International Hydrographic Review, Monaco, LIV (1) January 1977.

THE PROPAGATION VELOCITY OF DECCA-FREQUENCY TRANSMISSIONS OVER SEA ICE

by David H. GRAY
Canadian Hydrographic Service, Ocean and Aquatic Affairs,
Department of the Environment, Ottawa, Canada

Reprinted from "*The Canadian Surveyor*", Vol. 29 (3), Sept. 1975.

ABSTRACT

In April and August 1973, a phase lag comparison test was performed using a double monitor system with the hyperbolic Decca chain established for various scientific surveys in the Amundsen Gulf. The test compared the secondary phase lag effect of sea ice and sea water. The observed values of the August test over sea water are consistent with the theoretical formulas of J.R. JOHLER. The observed values of the April test over sea ice cannot be compared with the formulas because the formulas are based on the assumption of a vertically homogeneous medium and this assumption is not valid in a sea-ice situation. The observed average velocity over sea ice is 299 510 km/sec and over sea water is 299 610 km/sec.

BACKGROUND

The demand for petroleum products has increased to such an extent that oil companies are now exploring the offshore and arctic regions of Canada. In the areas offshore, they are faced with the problem of determining the precise geographical location of exploratory and, eventually, production wells.

The regulations for surveys of offshore oil and gas wells require a survey system with adequate checks against gross errors or an independent check by another method. In the area out of sight of land, several methods of determining geographic location are available:

1) Satellite navigation : an effective, all-weather, low logistic support method;

2) 10 kHz VLF radio navigation (Omega) : a worldwide system that is below the required survey accuracy even with differential operation to predict local skywave correction. A slight improvement is possible with an atomic clock to permit range measurements and to give redundant observations. This system suffers from regional anomalies in the Arctic, but is probably unaffected by propagation over sea ice;

3) 100 kHz LF radio navigation (Loran C and Decca) : good positional accuracy obtainable within the specific survey area, but with a high operational cost for shore stations. It is affected to some extent by over-sea-ice and by over-land paths;

4) 2 MHz MF radio navigation (Hi-Fix, Raydist, Toran) : very good positional accuracy within a short range from the transmitters. Its range is severely affected by propagation over sea ice;

5) Long-range Shoran : it uses the direct radio wave and hence is unaffected by the presence of sea ice.

As oil exploration is a year-round operation, the positioning systems must be operable in all seasons. In the Arctic, there is generally ice coverage for eight months or more, and the positioning systems have to work effectively during this period. Therefore, the preferred systems for use in the offshore areas of the Arctic are satellite navigation, long-range direct wave (Shoran) and 100 kHz radio navigation, provided the effect of sea ice on the propagation velocity is known. It was this problem that prompted the Canadian Government's Coordinating Committee on Offshore Surveys to request a test of the velocity of Decca-frequency radio transmissions over sea-ice conditions.

RATIONALE

The problem of determining the over-sea-ice velocity of 100 kHz radio waves necessitated a specific field project as opposed to abstracting data obtained through normal survey projects. The only available Decca chain operating in solid sea-ice conditions in the winter of 1972-73 was a hyperbolic survey chain in the Amundsen Gulf (figures 1 and 2). In July and August 1973, it was also operating in support of a ship-based scientific survey. The method selected for the test was to use two monitors, one near the master and the other near one of the slaves. Ideally, both should be on the baseline with no overland path between them, and also outside the induction fields of each transmitter.

There are two common ways of evaluating the results. The most usual is to assume that all Decca radio waves have a uniform and identical velocity irrespective of the frequency, distance or any other parameter. This method is most useful in drawing lattices of constant phase differences and computing positions to a sufficient accuracy for most purposes. But if positions are to be computed to the highest accuracy possible, then another, more precise, method that takes account of the primary and secondary phase lags is required.

Fig. 1. — Map of Canada showing survey area.

