Deep-Sea Research, 1972, Vol. 19, pp. 165 to 169. Pergamon Press. Printed in Great Britain.

INSTRUMENTS AND METHODS

Quartz crystals as multipurpose oceanographic sensors—I. Pressure

J. D. Irish* and F. E. Snodgrass*

(*Received* 21 *June* 1971; *accepted* 22 *July* 1971)

Abstract—A quartz crystal pressure sensor is evaluated for use on the deep ocean floor. Drifts are less than 1 cm of sea water pressure per day. The instrumental noise spectrum is sufficiently low that 1 mm waves of period 1 h could be detected.

INTRODUCTION

This and the adjoining contribution evaluate the use of quartz crystals as multipurpose oceanographic sensors. Caldwell, Snodgrass and Wimbush (1969) have previously evaluated quartz crystals as temperature sensors. Resch and Irish in the adjoining contribution evaluate these temperature-sensitive crystals as speed sensors. This paper considers quartz crystals as pressure sensors.

The Hewlett-Packard 'Sonde' (Karrer and Leasch, 1969, Hewlett-Packard, 1970) consists essentially of a crystal disk resonating in a torsional mode near 5 MHz at the center of an evacuated quartz cylinder. When exposed to fluid pressure, the cylinder transfers the pressure to radial forces on the disk and so increases its resonance frequency. By heterodyning the signal from the sensing crystal with a reference crystal, a frequency below 100 kHz is obtained.

CALIBRATION

The pressure sensitivity is about 12·3 Hz/m of sea water (1 m of sea water = 0·1010 bars). To consider slight nonlinearities, the frequency f of three Sondes was fitted to pressure P by the polynomial

$$f = A + BP + CP^2 + DP^3. \tag{1}$$

Table 1. *Pressure calibrations at 1°C* [*see equation* (1)].

Sonde	*A*	*B*	*C*	*D*
5	725·16	12·44	$-3{\cdot}80 \times 10^{-5}$	$-7{\cdot}67 \times 10^{-10}$
6	237·07	12·49	$-3{\cdot}78 \times 10^{-5}$	$-1{\cdot}67 \times 10^{-9}$
9	32,475·94	12·421	$-3{\cdot}82 \times 10^{-5}$	$8{\cdot}14 \times 10^{-11}$
	Hz	Hz/m	Hz/m^2	Hz/m^3

The results (Table 1) show that coefficient A varies widely among the Sondes, and is adjusted by selection of the reference crystal. Coefficients B and C are similar and D non-systematic. The sensitivity

$$\frac{\delta f}{\delta P} = B\left(1 + \frac{2C}{B}P\right) \tag{2}$$

varies by only 1·7% between 0 and 5000 m depth.

The temperature sensitivity would be zero if the sensing and reference crystals could be perfectly matched. In actuality this is possible at only one temperature. For use on the deep-sea floor the

*Institute of Geophysics and Planetary Physics, University of California, San Diego, La Jolla, California.

Table 2. Temperature sensitivity in Hz per °C *at* 30·92 *m pressure*

Sonde	Temp (°C) −1	0	1	2	3	5	7	9
5	3·4	2·3	1·6	1·2	1·0	0·7	0	−1·6
6	4·3	3·8	1·8	0·9	0·4	−0·3	−1·2	−3·8
9	0·5	0·4	0·2	0·1	0	0	—	—

