are that an ROV deployment is necessary (expensive, but less expensive than a cable ship), and the previously mentioned drawbacks of the cable system, rental (purchase) and location. This is still an experimental technology, but it is a promising one.

The third variant of real-time tomography we will discuss is "moving ship tomography," in which one deploys either the source or receiver from an oceanographic or naval vessel. (Current practice is to deploy the receiving array from the ship.) This technique, which has been tested at sea during both the Greenland Sea and AMODE tomography experiments [7], was originally proposed to allow one to obtain greater spatial resolution of ocean features, i.e., fill in "spatial wave number gaps" left by standard moored arrays. This technique also allows the Navy to map sound speed in areas of fleet activity, a great tactical advantage, using existing systems such as SURTASS (Surveillance Towed Array System).

The disadvantages of this technique, as currently practiced, are as follows. First, due to the slowness of the ship, which typically occupies one receiving station every three to four hours, oceanographic maps made of a large region are temporally undersampled in a peculiar way. Specifically, the area along the most recent 2-D slice is well sampled, but the rest of the area to be covered is not. Spatial maps made from a ship covering a large area with fine spatial resolution will of necessity suffer from the lack of synopticity over the course of the survey, much as happens with CTD work. Use of only one realization per path also means more internal wave noise compared to conventional tomography, where one often averages many transmissions to reduce noise. Another present drawback of this concept is its need for extremely precise measurements of array element locations. High accuracy GPS positioning, short baseline array sensor localization, and precise measurement of hardware positions aboard ship have been needed to get adequate sensor location information, a taxing chore even for a highly trained scientific party. Both the deployment and analysis are very labor intensive in this scheme, also. Finally, one still needs the clock and mooring motion corrections for the source (as with SOSUS) for this technique to be truly real time.

A variant of moving ship tomography has recently been proposed by Duda and Lynch, called "relative arrival structure tomography" [8]. It has been well known to tomographers that the relative structure of the acoustic multipath arrivals contains information about ocean structure, though the ability to resolve features is degraded relative to the careful monitoring of the time changes of individual multipaths. Due to the somewhat poorer information content, tomographers have largely ignored relative structure information. However, recent studies indicate that, at least in some cases, the information content is substantial and as a result, the technique is being pursued. The advantages of relative arrival tomography are as follows. First, it is robust, as only wristwatch accuracy time and LORAN accuracy position (GPS at worst case) is needed for the measurements. Second, it is cheap; shot sources can be used with sonobuoys as receivers. Third, it's fast; an aircraft can be used to deploy shots and to survey a large area. And finally, it is simple to handle computationally, i.e. the inverses do not have any extra complication due to clock or mooring motion corrections. On the negative side of the ledger, relative arrival tomography gets less information than "standard" tomography, as mentioned. The theory is not yet fully developed for this technique, though preliminary inversion results are encouraging. (Simulations are being performed to find out the range of geometries, conditions, and environments under which the technique works well). Also, as with moving ship tomography, only one realization of a path is used, thus increasing sensitivity to internal wave noise.

The final variant of real-time tomography we will discuss, before moving on to the S-Tether system which is the focus of this report, is multiple convergence zone acoustic telemetry. Recent at-sea tests by Catipovic have demonstrated that one may send data at extremely high bit rates over many convergence zones (4-5) using low frequency acoustic sources [9]. This would allow one to use the tomographic sources themselves to transmit tomographic data (clock times, travel times, mooring motion) to SOSUS station "relays." This also allows the tomographic mooring to be reasonably remote from the SOSUS receiver, thus avoiding classification problems, as well as permitting the transceiver to be near the SOFAR axis, its optimal position.

The weak points of multi-CZ acoustic telemetry are as follows. First, it is a high power consumption technique, using of the order of 1 joule/bit. Due to this power consumption, standard mooring battery capabilities limit total data transmission to ~2-3 Mbyte/yr, the same as is achievable with the Argos system. This rate could improve in the future, however, and work on multi-CZ telemetry is being pursued. This technique is also limited to within a few CZ's of the SOSUS stations (or other suitable relays), so that, again, it is not optimal for mid-ocean coverage.

