TEST BAN VERIFICATION MATTERS

Hydroacoustic Monitoring of the World's Oceans

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TEST BAN VERIFICATION MATTERS: HYDROACOUSTIC MONITORING OF THE WORLD'S OCEANS

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Contents

Executive summary

- There is no doubt that, to ensure verification of a Comprehensive Test Ban Treaty (CTBT), hydroacoustic monitoring of the world's oceans is essential.
- As underground nuclear testing on land becomes easier to detect and testing controls are tightened, there may be a temptation to seek other means of evasion. The world's oceans offer an attractive alternative — they are easily accessible, in large part non-territorial, and much of the area available is remote. These factors make identification of offenders difficult, and policing a problem.
- Hydrophones (underwater microphones) detect sound in water. They are most useful when connected in groups called arrays.
- The installation of an adequate hydroacoustic system will complement other networks to a degree much greater than the sum of the individual data components. Attachment of other modules to the arrays, at minimal cost, which would probably be shared between several organisations, would provide further information on events, increase the confidence factor in the system by eliminating many false alarms from explosions other than nuclear, and provide a database that would prove invaluable for future generations to study.
- Complete cover, to enable event detection with confidence and speed, and location with accuracy, will require an integrated cable system of between 20 and 25 moored hydrophone arrays, using state-of-the-art technology.
- Each array should comprise about 10 hydrophones, at least three of which should be sited at the seafloor. Although this system would require the greatest initial outlay, the maintenance and running costs would be comparatively low.
- It will, therefore, be essential that the monitoring parameters be firmly established and adhered to when choosing the system required. Costs and data quality will vary considerably with differing parameters, and upgrading at a later date will be both difficult and expensive.
- By integrating the hydroacoustic network into the seismic network, and by attaching other monitoring modules such as water samplers and temperature gauges, the scientific and environmental communities will help sustain an interest in the operation and management of the network.
- Many countries will be more interested in supporting a broadly targeted network than isolated, mono-disciplinary stations whose sole purpose is verification. For example, the network could contribute data for earthquake hazard prediction and scientific exploration of the Earth's structure and dynamics.
- A successful outcome of the CTBT would be a nil-result data set, where no violations occur to be detected. However, in such circumstances, there will be a great temptation to reduce or withdraw funding for the monitoring system. Integration with and co-operation with other purposes will ensure continued interest and funding for the network, if not by the same agencies as originally envisaged.

BENEFITS OF OCEAN MONITORING FOR A CTBT

- Very high detection rate — 100% if coverage complete.
- Corroboration of land-based seismic data in some areas, especially if used in conjunction with ocean bottom seismometers.
- May eventually enable distinctions to be made between man-made and "natural" explosions and between different kinds of explosions.
- May be the only form of detection of cloudy-day nuclear test evasion scenario at low altitudes or on sea surface. Would give good location if flash undetected.
- Continuous monitoring (non-sleeper) — in contrast, satellites make passes and may miss a test if it is carefully timed.
- Possibilities of set-up cost-sharing with *e.g.* WMO, UNEP.
- Likelihood of great advances in scientific understanding in many fields, especially if used in conjunction with complete seismic data.
- If coverage complete and bolt-on options used, the potential for knowledge for other fields may allow costs to be shared not only with other agencies, but also with other departments within the same government, *e.g.* health, education, science, environment.
- Possible detection of illegal drilling/mining activities in sensitive areas such as the Antarctic.
- Boost to States Parties if components manufactured/bought as widely as possible — also spur to technological development.
- Possibilities for training of graduate/postgraduates in IDC and equally high standards throughout all States Parties. Exchanges and cross-checking of data would ensure openness and completeness of data.
- If new fibre-optic cables laid, may be potential source of income if capacity not fully utilised. Possibility for cost-sharing.
- Detection of missile launches and meteor trails possible if desired. New advances enable "track-back".
- System totally passive and environmentally suitable.
- Income generation potential by leasing facilities for short/long term or permanent experiments by research institutes, especially if all available bolt-on options utilised.
- If data shared with *e.g.* WMO there is a cross-check for each agency. Providing independent back-up if disaster happens and another guarantee of openness.
- May act as deterrent if data sold to requesting non-States Parties who would then realise its detection capability.

NB These benefits are in no particular order of importance

Notes

- Detection of underwater events is guaranteed, but detection of offenders is not. However, although in theory a device may be made small enough to carry aboard a ship, to be pushed over the side and detonated at some later convenient time, in practice, manufacture of such a device is a sophisticated and high-technology process. States possessing this ability are unlikely to need to test in this fashion.
- Because of the volume of data, much initial processing will need to be automatic with a triggering mechanism for suspicious events. While this is not difficult, it does mean that small or carefully positioned events may go undetected at this stage *e.g.* low-yield explosion triggered in deep sea trench or sub-surface volcano.
- A decision would be needed on how often data is to be sent from the national data centres to the international data centre and how to trigger if required sooner. This is dependent on the volume of information.
- Each cable comes ashore to a data collation point, for forwarding to the IDC. These points will be territorial and are, in theory, vulnerable to changes in policy of the country in which they exist. Even if all such equipment was the property of the group, litigation is costly, time-consuming and, of course, there is no guarantee that the item(s) in question will be recovered or remain viable. However, this would be the case whether the system was in group ownership or not.
- Large initial cost for totally compatible and complete oceanic monitoring system.
- Because of complete detection rate and therefore good deterrence, there is high risk that the information base will never show a nuclear test result, except in corroboration of a land-based event. There may be a great temptation, therefore, for participating Parties to reduce or terminate funding because the exercise will be deemed to be a waste of resources.

Introduction

The 1979 Double Flash

In the early morning of 22 September 1979, as storm clouds broke over the South Indian ocean, two bright flashes of light were recorded by a passing VELA satellite. Although previous similar recordings had been subsequently linked to confirmed nuclear explosions, this sighting has caused a great deal of speculation as to the cause, even amongst scientists who have studied the relevant data. Over 15 years later, the debate continues.

Integration of technologies

This event illustrates vividly the problem of acquiring diagnostic data — at that time, only one satellite of the whole VELA series was working and there was no corroborating evidence from either another satellite or any other source. Up to now, verification of suspected nuclear testing has always been made piecemeal. During the 1994–5 Conference on Disarmament negotiations for a comprehensive test ban treaty (CTBT), consideration has been given to the integration of the various methods and techniques to provide comprehensive, global coverage that would enable and facilitate identification and location of nuclear explosions. The integration of the various systems would also make possible a greater degree of confidence in the results (or lack of them), by providing fewer false positives and a high level of certainty of detection to whatever level is mutually agreed.

Evasion at sea

As underground nuclear testing on land becomes easier to detect and testing controls are tightened, there may be a temptation to seek other evasion scenarios. The world's oceans offer an attractive alternative — they are easily accessible, in large part non-territorial and much of the area available is remote. These factors make identification of offenders difficult, and policing a problem.

The seas cover 70 per cent of the planet's total area and provide many ideal nuclear testing sites, both underwater and on the surface. Four different oceanic areas exist for potential testing: (i)in the air/atmosphere above, perhaps by balloon; (ii) at surface level, on towed barges, for instance; (iii) within the water; (iv) buried beneath the ocean floor. The first area (air/atmosphere) will be principally monitored by satellite observation and by electromagnetic pulse, infrasound and radionuclide detectors, and the last (under the sea floor) by seismometers. Both of these out-of-water sites will create sound energy that may well enter the ocean below or above which the explosion took place.

If a device is exploded from a towed barge or only a short distance above the sea surface during a storm, detection by means other than hydroacoustics will be extremely difficult — both lightning and nuclear explosions create an electromagnetic pulse and the plume containing radionuclides will be rapidly dispersed.

High detection rate

Explosions within the water could have a 100 per cent detection rate if cover within the seas were adequate. They could be detected hydroacoustically to at least 900 km inland if the geology between the explosion site and the land/water interface allows an acceptable transmission path[1].

1.*D. B. Harris, G. D'Spain and A. Goldner, "Regional observation of a nuclear test from a vertical hydrophone array", Bulletin of the Seismological Society of America, Vol. 84 No. 4, August 1994, pp 1148–1153*

In the 1960s, the creation of the World-Wide Standard Seismological Network (WWSSN), in response to the need for remote nuclear test monitoring and as a partnership between development and research, provided the data for our current ability to detect, locate and discriminate explosive underground events to below 10 kilotons. The network not only provided data for effective nuclear monitoring, it was also a tool by which earth scientists could study natural phenomena such as earthquakes, a tool that has led to the understanding of the geophysical framework of plate tectonics. This network is now obsolete and needs to be replaced by new technology which is integrated with other systems.

A new opportunity

Because of the requirements for verification of a Comprehensive Test Ban Treaty, and because the WWSSN is now obsolete, a similar opportunity to implement global research and development has been presented to this generation of politicians and scientists that now includes the world's oceans.

This paper describes the available technology for hydroacoustic monitoring and analyses the strengths and weaknesses of this method, including vulnerabilities in the possible systems. The paper also examines the cost-effectiveness of hydroacoustic monitoring options for inclusion in a CTBT verification regime.

Methods of Monitoring

Sound energy in water

Explosions, whether natural or man-made, produce several different forms of waves, or phases, which travel at different speeds and produce different effects. Two of these waves, which travel through the earth, have been extensively studied by seismology and are called P (Primary) and S (Secondary). The energy that travels through water as sound can be picked up by hydrophones (underwater microphones) and the information is then forwarded, by cable or satellite transmission, to a suitable centre for interpretation.

The difference between earthquakes and explosions

Man-made explosions in water differ in one major respect from tectonic events. Artificial explosions have a very sudden rise time, with no preliminary warning of the large jump made by the recording instruments. An earthquake or volcanic explosion has a build-up to the event, even if the rise time is extremely short, and the event itself will be spread across time to a different extent[2]. A nuclear explosion releases its energy in less than 1/1,000,000 of a second while earthquakes typically rupture over several seconds, or even tens of seconds.

Characteristic bubbles

If an artificial explosion is sufficiently deep, relative to yield, a bubble will be produced that, because of chemical processes within the bubble and in response to external pressure, expands and contracts repeatedly whilst rising to the surface. This feature produces a sound so characteristic that it may form one of the triggers for automatic monitoring.

Explosions occurring at depths that do not allow time for bubble formation, at the sea/air interface or within the low atmosphere, will also generate sound that can be picked up hydroacoustically.

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2. *Gregory E. van der Vink and Jeffrey Park, "Nuclear test ban monitoring: new requirements, new resources", Science Vol. 263, 4 February 1994, pp 634–635*

The land/sea interface

Land-based explosions are capable of being detected in the ocean if the geology and rock types between explosion site and the coast enables adequate energy to reach the water. The energy is converted to sound waves at the land/sea interface and can then be detected by hydrophones. A nuclear test that, by accident or design, selectively focuses more P-energy into paths that emerge in the oceans and consequently defocuses energy along paths that emerge on continents, will be seismically measured as smaller than actual size. If the oceans have adequate hydroacoustic coverage, underestimation is less likely to happen[3].

If the underwater sound energy reaches land it is called the T (Third) wave and land-based seismographs can detect it. It reaches the seismographs later than the P and S waves because the water path is slower.

Hertz, decibels and bandwidths

Sound may be measured in two ways: (i) via its frequency (how low or high pitched it is) and (ii) by its intensity (how loud the sound is). The former is measured in Hertz (Hz) and the latter in decibels (dB). The sensitivity of the system will therefore depend on the range of frequencies listened for (bandwidth) and the number of decibels for which the system is set, as well as the number of samples taken per minute.

Hydroacoustic signals contain useful information up to a frequency of 100 Hz, a feature which enables more effective event identification than land-based information. Seismic systems are limited to a few Hz due to the preferential absorption of the higher frequencies during their propagation through the Earth[4].

The SOFAR channel (Sound Fixing and Ranging)

The natural deep sound channel

The oceans, whilst having local as well as large scale features that affect sound transmission in the water, share one major and unique property that enables effective acoustic monitoring of explosive events — the SOFAR channel, also known as the deep sound channel.

Long distance waveguides

Transmission of sound in water is dependent on water properties such as pressure, temperature and salinity, which vary according to, for instance, depth of the water and seasonal fluctuations. Energy is lost by reflection and refraction off the sea bottom and at the sea surface. The SOFAR channel, typically at 1 km depth and 1–2 km wide, provides a balance between the effects of temperature and pressure. The resulting stability forms a waveguide capable of transmitting sound for very long distances, to 18,000 km or halfway around the world[5], and even explosions of 1 kg can be detected across thousands of kilometres.