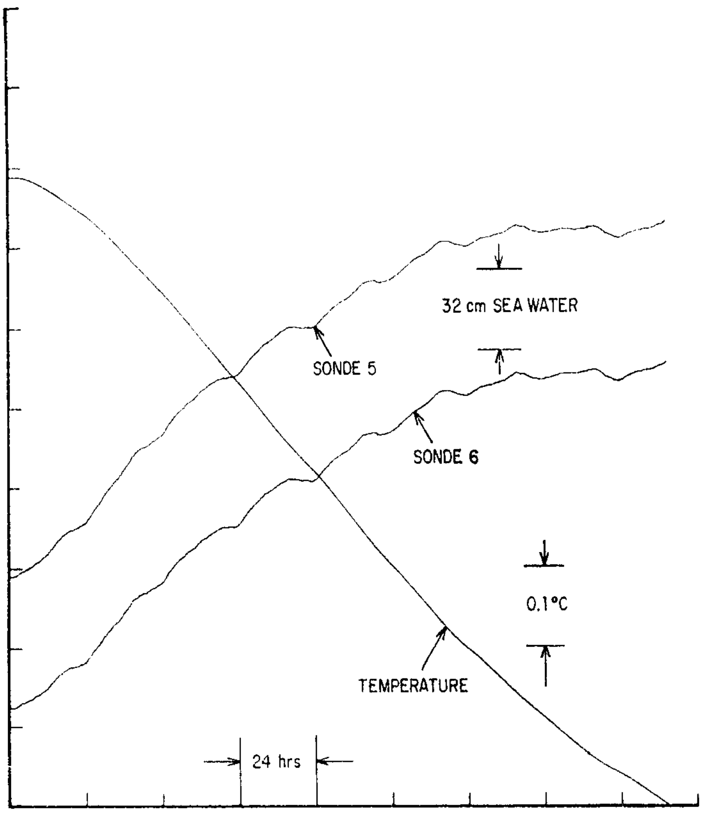

Fig. 1. Sonde pressure records and a quartz-crystal temperature record for a 210-hr noise test in ' flower bed '.

crystals were matched between 1 and 5°C (Table 2). Thus, variations by 1 millidegree (typical of abyssal conditions) produce signals of the same order as 10^{-2} cm of sea water pressure.

In the 1 to 5°C temperature range, the pressure sensitivity [B in equation (1)] changes with temperature by less than 10^{-4} per °C. The voltage sensitivity at constant pressure is −0·9 Hz/V (−0·7 cm of sea water/V). The hysteresis and zero return errors are both less than 1 cm of sea water, and the laboratory drift rate less than 1 cm per week (Hewlett-Packard, 1970).

'FLOWER BED' TEST

Even under carefully controlled conditions, the background noise exceeds the instrument noise, and one has to depend on coherence tests between several instruments to estimate the instrumental (non-coherent) noise spectra (Caldwell, Snodgrass and Wimbush, 1969). Therefore, Sondes 5 and 6, and a quartz crystal temperature sensor, were thermally connected and buried 1·5 m in a flower bed. The raw record (Fig. 1) consists of a drift, primarily due to temperature, plus diurnal and high-frequency fluctuations. After removal of the temperature effects on the basis of the recorded temperature, and further removal of the low frequencies by numerical filtering, the noise spectrum $N(f)$ for each Sonde was estimated from the equation

$$N(f) = S(f) - C(f) \tag{3}$$

where $S(f)$ is the observed power spectrum, and $C(f)$ is the co-spectrum between the two Sondes. (The quadrature spectrum is negligible.) A representative upper estimate is plotted in Fig. 2.

SAN CLEMENTE ISLAND TEST

To evaluate the Sondes under actual operating conditions, two Sondes, a 10,000-psi Vibrotron and a quartz-crystal temperature sensor were mounted on a deep-sea instrument capsule (SNODGRASS, 1968). The capsule was dropped to the sea floor in 1·26 km of water near San Clemente Island, California, where it remained for 92 hr. The frequencies of the sensors were determined by counting

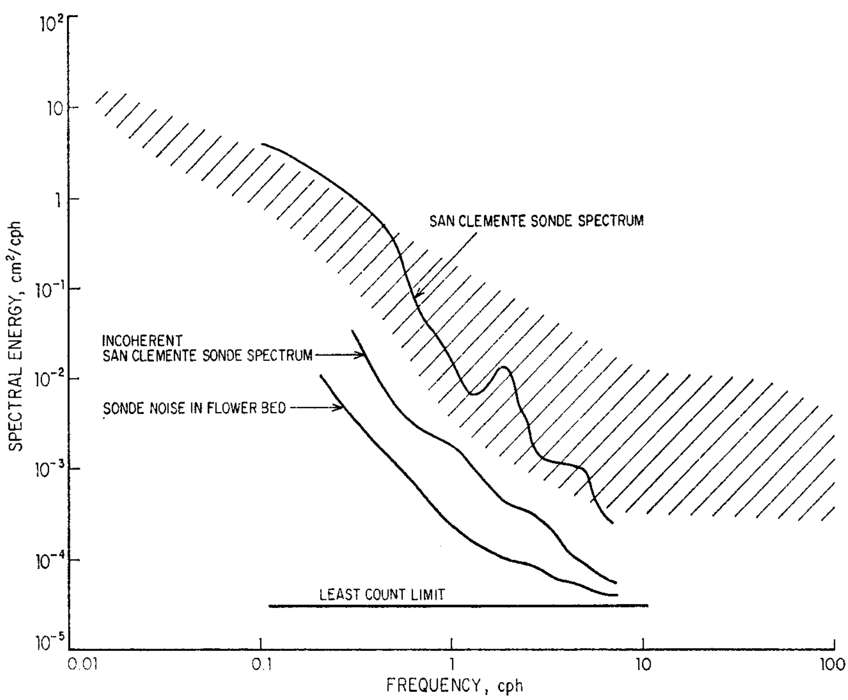

Fig. 2. The shaded band is based on 10 yr of measurements of background sea level oscillations. The San Clemente Sonde spectrum falls in the band and is more than 10 db above noise level.

