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Offshore Reconnaissance Geophysical Techniques

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K.R. Vale, A. Turpie & R. Whitworth

Paper Presented at Fourth ECAFE Symposium on the Development of Petroleum Resources of Asia and the Far East, Canberra, October - November 1969

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SUMMARY

Advancing technology has seen the emphasis in oil exploration in Australia shift to its large and highly prospective continental shelf. A programme of reconnaissance geophysical surveys started by the Bureau of Mineral Resources in 1965 has made use of recent and developing techniques in navigation and in gravity, magnetic and seismic measurements. Economic operation has been achieved by developing a satisfactory 24 hour-a-day navigation system and geophysical equipment capable of operation at 10 knots. It is emphasised that, in a survey of this nature with a large daily expenditure and limited budget, once work has started, then in most cases the best results obtainable under existing conditions must be accepted. Since difficulties and failures must occur, back-up for as many important systems as possible is required so that failure will not prevent continuation of worthwhile operations.

In 1968, a satellite Doppler navigation system gave reliable position fixes at roughly 2-hour intervals. Intermediate positions and velocities were derived mainly from an electromagnetic ships log. A sonar Doppler velocity measuring system proved generally unsuccessful, as did the V.L.F. radio location system. Positions are believed to be accurate to the order of 0.2 to 0.5 mile.

A La Coste-Romberg marine gravity meter was used for gravity measurements. Meter drift was negligible, and the accuracy of observations as determined by differences observed at traverse line intersections was just under 2 milligals. This figure gives the best indication of the accuracy of velocity measurement (equivalent to the order of 0.2 knot).

Continuous seismic reflection profiling was carried out using a 21,000-joule sparker and single channel cable. Reflections down to about 5,000 feet below the sea bottom were obtained except in shallow water where ringing and multiples interfered greatly with the reflections. A seismic refraction system was used for the first time in 1968, and gave worthwhile data to about 8 miles. The energy source consisted of two air guns with a total capacity of 600 cubic inches at 2500 p.s.i., while a sonobuoy transmitted the refracted signals back to the ship.

Magnetic profiling was carried out using a proton precession magnetometer with the sensor towed 600 feet behind the ship. Failure of a shore magnetometer monitoring diurnal variation reduced the accuracy of the results. An accuracy of about ± 25 gammas was achieved.

INTRODUCTION

The current decade has witnessed a shift in emphasis in oil exploration towards offshore areas. Before 1960 the only offshore activity in Australia was some offshore aeromagnetic surveying notably in Bass Strait, the Bonaparte Gulf, and the Perth Basin, mainly by the Bureau of Mineral Resources and aimed more at evaluating the prospects of onshore coastal basins rather than defining offshore targets. About half the coastline of Australia lies within sedimentary basins. The continental shelf has an area of some 800,000 square miles. Virtually all of it is covered by at least a veneer of sediments and very little of it can be written off as totally unprospective. Reasonable estimates place the average thickness of Tertiary-Mesozoic at about 6000 feet (1800 m.) and Palaeozoic at about 3500 feet (1000 m.). The Tertiary-Mesozoic undoubtedly extends down the continental slope and out into the deep ocean. This is illustrated by the paper presented by R. Whitworth.*

Plate 1 compares the estimated average thickness and volume of sediments of Tertiary-Mesozoic and Palaeozoic eras on land and offshore for Australia. It is not surprising that, with advancing offshore technology, Australia has joined the rest of the world in the shifting emphasis towards offshore oil exploration. While exploration by private industry tends to be directed towards obtaining relatively early economic rewards, the Bureau of Mineral Resources has initiated a program of regional-reconnaissance mapping of superficial sediments, magnetic and gravity fields, and seismic reflection horizons to moderate depths and velocity regimes. The geophysical results of such a survey carried out in 1968

* A marine geophysical survey of the Northwest Continental Shelf of Australia, 1968 presented at 4th ECAFE Petroleum Symposium, Canberra 1969

on the northwest continental shelf has been described by Whitworth elsewhere. This survey cost substantially less than $1,000,000 and is considered to be good value. It is believed that such surveys greatly aid the integration of previous surveys, gives a better appreciation of the regional tectonics, and assists in the planning and direction of future independent surveys. It is hoped to cover the continental shelf within Australian jurisdiction within ten years with surveys that will continue to improve in quality and economy. This paper sketches the geophysical systems used on the 1968 survey, some of the problems encountered and plans for the future.