1.3. S-Tether Design

Developed originally for telemetering standard oceanographic sensor data (currents, temperatures, etc.), the S-Tether system, shown in Figure 1, has been adapted for use with tomographic transceivers under a contract with the Office of Naval Technology. The system consists of a surface telemetry float which sends information to shore via RF (usually satellite) transmissions. It is connected to the tomography transceiver directly by electromechanical cable, permitting high baud rate information transfer from the transceiver to the surface telemetry buoy. By using the S-Tether design, in which a slack tether mechanically decouples the surface buoy motion from the tomography mooring, the effects of surface waves and currents on the mooring, which can be particularly deleterious for tomography, are minimized.

The advantages of using an S-Tether system are numerous. The primary advan-

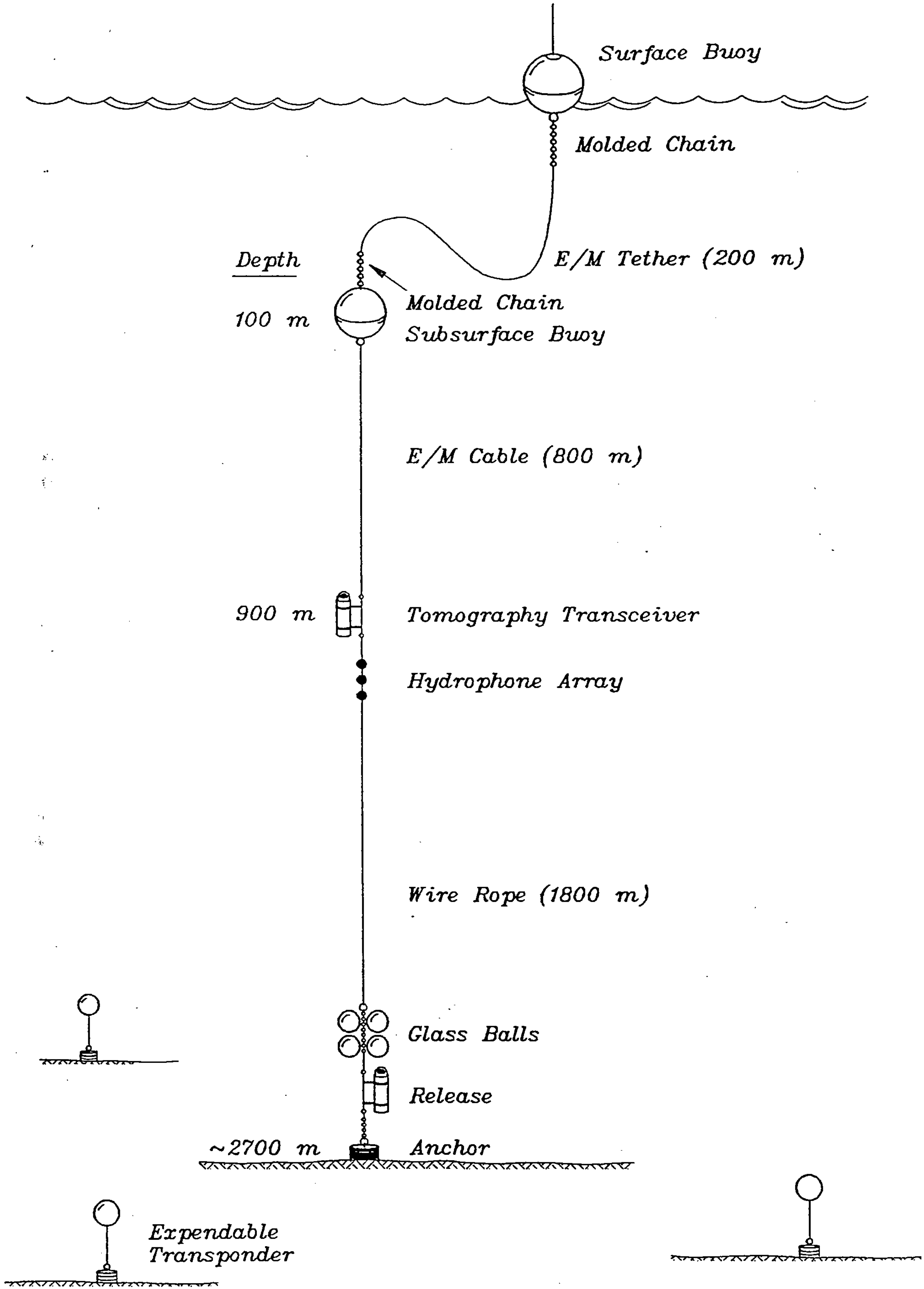

FIGURE 1: Real-time tomography mooring

tage is that its surface expression (which also has disadvantages, to be discussed later) allows use of the RF communication channel. While limited in bandwidth at present, this approach will eventually provide a very high bandwidth, low power transmission path – indeed, only cable communication options can compete in bandwidth. Presently, we are limited in ocean applications to the Argos system bandwidth, which allows us to send about 2.2 Mbyte/yr over four Argos ID's. This does not represent even a fraction of the potential bandwidth of RF channels. In Table 1 (from [10]), some of the present and future options for RF communications from ocean surface buoys are shown. In addition to data telemetry, the surface expression allows accurate time from the GPS system to be obtained. The surface buoy has a GPS receiver which outputs an accurate time tick once per second allowing the tomographic clock on the S-Tether mooring to maintain an accuracy of 20 μsec, far better than the 1 msec accuracy (at best) of the tomographic signal arrival time determination. Moreover, if the surface buoy breaks loose, it is easily tracked by its Argos transmissions and recovered. It should be noted that should the S-Tether system break loose, only the real-time capability is lost in the tomographic system. The transceivers also record internally, in addition to sending a subset of the data in real time via the S-Tether system, so that no valuable oceanographic information is permanently lost.

Another advantage of S-Tether is its ability to operate in most deep ocean locations, which makes it suitable for "regional focus" array systems, as opposed to the telephone cable or SOSUS systems which serve only fixed locations. The transceiver can also be placed at any depth with an S-Tether system. Two-way communications with the buoy are possible, both in the reciprocal tomography (current measurement) sense and the interactive communication sense (e.g. for changing system tasks or schedules). Finally, the S-Tether unit is comparatively cheap – production copies are expected to be less than $100k, and only a few systems are needed to give real-time capabilities to a large tomographic array.