If a uniform velocity is assumed, the decometer difference between A and B in figure 3 is :

$$\Delta r = \frac{1}{2W}[(c - d) - (a - b)] \tag{1}$$

where: $\boldsymbol{\Delta r}$ = decometer difference,
W = lane width on baseline,
a = length, monitor A to master,
b = length, monitor A to slave,
c = length, monitor B to master,
d = length, monitor B to slave.

Hence, the equation can be changed to

$$W = \frac{1}{2\,\Delta r}[(c - d) - (a - b)] \tag{2}$$

The uniform velocity can be computed from:

$$V = 2Wf \tag{3}$$

where: f = comparison frequency.

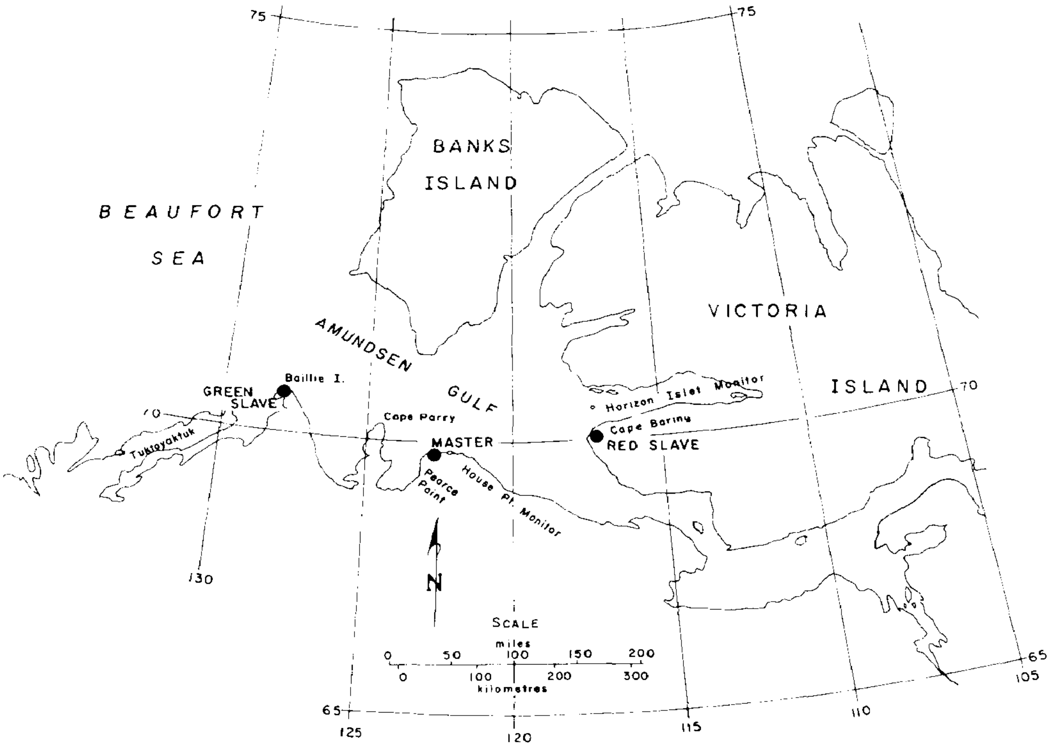

FIG. 2. — Amundsen Gulf showing Decca transmitters and monitor sites.

