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Acoustics, Ocean Observatories, and the Future

Bruce M. HOWE
Applied Physics Laboratory, University of Washington

ABSTRACT

Integrated acoustics systems providing navigation and communications and conducting acoustic measurements in support of science applications are, in concept, analogous to the Global Positioning System, but rely on acoustics because the ocean is opaque to electromagnetic waves and transparent to sound. A series of nested systems is envisioned, from small- to regional- to basin-scale. A small number of acoustic sources sending coded, low power signals can service unlimited numbers of inexpensive receivers. Drifting floats with receivers can be tracked accurately while collecting ocean circulation and heat content data, as well as ambient sound data about wind, rain, marine mammals, seismic T-phases, and anthropogenic activity. The sources can also transmit control data from users to remote instruments, and if paired with receivers enable two-way acoustic communications links. Acoustic-based instrumentation that shares the acoustic bandwidth completes the concept of integrated acoustics systems. The ocean observatories and ocean observing systems presently in the planning and implementation stages will require these integrated acoustics systems.

1. INTRODUCTION

1-1. Overview

Recent advances in oceanography have prompted investigation of integrated acoustics systems for ocean observatories (IASOO) [1]. Navigation, communications, and acoustical oceanography all contribute simultaneously to a unified system. Integrated acoustic systems may be considered a combination of Underwater GPS (UGPS), communications capability, and acoustic sensor systems that support science. The purpose of this paper is to investigate the concepts and to describe briefly some technical aspects; it is a work in progress.

We examine first some of the results from the last decades in the fields of ocean acoustics and acoustic tomography, because precise timing and navigation are required for tomography to work. Then, because this concept has obvious analogies with the satellite-based Global Positioning System (GPS), we examine a few results and lessons from using GPS for ionospheric and atmospheric tomography. Lastly, we discuss some science scenarios and the integration of these ideas into the infrastructure of planned research oriented ocean observatory and operationally oriented observing system efforts.

The provision of such a transformational infrastructure to the ocean community is expected to be one of the enabling technologies fueling a revolution in ocean observing, leading to many science and non-science applications. The IASOO Committee[1] was recently formed as a committee of the Acoustical Oceanography Technical Committee of the Acoustical Society of America. Its primary purpose is to stimulate discussion and to raise the awareness of the community.

2. TOMOGRAPHY

2-1. Moving ship tomography

During 50 days in June and July 1991, a ship circumnavigated a 1000-km diameter array of 6 acoustic sources, deploying a vertical receiving array every 3 hours every 25 km, Fig. 1[2]. The travel time data along the many acoustic paths crossing at many different angles were then used to reconstruct the ocean sound speed (temperature) field in a way very analogous to a medical CAT-scan. This experiment demonstrated that high resolution maps could be obtained with this technique in the ocean, and that the navigation challenges could be overcome (using in this case a combination of floating long baseline GPS/acoustic spar buoys and an ultra-short baseline acoustic tracking system); if repeated today, commercial tracking systems would simplify the experiment.

2-2. Heard Island Feasibility Test

The Heard Island Feasibility Test conducted in 1991 showed that mechanically generated (in contrast to explosive) signals could propagate over basin and global distances[3]. Power spectra of the received signal at 18 Mm shows that sound energy can be detected over such ranges, Fig. 2. The Doppler shift of the signal due to ship drift could be tracked over 9 Mm using a 10-s integration time, Fig. 3; estimated rms uncertainty in this position was 10 m[4].

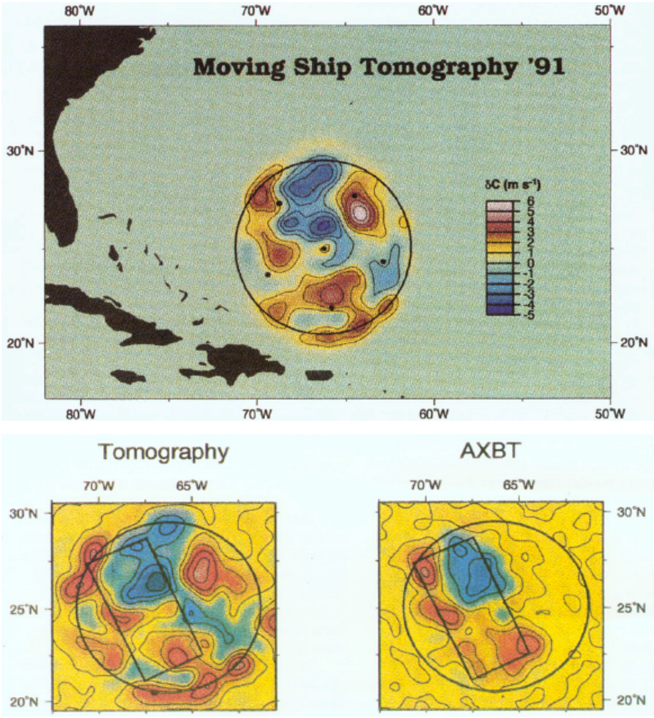

FIG. 1. The moving ship tomography experiment showing the sound speed perturbations at 750 m depth (peak to peak variation of 10 m s^{-1}) as determined acoustically and with air-expendable bathythermographs (AXBTs). The small panels show the spatial sampling and estimated errors of each.

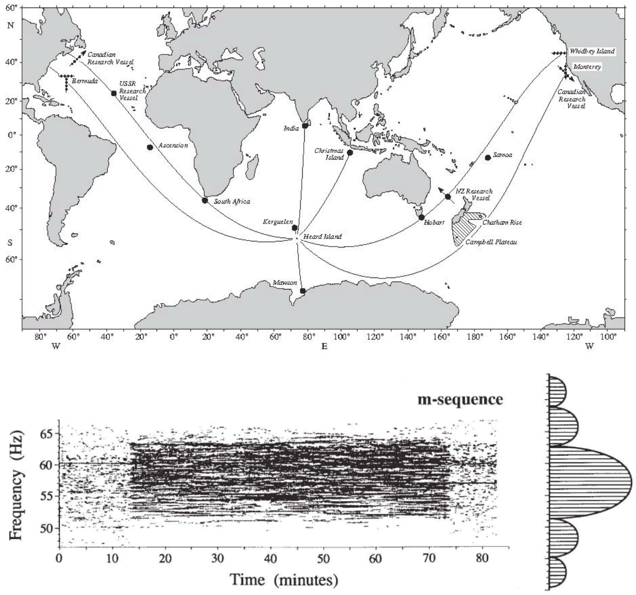

FIG. 2. (Top) Map showing the source and receiver locations for the Heard Island Feasibility Test. (Bottom) The received and transmitted spectra at Bermuda, 18 Mm distant[3].