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3 *Charles S. McCreery, "Yield estimation from spectral amplitudes of direct P and P Coda recorded by the Wake Island deep ocean Hydrophone Array", Bulletin of the Seismological Society of America, Vol. 77 No. 5, October 1987, pp 1748–1766*

4 *Martin Lawrence, "Hydroacoustic monitoring of CTBT compliance: overview and summary", Conference on Disarmament, Ad Hoc Committee on a Nuclear Test Ban Australian Working Paper, CD/NTB/WP.75, 1 June 1994*

5 *Arthur Baggeroer and Walter Munk, "The Heard Island feasibility test", Physics Today, September 1992, pp 22–30*

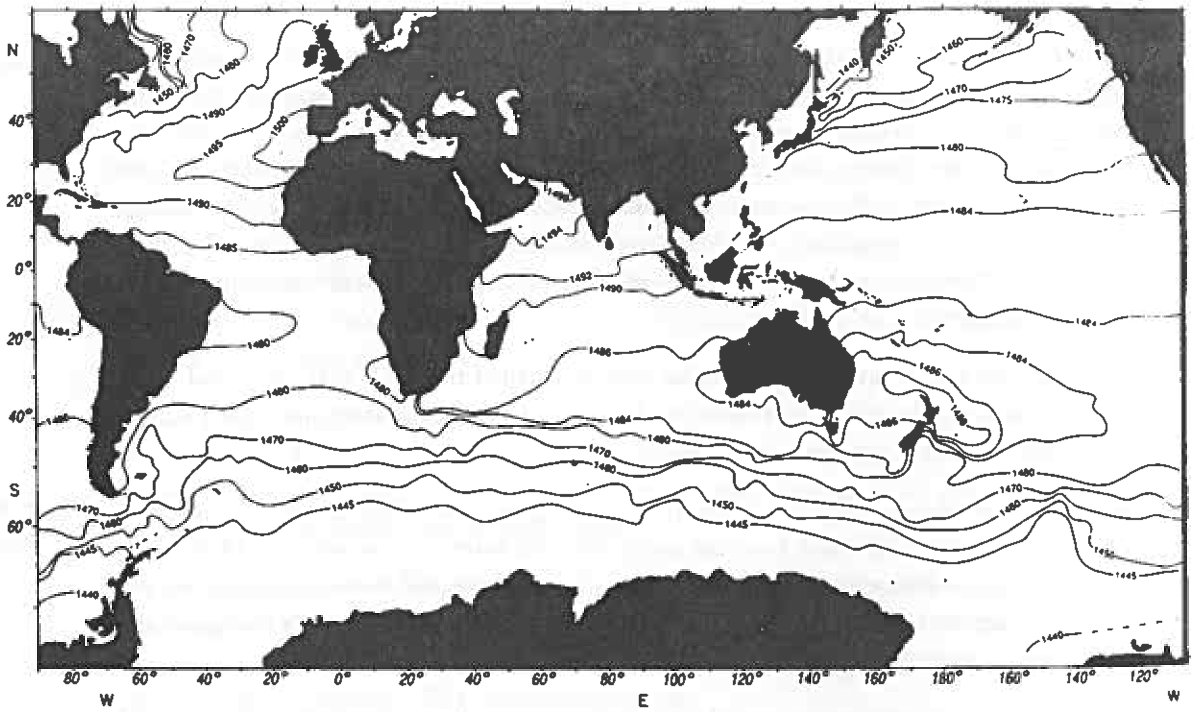

Figure 1: The SOFAR Channel showing the channel sound speed in metres per second

(from W.H. Munk and A.M.G. Forbes, Global Ocean Warming: An Acoustic Measure?, Journal of Physical Oceanography Vol. 19 (11), American Meteorological Society, November 1989, p 1768)

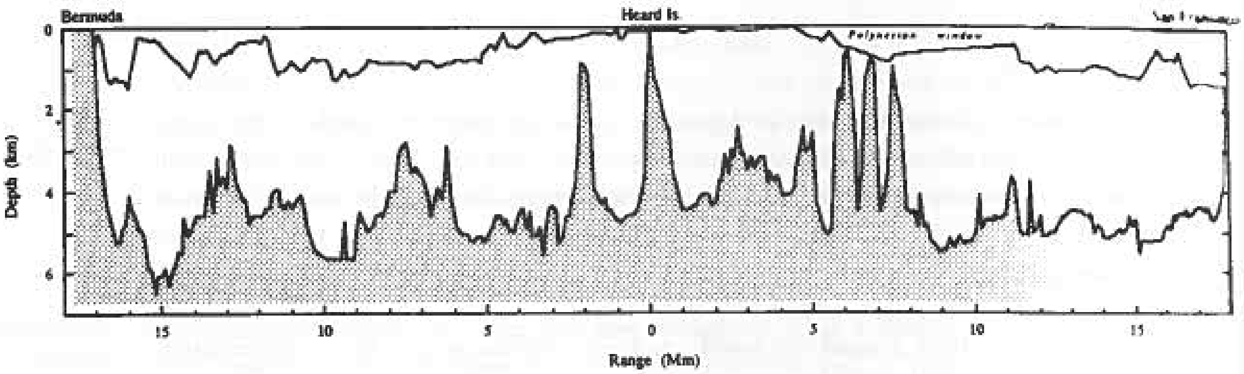

Figure 2: Profile of the ocean bottom and the sound channel between Bermuda, Heard Island and San Francisco

(from W.H. Munk and A.M.G. Forbes, Global Ocean Warming: An Acoustic Measure?, Journal of Physical Oceanography Vol. 19 (11), American Meteorological Society, November 1989, p 1770)

Areas of acoustic shadow

Because the channel is a function of the temperature/pressure (depth) ratio, the channel becomes shallower as the water cools and eventually reaches the surface at both Poles[6] (see figures 1 and 2). There are also areas where, because of coastal morphology, the channel is in acoustic "shadow", and sound originating or passing through such an area from a land-based explosion cannot reach the SOFAR channel directly (figure 3).

Pin-pointing locations

Sound velocity has been mapped very precisely in the world's oceans; velocity decreases by 4.6 m/s per centigrade degree from the sea surface to a minimum of 1.5 km/s between 700 and 1300 m depth and increases again from that depth to the bottom at a rate of 0.017 m/s per metre depth (see figure 1)[7]. This means that the capture of hydroacoustic signals in the sea can be used to calculate distances, location and temperature fluctuations within the oceans down to very fine levels.

Shadowed areas

Inland and territorial waters

As well as the shadowed areas indicated in figure 3, there are inland seas and lakes that would be suitable for nuclear testing, most notably the Caspian Sea, the Black Sea, the Great Lakes in the USA and Lake Baikal. However, because of the good acoustic transmission in water, and because of the wide coverage of the various existing seismic networks, there is every probability that any testing in these waters will be detected when the energy reaches the water/land interface and continues the journey through rock to reach the seismic sensors. Event location would be the determining factor in deciding whether to cover all shadowed areas or only those most tempting for would-be violators. A factor for consideration is that virtually all these areas are in territorial waters.

System components for hydroacoustic monitoring

The Hydrophone

A hydrophone is an underwater microphone

A hydrophone (see figure 4) is an underwater microphone by which sound travelling in water is detected, usually by means of polarised piezo-electric ceramic plates or rings. These are sealed within a waterproof, acoustically transparent sheath such as rubber or polyurethane, which can also isolate the sensors from vibrations of the attaching cable or mountings. The pressure waves are converted into electrical signals that can then be stored or sent down-cable to a data collection centre.

Laser-driven hydrophones are less vulnerable to connection failures

However, there are now available laser-driven hydrophone systems which require no maintenance at sea. The systems are very low-cost and require only lightweight cable and are therefore rapidly deployable[8]. This system requires fewer connections and is therefore less vulnerable to connection failures. The life of these types of hydrophones, if no exceptional external damage is sustained directly, is of the order of tens of years and the quality of transmitted data should remain consistent.

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6 F. B. Jensen et al, "Computational ocean acoustics", American Institute of Physics Press, New York, 1994

7 Baggeroer & Munk 1992, see note 5; R.D. Adams, "T-Phase recordings at Rarotonga from underground nuclear explosions", Geophysical Journal of the Royal Astronomical Society, Vol. 58, 1979, pp 361–9

8 Roger Demain-Griffiths, GEC-Marconi Naval Systems, personal communication, 1994

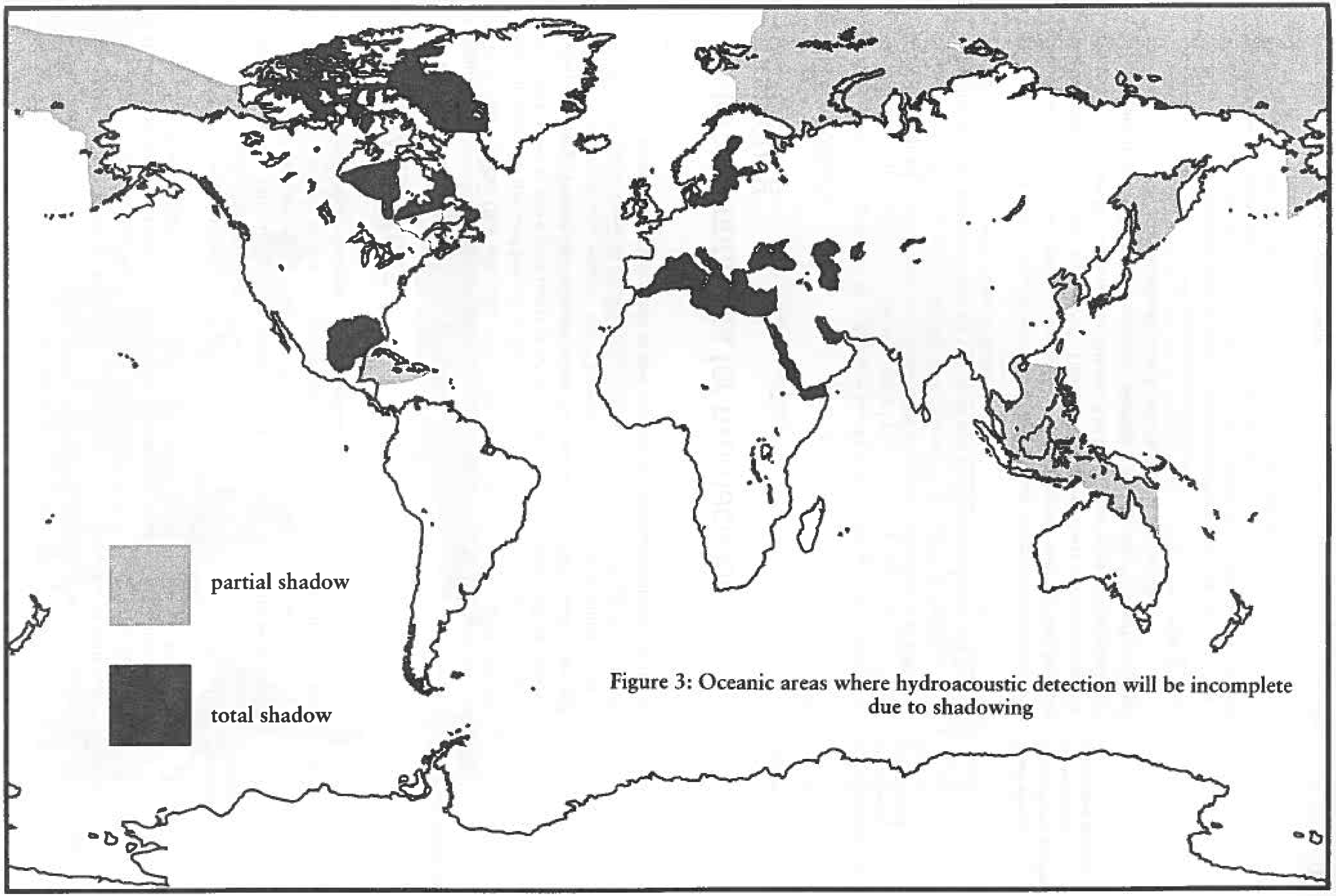

Figure 3: Oceanic areas where hydroacoustic detection will be incomplete due to shadowing