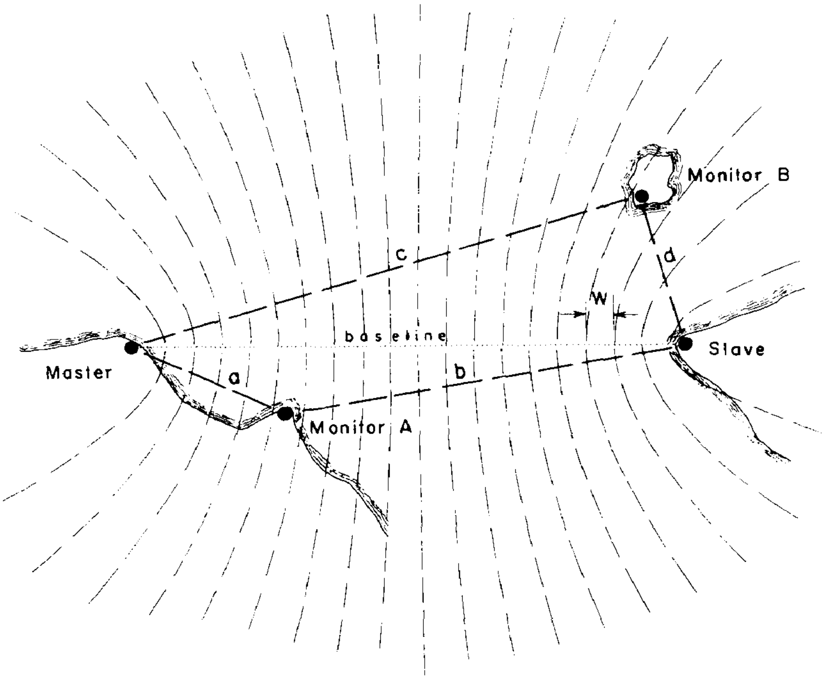

FIG. 3. — Geometry of two-monitor system.

From (2) and (3) :

$$V = \frac{f}{\Delta r}[(c-d)-(a-b)] \qquad (4)$$

When the primary and secondary phase lags are considered, the decometer difference between A and B is :

$$\Delta r = \frac{1}{2W}\{[(c + \mathrm{Pr} + \mathrm{Sec}) - (d + \mathrm{Pr} + \mathrm{Sec})] - [(a + \mathrm{Pr} + \mathrm{Sec}) - (b + \mathrm{Pr} + \mathrm{Sec})]\} \quad (5)$$

where: W = lane width on baseline, using the velocity of radio waves in a vacuum ($V = 2.9979250 \times 10^8$ m/s),

Pr = primary phase lag, based on index of refraction of the air and distance (a, b, c or d),

Sec = secondary phase lag, a non-linear function of the distance (a, b, c or d), transmitted frequency (master or slave), conductivity, permittivity, and other less significant parameters.

It should be noted that the baseline length and its phase-lag corrections are not involved in the equation. Only the lengths from the transmitters to the monitors and the associated phase-lag corrections are considered. Similarly, any constant can be added to the lane count of the individual points and it will be eliminated when the lane-count difference is considered. Therefore, any delay put into the pattern at the slave to produce a specific reading at a specific point has no effect on the lane-count difference. This is the reason for using the lane-count difference between two monitors.

To obtain an accurate determination of the velocity, in Equation 4, the distance, frequency and difference in decometer readings have to be known accurately. The accuracy of the decometer difference is essentially independent of the magnitude of that difference; therefore, the accuracy of the computed velocity increases with increasing magnitude of the decometer difference. It is desirable to have the monitors as far apart as possible to maximize the decometer difference. The monitors must be outside the induction fields of the transmitters to justify the uniform velocity assumption. The monitors have to be on, or near, the baseline to have the sea ice, or sea water, conditions the same for all radio paths. All radio paths must have no overland path because any interruption caused by land would change the average velocity.

The final selection of the monitor sites did not meet all specifications completely. The red baseline of the Amundsen Gulf chain was almost completely over water (figure 2). The monitor near the master was selected to be at House Point, 13 km east of the master with over-water paths to both the master at Pearce Point and Red Slave at Cape Baring. It is also very close to being on the baseline. There being no site to the west of Cape Baring for the monitor on the baseline near the Red Slave, the monitor was set up on Horizon Islet, 37 km north of Cape Baring. It provided over-water paths to both master and Red Slave. Out of a possible 489 lanes in the baseline, there are 420 lanes between the two monitor sites.

FIELD OPERATIONS

The field operations commenced with the personnel arriving at Cape Parry on March 29, 1973, where all the necessary monitoring and camping equipment had been sent previously. The equipment was checked over and delivered by a single-engined aircraft to the sea ice near the two monitor sites. The equipment was lifted from the ice onto the island at each monitor site by helicopter. On April 8, 9 and 10, the chain was monitored. After several days of poor weather, the camps were evacuated and, in the succeeding days, the equipment was returned to Cape Parry by the combination of helicopter and aircraft. On April 14, the ice thickness was measured in three spots between the monitor sites.