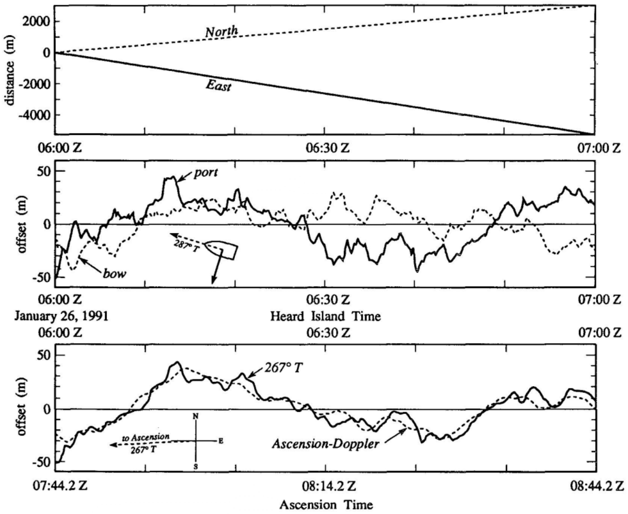

FIG. 3. Heard Island Feasibility Test ship drift and Doppler measurements[4]. (Top) Linear trend to the ship drift. (Middle) deviations from the linear trend, and (Bottom) the GPS-measured and Doppler-measured components in the direction of the acoustic path to Ascension Island, 9 Mm distant.

2-3. Acoustic Thermometry of Ocean Climate

In the ATOC project various sources and receivers were deployed in the Pacific[5, 6]. The ATOC sources, one on Pioneer Seamount off California and one north of Kauai, Hawaii, transmitted 75-Hz *m*-sequence codes for 20 minutes at 250 W. The signal quickly falls with range below the noise level (according to spherical and cylindrical spreading), and matched filter "replica cross-correlation" signal processing is used to make it appear as if one very short, loud pulse were transmitted (i.e., 20 minutes of energy "compressed" into 28 ms). The "shadow" plot for the Pioneer Seamount source is shown in Fig. 4. This illustrates the volume of the ocean that could be ensonified by such a source (or conversely monitored by a receiver), given the bathymetry and average ocean temperature and salinity (sound speed). Note, this type of plot does not give any signal level or signal-to-noise ratio information.

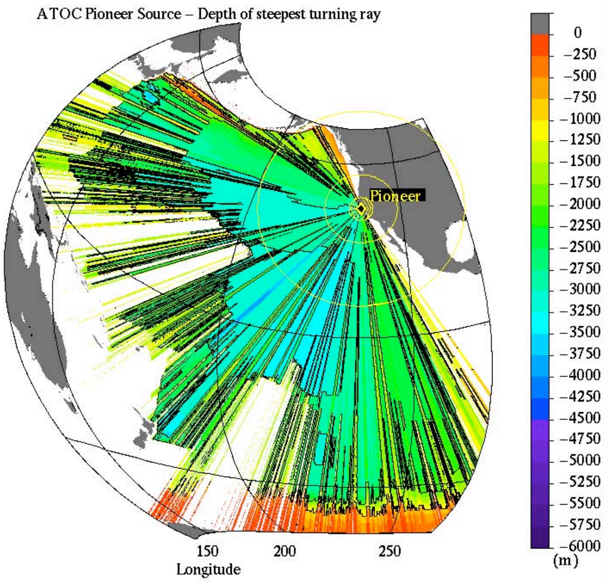

FIG. 4. A "shadow" plot for the ATOC source on Pioneer Seamount. The color shows the lower turning depth of the steepest possible RSR (refracting, surface reflection, refraction) ray that does not contact bathymetry on radial lines from the source[7].

2-4. State of Knowledge

These and many other experiments since the late 1970s have demonstrated that acoustic arrays as envisoned by Munk and Wunsch 1979[8] are entirely feasible[9], having been used in all oceans. High resolution mapping is possible. Ray arrivals with adequate signal-to-noise ratio have been measured at ranges up to 5 Mm on single phones[10]. Doppler signals have been measured to 9 Mm with 10-s integration times[4]. The *m*-sequence signals and signal processing methods typically used are proven; in the Arctic integration times from hours to days are possible at 19.6 Hz[11] while for non-polar waters, 14-minute coherent integration times have been measured at 75 Hz[12]. Precise timekeeping and positioning have been demonstrated[13], and the empirical equation for the speed of sound in seawater is being continually improved[14].

However, more work is needed in several areas. Experiments are needed to empirically determine coherence as a function of distance, frequency, vertical/horizontal separation, modes, rays, etc. Better theory and modeling are necessary to understand the causes of the loss of coherence, i.e., the oceanography such as internal waves and spice. Bottom interaction has proven to be sufficiently difficult that one should try and avoid it whenever possible. Lastly, more efficient sources and inexpensive receivers with arrays providing directionality are needed.

3. A BRIEF REVIEW OF GPS SCIENCE

The advent and availability of GPS has proven to be a revolutionary enabling technology not just for navigation but for science applications. It has lead to a wide range of applications in the space, earth, and ocean sciences. T. Yunck and others at JPL started to outline the potential uses of GPS in the 1980s as it was becoming an operational navigation system[15]. While we address only the use of GPS in atmospheric and ionospheric tomography here, the use of GPS for "real-time" geodesy showing plate tectonic motion is noted.

GPS signals (the group delay) are sensitive to the index of refraction (proportional to the temperature and precipitable water vapor) of the intervening air. The phase delay is sensitive to the electron content in the intervening ionosphere. Two fundamental path geometries are possible, GPS satellites to ground stations, and GPS satellites to low earth orbiting (LEO) satellites, Fig. 5. The paths to ground stations are predominately vertical and necessarily do not extend to cover the ocean. The LEO paths are nominally horizontal sampling a vertical profile at the "tangent" point, evenly distributed over the surface of the earth.