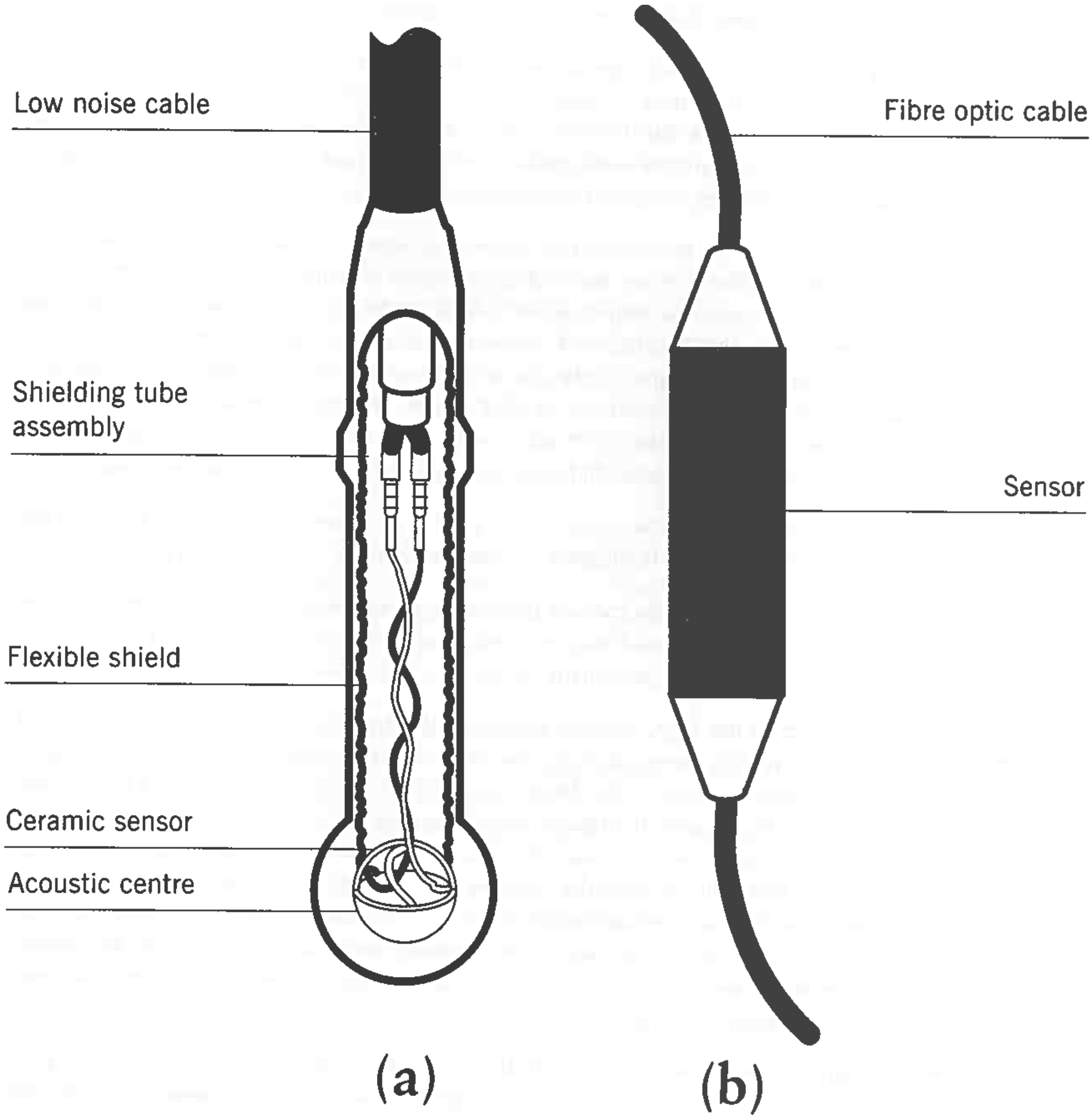

Figure 4: Diagrammatic representation of (a) a conventional piezo-electric hydrophone and (b) a laser-driven fibre-optic hydrophone

The system may be calibrated and otherwise serviced from a land-based point; only severance or damage of the cable will require servicing at sea.

Some hydrophones are capable of active transmission as well as reception and are therefore useful for calibration, but it is unlikely that the demands of a hydroacoustic network as envisioned will require an active system.

Hydrophones are robust

Hydrophones are robust; special small hydrophones (1.5–2.5cm)[9] and laser–driven hydrophones may be used to depths of more than 1600 m. Either of these types have such low failure rates that the lifetime of the system depends on other components. The weak points for non-laser hydrophones are the electrical components, however these have improved greatly over the last few years.

Signal–to–noise ratio

One of the problems encountered by monitoring instruments such as hydrophones is the background "noise". At sea this is a combination of wind, shipping, breaking waves and marine animals. As sound carries so well in the oceans, increasing distance from possible sources is no guarantee of a quiet environment. In addition, there will be some noise from the arrangement itself and it is this signal–to–noise ratio (SNR) that will determine the sensitivity of the desired system. The International Electrotechnical Committee standard (IEC–565) states that the noise level, whether acoustical or electrical, shall be at least 20 dB lower than the signal level to facilitate interpretation.

Advances in technology have given much greater sensitivity through better SNR and the ability to monitor more frequencies via the availability of broader bandwidths.

System sensitivity may be reduced to screen out unwanted noise. Self-generated noise and other small events, such as passing shipping, will then not be recorded, though this also means that smaller, potentially significant, events may go undetected.

Dynamic range and frequency filters

In a system of this type, the bandwidth and the decibel levels will be the determining factors in deciding "how low to go" for event detection below 1 kt and how accurately event location is required. The desired bandwidth is obtained by means of a filter which allows only the required frequencies to pass without distortion (IEC–565). A bandwidth of 0.5–50Hz and a sampling rate of at least 100 Hz would provide adequate coverage for event detection. Bandwidths could be both raised and lowered if the system had other tasks. Dynamic range would need to be decided for security considerations. Coverage to 150 dB would enable environmentalists to monitor most, if not all, marine mammalian output, thereby making the system most attractive for joint funding and short-term project funding (see below).

Digital sound processing

Adaptive filtering and high-speed digital signal-processing have greatly increased processing capabilities. The electrical voltage of the sound received from a conventional hydrophone is measured and each measurement converted into a numerical value which is either stored on site (in a buffer) or sent down-line for taping as a set of binary digits (bits) or as a series of pulses. From a laser-driven hydrophone it is modulated light that is measured and converted into numerical values.

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9 *J. Ginzkey, Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik, personal communication 1994*

Sampling frequency

The number of samples taken per second will depend on the quality desired; 100 samples per second will produce very good quality data without impinging on national security considerations.

Triggers may be set on specified channels if required, enabling speedier processing[10] and preventing computer indigestion. Additionally, data streams may be split by data acquisition equipment prior to transmission[11] for direction to different locations for analysis, storage and so on.

Time calibrations

Events are time-labelled, and time calibration is an important part of the whole process; it is time-lapses between recordings at different localities that determines location. Time calibration may occur down-cable or via satellite communication, depending on data transmission technique.

Installation

There are two main ways to install hydrophone stations: (i) moored to the sea bottom, monitoring at desired depths and locations including the sea floor, or (ii) floating in the water at desired depths and locations (see figure 6). Hydrophones may also be suspended from rock or ice and towed behind shipping (streaming), but although frequently used for mapping ocean and sea floor characteristics, the high operating costs involving ships make continuous streaming unsuitable for long-term monitoring. This method may be used if a test is imminently suspected, but adequate hydroacoustic coverage should render this unnecessary.

Connecting and amouring cable

The hydrophone is connected by cable to its buffer and amplifier, to other hydrophones, to its anchor and buoy or to a transmission cable. Wherever necessary these cables must be armoured to prevent damage or severance by "fish-bite" and trawling.

The hydrophone array

Vertical and horizontal arrays

Hydrophones are most useful when connected in groups called arrays. Such arrays may be vertical only *i.e.* with single hydrophones at differing depths, horizontal only, *i.e.* with hydrophones at differing locations at the same depths, or a mixture of both vertical and horizontal, with hydrophones at differing depths and locations (see figure 5).

US MILS

The Wake Island Hydrophone Array (WIA) is an example of the latter and has been in use since the 1960s, originally as part of the US MILS (Missile Impact Location System). It serves as a wonderful illustration of the productivity of an individual array and of the potential for a network of such arrays.

The Wake Island Array

The WIA consists of six hydrophones sited on the ocean bottom at 5.5 km depth to the North of Wake Island in the Pacific, and five hydrophones at three moored platform sites at 0.8 km depth in the SOFAR to the south and west of Wake[12]. The hydrophones are unpowered with approximately 150 dB of dynamic range, sampling at

10 *D. J. Houliston, J. Laughlin and G. Waugh, "Event triggered seismic detection systems developed by the BGS", in "Earthquake Engineering in Britain", Thomas Telford Ltd., London, 1985*

11 *R.G. Adair, J. A. Orcutt, W. E. Farrell, "Infrasonic seismic and acoustic measurements in the deep ocean", in Michael A. Deaett,*"Toward a low frequency future", *IEEE Journal of Oceanic Engineering, Vol. 13 (4), 1988, pp 245-253*

12 *Charles. S. McCreery and Daniel A. Walker, "The Wake Island hydrophone array", 83rd Annual Meeting of the Seismological Society of America (Eastern Section) Seismological Research Letters, Vol. 59 (1), 1988, p 22*

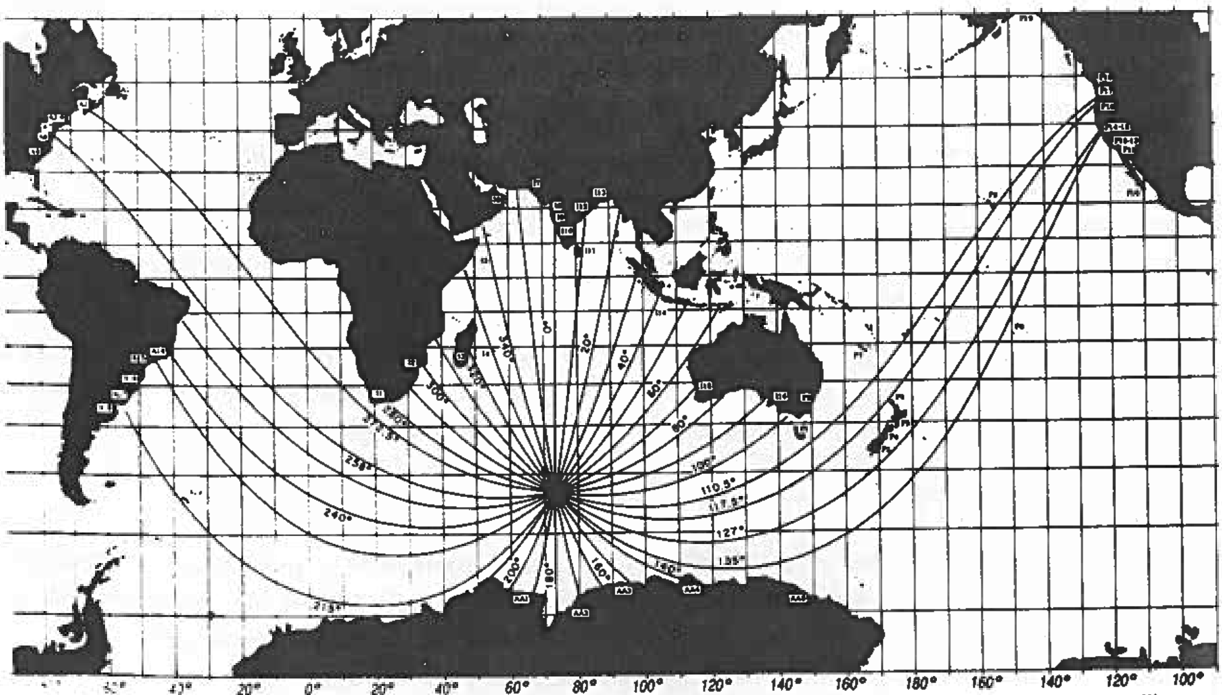

Figure 5: Diagram to show efficiency of SOFAR Channel — in this case from Heard Island (Indian Ocean). The square boxes represent research stations positioned for a sound travel experiment

(from W.H. Munk and A.M.G. Forbes, Global Ocean Warming: An Acoustic Measure?, Journal of Physical Oceanography, Vol. 19 (11), American Meteorological Society, November 1989)

100 samples per second.[13] The entire array covers an area of about 300,000 sq. km and was originally used to investigate the generation and propagation of T phases.

Long-term research

These T phases recorded via the WIA were, in turn, used to locate seismic events throughout the Pacific, including events from previously unknown submarine volcanoes. Subsequent research has investigated P waves from nuclear explosions in the former Soviet Union, the United States and Moruroa Atoll[14]; mapping and studying the Earth's deep interior[15]; determining ambient ocean noise between 0.05 and 30 Hz; the revelation of the tectonic (earthquakes and volcanoes) activity in the Micronesian subduction zone. Current work includes monitoring of seismic activity at the Juan de Fucar Ridge.

Established database

While it may be argued that much of this data is irrelevant to the CTBT it does provide, firstly, a huge addition to the database for automatic processing, thereby keeping costs down and increasing the confidence factor and, secondly, an attractive option for cost-sharing with other organisations, a subject that will be explored further.

Calibration changes and data consistency

If existing arrays are incorporated into the network, there will be differences in calibration between older and newer hydrophones, affecting data consistency. Changes in calibration may be detected either in an individual hydrophone or throughout an array by field testing. However, this will not eliminate the (unknown) performance differential between arrays. If an entirely new network is installed, all participating hydrophones will have been manufactured to the same, known specifications and will share the same high technological standards and life expectancy.

Significant differences have been found between spectra of shallow-focus earthquakes and explosions making use of different dB levels at different frequencies. However, work on this using the WIA has been hampered because of the age of the array, its formerly classified status and the original bandwidths of interest (less than 10 Hz) to those who installed the array[16].

Beamforming

If a very sensitive system is desired, bandwidth may be broader and the SNR improved by beamforming, which calibrates the information received from different hydrophones and produces a much clearer data trace. The spatial response of a hydrophone is wide, often omni-directional. In a hydrophone array it is possible to combine the various outputs with suitable time delays to limit the spatial response to a narrow direction that points to the signal source. This is known as beamforming[17].