The summer field operations included determining the position of the Decca transmitters by Doppler satellite positioning over a period of several days as well as taking astronomic azimuths required for conventional ground surveys. Thus the various required lengths could be computed from the geographic positions. All equipment had to be transported from Cape Parry by helicopter. The two monitor sites were re-established in exactly the same locations as in April. On August 23, 24 and 25, the monitoring of the chain was done. The necessary ground survey connections were performed on several days throughout the test as opportunity permitted. Five sea water samples were taken from the hovering helicopter between the monitors on August 28.

DECCA MONITORING

Monitoring of the Decca chain was carried out in such a manner as to reduce all effects on the lane reading other than that caused by meteorological conditions and the change from sea ice to sea water conditions. The same receivers and antennas were used at each monitor site in August as in April. To avoid electrical interference, no other electrical device was operated at the time of the monitoring. The power source for the receivers was two 12-volt batteries connected in series, which were charged during periods that the monitoring was not being done. The monitoring was done during the local early afternoon (1915-2235 GMT) to obtain the most stable pattern readings. During each hour, the routine was the same. At 14 minutes after the hour, both decometers were referenced. From 15 to 24 minutes, the decometers were read once a minute. The amplitude of any swing in the red decometer during the previous minute was also noted. The decometers were then switched to reference and the readings noted, but they were not reset to zero. From 25 to 34 minutes, ten more readings, once per minute, were taken after which the decometers were switched to reference and the readings were taken. From then until ten minutes after the next hour, the batteries were recharged. This sequence occurred four times each day (1915, 2015, 2115 and 2215

GMT). There were time checks between the two monitor sites at the beginning of each day to synchronize the monitoring to the accuracy of one second of time.

RESULTS

Doppler satellite positioning

Because the original ground surveys connecting the three Decca transmitters and the two monitor sites were considered to be of insufficient accuracy, Doppler satellite positioning receivers were used at each of the transmitter sites to check the positions as derived from the ground surveys. The ground survey connections between master and the House Point monitor and between Red Slave and the Horizon Islet monitor were sufficiently accurate. The comparison between the chord distances ($\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$) between the satellite receiver antennas as derived from the Doppler satellite point positioning, and those from the ground surveys shows an agreement of 2.3 m on the Red baseline. This is about the accuracy of the Doppler measurements. So, to avoid recomputation, the ground survey positions of master and Red Slave were used as correct (Table 1).

TABLE 1

Chord distances between satellite receiver antennas as derived from Doppler satellite positioning and ground surveys

Chord	Chord length	
Between satellite receiver antenna at	Doppler satellite point positioning using NWL precise ephemeris	Ground surveys
Master - Red Slave Master - Green Slave Red Slave - Green Slave	206 045.94 m 226 825.94 413 207.42	206 048.2 m 226 815.0 413 196.4

Decometer readings

The decometer readings were divided into groups of ten, corresponding to the ten readings taken between referencing the decometer to form a

TABLE 2

Decometer readings at monitor sites in April and August

	April	August
House Point Red pattern	31.331 ± 0.011 lanes	31.386 ± 0.017 lanes
Horizon Islet Red pattern	451.387 ± 0.026 lanes	451.297 ± 0.013 lanes

set. The mean of the reference reading before and after each set was subtracted to get the true decometer reading for that set. The means and standard deviations of these sets are listed in Table 2. These standard deviations give some indication of the accuracy of a corrected ten-minute mean under the conditions described.

The difference between the lane counts at any two sites at any instant is theoretically independent of the delays set into a pattern. If the pattern is shifted so that the reading at one monitor is increased by a certain amount, the reading at the other monitor should increase by that same amount. Let the function expressing the lane difference between two monitors be

$$\Delta r = x - y$$

where: x and y are the mean values of the sets of decometer readings at the two monitors taken during the same time intervals.