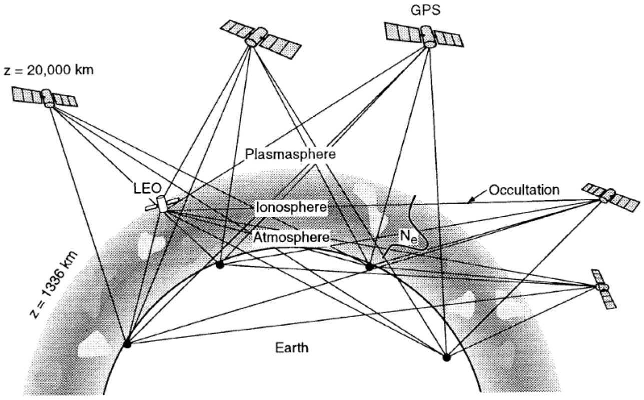

FIG. 5. GPS satellites transmitting to ground stations and LEO satellites[16)].

In Japan, the spacing of GPS receiver stations, set up primarily for geodetic monitoring purposes, is about 25 km. With this spatial density, maps of precipitable water can be directly estimated, Fig. 6.

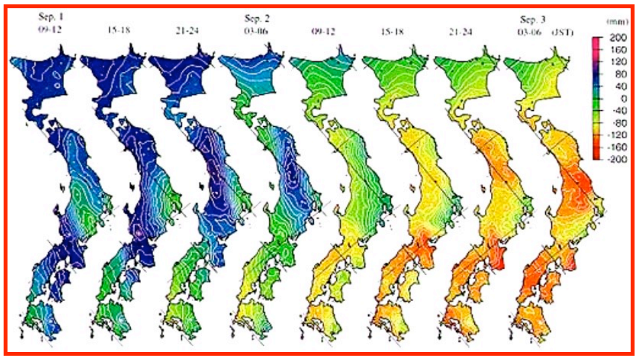

FIG. 6. Using extensive arrays of ground stations, maps of precipitable water are possible, in this case operationally every 3 hours[17)].

The Taiwanese, with U.S. help, are launching in late 2005 six satellites with GPS receivers specifically for atmospheric and ionospheric tomography (operating in an occultating orbit geometry, Figs. 7 and 8), with data assimilation into operational models[18)]. The atmospheric community demonstrated as early as 1993 the benefits of this data type in data assimilating models[19)]. The U.S. Department of Defense is actively pursuing ionospheric data assimilation that will be using this and other GPS data[20)].

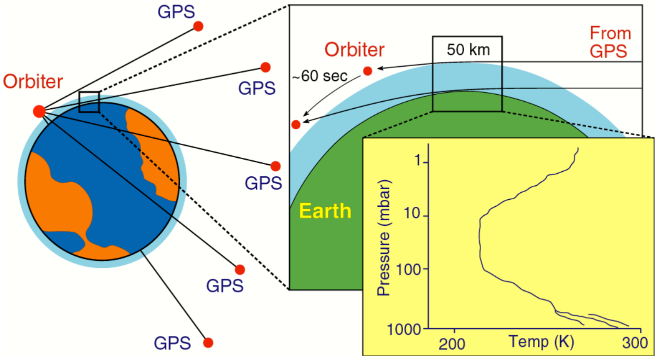

FIG. 7. Conceptual illustration of GPS atmospheric occultation (from the 1988 JPL GGI proposal[15)]).

Several advantages of the radio occultation method are:

1. High accuracy: single profile ~0.5 K; averaging < 0.1 K
2. High stability: all measurements absolute for all time
3. All-weather operation – visibility everywhere, all the time
4. Full 3D coverage – pole to pole, stratopause to surface
5. High vertical resolution – <100 m in lower troposphere
6. Independent height and pressure/temperature data provides geopotential heights and wind fields
7. Compact, low-power, low-cost sensors

The impact these kinds of measurements are having is reflected in the statement "GPS occultation is the most important new development in atmospheric sensing in the past 20 years." (B. Serafin, NCAR President, 2002) and the recommendations of the NASA "Easton" Workshop ('98) calling for a "GPS Constellation for atmospheric sounding" with global horizontal resolution of 50 km and a revisit time of twice per day.

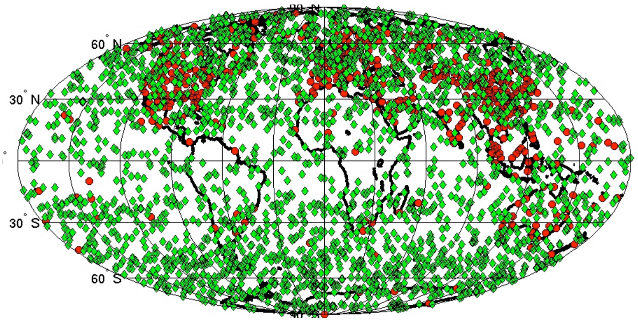

FIG. 8. COSMIC occultation soundings in a day (assumes 6 spacecraft). Red dots are current radiosonde sites.

4. OCEAN OBSERVATORIES

The U. S. National Science Foundation (NSF) has created the Ocean Observatories Initiative (OOI) to further the sustained study of the ocean[21)]. It has three elements: a coarse global array of buoys (Fig. 9)[22)], a regional cabled observatory such as NEPTUNE (Fig 10)[23)], and enhanced coastal observatories. A unifying theme for the initial infrastructure investment is the provision of seafloor junction boxes providing power and communications for sensor networks in the water column and on the seafloor and beneath. The expectation is that this request for major research equipment will be included in the 2006 U. S. federal budget. This infrastructure investment (equivalent to an icebreaker) will, with planned increases, lead to a concomitant large science investment.

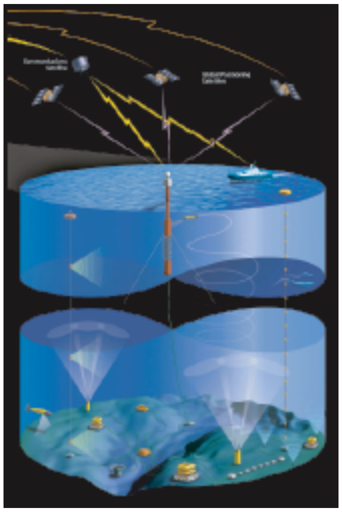

FIG. 9. A “global” buoy with seafloor junction box providing power and communications supporting a local sensor network.