Looking at S-Tether's liabilities, the surface expression and low bandwidth of the Argos link are the main weaknesses. The surface expression has three liabilities: 1) collisions with shipping, 2) breaking of the E/M cable due to dynamic loading by surface waves, and 3) submergence of the float by high current drag. The first liability can largely be avoided by placing the moorings outside of shipping lanes. The second liability has led to the failure of two S-Tether moorings due to cable fatigue. However, a new design using chain at the buoy-cable interface should avoid this problem. The third liability, submergence of the float, will result only in loss of real-time information during the period the float is submerged. The float itself is designed to be capable of submergence to 300m or greater over extended periods with no damage.

The low bandwidth limitation of Argos restricts the data stream to either six transmissions from one remote mooring per day or daily averages from six remote moorings. For testing purposes, the S-Tether is configured in the former mode; in

Telemetry Option	Coverage	Typical Throughput	Power Requirement J/bit	Platform Location	Long-Term Availability	Receive Station
ARGOS	Worldwide	0.02-0.2 bps	1-10	+/- 1 km	Yes	Not required, but available with limited coverage
ATS	Hawaii to Azores but Non-Polar	0.3-1.2 kbps	0.5-1	N/A	No	Not required, but available
GOES/METEOSAT/ GMS/INSAT	Worldwide Except Polar Regions	0.2-2 bps	1-2	N/A	Yes	Not required, but available
VHF[a] (Line-of-sight)	10-50 km from Receive Station	0.3-1.2 kbps	0.02-0.1	N/A	Yes	Required
Meteor-Burst[a]	2000 km from Master Station	1-20 bps	0.2-1	N/A	Uncertain due to licensing	Required
HF Packet[a]	Variable up to Worldwide	1-30 bps	1-10	N/A	Yes	Required.May need several
Inmarsat[a] Standard-C	Worldwide except Polar regions	10-100 bps	0.5-1	N/A	Yes	Not required
Microsats[a/b]	Worldwide	10-100 bps	.01	N/A	Unknown	Unknown
Irridium[b]	Worldwide	Unknown	Unknown	N/A	Unknown	Not required

NOTES: (a) Two way communication
(b) Future systems - estimated throughput and power

TABLE 1: Telemetry options for offshore buoys

actual operations, it will be configured in the latter. Even with the Argos system, a six mooring reception capability is useful, as most tomographic deployments to date have included only about half a dozen systems. Moreover, it is felt that with the advent of new satellite communication systems, and the further development of existing ones that the bandwidth available for ocean data telemetry will soon improve dramatically.