The correlation coefficient is

$$\rho_{xy} = \frac{\operatorname{cov}(x, y)}{\sqrt{\operatorname{var}(x)}\sqrt{\operatorname{var}(y)}} \tag{9}$$

where: $\operatorname{cov}(x, y)$ = covariance of x with respect to y,

$$= \frac{\operatorname{var}(x) + \operatorname{var}(y) - \operatorname{var}(\Delta r)}{2}$$

$\operatorname{var}(x)$ = variance (standard deviation squared) of x.

The theoretical range of values for the correlation coefficient (ρ_{xy}) is from -1 to $+1$.

A value of $\rho_{xy} = -1$ means that as x increases y decreases,
$\rho_{xy} = 0$ means that x is independent of y,
$\rho_{xy} = 1$ means that as x increases y increases.

TABLE 3

Lane differences between monitor sites in April and August

	Lane differences (Δr)	Standard deviation ($\sigma_{\Delta r}$)	Correlation coefficient (ρ_{xy})
April	420.056	± 0.018	+ 0.84
August	419.911	± 0.009	+ 0.86

The lane differences, their standard deviations and the correlation coefficients for April and August betweeen House Point and Horizon Islet in the red pattern are shown in Table 3. The high correlation coefficient confirms the assumption that the lane difference is essentially independent of any pattern shifts that occurred during the tests. The generally higher standard deviations during the April test indicate a higher noise level in over-ice conditions and also a more variable velocity during the three days of the test.

Goniometer correction

Goniometers are available on the Decca receivers that were used to provide an additional and optional electronic delay. They were set to zero during the tests, but they were used to check the linearity of the decometers each day. Since the goniometer corrections were sinusoidal and less than 0.005 lane and since these values are below the decometer reading accuracy, the goniometer corrections were not applied.

UNIFORM VELOCITY STUDY

Assuming that all Decca radio waves have a uniform and identical velocity, it is possible to compute the velocity from the observed decometer differences using Equation 4. The computed uniform velocity in April was 299 508 km/sec, and the velocity in August was 299 611 km/sec.

The standard deviation of the velocity can be computed from Equation 7 which is derived from Equation 4 by partial differentiation.

$$\sigma_V = \left[\frac{f^2}{\Delta r^2} (\sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \sigma_d^2) + \frac{[(c - d) - (a - b)]^2}{\Delta r^2} \sigma_f^2 + \left(\frac{(c - d) - (a - b) f}{\Delta r^2} \right)^2 \sigma_{\Delta r}^2 \right]^{1/2} \quad (7)$$

where σ_V = standard deviation of velocity,
σ_a = standard deviation of length '*a*',
σ_b = standard deviation of length '*b*',
σ_c = standard deviation of length '*c*',
σ_d = standard deviation of length '*d*',
σ_f = standard deviation of frequency,
$\sigma_{\Delta r}$ = standard deviation of decometer difference.

Using the following standard deviations, which were arbitrarily chosen based on past experience :

$\sigma_a = \pm$ 0.2 m,
$\sigma_b = \pm$ 3 m,
$\sigma_c = \pm$ 3 m,
$\sigma_d = \pm$ 0.4 m,
$\sigma_f = \pm$ 0.5 hertz,
$\sigma_{\Delta r} = \pm$ 0.02 lane,

the computed standard deviation of the velocity is ± 15 km/sec. Therefore, the quoted uniform velocities can be rounded off to eliminate insignificant figures. That means the velocities are 299 510 and 299 610 km/sec for April and August, respectively.

PHYSIOGRAPHIC CONDITIONS

Index of refraction

The index of refraction was derived from air temperature, air pressure and humidity, which is measured indirectly by means of wet and dry bulb temperature. The weather conditions observed during the monitoring periods are given in Table 4.

TABLE 4

Weather conditions during monitoring periods

	April	August
Temperature	− 23° to − 9°C	5° to 9°C
Temperature depression (dry bulb − wet bulb)	not taken	0° to 1°
Pressure	759 to 776 mm	752 to 761 mm
Cloud cover	CAVU* to 10/10	5/10 to fog
Visibility	CAVU to 1/2 km	32 km to 1/2 km
Wind speed	11 to 55 km/hr	13 to 42 km/hr
Mean index of refraction	1.000317	1.000325

(*) CAVU = an acronym for ceiling and visibility unlimited.