As the accurate determination of gravity at sea depends on precise navigation and as this is a difficult problem, much effort and cost is expended on fixing the position and velocity of the ship. For example, to achieve an accuracy of 1 milligal in the gravity results, the ship's speed needs to be known to about 0.1 knot, and latitude to the order of 1 minute.

In 1965, the Bureau conducted a survey of some 3,600 miles mainly confined to the Joseph Bonaparte Gulf (Smith, 1966,). Navigation was by the Toran hyperbolic radio location system which, while accurate, is expensive to install and operate, and over large distances (100+ miles) operates satisfactorily only during the daylight hours. The seismic reflection system used a single channel recording cable together with a spark-array energy source of 14,000 joules. A La Coste and Romberg gimba-mounted surface gravity meter was installed on the ship and gave a standard deviation of the gravity difference at line intersections of 3 milligals.

The Toran navigation system was replaced by a very low frequency radio navigation system (V.L.F.-OMEGA) in 1967 which, though of lower accuracy did, in the end result, prove reasonably satisfactory and enabled 24 hour-a-day operation to be maintained. A continuous wave sonar Doppler system was also provided to complement the V.L.F. It proved generally unsatisfactory although it worked moderately well in the forward mode by the end of the survey, and the principal burden fell on the V.L.F. Dawn and dusk star fixes and all possible radar fixes were also taken and proved extremely valuable in adjusting the V.L.F. determined track. It was obvious that future surveys should plan for higher reliability and accuracy in their navigation. As the seismic system had proved successful in 1965, the source energy was increased to 21,000 joules to give greater depth of penetration. Multi-channel magnetic tape recording and a six-channel seismic cable were added. Unfortunately the six-channel cable was lost at sea shortly after the start of the survey, so only single channel seismic information was obtained for most of the survey. An Askania marine gravity meter on a gyro-stablished platform gave a slightly improved performance despite the less accurate position and consequent velocity determination. A mean difference of 2.5 milligals was achieved at traverse intersections (equivalent to a standard deviation of 2.8 milligals). Continuous magnetic profiling was carried out using a Varian proton precession magnetometer with the sensor towed behind the ship and a magnetic diurnal monitor installed at Darwin.

In 1968 a satellite Doppler navigation system was introduced to give position fixes accurate to the order of 600 feet once every two to three hours. A pulsed continuous wave sonar Doppler unit replaced the continuous wave unit and was expected to achieve 0.1 knot accuracy in shallow water and a somewhat lower accuracy in deep water when operating off water mass back scatter. It was thought that V.L.F. derived position fixes would approach an accuracy of about half a mile when tied to the satellite Doppler fixes. Star fixes were again taken at dawn and dusk when weather permitted, and also radar fixes to land when near to the coast.

The seismic equipment was basically the same as in 1967; a 21,000-joule sparker energy source, six-channel cable, a single chanel cable, a single channel high resolution cable, and a reserve single channel cable. Recording was on an Ampex 14 channel FM magnetic tape recorder and visual monitoring was by means of two facsimile wet paper recorders displaying the long cable and high resolution cable outputs. Refraction profiling was added to the seismic work to obtain velocity determinations throughout the survey area. It is hoped that correlation of the refractors with known onshore stratigraphic horizons may be possible. Two air guns with a capacity of 300 cubic inches each and fired simultaneously were provided as an energy source for the refraction shooting and were expected to give greater depth of penetration than the sparker system. Sonobuoys were used as detectors. They were dropped overboard in suitable areas and telemetered data back to the ship as it continued to move on at 10 knots.