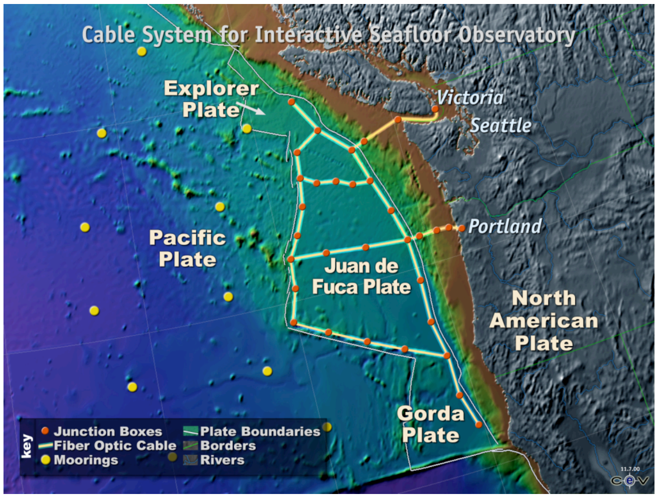

FIG. 10. The NEPTUNE cabled ocean observatory. Each node can provide up to 10 kW and 1 Gb/s to a multitude of sensor networks. The northern portion is already funded by Canada[24].

The coarse global array of about twenty buoys was originally motivated by the desire to site seismometers in remote locations, such as the southern ocean. Since then, the concept has expanded to include acoustic tomography to sample the ocean between sites, and all other ocean disciplines. Further, the Global Eulerian Observatories (GEO)/Reference Time Series Moorings program[25] is proposing a permanent global array of fifty moorings for multidisciplinary sustained time series observations; this program is part of the Climate Variability Program (CLIVAR) and the Global Ocean Observing System (GOOS)/Ocean Observing Planning Committee (OOPC). These arrays could contribute to an integrated system by supporting acoustic instruments that transmit navigation/tomography signals and receive the same signals, listen for ambient sound (wind, rain, marine life, etc.), and provide two-way acoustic communications as needed.

The above observatory efforts are research oriented, in contrast to an operationally oriented ocean observing system. An example of the latter is the Argo program. Argo is an in-progress global array of 3,000 (planned) free-drifting profiling floats that will measure profiles of temperature and salinity in the upper 2000 m of the ocean[26] (Fig. 11). This will allow continuous monitoring of the climate state of the ocean.

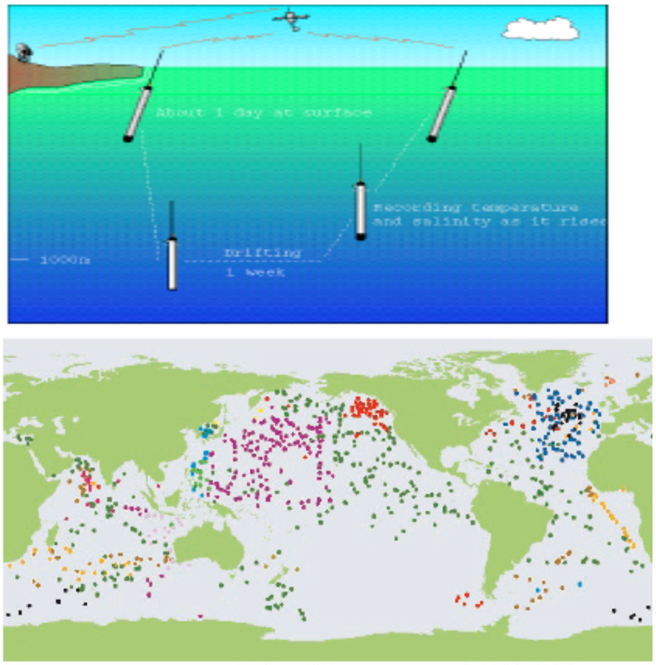

FIG. 11. (Top) Schematic showing the operation of Argo profiling floats. (Bottom) Locations of the 815 Argo floats as of June 2003.

5. SCIENCE SCENARIOS

There are several use scenarios for integrated acoustics systems. These scenarios, though covering different spatial scales and geographic regions and certainly not exhaustive, have in common the following characteristics and components:

- Precision navigation of moving platforms (e.g., large numbers of floats over wide areas, gliders, autonomous undersea vehicles and other robots, moorings, etc.)
- Tomography using the navigation transmitters and receivers, both on fixed and moving platforms
- Ambient sound using the receivers (e.g., marine mammal tracking and behavior, wind and rain, seismics [T-phases], ships, etc.)

The scenarios will be described in this section. Technical aspects of UGPS and integrated acoustics systems are then presented, but only very briefly and often as questions to be addressed. Answering the questions will be a major upcoming task for the committee.

5-1. Ocean circulation and heat content

The use of neutrally buoyant and profiling floats has been a cornerstone of oceanography for the last half-century. In the late 1950s Swallow floats misbehaved by moving at “high” speed (10 cm s^{-1}) in seemingly random directions rather than slowly in a straight line (baffling the crew on the sailboat trying to track them acoustically), thus awakening oceanography to the presence of the mesoscale “weather”. Since then it has become abundantly clear that the ocean circulation needs to be measured on all scales, from global and basin scales that are climatically relevant down to the small scales that are important to determining elusive mixing processes. There are complementary observing technologies that are relevant—satellites for the surface (not considered here), and Lagrangian platforms and fixed Eulerian sensors for *in situ* point measurements, both of which can be spanned by acoustic tomography.

These autonomous profiling floats, such as Argo introduced above, typically come to the surface once every ten days to telemeter temperature and salinity data and to obtain a navigation fix. During the time submerged the float is untracked. According to Davis and Zenk, 2001[27]:

> "Some studies place a high premium on using floats to represent fluid-parcel trajectories requiring the uninterrupted current following that can be achieved only with acoustic tracking. The penalty for autonomous [profiling] operation is a long time interval between known positions, which precludes resolving eddies unless cycling is rapid, and periodic surfacing that interrupts the quasi-Lagrangian trajectory. For observations of subsurface velocity, it is likely that both the continuously tracked neutrally buoyant RAFOS floats and autonomous floats will be needed. For acoustic floats a major limitation to economical sampling can be overcome by widespread deployment of high-energy sound sources. It is, for example, entirely feasible today to install enough sound sources that a float could be continuously tracked anywhere in the tropical or North Atlantic. Since sound sources, like radio stations, can serve different users, the presently rather simply structured network of moored sound sources will require greater international coordination in the future. The benefits of an organized RAFOS network will be linked with the responsibility of contributing parties to maintain such arrays of sound sources over an extended period of time on a basin-wide scale. Miniaturization of receiver electronics and production in great numbers could result in significant decline in float prices. This, and the development of new sensors, could open other fields of research…"

This statement is one motivation for the present work.