Accurate mapping

Because the depth and sound velocity of the SOFAR have now been accurately mapped, it is possible to determine the event site by comparing arrival times of signals at different

13 *United States of America, Working Paper to the Ad Hoc Committee on a Nuclear Test Ban, Conference on Disarmament, "Hydroacoustic method for monitoring a comprehensive test ban treaty", CD/NTB/WP.70 27, May 1994*

14 *Charles. S. McCreery and Daniel A. Walker, "The Wake Island hydrophone array",see note 12.*

15 *S. Nagumo and C. S. McCreery, "PcP and ScP beneath the western Pacific detected by a deep ocean-bottom hydrophone array", Geophysical Research Letters, Vol. 19 (15), 1992, pp 1559-1562*

16 *C.S. McCreery, D.S. Walker and G.H. Sutton, "The Spectra of Nuclear Explosions, Earthquakes and Noise from the Wake Island Array", Geophysical Research Letters, Vol. 10 pp 59-62, 1983*

17 *United States Congress, Office of Technology Assessment, "Seismic verification of nuclear testing treaties", OTA-ISC-361, Washington , DC; US Government Printing Office, May 1988, p50*

hydrophonic stations[18]. Precision, however, depends on sensitivity of hydrophones, on completeness of ocean coverage and on beamforming.

Link to data centres

Options for data retrieval

There are three main ways in which to retrieve the data from the hydrophones, whether from singles or arrays — by cable, by direct radio-link or by satellite. It is also possible to retrieve the data via a sea-going vessel, but cost is prohibitive and, in some areas of meteorological uncertainty, may not always be possible when required.

Cable

Continuous cable transmission

Data may be transmitted continuously down a cable to a shore-based receiver. There are now available for use redundant telephone cables, for example trans-Pacific and trans-Atlantic. However, connection to these cables will be costly and data transmission will be comparatively slow. It is not known how long these old cables will remain viable, nor how much data will be lost during transmission. It is also unlikely that such redundant cable will be available for every location, although it is possible to provide extensions.

Problematic old cables

Again, there will be problems with, firstly, differing capacities of old and new cable lengths and secondly, old cable becoming unavailable for repair within a few years, as it is highly probable that this type of cable will be fully replaced world-wide with fibre-optic cable. Where old telephone cable is required to interface with fibre-optic cable, there will be problems with transmission capabilities that may require untried technologies to achieve satisfactory interfacing, especially if applied at great depths[19]. Powered cables can suffer from sun spot activity, which causes induced voltages, affecting both power supply and transmission (including satellite transmission).

Modern fibre-optic cables

Modern fibre-optic cables use energy in the form of light to drive the data pulses down-cable. They are less vulnerable to external interference as described above and data integrity is kept throughout. These cables have enormous transmission capacities and may be used for a variety of other purposes, for example, two-way communications, which would provide another means, via leasing or joint funding, of off-setting costs. These transmissions could be instructions to the bolt-on modules and other equipment.

Buffer-free

Cabling, because of continuous transmission, would not require buffers to be attached to the hydrophones, eliminating a potential source of data corruption, data loss and additional cost in both purchase and maintenance.

Low-cost cable laying

To minimise the costs associated with cable laying, purchased cable must be of the highest quality — possessing strength and flexibility in order to prevent damage while passing over the ship's stern during the laying process, and to prevent severance during recovery from the sea-bed.

Cable expense

Cabling has four elements incurring expense — purchase of cable, connection, laying (including burial if required) and maintenance.

Cables may be laid either on the sea floor or buried within it. The former is cheaper and lightweight, unarmoured cable may safely be laid this way on the deep sea floor,

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18 *W.H. Munk and A.M.G. Forbes, "Global ocean warming: an acoustic measure?" Journal of Physical Oceanography, Vol. 19 (11), November 1989, pp 1765-1778*

19 *Leo H. Townend, CRADO Ltd Hants GU33 6NS UK, personal communication*

vulnerable only to subterranean landslides and volcanic action. On the continental shelf areas, cables are vulnerable to damage from ships anchors, fishermen using trawling equipment, mudslides and from dredging in shallow water. Sea floor burial in such areas requires single armoured cable to protect against these hazards. If burial is not carried out, the most expensive rock-armoured cable will be required.

Stressful environments

In the surf zone, which is a particularly stressful environment, maintenance and replacement costs for unburied cable are likely to be high. Provided the cable is laid properly in ducting on land sections, and local authorities, gas, water and electricity suppliers *etc.*, are aware of the existence of the duct, disturbance and resultant failure is extremely rare. Similarly, if cable is properly buried on beach sections, disturbance is rare. Periodic checks of beach sections will be necessary to ensure that the cable has not become exposed due to the action of the sea.

As an example, the WIA data is cabled to a shore station, using a signal amplifier in the surf zone. The amplifier would not be required in a fibre-optic system.

Repair capabilities

There are two methods of acquiring repair capability — by chartering a ship as required, or entering the system into a maintenance agreement for telecommunications cables that provides ships for an annual standing charge. The cost is principally related to cable length and will not include costs such as running costs of the ship or stock cable costs used for repair. If fibre-optic cable is used throughout, and adequate protection given as described above, then chartering of ships as required will probably be a cheaper option in the long-term.

Onward transmission

Although the initial installation cost of a cabling system dictates that it should be beached at the earliest available opportunity, this will influence not only the choice of site for onward transmission but also the quality of such a site; an unmanned island data transmission station will be cheaper to set up than a manned, fully computerised national data centre. There may therefore be a balance struck between the costs of each.

Satellites

Surface transmitter

For transmission to satellite, the hydrophone data must have access to the sea surface.

Up-cable or pop-up packages

Data is stored in a buffer, and at set times, either when the buffer is full or at predetermined intervals, it will be transmitted to a communications satellite. This may be achieved up-cable to the surface transmitter or via a pop-up package. The latter, however, requires continuous renewal and therefore expensive ship-time, is vulnerable to capture or damage by underwater or surface hazards and the data is not continually available. This option therefore, will not be considered further.

Laser transmission

Data is transferred as a series of coded pulses, but may also be sent by laser transmission. This latter method carries a risk of eye damage, however, if directly observed with a telescope larger than 150.5 cm (6").

No intermediate stations

The great advantage of satellite communications is the ability to transmit the data directly to whichever reception centres are required without the need for intermediate stations.

Many communication satellites available

There are now many telecommunications satellites available; low earth orbit satellites are especially useful for this function, and availability will be increased in the near future as the mobile telephone companies launch even more. An example of this potential, is INMARSAT — a venture involving 75 countries, all of whom would benefit from use of the network by the hydracoustic requirements. It may well be possible to negotiate special concessions for a world-wide network with a commercial company. This should negate local political considerations, problems with differing technologies and ageing components, and possible future funding difficulties. The drawback, of course, is the vulnerability to commercial interests and considerations.

Intermediate stations and national data centres (NDC)

For cabled arrays, keeping costs down involves bringing the cable ashore at the earliest available opportunity. The data must then be transmitted to the International Data Centre (IDC) of the CTB Implementing Agency.

Three options are available:

i) Direct linkage to a telephone line;

ii) Transfer to an NDC, either manned or fully automatic, for forward transmission and possibly local analysis;

iii) Transfer to a local buffer for satellite transmission.

Ownership, analysis and responsibility

There are many considerations at this juncture, such as: who owns the facility at which data transfer occurs? If the network is group-owned, will sole responsibility for maintenance *i.e.* actual servicing and repair as opposed to funding, rest with the State Party in whose territory such a facility may lie or should maintenance be shared amongst all Parties, providing good training opportunities? If the facility has analytical ability, should the State Party in whose territory it lies have first/sole access to the data? How will States Parties be compensated if, because of simple geography, they do not have such access or facility?

Automatic triggering

Whatever is decided, a trigger will be required to advise if expected data is not received. This trigger may be for a local query, for manual forwarding of a query to the Centre concerned, or for an automatic query from IDC to NDC with a local alert system. The final decision as to the triggering system will depend on local/IDC links chosen, system capability and how quickly the data is required.

Data archiving

If data is transferred to an NDC prior to onward transmission to the IDC, advantage should be taken of the opportunity to make copies of the raw data, to be used for verification of the continuing integrity of the hydrophone system(s) involved and against any data corruption that may occur at IDC. If data reformatting is not required, or raw data is archived, it may be transferred onto standard nine-track computer reels. It might be desirable to include digital–to–analogue converter outputs for each channel to permit display of detected events on a triggered recorder. This would give an instant hard copy showing type of event and initial event parameters and would allow an analyst to pick out events requiring further investigation. The digital–to–analogue conversion also allows an instant check on system performance by reproducing the original sound "picture" from the binary notation that the computer processes [20].

NDC/IDC link:

Existing telecommunication network

In many places around the world, cabling — whether fibre-optic or conventional — may be interfaced to existing telecommunications networks. Therefore interfacing requirements and costs would depend entirely on local available technology.

Alternatively, satellites may provide the link. Cost of these links will vary according to local conditions, local costs and system availability. Canadian experience has shown that satellite links are cheaper for distances over 200 km[21] but this will vary according to local conditions.

Dedicated telephone network

Where telecommunications is perceived to be a preferred option, it is possible to lease telephone lines for a dedicated network. The actual cost will be determined by the sophistication of the technology required (analogue or digital), the grade of service (in this case data rather than voice or video), speed of transmission and bandwidth. In general, there is an installation fee and a fixed monthly charge without any extra fee based on usage, but some nations, for example Germany, add volume charges for fixed lines and others, such as Switzerland, include compensation payments for lost traffic on public switched networks[22].

Dedicated networks are less vulnerable to switching problems between local stations, to channel variations and, because of precise definition of channel capacity, to failures caused by system overload.

Data should be transmitted in digital mode for which there are four suitable line types available for lease:

Data channels carrying 2.400 – 50 kilobits/second

DS-1, US and Japan, carrying 1.544 megabits/second

E-1, European standard, carrying 2.048 megabits/second

DS-3, US (equivalent to 672 voice channels), used for full motion video and large data movements.

As a short-range example, data from GERESS was transmitted to Ruhr-University Bochum and NORSAR via 64 kilobits/second telephone lines[23].

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20 *D. J. Houliston, J. Laughlin and G. Waugh, "Event triggered seismic detection systems developed by the BGS" see note 10*

21 *Bob North and Ken Beverley, "The Canadian National Seismograph Network", Iris Newsletter Volume XIII, No 2, Summer 1994, p20*

22 *Phyllis W Bernt, Martin B.H. Weiss, International Communications SAMS Publications, 1993*

23 *Hans-Peter Harjes, M.L. Jost, J. Schweitzer and N. Gestermann, "Automatic seismogram analysis at GERESS" in "Analysis and interpretation of digital seismograms", W.T.C. Sowerbutts and A. Plesingers, Computers and Geosciences, Vol. 19 (2), 1993*

International Data Centre

IDC on cutting edge

The recent, enormous advances in computing technology enables the International Data Centre (IDC)to make full use of all the seismic knowledge garnered to date and to be in the forefront of advances in this field in the future.

Intelligent Monitoring System

It is expected that a version of the Intelligent Monitoring System[24] will be used to assist in analysis and interpretation of the huge volumes of data forthcoming from all the various verification procedures required by the CTBT.

Hydroacoustic data easily integrated

The Intelligent Monitoring System uses a database of as many previous events as possible in known locations to automate most of the seismic identification process. Because the hydrophonic data has now been co-ordinated many times with seismic data for given events, such interfacing is of proven quality and can therefore be integrated easily into the seismic data. In this section, therefore, all references to seismic data will apply to hydroacoustics.

Knowledge-based system

The Intelligent Monitoring System uses its database for comparison with new events and is known as a knowledge-based system (KBS). Because the components of the system do not have to be housed together, they may provide the basis for NDCs.

The potential of the Intelligent Monitoring System is shown in the example using the NORESS and ARCESS seismic arrays in Norway. This experiment used the system to process all data received by the two arrays, covering the major part of Northern Europe over eight weeks. In this period, there were 1580 recorded events and the emphasis was focused on the detection and location of these events[25]. The computers and functions were distributed between the NORSAR Data centre near Oslo and the Centre for Seismic Studies in Arlington, Virginia, USA.

Database management system

The system automatically retrieved data from the disk buffer, detected signals and then computed the signal attributes, such as amplitude, speed and bearing. The information was then stored in a commercial relational database management system (DBMS). Scheduled transfers of data to DBMS at the relevant centre automatically initiated the KBS which then interpreted the data to locate and identify events — earthquakes, mine blasts and so on[26]. The information thus gathered will be incorporated into the next version of the Intelligent Monitoring System to use case-based events for known areas, where events are identified by comparing them to previous events or cases that occur in the same or similar tectonic environment[27].