A La Coste and Romberg surface marine gravity meter was provided by the contractor for the survey. Unlike earlier La Coste meters which were gimbal mounted, this meter was mounted on a gyro-stabilised platform. Corrections for cross-coupling errors were made by an analogue computer. Recording was by strip chart pen recorder and a digital magnetic tape system that was also used to record magnetic readings, ship's speed and heading at one minute intervals.

The magnetometer used on the ship was a Varian proton precession magnetometer using a phase-lock frequency multiplier to give direct read out in gammas. The sensor was towed about 600 feet behind the ship to remove it from the magnetic effect of the ship's hull. An Elsec proton precession magnetometer with strip chart recorder was stationed at Broome to monitor diurnal changes in the earth's magnetic field. This unit did not function effectively for much of the survey, so most of the diurnal variation corrections will have to be obtained partly by adjustment at traverse intersections and partly by extrapolation from Port Moresby and Mundaring geophysical observatories.

A block diagram of the 1968 system is shown in Plate 2.

EQUIPMENT DESCRIPTION AND SYSTEM PERFORMANCE

At present only preliminary results at one hourly intervals are available. Some analysis of this data preparatory to final data reduction has been made. The most significant results are outlined briefly below mainly to show that accuracy and limitations of the various survey techniques, and to provide a guide for further work of this type.

Satellite Doppler system

The U.S. Navy satellite navigation system (illustrated in Plate 3) uses up to four satellites in nominally polar orbits. The system provides a position fix every two to three hours on the average. Basically, the technique measures the change in slant range from ship to satellite over a two-minute interval by integrating the Doppler shift in the satellite's transmitted frequency over the interval. If two such changes in slant range are measured, the ships position is given by the intersection of the two surfaces of revolution defined by the slant range differences and the surface of the earth. In practice, a minimum of three two-minute intervals must be measured using two frequencies to remove bias frequency and ionospheric refraction effects.

The computations required to determine the ship's position are laborious and fairly complicated, and as the ship's position must be determined quickly for it to be of much use for course control, a digital computer is required. The contractor provided an I.T.T. AN/SRN-9 radio navigation set, a Digital Equipment Corporation PDP8/S computer and a teletype unit for this purpose.

Satellite passes below 10 degrees or more than 75 degrees above the horizon are classed as unreliable. Of the acceptable passes, some may be rejected before computation because of excessive noise interfering with the Doppler count or an erratic refraction count. Following computation, some further editing based on Doppler count residuals is possible, followed by recomputation.

Certain precautions must be taken during reception of the satellite signal. The ship's course and speed must not be changed during this time which can last up to 18 minutes. Although reception and computations are carried out almost automatically certain important data must be hand fed into the computer. The data include the approximate position of the ship, height of the receiving antenna and the ship's course and speed during the fix. Errors in determining or feeding in these data can lead to errors in the ship's position.

The inherent accuracy of the method depends on how well the path of the satellite is known. In part this depends upon how well the earth's gravity field is known. This form of error becomes more significant in the souther hemisphere because of lack of data. When the ship is stationary the accuracy is of the order of ± 300 feet, as shown by multiple readings taken in Broome harbour during the survey. Under way the accuracy is reduced by uncertainties in the ship's velocity. A few tests carried out on survey suggest that errors could rise as high as 0.8 nautical mile per knot, and appear to occur mainly in longitude. However about 0.1 to 0.2 nautical mile is more common.

V.L.F. navigation system

The V.L.F. radio navigation (illustrated in Plate 4) is a world wide system that works by effectively determining the range of the receiver from various low frequency radio transmitters by phase comparison with a local standard oscillator. Frequency stabilised transmissions in the range 10 to 30 KHz are propagated in a duct between the earth's surface and the ionosphere. Radio transmission suffers little attenuation in this frequency band and has a world wide range, but is affected by diurnal variations in the state of the ionosphere. Navigation using this system is effected by commencing from a known point and determining the changes in phase of two or more transmissions relative to a very stable local oscillator, usually an atomic frequency standard, and outputting the information in cycles or microseconds.