In regions of high shear, profiling floats can give erroneous estimates of velocity if the latter are based solely on surface fixes. Similarly, if trying to measure abyssal currents, estimates could be severely compromised if the float comes to the surface. In these cases, it is advantageous to remain submerged for most of the mission. The same might be said of more active mobile instrument platforms such as gliders, autonomous undersea vehicles (AUVs), and bottom rovers. With UGPS (using low amplitude, long duration, coded, high bandwidth signals), the precision and accuracy of the tracking can be much better than with RAFOS systems (cf. LORAN and GPS) resulting in correspondingly better velocity estimates. It may be possible that near-instantaneous Doppler shifts can be measured and therefore point-wise fluid acceleration measured directly. With appropriate transmission schedules high temporal resolution is possible and at the limit (depending on the spatial array size) internal wave time and space scales, and perhaps even mixing scales, could be approached.

Acoustic tomography can complement the point float and moored measurements by providing spatial integrals between the navigation sources and the receivers, whether fixed or moving. Acoustic tomography is inherently averaging in space, and can sample at the speed of sound. It can very efficiently measure depth average temperature and velocity (if reciprocal transmissions are used), with the amount of depth dependent information a function of geographic location and the sound speed profiles. Tomography over a 1000-km scale with a drifting hydrophone receiver has been demonstrated [2]. There are numerous simulation papers describing tomography using drifting receivers, where the position is simultaneously determined [28, 29, 30] (as seismologists do to determine earthquake location). This scenario of simultaneously determining float/receiver position and the sound speed field will require three or more sources to be "in view." A possible array showing the scale and the nesting aspects builds upon the Acoustic Thermometry of Ocean Climate / North Pacific Acoustic Laboratory array, using the future capability of seafloor junction boxes provided by NEPTUNE and other programs, Fig. 12. Note that when one source is added, data along the paths to *all* the receivers are obtained.

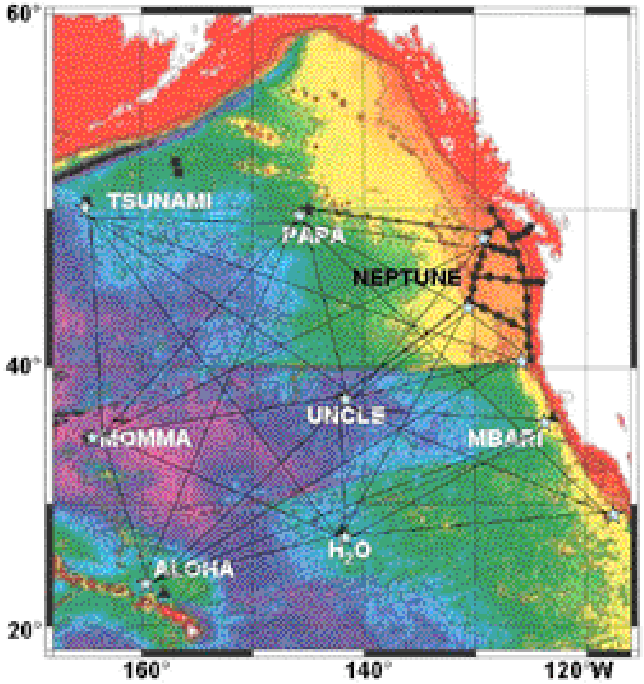

FIG. 12. A possible acoustic array on regional and basin scale meeting navigation and communications requirements to collect ocean circulation and heat content data.

These ideas can be extended to under-ice operations in polar regions. One funded project will deploy gliders under the Labrador Sea winter ice with real-time RAFOS tracking; another will deploy profiling RAFOS floats under the Antarctic ice (C. Lee and S. Riser, personal communications, 2003). In some cases, it may be advantageous to implant a satellite-acoustic transponder in sea ice to provide two-way communication to mobile platforms (J. Morison, personal communication, 2003).

If mobile platforms are used as receivers it is likely that a data assimilation system will be used that takes in surface fixes, travel times, Doppler velocities, depths, estimates of $C(\mathbf{x}, t)$, etc., to simultaneously estimate the float state (position, velocity, and acceleration as a function of time), along with the ocean state (e.g., temperature, salinity, velocity).

5-2. Wind and Rain

In the frequency range from 500 Hz to 50 kHz, the dominant sources of underwater ambient sound in the ocean are bubbles generated by breaking waves and raindrop splashes[31, 32]. Fig. 13 shows the mean spectral shapes of rain- and wind-generated underwater sound gathered from over 100 months of ambient sound measurements on deep-sea moorings. The spectral shapes associated with wind and rainfall are distinctive, allowing quantitative measurements of wind speed and rainfall rate. The signal from wind has a characteristic shape that rises and falls in amplitude with wind speed. The signal from rain is much louder, containing relatively more high frequency sound. In particular, there is a unique bubble entrapment mechanism associated with small raindrops that produces sound at 13–25 kHz. This is a surprisingly loud sound that allows the acoustic detection of light drizzle at sea. While biological and anthropogenic noises can also occur in this frequency band, these noises are generally local or intermittent and usually do not interfere with acoustic wind speed and rainfall rate measurements. The measurement of wind and rain at sea is notoriously difficult, especially under storm conditions (when air-sea fluxes are highest), and the acoustic method provides one of the few ways, if not the only, to do so reliably with exceptionally robust instrumentation—a simple hydrophone. It can be a cornerstone of widespread verification of satellite derived wind and rainfall estimates.