The output data was an on-line database including phase detection, located seismic events, waveform segments and a history of the decision-making process. The availability of interactive analysis provided integrated waveform and map display, as

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24 *S. R. Bratt, H.J. Swanger, R.J. Stead, F. Ryall and T.C. Bache, "Initial results from the Intelligent Monitoring System", in F. Ringdal,"Regional seismic arrays and nuclear test ban verification", Bulletin of the Seismological Society of America, Vol. 80, No 6(B), 1990, pp 1852-1873*

25 *ibid*

26 *T.C. Bache, S.R. Bratt, J. Wang, R.M. Fung, C. Kobryn and J.W. Given, "The Intelligent Monitoring System" in F. Ringdal, "Regional seismic arrays and nuclear test ban verification", Bulletin of the Seismological Society of America, Vol. 80, No 6(B) 1990, pp 1833-1851*

27 *R. Baumgardt-Douglas and G.B. Young, "Regional seismic waveform discriminants and case-based event identification using regional arrays", Bulletin of the Seismological Society of America, Vol. 80 No 6(B) 1990, pp. 1874-1892*

well as manipulative tools for the efficient review of automatically produced solutions. Each solution was reviewed by an analyst and validated, corrected or rejected as necessary. Thorough review of one day's data from two arrays required four to six hours, with the Final Bulletin averaging 28 analyst-approved events per day, completed within one day of event.

The Final Bulletin

By the end of the experimental period, the system required one system administrator, to maintain the automatic process and one seismic analyst to review the results, with occasional hardware and software support[28]. As Bratt *et al.* state, "The potential capability of a seismic monitoring network is defined by the signal-to-noise ratio of the stations that comprise it. But it is the Final Bulletin produced from the network data that defines it. In the past, this has required detailed and careful interpretation of data, which is very labour-intensive. The Intelligent Monitoring System provides consistent, reliable and steadily-improving data". The potential for the future from a complete global hydroacoustic network in conjunction with a complete seismic network using a tool like the Intelligent Monitoring System has enormous implications which will be explored further.

Analysis by computer

As well as fully automated systems, there are also individual computer programmes, which can analyse digital seismic data by operating on different types of data records, for example 3-component records, array seismograms and sets of globally distributed stations of arbitrary sample rates. This will have a special user interface for the handling of seismic data. The main part of such a programme is machine independent and can therefore be used easily on other computers[29]. This option could be used for downloading to participating institutions as required, for local analysis. Various versions are already in use.

Electronic output

The Final Bulletin, listing the day's events, need not, of course, be a paper output, but may be sent electronically to all participants if the appropriate technology is available locally and if the data is required at speed.

Storage of data

Copies of raw data

Copies of the raw data should be made on receipt at both NDC and IDC, and be kept in a magnetically sealed, fireproof environment. At least two copies should be kept, well apart from each other, and one set should be available for copying on demand.

Low space requirements

This form of data does not now require large amounts of space; one small 4-track cartridge may store 8,000 bits per inch, with up to 26 megabytes stored on one such cartridge[30]. As technology advances, it may for instance be possible to store many weeks' worth of data on one CD-ROM disc, at a few cents per disc and taking a few millimetres of shelf space. A single room, under such conditions, will house many years worth of data, providing a most invaluable archive for future research.

28 *S. R. Bratt, H.J. Swanger, R.J. Stead, F. Ryall and T.C. Bache, "Initial results from the Intelligent Monitoring System", see note 24*

29 *K. Stammler, "SeismicHandler-programmable multichannel data handler for interactive and automatic processing of seismological analysis" in W.T.C. Sowerbutts and A. Plesingers, "Analysis and interpretation of digital seismograms", Computers and Geosciences, Vol. 19 (2) 1993*

30 *D. J. Houliston, J. Laughlin and G. Waugh, "Event triggered seismic detection systems developed by the BGS" see note 10*

Current situation

The "hole in the road" syndrome

Because of national security considerations, it will probably never be known exactly how many, of what abilities and in which locations existing hydrophone arrays are installed. The current situation is analogous to the "hole in the road" syndrome: as soon as one array is installed then another reason is found to drop yet more.

Available arrays

Some arrays have been/are being installed for environmental research, for example Acoustic Thermometry of Ocean Climate (ATOC), Global Ocean Observation System (GOOS), GAMOT (Global Acoustic Mapping of Ocean Temperatures)[31], while others, originally used for national security purposes, are becoming obsolete and are being offered for environmental and CTBT monitoring[32]. Examples include the Wake and Heard Islands Arrays (part of the American MILS system) and the American SOSUS, both now useful in geophysics. AFTAC (the US Air Force Technical Applications Centre) also use hydrophones[33]. Mining and exploration companies are another source of hydroacoustic users and there are many smaller projects that are interested in monitoring marine mammal movement and ecology via their acoustic output.

Gaps in coverage

Despite all the above, there is as yet no hydroacoustic coverage of the South Indian Ocean and Coral Sea. This will have to be addressed if CTBT verification demands complete hydroacoustic monitoring.

Coordination is paramount

Lack of co-ordination and co-operation is resulting in the wasting of scarce resources (particularly money and specialist personnel), re-invention of the wheel, and lost opportunities for information exchange. Problems with data accuracy will influence conclusions if source equipment is not compatible and data has been acquired "second hand" or by unconventional means.

Options

Fixed stations vs drifting

Fixed station needed for event location

A fixed (moored) station is essential if precise event location is desired; drifting stations cannot, by definition, give the fine time resolution essential for distance-from-source calculations, unless the global positioning system is used to locate them (*i.e.* via a special satellite system). — see figure 6.

Costs of moored stations will be higher at installation; maintenance costs will depend to some extent on local conditions for both fixed and drifting stations. The longer the cable length, the greater its vulnerability, although deep stations will be less vulnerable than shallower installations.

Place in stable regions

Siting of all stations, whether fixed or drifting, must be distanced from shipping lanes and in tectonically stable areas wherever possible.

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31 *K. Schmidt, "ATOC delayed as report laments research gaps", Science, Vol. 264 (5157) 1994, pp 339-340*

32 *United States of America Working Paper, "Hydroacoustic method for monitoring a comprehensive test ban treaty", Ad Hoc Committee on a Nuclear test ban, CD/NTB/WP.70, 27 May 1994*

33 *T. Findlay, "Verifying a Test Ban", Peace Research Centre, Research School of Pacific Studies, Australian National University, 1989, p 110*

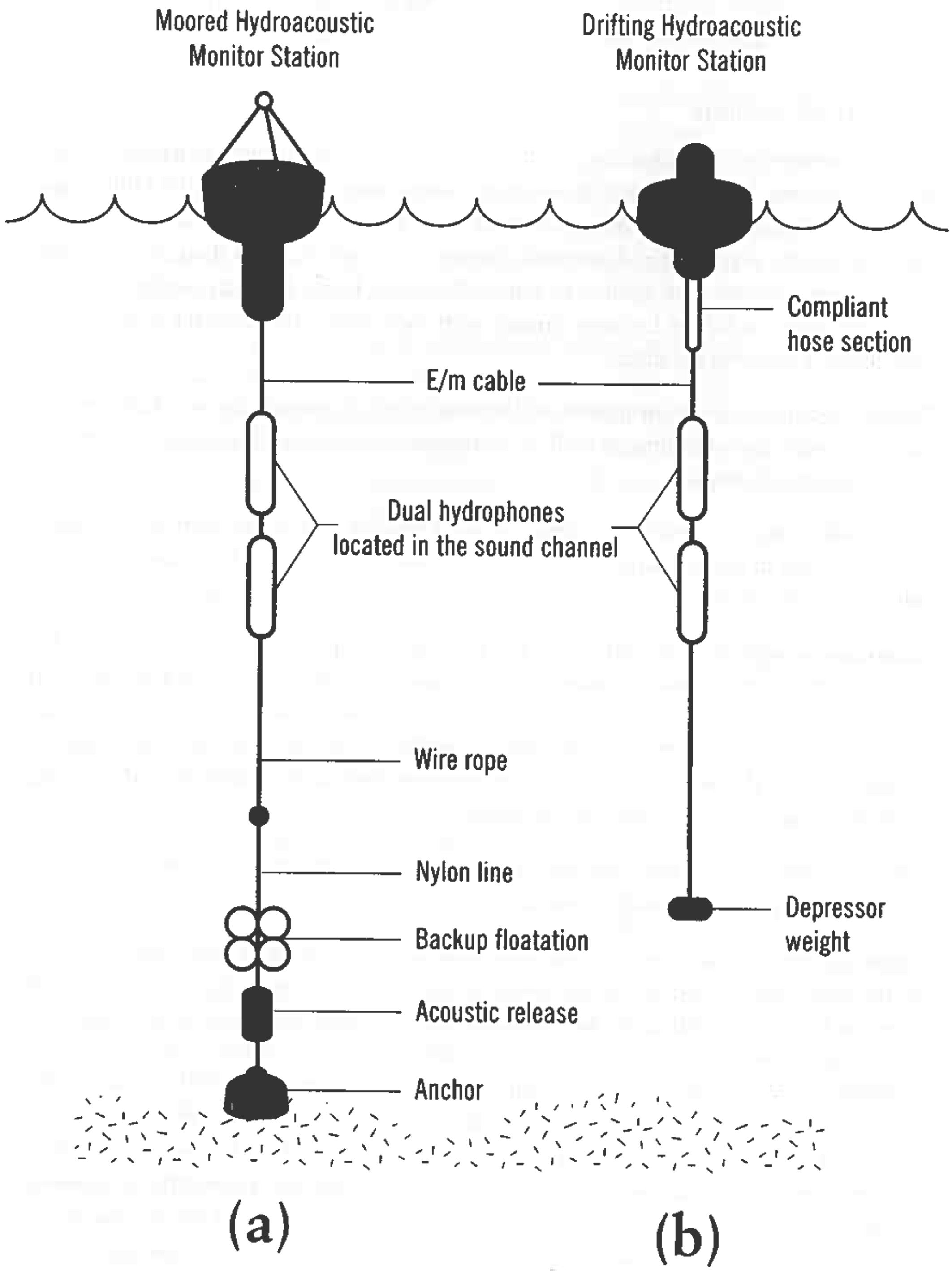

Figure 6: Diagrammatic representation of (a) a fixed (moored) hydroacoustic station and (b) a drifting hydroacoustic station.

For great depths, mooring only is suitable because of the great lengths of cable requir to reach the surface for a drifting system, and because of accessibility for the high maintenance required of such a system.

Stations can be suspended from ice

Where precise event location is required but bottom-fixing is not possible, for examp in Polar or shadowed, unstable continental shelf areas, it is possible to suspend statio from ice in stable locations, from moored barges capable of precise locati identification or from surface features such as isolated promontories.

Buoyed vs cabled

Buoyed systems are vulnerable to surface hazards

Any arrangement that reaches the sea surface is vulnerable to all surface hazards: win electrical storms, high seas, passing shipping, transmission interference and failure, a sabotage. A buoyed system is reliant on buffers for storage of data until transmission a source of both extra cost and potential corruption or failure. Then there are three s of data transmission: hydrophone to buffer; buffer to buoy; buoy to satellite. Risk data corruption or failure becomes greater with each move, and once the data has l each stage, it is lost to the next.

Batteries require constant upkeep

The batteries powering transmission will require constant monitoring and replaceme involving expensive ship time as well as replacement costs, and the system is relativ easy to locate and disable.

While cable length is a feature common to both buoyed and cabled stations because may be as long in one scenario as the other, the closer it comes to the surface, the mo vulnerable it becomes.

Fibre optic cable is safer

Transmission cabling from stations is the most secure option available — data is f directly from capture into the transmission system and the single potential source failure is the cable connection points. If fibre-optic cable is used, data will not be l during transmission and risk of corruption is negligible. It will also not be necessary fit amplifiers at the surf zone to boost the sound ashore as the MILS system requir another saving in both cost and maintenance.

While, as with every system, sabotage is always a possibility, precise location of cabl stations might prove too costly to pursue.

Buried cable is secure from damage

Greatest security, both from damage and interference, is obtained from cable burial the sea-floor and ducting at coastal and shore areas. The greatest risk to cabling is fr ships' anchors and trawling. A cable laid beyond any continental shelf, away from are subject to subterranean landslides and violent tectonic action, should rem undisturbed. If fibre-optic cabling is utilised, this carries a very low failure rate. Init costs for this system is high, but maintenance and running costs will be negligib bringing in high quality data for minimal yearly upkeep. Costs for interconnection existing deep cables may prove to be high in developing and testing the technolo required and would depend upon the availability of a spare pair of fibres. The wh system then becomes an attractive cost-sharing option because of the system potential

Transmission delays

A further factor for consideration is the speed with which data is required. Satell transmission will have a predetermined delay factor which may be overridden using preset trigger for definite events. However, if an event falls outside the given paramete speed of detection will be affected. The delay may be a few minutes or several hou depending on the linkages invoked. Cable transmission is instantaneous at point of cable entry and is continuous and real-time, dependent only on the forward-transmission method utilised.