Ice thickness

The ice thickness was measured in three locations in the Amundsen Gulf between the monitors on April 14 (five days after the test). Thicknesses were 0.8 m in a lead that was frozen over, 2.3 m and 1.8 m in normal ice conditions. There were no open leads. The salinity of the water in the drill holes ranged from 27.026 to 28.569 parts per thousand. The resultant average conductivity of the sea water is 2.119 mho/m. The conductivity of the surface ice was not measured because the time allotted to measuring it had to be eliminated.

Sea water conductivity

On August 29 (three days after the test), five sea water samples were taken between the monitor sites by lowering a sampling bucket from the helicopter. The salinity ranged from 23.578 to 28.141 parts per thousand and the water temperature 6.5° to 7.1° C. The resultant mean conductivity is 2.775 mho/m.

DETAILED PHASE LAG STUDY

Using the observed meteorological factors to compute the primary phase lag and the August sea water conductivity of 2.775 mho/m in JOHLER's formulas for secondary phase lag, the theoretical difference in decometer readings is 419.920 lanes, which compares very closely with the observed value of 419.911 lanes. This agreement between observed and computed values confirms the prediction of the theoretical formulas of JOHLER *et al.* (1956).

For the April test, the conductivity of the sea ice was not measured and the effect of the sea water under the ice was also unknown. Therefore, the reverse approach was taken, namely, to find what conductivity satisfies the observed value for the difference in decometer readings. Table 5 lists values of the differences in decometer readings derived from Johler's formulas using various conductivities.

Table 5

Computed difference in decometer readings using different conductivities

Conductivity	Computed difference in decometer readings
0.04 mho/m	420.120 lanes
0.06	420.077
0.08	420.052
0.10	420.035

When a conductivity of 0.08 mho/m is used, the computed difference in decometer readings is 420.052 lanes, which agrees with the observed difference of 420.056 lanes.

From the values quoted in various publications read, there is a large range in the conductivity of one-year-old sea ice; the numerically largest value is 0.013 mho/m (Addison, 1969), quoted in Hoekstra and Cappillino (1971). From this, it is evident that sea ice is most unlikely to have a conductivity of 0.08 mho/m. Any snow that is lying on top of the sea ice is likely to have a still lower conductivity. Noting that the sea water conductivity is of the order of 2 mho/m, it is evident that the conductivity of 0.08 mho/m derived from the experiment must reflect, in part, the effect of the underlying sea water.

To get some feeling for the probable mode of transmission of radio waves over sea ice, a search of the literature indicated that, in a homogeneous dielectric, the intensity of the radiation at various depths is an inverse exponential function of the depth. The depth at which the intensity of the radiation is $1/e$ (0.368) of its value at the surface is given by I.T.T. (1966) :

$$x_0 = \left[\frac{2}{\omega^2 \mu_0 \epsilon \left(\sqrt{1 + \frac{\sigma^2}{\omega^2 \epsilon^2}} + 1 \right)} \right]^{1/2}$$

where x_0 = the depth in m, where the intensity is $1/e$ (penetration depth),
ω = frequency (radians/sec),
μ_0 = permeability of free space ($4\pi \times 10^{-7}$ henrys/m),
ε = absolute permittivity

$$\left(\epsilon_{\text{rel}} \times \frac{1}{36\pi} \times 10^{-9} \text{ farads/m} \right)$$

ε_{rel} = relative permittivity (electrostatic units, esu),
σ = conductivity (mho/m).