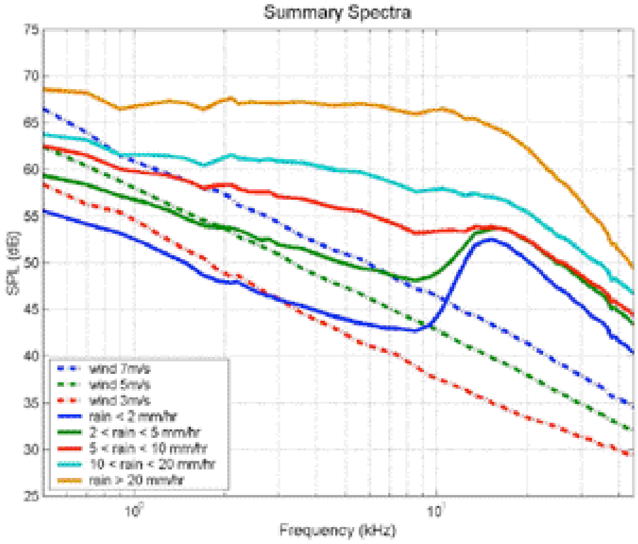

FIG. 13. Wind- and rain-generated underwater sound has unique characteristics that allow acoustic measurements of wind speed and rainfall rate (courtesy of J. Nystuen, APL-UW)

5-3. Marine Animals

Underwater sound is produced by marine mammals over a very wide frequency range, from a few Hz to hundreds of kHz. These sounds are used for communication, navigation, and hunting. The signals are generally unique to animal species and can therefore be used to monitor animal behaviors, including migration patterns, feeding behaviors, and communication between animals; an example of blue and fin whale spectra is shown in Fig. 14. Because sound travels through water more easily than light, acoustic rather than visual investigations of marine animal populations is usually more effective. By listening to the animals' signals on multiple hydrophones they can be tracked. A possible scenario for studying large numbers of marine mammals is to use arrays of mobile receivers (serving multiple users, such as Argo floats) positioned using a combination of UGPS and/or GPS to track the animal vocalizations. This assumes that future *in-situ* recording/processing and communications capabilities increase, as is expected with time.

Both marine mammals and fish can be tracked using acoustic tags, either passive (in the RAFOS mode) or active (in the SOFAR mode) depending on the situation. There have been significant developments in tagging technology for marine mammals and fish. For example, G. Fisher, C. Recksiek, and T. Rossby at University of Rhode Island are developing a "fish chip" RAFOS receiver that could operate 2–3 years with a 100-mA-hr battery. The entire tag is 2.5 cm long and 1 cm in diameter. In addition to position, the tag provides temperature and pressure that can be stored in non-volatile memory. The small size and long lifetime would allow individual fish to be tagged and potentially tracked in an appropriately instrumented ocean basin. When the fish are caught, the tag can be returned for downloading. In the SOFAR mode, several groups are working with small active tags in salmon, and these are counted as they go by a bottom-mounted hydrophone array with a range of several hundred meters at best.

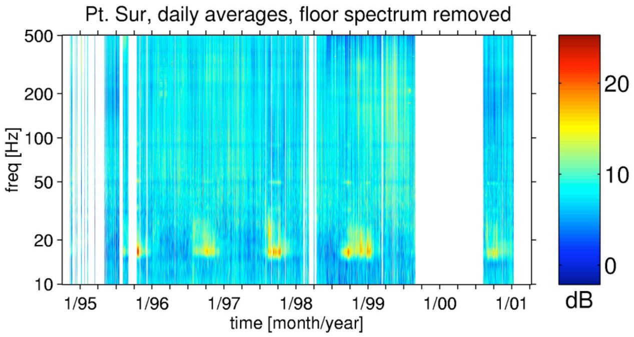

FIG. 14. Multi-year ambient sound spectra from Point Sur, California. Daily average spectra are plotted, so signals from earthquakes, ships, and other sources are not shown.

5-4. Seismics

Any and all receivers can be used to measure seismic T-phases (water borne signals). When signals from multiple receivers are combined, earthquake location can be determined. This has been applied with success in monitoring the Juan de Fuca plate for volcanism and seismicity. Recently, these water borne signals have been used to infer information on the state of icebergs and ice sheets in Antarctica. Deep "shadow zone" arrivals[33, 34)] have been detected below the sound channel. While the theoretical explanation for these is lacking (it is thought some scattering process is responsible), this means that navigation in parts of the deep ocean that were previously thought to be excluded should be possible at some level. These T-phase data can be used for Comprehensive Test Ban Treaty (CTBT) monitoring purposes, and could contribute to tsunami early warning systems.

5-5. The Seafloor

AUVs have been used recently to map the seafloor. While near-autonomous mapping is just beginning (Fig. 6), it is expected that long duration missions will be possible in the future, making use of seafloor charging and communications stations/docks. This is seen as one possible way to cover relatively large areas at a reasonable cost. In many situations precision repeat surveys over large areas (100s of kilometers) are desired as in, for example, studies of seafloor deformation near subduction zones (with centimeter accuracy) and deep sea ecology. Fig. 7 shows a possible sensor network on the active Axial Volcano, which includes navigation and communication with AUVs and bottom rovers. The latter might be controlled in real time using two-way acoustic communications to make routine areal surveys, and then during an eruption, to concentrate activity around lava flows. In the past, temporary local transponder nets have been set up at significant expense for a particular operation; future work will require permanent navigation and communications capability.

It is often stated that we know the topography of Mars and Venus better than we do our own earth, largely because of the masking nature of the oceans. Mapping is one of the natural first tasks of exploring a new environment, and its importance in understanding and developing the oceans over the next century should not be underestimated.

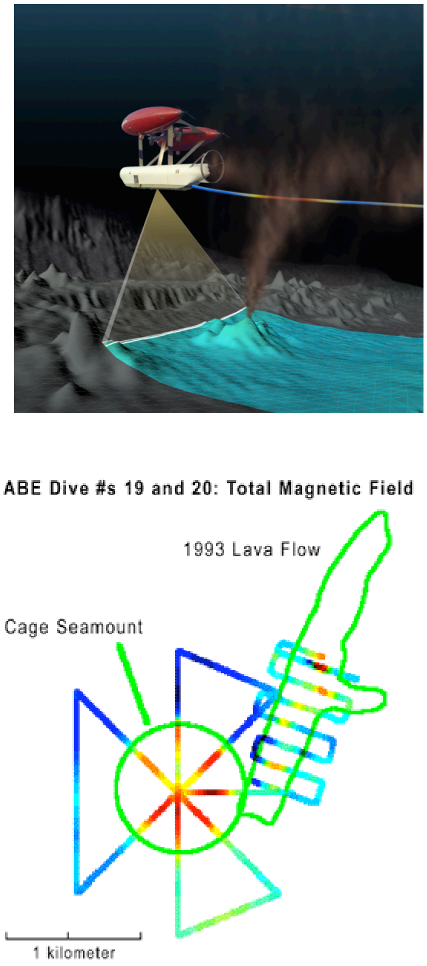

FIG. 15. Autonomous Benthic Explorer (ABE) track-lines showing magnetic field (courtesy of D. Yoerger, Woods Hole Oceanographic Institution).