2.0 THE TOMOGRAPHY SYSTEM

The Webb tomography transceiver consists of a high power acoustic source, an acoustic receiver, a stable clock, an acoustic navigation interrogator and a sequencing controller all interconnected with a simple open collector SAIL [11] bus. The system design allows the transceiver to accurately measure and record the arrival times, over many paths, of signals generated by similar instruments moored at ranges of up to 500 km. The recorded travel times are later processed to obtain the intervening sound speed field. Since temperature, salinity, and density are the chief factors influencing sound speed in the ocean, these properties can in theory be derived from the data. In practice, salinity (and thus density) is too weak an effect on sound speed to be measured by tomographic techniques.

Due to attenuation and spreading of the acoustic signal, the source's signal is actually below the ocean ambient noise level by the time it reaches the receiver. For this reason the source generates a signal based on a phase encoded pseudo-random sequence which allows the receiver to employ a simple signal processing technique to enhance reception levels. Signal phase stability must be maintained during receptions and transmissions or a loss in processing gain will occur. Also, the transmit time and the receiver's acquisition time must remain synchronous for travel time to be inferred from arrival time. The transceiver's clock satisfies the first requirement utilizing its temperature-compensated output frequency. However, the second requirement is only satisfied after end-point corrections are applied to the data since the clock's time may be in error by up to 30 ms at the end of a six-month deployment.

Mooring motion due to currents and tides alters the range between the source and the receiver. Even with high tension moorings, movements in excess of 100 meters are not unusual. There is no way (without sacrificing some useful multipath data) to distinguish between altered arrival times which result from mooring motion and those that result from the effects of oceanic variations. For this reason each transceiver is equipped with an acoustic navigation interrogator. This device, prior to each reception, obtains round-trip travel times between the tip of the receiving array and three bottom-mounted transponders. These times define a unique instrument position and allow the data to be corrected for the effects of mooring motion.

The tomography transceiver controller allows communication with an external computer via a 20 mA SAIL loop. This module also contains the sensor interface electronics and the digitizer necessary to monitor all system voltages as well as pressure and temperature both internally and externally. The system controller's primary function is to execute the program which, following a task table downloaded via SAIL, sequences all instrument activity. The current version of this program is capable of handling up to 12 task tables which allows the instrument to alter its behavior up to 12 times during the course of an experiment.

Real-time tomography requires access to the acoustic travel times, mooring location data and time correction data in real time. To meet this requirement using the limited Argos bandwidth requires compression of the acoustic data set. This compression is performed by correlation of the demodulates against a replica of the transmitted signal followed by peak picking and sorting. A dramatic reduction in the amount of data to be transmitted is the result of this processing.

2.1 Controller

The transceiver architecture consists of loosely coupled modules, each performing an individual function. The operation of the modules is coordinated by the controller, which operates from task tables to determine when each module should be enabled. The modules are connected to a simple bussed backplane which provides power, communication via open collector SAIL, synchronization and individual reset. A more complete description of the controller is provided in [12].

Most of the modifications required to achieve real-time operation were changes to the controller. The addition of a navigator to the system required no change to the controller since provision for its addition was included in the original design. It is necessary to include navigator information in the task table to enable its use during a deployment.

Telemetry between the tomography transceiver and the surface buoy controller is implemented with a frequency shift keyed (FSK) modem using the E/M cable. This requires mounting the FSK modem adjacent to the controller and performing wiring modifications to existing controller boards. These were needed to control the modem, to provide the required power and clock frequency, and to transfer data to and from the modem.

Other changes to the controller were implemented in software. These changes included modifications to the BIOS to support the low level hardware changes, addition of new virtual devices, and modification to existing device drivers. The new virtual devices are called "time check" and "calculate". Time check instructs the surface unit to enable the GPS receiver and execute a comparison with the internal transceiver clock. The calculate function uses the acoustic data to perform correlation and peak picking; then it formats a message which is sent to the surface unit to be telemetered. Modification to existing drivers is required to extract data from various devices to be used by the calculate function.

2.2 Signal Generator

The signal generator module, on command from the controller, synthesizes a phase encoded pseudo-random sequence. This signal, applied to the module's power amplifier is level shifted and appropriately conditioned to drive the transceiver's outboard ceramic transducers which generate the acoustic signal. For details of the signal generator's hardware/software configuration and for its operation, refer to Appendix D.