For sea water with a conductivity of approximately 3 mho/m and Decca frequencies, the penetration depth is about 0.75 m. This is why only surface conductivities are significant when working with sea water. The penetration depth for continuous sea ice with a conductivity of 0.013 mho/m is 13 m. For ice with a lower conductivity, the penetration depth is greater. But the depth of ice was only 2 m during the test, and by the properties of an inverse exponential function, the intensity at that depth is 0.86 of the surface intensity. Clearly, both the sea ice and sea water under the ice affect the propagation of the radio waves. Since JOHLER's formulas are based on the assumption of both a horizontally and vertically homogeneous medium, they cannot be used to predict secondary phase lag in sea-ice conditions.

CONCLUSIONS

This test confirms for sea water under arctic conditions the theoretical secondary phase lag calculations put forward by JOHLER (1956). It is not possible to confirm JOHLER's formulas for sea-ice conditions since the assumption of a vertically homogeneous medium is not valid. The mean velocities observed were 299 510 km/sec over 2 m of sea ice and 299 610 km/sec over sea water.

A consideration of various reports on the conductivity of sea ice and the penetration of radio waves into it, indicates that the effective conductivity of the surface will be dependent on the ice thickness, ranging from about 0.013 mho/m for 13 m of sea ice to 3 mho/m for a thin film of ice over sea water. The effective conductivity of 0.08 mho/m computed from these tests over approximately 2 m of sea ice is in agreement with this relationship.

ACKNOWLEDGEMENTS

The successful execution of this test is the result of the cooperative effort of many people and organizations. The hydrographers of the Central Region of the Canadian Hydrographic Service included most of the field staff. The Navigation Group of the Atlantic Region of CHS provided some field staff and the monitoring specifications; the Nautical Geodesy Section of CHS headquarters, one field staff member and the ground survey specifications; the Polar Continental Shelf Project of the Department of Energy, Mines and Resources, the aircraft and logistic support required for the test, and the Geodetic Survey Division of the Surveys and Mapping Branch of the Department of Energy, Mines and Resources, the Doppler satellite positioning and astronomic observations that were required for this test. Computing Devices of Canada provided technical assistance as well as the operating of the Decca chain.

REFERENCES

ADDISON, J.R. (1969) : Electrical properties of saline ice. *Journal of Applied Physics*, Vol. 40.

HOEKSTRA, P., P. CAPPILLINO (1971) : Dielectric properties of sea and sodium chloride ice at UHF and microwave frequencies. *Journal of Geophysical Research*, Vol. 76 (20), July.

I.T.T. (1966) : *Reference data for radio engineers,* fourth edition, International Telephone and Telegraph Corporation.

JOHLER, J.R., W.J. KELLAR, L.C. WALTERS (1956) : Phase of the low radio frequency ground wave, U.S. National Bureau of Standards Circular 573.

THE ULTIMATE IN BATHYMETRY

History was made on 23rd January 1960 when the bathyscaph *Trieste* carried Jacques Piccard and Lieutenant Don Walsh of the U.S. Navy to the deepest known part of the world's oceans, the bottom of the Challenger Deep in the Mariana Trench in the Pacific. (Latitude 11°18.5′N; Longitude 142°15.5′E).

This is Jacques Piccard's description of the moment of reaching the oceanbed in 5,966 fathoms (10,910 metres).

"And as we were settling this final fathom, I saw a wonderful thing. Lying on the bottom just beneath us was some type of flatfish, resembling a sole, about 1 foot long and 6 inches across. Even as I saw him, his two round eyes on top of his head spied us — a monster of steel — invading his silent realm. Eyes? Why should he have eyes? Merely to see phosphorescence? The floodlight that bathed him was the first real light ever to enter this hadal realm. Here, in an instant, was the answer that biologists had asked for decades. Could life exist in the greatest depth of the ocean? It could! And not only that, here apparently, was a true, bony teleost fish, not a primitive ray or elasmobranch. Yes, a highly evolved vertebrate, in time's arrow very close to man himself.

Slowly, extremely slowly, this flatfish swam away. Moving along the bottom, partly in the ooze and partly in the water, he disappeared into his night. Slowly too — perhaps everything is slow at the bottom of the sea — Walsh and I shook hands".

From : *Seven Miles Down* by Jacques PICCARD and Robert S. DIETZ. *Longmans, Green, and Co. Ltd., London,* 1962.