over a 4-min sample interval. The least-count sensitivity of both Sondes was 0·33 mm of sea water, of the Vibrotron was 0·96 mm of sea water, and of the temperature sensor was 4·2 μ°C. The corresponding least-count noise for all sensors was well below the background spectra, so the sensors were not least-count limited (Fig. 2).

The data from Sonde 5, the Vibrotron, and temperature sensors were without noticeable errors. The data from Sonde 6 were erratic during the first 14 hrs, then gradually became steady at 2/3 the expected value. This behavior was attributed to marginal operation of the digital recording circuits. Accordingly, the recorded frequency of Sonde 6 was multiplied by 3/2 and the data from all four sensors plotted (Fig. 3). The tides dominate the pressure record and were removed by the response method (MUNK and CARTWRIGHT, 1966) and the residuals plotted. These plots clearly show the lower noise and drift rates of the Sondes' residuals over the Vibrotron's residuals. A plot of the Sonde residuals on an enlarged scale (Fig. 4) shows a high degree of coherence, indicating that a true ocean background is being measured. In fact, the spectrum of Sonde 5 (Fig. 2) is consistent with the sea level spectra between 0·1 and 7·5 cph inferred from previous measurements of sea level (MUNK, SNODGRASS and TUCKER, 1959, plus unpublished observations by the same authors).

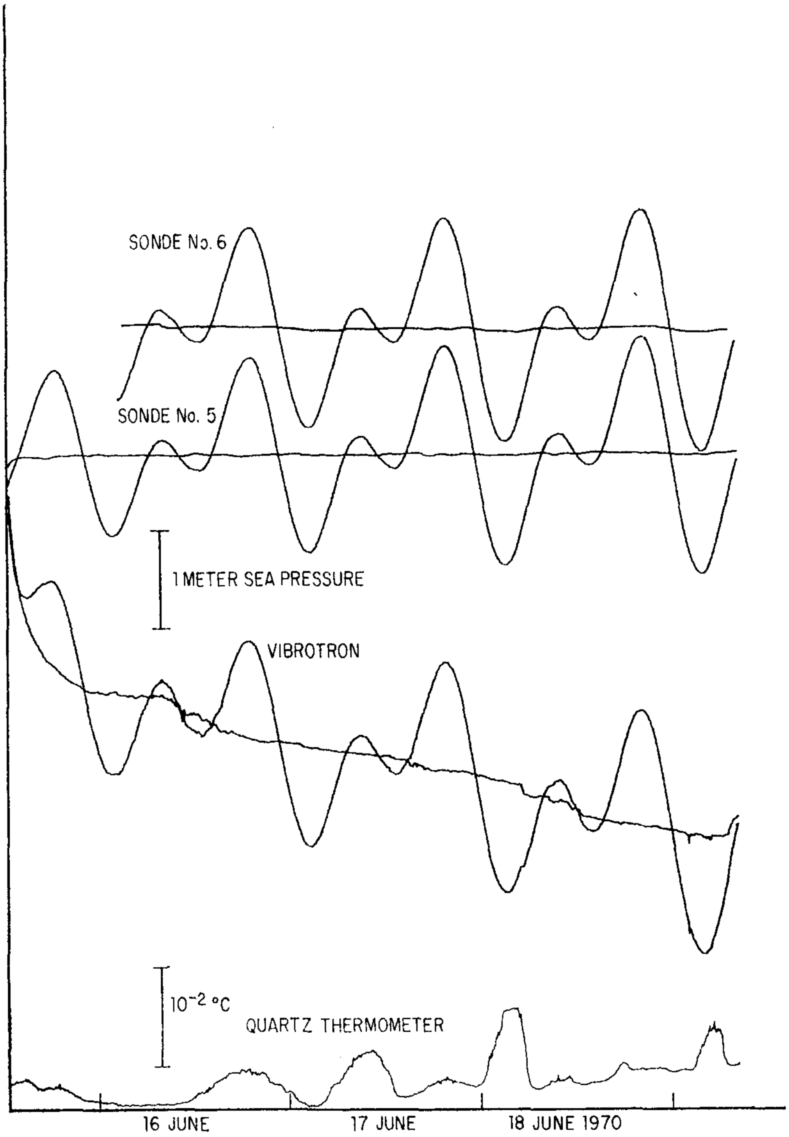

Fig. 3. San Clemente Sonde and Vibrotron pressure records, and a quartz-crystal temperature record. The residuals (after removal of the tides) are plotted with the record of each pressure sensor.