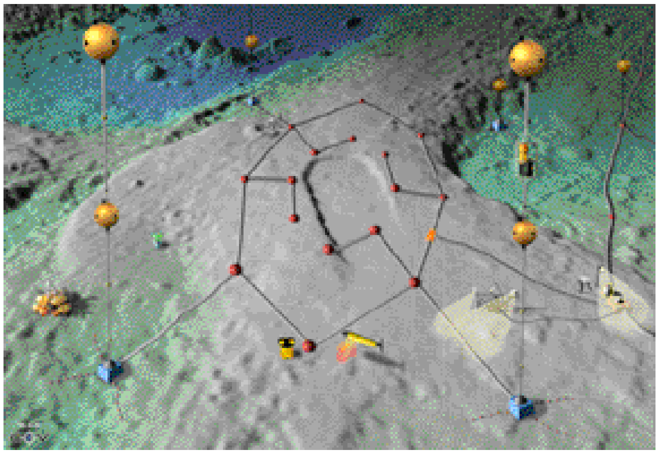

FIG. 16: A possible sensor network surrounding Axial Volcano on the Juan de Fuca Ridge. The network is connected to a NEPTUNE primary science node to the right; the red dots represent secondary junction boxes, to which many sensors would then be connected. Acoustic navigation and communication for AUVs and bottom rovers, as well as tomography and geodesy, are part of the system.

6. INTEGRATED ACOUSTICS SYSTEMS

6-1. Navigation

Acoustic navigation has followed two paths: fixed tracking ranges and float tracking. Various navies of the world have long had underwater tracking ranges. These have typically used simple pings or relatively simple coded signals over limited areas. Floating ranges became practical with GPS$^{35)}$ and there are several commercial products offered. There is at least one commercial product that has a bottom mounted system directly analogous to GPS, with continuous transmissions of broadband pseudo-random noise (PRN) signals. Float tracking occurred first using the SOFAR mode (drifting sources, fixed receivers) and then the RAFOS mode was introduced (fixed sources and drifting receivers). Tomography instrumentation evolved from these efforts but immediately used PRN signals. Because a prerequisite for tomography is accurate navigation of the instruments (perhaps implicit), tomography arrays can be immediately used for navigation purposes and vice versa (cf. atmospheric and ionospheric tomography above).

Because of bathymetry and the nature of the sound speed field throughout the oceans, we must recognize that we do not have an ideal geometry and cannot have the coverage that GPS does. There will be areas and depths outside coverage. It will be necessary to treat special cases (e.g., shallow seas, deep trenches, double ducts, polar seas, stripping of steeper angles by bathymetry) with creativity, understanding there may not be just one solution.

6-2. Communications

Simultaneously satisfying all the science, navigation, and communications requirements of an integrated system will be challenging. Acoustic communications have proven to be difficult. While basin-scale communications have been shown to be feasible$^{36)}$, most effort has been devoted to short-range (kilometers) applications either in shallow water (with relay stations, for instance) or with vertical paths in deep water (bottom to a surface mooring). Signal processing has included both coherent and incoherent methods. Clearly more research and development is necessary, but the community should strive to converge to a common set of standards that will accommodate the limitations of the medium and instrumentation while spanning the wide range of space scales, frequencies, noise conditions, desired data rates and error rates, etc.

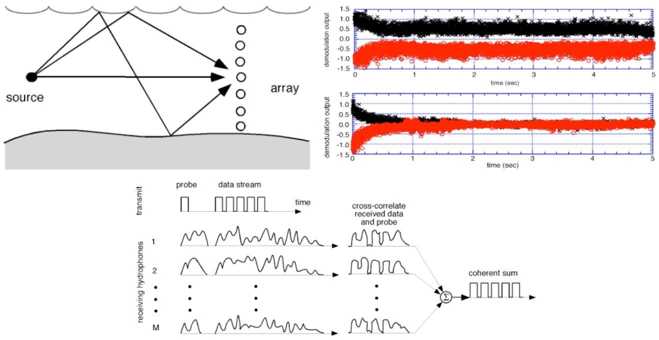

FIG. 17: Coherent signal processing for communications using spatial diversity$^{37)}$.

6-3. Implementation

Some of the uses of acoustics have been described briefly here. There are clearly many more including volume imaging, side-scan sonars, fish and bio-acoustic backscatter, turbulence and internal wave sensing, and sediment transport. In an observatory setting, a basic science/infrastructure element could be a single (in principle) bottom-mounted acoustic transducer that could serve multiple purposes: an inverted echosounder (depth averaged temperature), tomography, geodesy, ambient sound (wind, rain, marine mammals, T-phases, etc.), and navigation and communications. Together, all these applications will require management of the acoustic spectrum. How do we resolve conflicts between active and passive users? (A difference with respect to GPS is that active acoustic transducers are in the medium of interest, while in most cases GPS signals, with transmitters far out in space, are far below the noise level).

Following are some of the questions the IASOO Committee will address accompanied by brief comments.

What are the optimal frequencies and bandwidth to use? ATOC at 75 Hz has shown that adequate signal-to-noise (SNR) ratio can be obtained at ranges of 5 Mm. Are there advantages to transmitting two frequencies? Recent work by the NPAL Group[38)] has shown that signals at lower frequencies appear to suffer fewer of the detrimental effects from internal wave induced fluctuations (28 vs. 84 Hz).

What are achievable integration times? Experience shows that at 75 Hz coherent averaging times are about 14 minutes. In the Arctic, coherence times at 20 Hz are essentially infinite.

What data must be broadcast on top of the navigation signal? If a source is on a mooring should the source position be sent (or model parameters describing the motion), much as ephemeris data is transmitted as part of the GPS signal?

What are the optimal types of acoustic sources to use under various circumstances? Should they incorporate directionality?