There are many stations that transmit in the V.L.F. range, but the majority of these are not frequency stabilised, do not transmit continuously, or are too weak to receive in the Australian area. The following stations are reasonably good:-

ALDRA (OMEGA station), Norway - 10.2 and 13.6 kHZ
GBR, England - 16.0 kHz
HAIKU (OMEGA station), Haiwaii - 10.2 and 13.6 kHz
NPG, Jim Creek, U.S.A. - 18.6 kHz
NPM, Haiwaii - 23.4 kHz
NWC, North West Cape, Australia - 22.3 kHz
TRINIDAD (OMEGA station), TRINIDAD, B.W.I. - 10.2 and 13.6 kHz

Determination of the ship's position by phase changes relative to these stations is influenced by the diurnal variation in propagation velocity from day-time to night-time, and a decrease in signal amplitude at dawn and dusk, sometimes with a complete loss of signal. The variation may be computed from a priori considerations or determined empirically for the survey area. As diurnal characteristics are almost unknown in the Australian area, a shore V.L.F. monitor is used, and it is assumed that the diurnals so determined are also applicable at the survey ship's position. With a satellite Doppler system, a somewhat coarser shipboard diurnal shift can be determined for each position fix and the assumption tested.

The overall performance as a navigation system in 1968 was disappointing and much worse than in 1967. Diurnal variation was erratic, particularly with NPM, and a characteristic pattern was not well defined. The long term variation on ship and shore was inconsistent, both between channels and between ship and shore. The erratic variation from channel to channel indicates that it is not erratic atomic frequency standard drift, while the differences between ship and shore negates the possibility of varying transmitter frequencies. It does not seem likely that the diurnal variation would vary significantly over the survey area. The two likely causes are interference within the receiver by the U.S. Navy transmitter at North West Cape because of its proximity and high power, incorrectly adjusted cardioid aerials, and human error in reading and computing the data.

Preliminary analysis indicates that useable position fixes are obtainable on an empirical basis by using the shipboard diurnal computed by adjusting the ship range lane values to give correct positions at satellite fixes with linear adjustment between fixes, and disregarding shore diurnal values.

Sonar Doppler system

The speed of a ship may be determined by transmitting a beam of ultrasonic sound forward and downward from the ship (Plate 5), and measuring the Doppler frequency shift in the signal reflected back from irregularities on the sea bottom. Pitch, roll and heave of the ship introduce spurious velocity changes, so two beams are used, one pointing forward and one backward at an angle of about 30 degrees to the vertical and the difference in doppler shift used. Two similar beams to port and starboard enable the ship's sideways drift to be determined.

The system used pulsed waves to give improved signal-to-noise ratio over the simpler continuous wave technique. The time of reception relative to the instant of transmission could be varied up to the equivalent of 100 fathoms so guaranteeing a bottom reflection signal within that range of water depth. An accuracy of one percent was expected while in deep water the system was expected to work off water mass back scatter at a somewhat reduced accuracy.

The great advantage of the method, when operating off bottom reflection, is that water currents do not affect the velocity determination. The ship's true forward and sideways speed over the bottom are measured when operating in this mode.

The unit did not achieve the nominated specifications of one per cent accuracy in velocity or of working off water mass back scatter in water deeper than 100 fathoms. Sensible velocities were not obtained in deep water. In shallow water velocity values were consistently obtained, but there was a systematic error increasing from about 0.5 knot in 20 fathoms of water increasing to about 1.0 knot in 100 fathoms as deduced from comparisons between satellite Doppler and sonar Doppler average velocities between satellite fixes. The standard deviation of the sonar Doppler average velocities appears to be of the order of 0.2 to 0.6 knot.

The systematic error increasing with depth and the high scatter in velocities, which are undoubtedly instrumental in nature rather than real changes in boat speeed, has considerably reduced the value of the sonar Doppler unit in determining small scale fluctuations in the ship's velocity and hence Eotvos correction.