Old and new interfacing

MILS is 30 years old

As well as the problems directly incurred by utilising old cable, there will be problems interfacing new hydrophone technology with old, especially if precise event location is required. It has been found[34] that station-dependent effects are a more significant source of location differences than any other factor. As an example, the MILS system has been in place for at least 30 years. This is the estimated life-span of such a system and it can be expected that use of old systems and cabling incorporated into the hydroacoustic network will not only provide problems with data compatibility, but will prove, probably sooner rather than later, to require high degrees of maintenance and component renewal. Repair capability will decline as old stocks become depleted and new technology takes over completely.

Old equipment means high cost maintenance

If a mix of the old and the new is utilised for an effective global hydroacoustic monitoring system, initial setting-up costs will have to include a measure of sometimes-untried new technology for interfacing, the costs of which cannot be estimated at this point and will probably be unknown until system completion. Maintenance costs will be higher than for a new system. All older components will require continuous monitoring and even then data loss or corruption may not be detected.

Error reduction

All systems are liable to error

Any system is liable to error, of which there are three sources — corruption with bias accorded to experience, systematic errors and random errors.

A good example of the first is SNR, where background noise distorts original data, but where system operatives are aware of the distortion and can either account for it or eradicate it completely for standardisation. Constant research and refining of the data by using different methods of analysis will help to define and eradicate errors of this kind.

Systematic errors occur consistently within the system to bias data in a given direction. However, because the errors are consistent they will go undetected until there is a fundamental change to the system. It may be that a systematic error, although present, may not affect some uses of the data, while rendering others valueless.

Random errors fluctuate in a positive or negative direction and cannot be accounted for individually until they occur. The only prediction is that they do and will occur, often in the most unexpected places and at the most inconvenient moments, no matter how careful the planning and investment of resources.

34 C. *Frohlich, "An integrated approach to seismic event location: II Sources of location uncertainty for teleseismic and local network data", Final Report, Phillips Laboratory, Directorate of Geophysics, Airforce Materiel Command, Hanscom Air Force Base, MA 01731-3010, PL-TR-94-2035, 14 February 1994*

System weakness

Table 1. Weak spots and consequences (see figure 7)

System component	Vulnerability	Consequence
I. Hydrophones		
Conventional	Damage and failure and can wander off calibration	Data inaccuracy, corruption, lo
Fibre Optic	External damage only	Data loss
II. Arrays		
i) Arrays which transmit to satellites		
Antennae	Physical damage from storms, shipping *etc.*	Quality of transmission affecte
Buoys	Damage, jamming	Data corruption
Buffers	Data overflow and failure	Data loss/corruption
Amplifiers	Failure	Data corruption
Cable: Conventional/old	Damage/severance, decay and fluxes,	Data loss/corruption
Fibre optic	Damage/severance	Data loss/corruption
Anchors	Pull loose	Possible loss of array
ii) Arrays that transmit via cable		
Cable: Conventional/old	Damage/severance, decay and fluxes	Data loss/corruption
Fibre optic	Damage/severance	Data loss/corruption
Cable/cable connection (analogue to optical)	Interface damage or failure	Data loss/corruption
Analogue/old telephone cable	Unknown condition of cable. Vulnerable to sunspot activity and other interference	Data loss/corruption
Fibre-optic	Damage and severance but long-life — 25 years	Data loss/corruption
III. Transmission		
Satellite	Jamming, orbit decay, reception, buffer and transmission failure	Data loss/corruption
Sea/land connection	In surf and beach zones vulnerable to environmental conditions	Data loss/corruption

System component	Vulnerability	Consequence
Telephone links ashore	Vulnerable to local conditions e.g. fibre–optic to analogue cable interface	Data loss/corruption
Switching stations within local telephone networks	Damage, power failures, breakdown, computer error. Unknown rates and dependent on local conditions. Especially vulnerable point	Data loss/corruption
IV. Data Centres		
Transfer of data to buffer	Failure	Data loss/corruption
Computer	Failure	Data loss/corruption
Data display	Failure and misinterpretation	Data loss/corruption
Manual data input and manipulation	Human error	Data loss/corruption
Satellite transmission to IDC	Jamming, orbit decay, reception, buffer and transmission failure	Data loss/corruption
Telephone transmission to IDC	Vulnerable to local conditions e.g. fibre optic to analogue cable interface. Link may be made electronically computer-computer	Data loss/corruption
V. Data storage		
Storage tapes	Heat, fire, magnetics and wear during copying	Data loss/corruption
CD-ROM	Excess heat, inappropriate stacking leading to warp and surface damage	Data loss/corruption

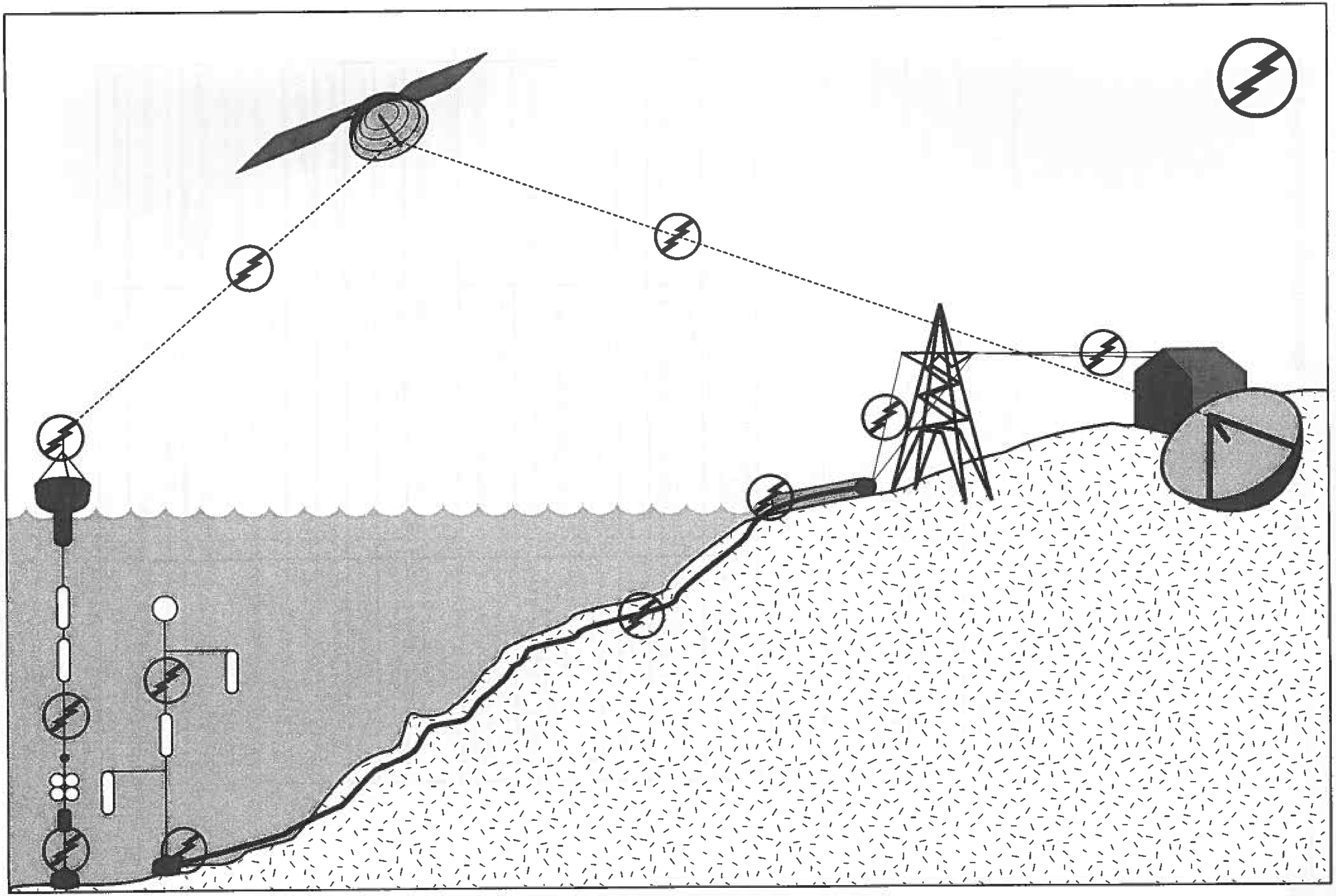

Figure 7: Diagrammatic representation of potential weak spots in the system

Synergy

Synergy can reduce costs and increase confidence

The installation of an adequate hydroacoustic system will complement other networks to a degree much greater than the sum of the individual data components. As well as the obvious boost to the available seismic data, attachment of other modules to the arrays — for comparatively low cost and probably shared with other organisations — would provide further information on the nature and size of detected events, increase the confidence factor in the system by eliminating many false alarms from explosions other than nuclear, and provide a data base that will prove invaluable for future generations to study. Many countries already recognise the synergistic potential, including France[35], Russia[36], Sweden[37], America[38] and India[39].

Ocean bottom seismometers (OBS)

Additional information from P and S waves

An OBS is a device for detecting and measuring P and S waves travelling through the ocean floor. These waves may have travelled from a land-based or deep ocean earthquake or man-made explosion, or have travelled from the opposite side of the planet via the deep-earth. If they transfer from the material of the sea floor into the water, they become sound and are picked up by hydrophones. However, these P and S waves contain much information as to their origin and the material through which they have travelled, and the addition of one OBS per deep-water station would greatly increase both the capability of the hydroacoustic network and its attractiveness for co-funding and leasing of facilities.

It has also been shown that the most sensitive sites for detection of short-period seismic signals may be in deep-ocean bottoms in regions with low average wind conditions. Such sites exist in the South Pacific, Atlantic and Indian Oceans[40].

If an event is detected by an OBS but is not picked up by hydrophones, this is positive confirmation that the event has not occurred in the water.

It has been found that, at a range of less than 35 km, an OBS is a better signal detector than an ocean bottom hydrophone and a sub-bottom seismometer is even better than an OBS. This appears to be true for both rock-borne and water-borne signals[41].

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35 *France Working Paper, "Seeking synergy between the various possible verification techniques", Ad Hoc Committee on a Nuclear Test Ban, CD/NTB/WP.117, 24 June 1994*

36 *Russian Federation Working paper, "Replies to questions to be dealt with by experts on non-seismic verification in the period 16-27 May 1994", Ad Hoc Committee on a Nuclear Test Ban, CD/NTB/WP.81. 6 June 1994*

37 *Conference on Disarmament Final Record of the Six Hundred and Eightieth Plenary Meeting, Palais de Nations, CD/PV.680, 2 June 1994*

38 *United States of America, Executive Summary and Working Paper, "A global infrasound method for monitoring a comprehensive test ban treaty", Ad Hoc Committee on a Nuclear Test Ban, Working Group on Verification, CD/NTB/WG 1.13 25 May 1994*

39 *India Working Paper, "Relevant techniques for detection of nuclear explosions in the atmosphere", Ad Hoc Committee on a Nuclear Test Ban, CD/NTB/WP.85, 6 June 1994*

40 *C.S. McCreery, D.A. Walker, F.J. Oliveira and G.H. Sutton, "Long-term temporal variation in ambient ocean noise, 0.1-30 Hz from Wake hydrophones", Transaction, American Geophysical Union, Vol. 66 (46), 1985,p. 107*

41 *R.G. Adair, J. A. Orcutt, W. E. Farrell, "Infrasonic seismic and acoustic measurements in the deep ocean", see note 11*

Examples of the use of OBS include recording of rock-borne energy waves to discriminate between earthquakes and explosions[42]; identifying background noise and its influence on ocean monitoring devices[43]; increasing precision in hypo-centre determination[44]; earth imaging in 3D[45]; for theoretic modelling and comparisons[46]; investigating ocean mantle phases[47].

Low cost

If cabling for an array is already being undertaken, siting of an OBS would not entail great cost. OBS data would be transmitted down-cable with triggers and channel markers as required, and could interface directly with incoming and existing seismic information to provide extra data and confirmation of an event, and possibly event discrimination.

Infrasound

Infrasound loses little pressure on entering water

Explosive events occurring less than 100 metres above the sea surface will be detected by conventional hydrophones. However, the shock wave produced by such events weakens and changes frequency as it moves further away from its source. At distances of ten to a few hundred kilometres, the frequency becomes sub-audible and is known as infrasound[48]. When infrasound enters the water, there is a 27 dB loss in energy but only a 7 dB loss in pressure (to which hydrophones are usually sensitive)[49]. In shallow water the energy will rebound from the sea bed to reflect off the sea surface[50] but may enter the SOFAR in deeper water. It may therefore be detected by sensors attached to existing hydrophonic cables to provide further confirmation of high altitude events and to confirm shallow-buried ground explosions wherever local geology permits satisfactory land/sea interfacing. Seismic and infrasound monitors should be co-located wherever possible.