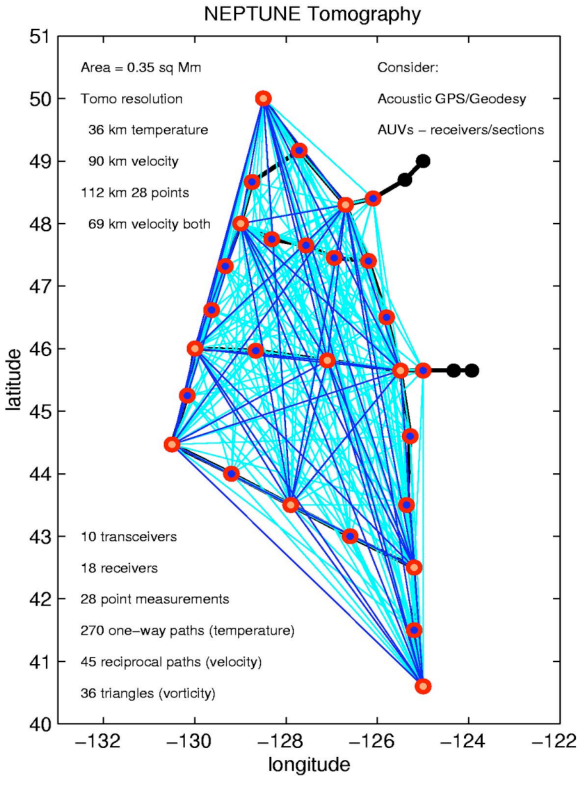

FIG. 18: Possible tomography array as part of the NEPTUNE cabled regional observatory in the Northeast Pacific[23)].

What type(s) of signals should be used? PRN signals are optimal in one sense (and are "orthogonal" to marine mammal vocalizations), but their use might exclude some types of sources. Code, time, and frequency division multiplexing are all possible.

What should the duty cycle be? If the source is deep, with a horizontally-oriented beam pattern, and relatively low level (all measures to mitigate possible effects on marine mammals), is it practical to consider continuous transmission?

While ambient sound variability is not well characterized, estimates are still required to determine SNR budgets.

Should receivers be arrays with vertical or horizontal directionality? It would seem reasonable to use two hydrophones on a float (top and bottom) to get an extra 3 dB of gain, for example.

For a given geometry of sources, a noise scenario, and the sound speed field, it will be necessary to estimate the signal level, SNR, and position error estimates (i.e., PDOPs) as a function of position. The estimated signal levels and SNR for a single receiver will be necessary to evaluate the ocean volumes in which marine mammals might hear the raw signal above the noise.

As the sampling of questions above indicates, there is much work that is required to mature this concept, let alone implement it. The development effort will include establishing the standards that will be essential to unify the field (such as signal protocols), work on more efficient broadband and directional sources and miniature acoustic receivers, research on coherence times and lengths as functions of frequency and range, ambient sound variability, using hydrophones on surface moorings, etc.

Actual fielding and operation of systems on various space scales might fall under the responsibility of the ocean observatories and ocean observing systems that are being planned. On a regional scale NEPTUNE will provide a relatively dense array of seafloor nodes that can support the acoustics sensor networks, Figs. 16 and 18, with extensions into the northeast Pacific, Fig. 12. On a global scale, Fig. 19 gives an indication of what might be possible with fixed instruments using ocean observatory and ocean observing system assets; augmenting this fixed array with receivers on floats will further extend the spatial coverage.

7. CONCLUDING REMARKS

A navigation and communications infrastructure is a prerequisite to sustained human endeavors in the ocean. Many applications require or are enabled by this infrastructure. Autonomous undersea vehicles (powered and gliding) can navigate themselves over the ocean bottom and through the water column without coming to the surface. They can navigate and communicate their data and status to users via acoustic modems to cabled or surface satellite telemetry systems without breaking away from their underwater missions. Profiling and drifting floats can more accurately measure the ocean's velocity structure, tagged fish and marine animals can be tracked with high precision, and bottom-fixed instruments can measure seafloor motion.

The acoustic sources and receivers of such a system can serve multiple functions: sources as navigation and communications components as well as multi-static active transmitters, and receivers as communications components as well as passive listening devices. With signal standards and protocols for managing the acoustic spectrum, the system will be an extensive, multipurpose acoustics infrastructure, capable of supporting applications even beyond our present vision. Drawing an analogy with the GPS and its use for tomography of the atmosphere and ionosphere, the various acoustic sources and multitude of receivers can function similarly in the ocean. This has significant implications for observing the ocean's interior in real time and measuring long-term climate variability. Receivers on globally distributed floats can also listen to ambient sound: wind and rainfall, seismic T-phases, marine mammals, and ships. Some of these natural sources of sound can in turn be used as sources of

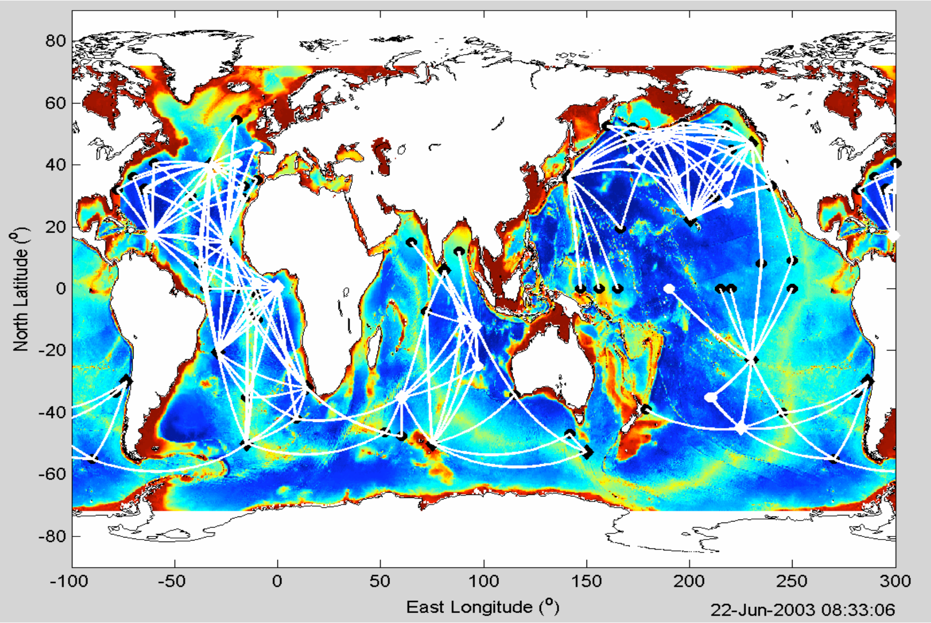

FIG. 19: Notional tomography array as part of the global ocean observatory and observing effort.

opportunity for other purposes.

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