Electromagnetic (E.M.) ship's log

The ship's speed through the water was measured by E.M. log unit. A voltage is electromagnetically induced in an underwater sensor proportional to the velocity of the water flowing past it. A digital display was available for speed, while distance travelled was output on a mechanical counter.

The E.M. log became inoperative about half way through the survey and stayed that way for the remainder of the survey. For the first half of the survey the mechanical counter registering distance travelled operated satisfactorily but the velocity output to the electronic Nixie tube display appeared to have too short a time constant. The velocity value was almost unreadable as variations of over one knot occurred in the display in a few tenths of a second.

Radar fixes

Two Decca radar units were available for use on the ship's bridge. Range expanders were not available. Radar fixes provide a useful adjunct to the more usual navigation techniques when close to land and fixed points at sea such as drilling rigs or buoys. Accuracy is variable depending upon the sharpness of the reflector and accuracy of available hydrographic charts. Based upon internal consistency, land radar fixes are estimated to be correct to the order of 0.3 mile.

Astro and sun fixes

Star fixes were shot every day at dawn and dusk, weather permitting. Multiple determinations on several stars distributed around the compass give a far higher accuracy than the standard sextant shot carried out at sea. Internal consistency suggests an accuracy of ± 0.7 mile.

Sun shots were made at noon when possible. Latitudes to an accuracy of about half a mile are obtainable by this method.

Buoys

A number of northeast-southwest tie lines were run across the east-west traverse lines. In deep water, the positions of the intersections can only be estimated, but in shallow water buoys were dropped and anchored at preselected points to act as a reference point on the later traverses. The intersection points are used to check the internal consistency of the navigation network and for removal of gravity misclosures.

The buoys were of simple, inexpensive construction, consisting of an aluminium rod passing through polyurethane float with a radar reflector at one end and a counterwieght at the other. A nylon mooring line was attached to a concrete block and sea anchor to prevent the buoy from drifting.

During the survey 87 buoys were dropped at intersections but only 23 were recovered. Maximum recovery occurred when the buoys were dropped in shallow water and revisited within 10 days. Loss of most of the buoys was ascribed to strong and unpredictable currents and a severe storm during the second cruise. Disintegration of some of the buoys suggests that a more robust buoy is necessary.

Raydist

Raydist type " N" was provided for part of the survey by courtesy of Burmah Oil Company. Three nets are available along the coast of the Northwest Shelf, but only one is occupied at any time. Accuracy depends upon position within a net but is generally better than 200 feet. Close to the transmitters twenty-four hour-a-day operation is possible, but at the extremities of the net only daylight operation is feasible because of sky-wave interference at night.

Final positions determined by Raydist have yet to be studied in relation to final results of other systems. A study of the shipboard computed values indicates systematic variation relative to satellite Doppler fixes of about 2,300 feet and a standard deviation of about 1,000 feet. It is expected that Raydist will give fixes accurate to the order of 200 feet on a relative basis, but the absolute accuracy depends upon the net geometry and other factors. The comparison of the final values should allow a reasonable estimate of the accuracy of satellite fixes while the ship is moving.

Gravity

The performance of the gravity meter during the survey appears generally satisfactory. During the first cruise, the digital recording system had a locked bit in the unit position resulting in only odd milligal values being recorded. The photo cell lamp in the beam servo mechanism failed after the end of the first cruise and the beam jammed hard against the stops. After lamp replacement, the meter continued to function normally, but had suffered a large datum shift. An engineer from the manufacturer was flown from the U.S.A., and readjusted the meter to close to its original values.

The drift during the survey was negligible, except at the end of the survey but even here it was within tolerable limits for this class of survey. The gravity ties made into ports along the coast from Brisbane to Broome prior to the survey show erratic difference up to 1.7 milligals. These erratic values may be considered as due to erratic meter drift. Otherwise they suggest that the calibration factor may not be constant throughout the range of the meter. A further look at these port values and more systematic tests are desirable. During the survey a progressive check was kept on the values found at line intersections. Where buoys were recovered, the gravity differences at the intersections were relatively small, but where the intersection points had to be estimated, then errors in position were necessarily included in the gravity values. One would therefore expect slightly higher errors in gravity in deep water. The mean mistie at intersections was 1.37 milligals, corresponding to a standard deviation of about 1.6 milligals.