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42 R.C. *Lilwall, "Regional mb:Ms, Lg/Pg amplitude ratios and Lg spectral ratios as criteria for distinguishing between earthquakes and explosions; a theoretical study," The Geophysical Journal of the Royal Astronomical Society, Vol. 93 (1), 1988, pp 137-147*

43 *A. Trehu, "A note on the effect of bottom currents on a ocean bottom seismometer", Bulletin of the Seismological Society of America, Vol. 75 (4) August 1985, pp 1195-1204; M.A.H. Hedlin and J. Orcutt, "A comparative study of island seafloor and subseafloor ambient noise levels", Bulletin of the Seismological Society of America, Vol. 79 (1) February 1989, pp 172-179*

44 *C.D. Lindholm and P.C. Marrow, "Ocean bottom seismometers in the northern North Sea: Experience and preliminary results with the Statfjord OBS", Bulletin of the Seismological Society of America, Vol. 80 (4) August 1990, pp 1014-1025*

45 *J. J. Nooteboom and C. Bukovics, "Integrated 3D land, shallow marine and deep channel acquisition", in H. Burkhardt, "Technical Programme and Abstracts", 51st meeting and technical exhibition, European Association of Exploration Geophysicists, Vol. 51 1989, p19*

46 *G.J. Tango and H.B. Ali, "Full wave theoretic modelling of comparative performance of deep sea floor and subsea floor hydrophone and geophone sensors", expanded abstracts of the 57th Annual International Society of Exploration Geophysicists Meeting and Exposition, SEG Abstracts, Vol. 57 1987, pp 188-191*

47 *D.A. Walker, Oceanic Mantle Phases recorded on hydrophones and seismographs in the north western Pacific at distances between 7 degrees and 40 degrees, 1971*

48 *United States of America, Executive Summary and Working Paper, "A global infrasound method for monitoring a comprehensive test ban treaty", see note 38*

49 *L. M. Brekhovskiyh, "Waves in Layered Media", Second Edition, Applied Mathematics and Mechanics, Vol. 16, Academic Press, 1980*

50 *D.M.F. Chapman, "Transmission of sound from air into shallow water" in D. Lee, A. Cakmak and R. Vichnevestky (eds.),"Computational Acoustics, Volume 3, Elsevier 1990*

Blast gauges

Surface ripple detection

Long wavelengths caused by energy release may be felt as wind in air or vibrations in more solid material. They may be measured as "ripples" over the surface of a sensitive instrument such as a blast gauge, which may be mounted on the sea bottom. This is specifically designed to give not only the detailed character and time of arrival of detected energy ripples, but also an accurate reading of its direction. Some of these instruments have already been commercially supplied for the purposes of monitoring and, if used, would be able to be integrated into the arrays and interfaced as required[51]. It may be worth installing one blast gauge per array if hydroacoustic location determination is incomplete.

Water samplers

Radionuclide sampling of the oceans would be a most attractive addition to the stations as an indication of yield and nuclear signature of any nuclear explosion[52].

Radionuclide plumes can keep together longer in the sea

A nuclear explosion produces a plume of emissions, amongst them rare gases and radioactive particles. In the seas, such a plume will keep its coherence and include particulates for much longer than an atmospheric plume, providing very good corroboration not just for the existence of a nuclear explosion but also for yield and type. These emissions may be detected via water samplers — data is transmitted at the required number of samples per second as a superimposed negative pulse on the hydroacoustic signal to confirm "normal" levels. Additional pulses are superimposed if the levels change. Bandwidth to 32 Hz and dynamic range of better than 40 dB give good results[53] — ranges falling well within the envisioned system.

Plankton sampling

Radioactive isotopes may also be sampled in plankton[54]. The type of radionuclides identified could provide information as to whether the device was sophisticated or crude. Had such a system been in place in September 1979, identification of those flashes in the sky may have been possible. Such sampling would also make it possible to identify the fissile fuel used for an event. Planktonic sampling for other elements would be an invaluable monitoring opportunity for environmentalists and others, and would provide further opportunities for cost-sharing or leasing.

Water oxygen, temperature, salinity and pH levels may be measured by water samplers this way[55] and would, as above, provide additional confirmation and cost-sharing opportunities.

Interfacing with atmospheric network

Decoding at NDC or IDC would require additional computer space and programming, but if atmospheric sampling were to be included in the verification programme, then interfacing with this would be possible.

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51 *Leo H. Townend, CRADO Ltd., Hants GU33 6NS UK, personal communication.*

52 *France Working Paper, "Seeking synergy between the various possible verification techniques", see note 36*

53 *A.B. Walker, D.W. Redmayne and C.W.A. Browitt, "Seismic monitoring of Lake Nyos, Cameroon, following the gas release disaster of August 1986", in "Geohazards: Natural and Manmade", . G.J.H. McCall, D.J.C. Laming and S.C. Scott,, (eds) Geosciences in International development Report, Liverpool University, Volume 15 1992, pp 65-79*

54 *T. Findlay, "Verifying a Test Ban", see note 33, p 112*

55 *A.B. Walker, D.W. Redmayne and C.W.A. Browitt, "Seismic monitoring of Lake Nyos, Cameroon", see Note 53*

Such additions to a global ocean network immeasurably increase the potential of an global ocean network and therefore the possibilities of co-funding and co-operation from research institutes around the world.

Costs

Table 2: Components

Item	Cost or cost consideration
Hydrophones, buffers, amplifiers	$1000–$1500 each
Buoys including transmission apparatus	$300,000
Cable laying	$100,000 per kilometre laying cost only
Fibre optic cable: i) lightweight, unarmoured, deepwater	$15,000 per kilometre
ii) single armoured shelf unducted	$23,000 per kilometre
iii) rock armoured unburied shelf *etc.*	$36,000 per kilometre
NDC — staffed	Dependent on technology involved, building standards, local labour costs and number of staff to be deployed
NDC — unstaffed	Dependent on technology involved, building standards and local labour costs
Satellite links	Dependent on contractor, availability, requirements e.g. number of transmissions per 24 hours
IDC — interfacing algorithms	Low cost because many already available
Staffing levels	Dependent on local costs and requirements and CTB requirements at IDC
Storage	Low cost — 1 large room per set at 2 different locations. Therefore dependent on local rates.

Table 3: Maintenance

Item	Cost or cost consideration
Hydrophone, buffers, amplifiers	Replacement, repair — ship time and parts
Buoys	Antennae and other repairs to an unknown extent. Includes ship-time and components
Cabling	Ship time and cable replacement
a) charter ship with repair capability	$45-$75K/day plus running costs during repair and costs of cabling *etc.*
b) enter cable into maintenance contract that provides ships for annual standing charge. Cost then principally related to system	Standing charges for length of system, running costs during repair and cost of cabling
Reattachment for broken moorings	Ship time and components, dependent on depth
NDC	Dependent on technology involved, local staffing levels and labour costs (Germany estimates $300/month for high performance digital station CD/NTB/WP.100)
IDC	Computer maintenance *etc.*

Table 4: Running costs

Item	Cost or cost consideration
Powering system if old cabling used	Dependent on cable length
Standing charges for telephone links and satellite links	Dependent on local conditions
Staff salaries	Dependent on number of NDCs, on local staff costs and on requirements at IDC
Consumables — batteries, computer paper and disks *etc.*	Batteries for buoys to be replaced minimum every 2 years. Dependent on form of bulletin, transmission, storage requirements *etc.*
Utilities charges	Dependent on local costs and levels of activity
Building leases or mortgages and insurances	Dependent on local costs and requirements

Option Costs (see table 5)

Integrated cable system of 20-25 moored arrays

Complete cover, to enable event detection with confidence and speed, and location with accuracy, will require an integrated cable system of between 20 and 25 moored hydrophone arrays, using state-of-the-art technology. Each array should comprise about 10 hydrophones, at least three of which should be sited at the sea floor. Although this system will require the greatest initial outlay, the maintenance and running costs will be minimal. Data would be of a quality and potential attractive to other organisations for joint and other funding. Costs for this system may be reduced by using the two MILS stations already in place, but data quality and potential may be affected.

Satellite transmission option

The above system may be implemented using moored buoys, *i.e.* satellite transmission of data instead of cabling. This would lower the initial set-up costs considerably, but the maintenance costs per year would be very much higher, probably by a factor of five, and system vulnerability would also be greatly increased. If event location was not important, the moored buoys could be replaced by cheaper floating buoys. These, however, have yet higher maintenance and running costs.

Reductions in numbers = reduction in data quality and reliability

Both of these networks and the number of hydrophones per station could be reduced to a level mutually decided by participating States Parties, with corresponding reduction in data quality and reliability. If detection only is required, the cheapest options would be a choice between using two MILS stations and three moored stations, two MILS stations and three buoyed stations, or two MILS stations and three floating stations. As set up costs and data quality decreases, maintenance and running costs rise, confidence and reliability decrease, too. Costs for various options are summarised in table 5.

Bulk-buying reduces costs

It is worth bearing in mind that set-up costs may be minimised if items are bought in bulk and contracts set for quantity and longevity wherever possible. It must also be remembered that maintenance and running costs will rise in the future to an unknown extent, but will be dependent upon availability of replacement parts as well as inflation.

Development and deployment is dependent to a large extent on the system chosen but, providing the tendering process is set in motion immediately after system choice is made, the system should be installed and ready for testing well within three years.

Off the shelf technology

There is now much "off the shelf" technology available which would need little adaptation to CTBT requirements. However, development of NDC/IDC facilities will be an important factor in the possibility of network testing for system reliability, interfacing success and data quality.

Cost benefit analysis

Cost versus sensitivity

The biggest problem posed by hydroacoustic detection is the balance between the cost factor and the decision as to what level of sensitivity is desirable or necessary.

High setting-up costs vs high maintenance cost

High initial investment = high quality long-life data

High initial investment will result in high quality data, low likelihood of data corruption, data compatibility, low maintenance, system life of over 25 years and enhanced opportunities for cost-sharing with other organisations, i.e. a system giving a high degree of confidence and reliability and fewer false positives.

Table 5: Example Costs and Comparisons of Options

Option	Discrimination Ability	Location Ability	Reliability	Longevity	Initial Costs	Annual Costs
20-25 new fibre optic moored stations	World-wide	World-wide and accurate	Highest	Longest (25 years)	$65-80 million	$1-1.5 million
2 MILS & 18 buoyed stations	World-wide	World-wide but less accurate	Medium	Low - medium 10-15 years	$10 million	$3.5-4.5 million
5 new fibre-optic moored stations	World-wide	Depends on placement	Highest	Longest (25 years)	$20 million	$0.3-0.4 million
2 MILS & 3 buoyed	World-wide	Depends on placement	Lowest	Low — about 10years	$2.5-3 million	$0.5-0.75 million

Notes:

1. The figures include no costs for the MILS as they are already in place; running costs for these stations have not been included since they are not available, nor is it possible to anticipate the life and component replacement requirement for them due to military sensitivities.

2. Initial costs are dependent on transmission methods and on cable lengths required and can therefore be only "guesstimates" for each option.

3. Annual costs will depend on transmission networks, types and status of national data centres, quality of components and level of intelligence data required. For example, the number of data interpreters, the frequency of event bulletins and so on.

Low initial investment = high maintenance costs

Low initial investment will result in high possibility of data corruption and loss, extra processing for incompatible data, higher failure rates, high maintenance costs, on-going replacement costs, fewer opportunities for cost-sharing with other organisations, — in other words, a lower degree of confidence and reliability, more false positives and possible failure to detect events.

There will be maintenance costs for as long as the system is required, therefore it may well be easier to obtain more resources for a higher initial outlay, when funding for verification is acceptable, than continuously funding the high running costs and unforeseen failures that a low-investment system would incur. There is a high risk that, when future budgets are revised, such projects, especially if producing a no-detection result, will be drastically pruned. The main considerations are as follows.

Cost vs totality of coverage

Coverage of shadowed areas

Detection in the major oceans is simple. Will it be necessary to cover all the shadowed areas, or only those, such as the South Pacific/Coral Sea area that are potential test sites and as yet uncovered?

Bolt-on modules increase capabilities

Bolt-on modules, such as radionuclide water sampling and temperature measurements would drastically increase pinpointing location and possible offenders of events, as well as increase the usefulness of the data to other bodies such as the WMO for income generation.

Fee-paying data users

Availability of data (for a fee of course) for non-participating states and the opportunity to assess for themselves the degree of coverage — and therefore chance of detection — may be a factor in dissuading potential testers to refrain from so doing in the oceanic environment.

Cost vs deterrent factor

More coverage = higher deterrence

A demonstrated totality of coverage may well have a deterrent effect. If cavity excavation at proposed island, offshore or coastal sites can be detected and this kind of evasion becomes too costly — deterrence in these areas may be 100 per cent.

Towed barges and low atmospheric explosions present a more difficult scenario and may perhaps be indicated prior to detonation by unusual shipping activity.

National security vs detection threshold

f very low-yield and accurate site location is required, this presents perhaps the greatest problem of all. A very sensitive system, capable of detecting and locating events to a few kilograms may, if necessary, include screening algorithms at data collection points to prevent incursions on national security in international and territorial waters.

MILS without beamforming

The USA is offering the MILS system without the beamforming facility. If a completely new hydroacoustic network is installed, it would be very easy to construct a system that is capable of detecting explosions only. Rather than limiting the system capability at the reception end, a screening-algorithm could be built into the computing system so that it would be a simple matter to restore full output data should increased sensitivity be required at any time. It would also make the entire network a more attractive proposition for potential cost-sharing.

