OCEAN ACOUSTIC TOMOGRAPHY

This is a continuation of application Ser. No. 08/424,630 filed on Jun. 30, 1994, now abandoned.

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BACKGROUND OF THE INVENTION

1. Field Of The Invention

This invention relates to a method and system for real-time monitoring of changes in ocean temperature over ocean basin distances, for example, from Hawaii to California within a time scale of one hour.

2. Description Of The Related Art

In 1979, W. Munk and C. Wunsch suggest in the article "Ocean acoustic tomography: a scheme for large scale monitoring", *Deep-Sea Research,* 26, 123–161, that ocean temperatures might be mapped by measuring travel times along acoustic multipaths, but conjectured that the technique would be limited to distances of 1000 kilometers (km) due to scattering of the acoustic field from internal waves. In their method of acoustic tomography, differences between measured travel times and predicted times derived from archival data are used to correct the reference field, using techniques similar to those employed by seismologists mapping the Earth's interior structure from sounds emitted by earthquakes. To test the method, a mapping experiment was conducted in 1981 over ranges of a few hundred kilometers. The storms of the oceans, eddies of about 100 km horizontal scale, were mapped using criss-crossing sound paths between many sources and receivers arranged on the perimeter of a rectangular region. The experiment was a success, proving the feasibility of the technique.

Our research group was eager to extend the range of acoustic signals and became interested in the idea of using basin-scale measurements to detect global warming trends. The idea was that if the Pacific warmed, the speed of sound would increase and the travel time would decrease. Basin-scale sound transmission is appropriate for detecting global warming because this is the scale over which temperatures are predicted to fluctuate from models. Most global warming models predict some ocean basins will warm, while others will cool.

In 1983, using conventional equipment, we began transmitting sounds with an intensity similar to the level of the calls of some whales across a 4000 km path through the Pacific Ocean. The 133 Hz signals were transmitted from a source cabled to shore from 180 meters (m) depth off Kaneohe Bay, Oahu, and were detected by a U.S. Navy Sound Surveillance System (SOSUS) station off the California coast. We showed that the travel time of sound across the Pacific could be converted into the change in the spatially averaged temperature between the two instruments. This kind of large-scale measurement had never been made before. Previous measurements of ocean temperature came from piecing together data taken from ships at points. There is much variability in temperature at small scales in the ocean. Thus it is difficult to see changes at large scales from point data. This small-scale variability s suppressed in basin-scale acoustic thermometry because the acoustic paths travel through many plus/minus variations in temperature which, when summed, amount to little.

In six years of intermittent tests, we found that the travel times across the Hawaii/U.S. Pacific basin varied by about ±0.2 seconds (s), corresponding to ±0.1° C. The measurements had an accuracy to within 0.02° C. This thermal variability is not a global warming signal but is probably generic to oceans. We found that the temperature variations in the Pacific had spatial structures smaller than 500 km and were unable to resolve the structure using SOSUS stations and existing cabled sources. It was apparent that new types of instrumentation would be required to provide a satisfactory understanding of this natural variability, and we turned to new technology using autonomous instrumentation. Thus, these measurements, obtained between 1983 and 1989, showed that travel times varied by about ±0.2 s at interannual time scales along basin-scale sections in the northeast Pacific. These are equivalent to spatially averaged changes of ±0.1° C. in the upper kilometer of ocean. Interannual variations can be resolved if travel times are measured to within 0.02 s; some ten times less than the measured variations.

One conventional tomographic scheme involves transmitting sound from autonomous subsurface moored sources to bottom-mounted receivers. Each source mooring includes batteries, clocks, computers and a local navigation system, and costs about $350,000. The source's clock errors amount to about 0.1 s per year. Travel times are normally corrected for these errors after the experiment. For real-time operation, corrections must be made for the source position which moves about ±300 m on the mooring, so that acoustic arrival times change accordingly by about ±0.2 s. Arrival times are conventionally corrected for wander during post-experiment analysis using navigation data stored in the source throughout the experiment. Corrections for mooring wander can be made in real-time if the mooring is attached to a surface unit which communicates to satellites. However, the surface unit may cost about $100,000 and the surface connection is subject to the action of waves and may fail. A reliable source is desirable because it is usually the most expensive component of an acoustic tomography system. In this application, real-time signifies that the acoustic data are transmitted into the laboratory one day following their measurement.

Real-time monitoring can be accomplished conventionally by cabling sources and receivers to shore. If the instruments are on the bottom, they do not move and there are no timing problems. Unfortunately, there are not enough sources and receivers for monitoring all oceans with sufficient resolution. Cabling a new source or a new receiver to shore is estimated to cost more than a million dollars. It is too expensive to cable enough sources and receivers to shore for monitoring ocean basins at the important climatic scales exceeding a few hundred kilometers.

T. G. Birdsall, "Acoustic telemetry for ocean acoustic tomography", *Institute of Electrical and Electronics Engineers Journal of Oceanic Engineering,* 9, 237–241 (1984) and H. M. Kwon and Birdsall, "Digital waveform codings for ocean acoustic telemetry", *Institute of Electrical and Electronics Engineers Journal of Oceanic Engineering,* 16, 56–65 (1991) have suggested that the local x-y-z coordinates of the source can be telemetered to fixed or moored receivers by transmitting M-sequence signals, one right after the other. Each coordinate can be digitized to eight bits and transmitted as one of 2^8 =256 different signals chosen from 16 different 255-digit M-sequences, each one of which is circularly rotated in time to 16 different start positions to make 16×16=256 different signals. Birdsall suggested transmitting the coordinate information at a reduced power level so as not to use additional battery energy over and above that ordinarily used for a tomography transmission. However, if