The incoherent spectra of the two Sondes on the sea floor should yield a second estimate of instrumental noise. Unfortunately, the record drift from Sonde 6 (perhaps associated with malfunctioning of the digital recording circuits) so dominates the spectrum that the coherence calculation is unreliable. We attribute the higher apparent noise level on the sea floor as compared to that in the 'flower bed' test (Fig. 2) to this circumstance, rather than to an intrinsically higher instrumental noise level under high pressures; but this problem needs further attention.

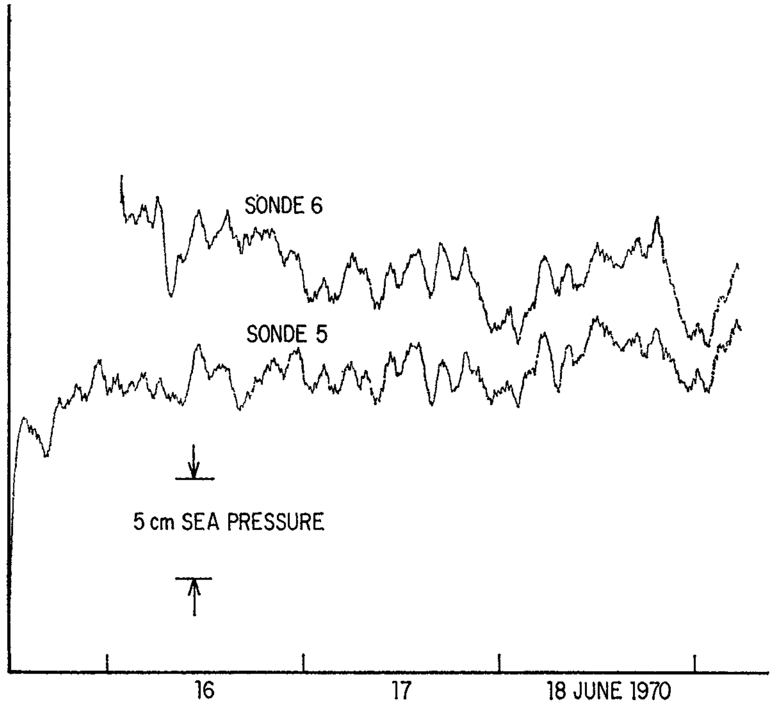

Fig. 4. The residual Sonde records.

CONCLUSION

The Sonde drift rate, after initial equalization, is less than 1 cm/day and appears to diminish further with time. The noise level decreases from 10^{-1} cm^2/cph at 0·1 cph to less than 10^{-4} cm^2/cph at 10 cph. The low energy background spectrum lies typically 10 db above this. The total noise energy in the frequency band is 10^{-2} cm^2 or equivalent to 1 mm sea level. Accordingly the Sonde on the deep sea bottom should be capable of measuring ocean waves of order 1 mm in the frequency band.

Acknowledgments—The authors wish to thank Hewlett-Packard Company for making available 2 early Sondes for our evaluation, JERRY LEASCH of Hewlett-Parkard for aid during the San Clemente sea test, and WALTER MUNK for advice in evaluating the spectra. This work was supported by the Office of Naval Research under Contract N0014-69-A-0200-6008.

REFERENCES

CALDWELL D. R., F. E. SNODGRASS and M. H. WIMBUSH (1969) Sensors in the deep sea. *Physics Today*, **22**, 34–42.

HEWLETT-PACKARD (1970) Hewlett-Packard quartz pressure probe prototype oceanographic model D-101, unpublished brochure.

KARRER H. E. and J. LEASCH (1969) A quartz resonator pressure transducer. *IEEE Trans.*, IECI, No. 1, 44–50.

MUNK W. H., F. E. SNODGRASS and M. J. TUCKER (1959) Spectra of low-frequency ocean waves. *Bull. Scripps Instn. Oceanogr.*, **7**, 283–362.

MUNK W. H. and D. CARTWRIGHT (1966) Tidal spectroscopy and prediction. *Phil. Trans. R. Soc.*, (A) **259**, 533–581.

SNODGRASS F. E. (1968) Deep sea instrument capsule. *Science*, **162**, 78–87.