If the hydroacoustic stations contain only a single hydrophone, then identifying event location may be possible through a similar process to triangulation on land. The result, however, will not be as accurate and may not be possible if the signal path is interrupted between stations.

Group ownership vs individual participating State ownership

Substantial discounts could be negotiated

Quality controls vary greatly between countries and only components with the highest specifications should be utilised. Because of the scale and prestige of the project, it will probably be possible to negotiate substantial discounts for many of the potential contracts.

Joint ownership

Equitable cost sharing will be necessary since most of the arrays will be outside territorial waters. Joint funding will induce a sense of ownership in both the system and its results, which in turn should result in increased interest in the longer term.

There are opportunities for reduced costs as other States join the Group and take their share.

Leasing/hiring of facilities to other groups for short/long term research would enable all member States to benefit from the cash injection.

Training for young scientists

There is the possibility for all States Parties to send postgraduate and post-doctoral researchers for training to all facilities, enabling a consistent level of expertise amongst the next generation of seismologists and geophysicists of all States Parties, regardless of any single member's seismic state or capacity. This system of training exchange would a) guarantee openness and reduce suspicion, and b) give exposure to a greater breadth of experience than may be available back home. This, in turn, would provide a highly trained resource in each participating state for research and education.

International cooperation

This degree of co-operation would foster very close ties within the scientific community at all levels and engender an atmosphere of interdependence that would reach far beyond a CTBT. At present, the USA, France, China, Canada, Italy, Germany, Japan and Australia are installing high-quality seismic stations, mainly for earthquake monitoring and research. Data exchange from these open stations is flourishing under bilateral agreements and informal arrangements[56].

There is also much international cooperation between naval establishments in the field of hydroacoustics. Such cooperation will further the understanding of the oceanic environment, as well as refining hydroacoustic techniques and applications[57].

Invaluable research archive

The complete records would form an invaluable archive for future research that would be independent of individual state's considerations, which would be available for sale and would therefore provide another source of income to benefit all members. Data archaeology is a new science from which this network's data output will benefit enormously — not only from the information that will be extracted and can be used to supplement the Intelligent Monitoring System database, but also from the gaps in the data, which will point the way to better coverage.

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56 G.E. van der Vink and J. Park, "Nuclear test ban monitoring: New requirements, new resources", Science, Volume 263, 4 February 1994, pp 634-635

57 The Netherlands Working Paper, "Verification techniques to monitor a CTBT", Ad Hoc Committee on A Nuclear Test Ban, Conference on Disarmament, CD/NTB/WP.55, 18 May 1994

States parties could use the facilities for their own, separate research purposes at no more than cost.

System integrity maintained

Integrity in the system would be retained if a State party withdrew from or reduced funding to the Test Ban; though costs may go up in the short term, no facilities should be lost.

Opportunities for Cost Reduction

Equable cost-sharing

If the network as a whole is owned by the group comprising participating states rather than according to territorial ownership, costs would be shared equitably. No country would be financially penalised for having a more suitable stretch of coastline than another.

Components could be bought from participating States and as widely as possible to enable an instant boost to States' economies, commercial development and to stimulate local interest.

Commercial funding

If network facilities are available at cost for research and training purposes, they would provide an attractive opportunity for co-funding from within each State, from other government departments, from research institutions and also from commercial companies, thus boosting local scientific know-how and benefiting local technological development.

Attractive system will increase funding potential

The best option for cost-sharing would involve installing the most comprehensive system possible, offering the opportunity for non-nuclear and seismic bolt-on modules to accompany the arrays and share the transmission facilities. There are many organisations that would be able to make permanent use of such an arrangement and who might well be interested in joint funding — the World Meteorological Office, United Nations Environmental Programme, large research laboratories and oceanic institutes, environmental groups and even commercial ventures such as GOOS (Global Ocean Observing System). Facilities could also be made available for lease to non-participants, to provide a continuing source of income.

Other projects

Currently, there are great demands for hydroacoustic monitoring. Three such projects, from which a hydroacoustic network might benefit in the future, are ATOC (Acoustic Thermometry of Ocean Climate), costing $35 M and involving seven countries; GAMOT (Global Acoustic Mapping of Ocean Temperature), a sister project to ATOC and WOCE (World Ocean Circulation Experiment).

The IDC will hold an enormous volume of data; it will become an increasingly valuable and sought-after resource as its capacity and potential become clear once it is fully operational.

Ecological understanding

One further consideration in support of a comprehensive network is that, as our understanding of the effects of sound on marine life and ecology improves, it is very possible that all "unnecessary" man-made explosions will be prohibited in the oceans.

Many marine animals, including whales, dolphins and turtles, use the SOFAR for communication, food location and navigation. Explosive events may cause fracture and other severe damage to the ears of such animals.

There are many experiments that currently require explosive charges being detonated to measure minute changes in acoustic travel time, and thereby water temperature, for mapping purposes by oil companies and for calibration of existing arrays.

Passive monitoring is the future

The USA already requires licensing for underwater detonations, a delaying factor in the ATOC experiment. As this kind of ban increases, there will be a desperate need for monitoring facilities that do not require explosive calibration and other detonations. Installation of temperature gauges, for example, by interested parties would negate the need to measure travel time of sound. The use of fibre-optic cabling throughout the network, enabling electronic calibration, would answer the requirements precisely.

Long-term commercial value

Finally, if adherence to the CTBT is total and, at some time in the future, it is decided that the hydroacoustic monitoring system is no longer needed, then it would have commercial value as a "going concern" and could be sold off to recoup some of the outlay.

Invaluable tool for future generations

With foresight and planning, a comprehensive global hydroacoustic network could provide the basis for research and information that would give the world the boost in knowledge that the World-Wide Standard Seismological Network did 25 years ago. With the basis of today's technology, such a network may go on providing useful information for far longer than that; the archived material would provide future generations with an invaluable tool towards an unparalleled understanding of our planet.

Conclusions

Hydroacoustic monitoring is essential

There is no doubt that, for complete coverage for CTBT verification, hydroacoustic monitoring of the world's oceans for violations is essential. It is important to recognise that no state entering the nuclear club is now likely to require a full-scale test with significant nuclear yield of any weapon resembling those in the first-generation of the American stockpile (20–30 Kt)[58].

Parameters must be established

It will, therefore, be essential that the monitoring parameters — how low to go (for yield) and how accurately event location is desired — be firmly established and adhered to when choosing the system and network(s) required. Costs and data quality will vary considerably with differing parameters, and upgrading at a later date will be both difficult and expensive.

Additional data is an asset

It must be remembered too, that much data will be collected that will not be of interest for verification. This data will have the potential for "filling out" the information collected from the seismic networks as well as containing much important environmental and other information. The whole system would be in great demand if it were as complete, both geographically and technically, as possible. By integrating the hydroacoustic network into the seismic network, and by attaching other monitoring modules such as water samplers and temperature gauges, the scientific community will help sustain an interest in the operation and management of the network. Many countries will be more interested in supporting a broadly targeted network than isolated, mono-disciplinary stations whose sole purpose is verification. For example, the network could contribute data for earthquake hazard prediction and scientific exploration of the Earth's structure and dynamics[59].

Potential for leasing facilities

Integration of such data and scientific networking would not only provide a potential source of co-funding for initial set-up, but also great potential for leasing of facilities for both long and short term experimentation and development.

There is currently an atmosphere in which international co-operation between civilian scientists and the military can flourish. The example was set 25 years ago by the WWSSN — the requirements for CTBT verification can now build on this and other examples to provide an inheritance for the future that would be unparalleled in its potential.

Verification deterrence

To quote Trevor Findlay, "Uncertainty about verification capabilities work in two ways: while the verifiers of a test ban can never be absolutely certain that they have detected all tests, a potential violator can never be certain that their violations will go undetected. A fully operational verification system for a CTBT will be replete with redundancies, all of which will give a potential violator pause"[60].

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58 Laurence. Nardon, "Test Ban Verification Matters: Satellite Detection", Verification Matters, No. 7 VERTIC, London 1994, p 23

59 G. van der Vink, "Nuclear testing and Nonproliferation: the role of seismology in deterring the development of nuclear weapons", Prepared at the request of the Senate Committee on Governmental Affairs and the House Committee on Foreign Affairs of the United States Congress, February 1994, The IRIS Consortium, Arlington Virginia, USA, p. V-11

60 T. Findlay, "Verifying a Test Ban", see note 33, p115

Detecting the cheats

To paraphrase US Secretary of State Harold Brown[61], there is a double bind which serves to deter cheating. To go undetected, any cheating would have to be on so small a scale that it would not be militarily significant. Cheating on such a level would hardly be worth the potential risks involved. On the other hand, any cheating serious enough to affect world security would be detectable in sufficient time to take whatever action the situation required.

Cooperation reduces chances of funding withdrawal

Hydroacoustic monitoring of the world's oceans would help to do precisely this. A successful outcome of the CTBT would be a nil-result data set, where no violations occur to be detected. However, in such circumstances, there will be a great temptation to reduce or withdraw funding for the monitoring system. Integration and co-operation with and for other purposes will ensure continued interest and funding for the network, even if not by the same agencies as originally envisaged.

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61 *Quoted in A.S. Krass, "Verification: How Much is Enough?", SIPRI, Taylor and Francis, London 1985, p.142*

Glossary

Amplifier	Device that boosts energy output
Analogue Recording	A process in which every part of a sound signal throughout its duration is converted to a series of varying electrical impulses. This produces a complete sound "picture"
ATOC	Acoustic Thermometry of Ocean Climate
Bandwidth	A given range of frequencies ((*q.v.*)
Beamforming	The process by which the various hydrophonic outputs are combined with suitable time delays to limit the spatial response to a narrow direction that points to the sound source
Buffer	A storage "area" for electronic information prior to its onward transmission for use
dB	Short form of Decibel (*q.v.*)
DBMS	Database Management System. See page 22
Decibel	Unit of measurement of sound intensity
Digital Recording	At certain points in the monitoring of a sound, its electrical voltage is measured. Each separate measurement is converted into a numerical value which is then stored as a set of binary digits (bits) in the form of a series of pulses. The presence of a pulse indicates a 1, its absence, a zero. This process is known as digital recording and allows faithful reproduction of the softest and loudest parts of any sound recorded
Frequency	The number of times a vibration repeats itself in a specified time, usually a second. It is measured in Hertz (Hz)
GAMOT	Global Acoustic Mapping of Ocean Temperature
GERESS	German Regional Seismic Array System
GOOS	Global Ocean Observing System
Hertz	Unit of measurement of frequency (*q.v.*). Often shortened to Hz
Hydrophone	Underwater microphone
Hz	Short form of Hertz (*q.v.*)
IDC	International Data Centre
KBS	Knowledge-based System. See page 22

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Hertz	Unit of measurement of frequency *(q.v.)*. Often shortened to Hz
Hydrophone	Underwater microphone
Hz	Short form of Hertz *(q.v.)*
IDC	International Data Centre
KBS	Knowledge-based System. See page 22

Kt	Kiloton — yield of a nuclear explosion equivalent to 1000 tons of TNT
MILS	Missile Impact Location System
NDC	National Data Centre
NORESS	Norwegian Regional Seismic Array System
NORSAR	Norwegian Seismic Array
OBS	Ocean Bottom Seismometer (see Seismometer)
P (Primary) wave or phase	Compression-type wave transmitted from an explosion or earthquake. These waves travel the fastest through rock and reach seismometers before S and T waves *(q.v.)*
S (Secondary) wave or phase	Shear-type wave transmitted from an explosion or earthquake. These travel more slowly through rock than P waves, but arrive before T waves
Seismometer	A device for measuring earth movements. Output is in the form of a seismograph or trace as well as electronic
SOFAR	The Sound Fixing and Ranging Channel — a stable channel in the oceans which is capable of transmitting sound through its entire length with little or no loss in energy. It is used extensively by marine mammals for navigation, food location and communication. It is also known as the Deep Sound Channel See page 9
SNR	Signal–to–Noise Ratio — the relationship between the desired signal being listened for and the background ocean noise *e.g.* waves breaking, wind, shipping, marine animals, as well as the system self-noise
Spectra	Plural of spectrum: ranges of distribution of energy, velocity, mass *etc.* with respect to its wavelength or frequency
T (Tertiary or Third) wave or phase	Sound generated or travelling within water from an explosion or earthquake which has been converted to dynamic energy at the sea/land interface for onward transmission through rock. Because the water provides a slower travel path than rock, these waves reach seismometers later than both the P and S waves *(q.v.)*
Wavelength	The distance between two points of the same phase in consecutive cycles of a wave
WIA	Wake Island Array. See page 15
WWSSN	World-Wide Standard Seismological Network

About VERTIC

What is VERTIC?

VERTIC, the Verification Technology Information Centre, was established in 1986 as an independent, non-profit making organisation of scientists in response to the needs of policy-makers, journalists, legislators, the academic community and others for reliable information on verification.

How does VERTIC operate?

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