Magnetic

The ship magnetometer operated satisfactorily throughout the survey. Some slight interference was experienced during transmission on the Raydist radio communications set on the third cruise but this was quickly cured. The shore magnetometer was either inoperative or excessively erratic for most of the survey. For about the first 20 days the sensor heads kept cracking, presumably because of overheating. Perhaps for the first 40 days, noise generated by nearby transmitters made the magnetic readings almost valueless. When removed to a less noisy site near the V.L.F. monitor station, the pen recorder kept breaking down, mainly because of sand getting into the gears.

Failure of the shore monitor magnetometer has seriously down-graded the quality of the shipboard magnetic readings. A mean mistie of 25 gammas at traverse line intersections was obtained, when it had been expected that a value of 2.5 gammas would be achievable. When line intersections are more accurately known the magnetic data will be adjusted to fit and note will be taken of the diurnal variations observed at Port Moresby and Mundaring geophysical observatories.

Seismic

A big set-back was experienced in the seismic work when the six-channel cable was lost shortly after the start of the survey. The cable broke at the rear of the first active section. The loss of the multi-channel cable seriously affected the overall quality of the seismic reflection work.

Using the single channel cable, the record quality was generally fair. Useful reflections were generally obtained down to about 5,000 feet below the sea bottom. However, in shallow water multiple reflections and ringing interfered greatly with the reflections, causing loss of continuity of events. In water deeper than about 100 fathoms, the multiple reflection problem was much reduced, and events could be followed for many tens of miles. Continuity was lost over the edge of the continental shelf, because of diffractions and side reflection off the steep slopes and disturbed sedimentary sequence. In deep water, reflection quality was good despite the very low energy return.

Only a few hours seismic record were lost during the survey because of equipment malfunction, except when the cable was lost. Some time was lost because of breakdown on the recorders but this must be expected under continuous operation. One cause of lost record was moisture getting into the electrode-sockets and wiring of the spark-array system. The heavy current pulses vaporized the moisture and blew the wiring apart.

The sonobuoy refraction system operated satisfactorily considering that the method was new to all parties concerned. The air-gun energy source gave usable refraction data out to about 8 miles, usually farther in deep water. Even the sparker was useful as an energy source when there were shallow, high velocity refractors. A maximum range of about 3 miles was obtained with the sparker. Some problems were experienced with ship generated noise swamping the incoming signal.

CONCLUSIONS

The preceding discussion has outlined the equipment used on the 1968 survey, some of the problems met and equipment failures that occurred. Despite the considerable number of breakdowns, redundancy in data collection, particularly in the navigational field enabled operations to be maintained continuously while the boat was at sea. A review of Whitworth's paper mentioned previously shows that an exceedingly valuable survey was carried out. Although the results achieved more than justify the expenditure, there is still considerable room for improvement. The lessons to be drawn are:

1. In a survey of this nature involving a high daily rate of expenditure and limited budget once the survey is started, it must be carried through to completion, or to the allowable limit on expenditure. The best results obtainable under these conditions must be accepted.

2. Because difficulties and failures are inevitable to greater or lesser degree, there must be back-up for all systems consisting of either duplication or acceptable substitutes so that no likely failure or series of failures will cause a suspension of worthwhile operations.

Looking to the future in the principal problem areas, the following action will be taken.

Seismic. A more reliable 6-channel cable will be sought. It is also proposed to use a small digital computer for on-line stacking of the 6-channel data. The air gun energy source for refraction may be replaced by one requiring less capital value and bulk than the air compressors. Various mini explosive sources are attractive since the utilisation is low and the quantity of explosives required per survey will be very small.

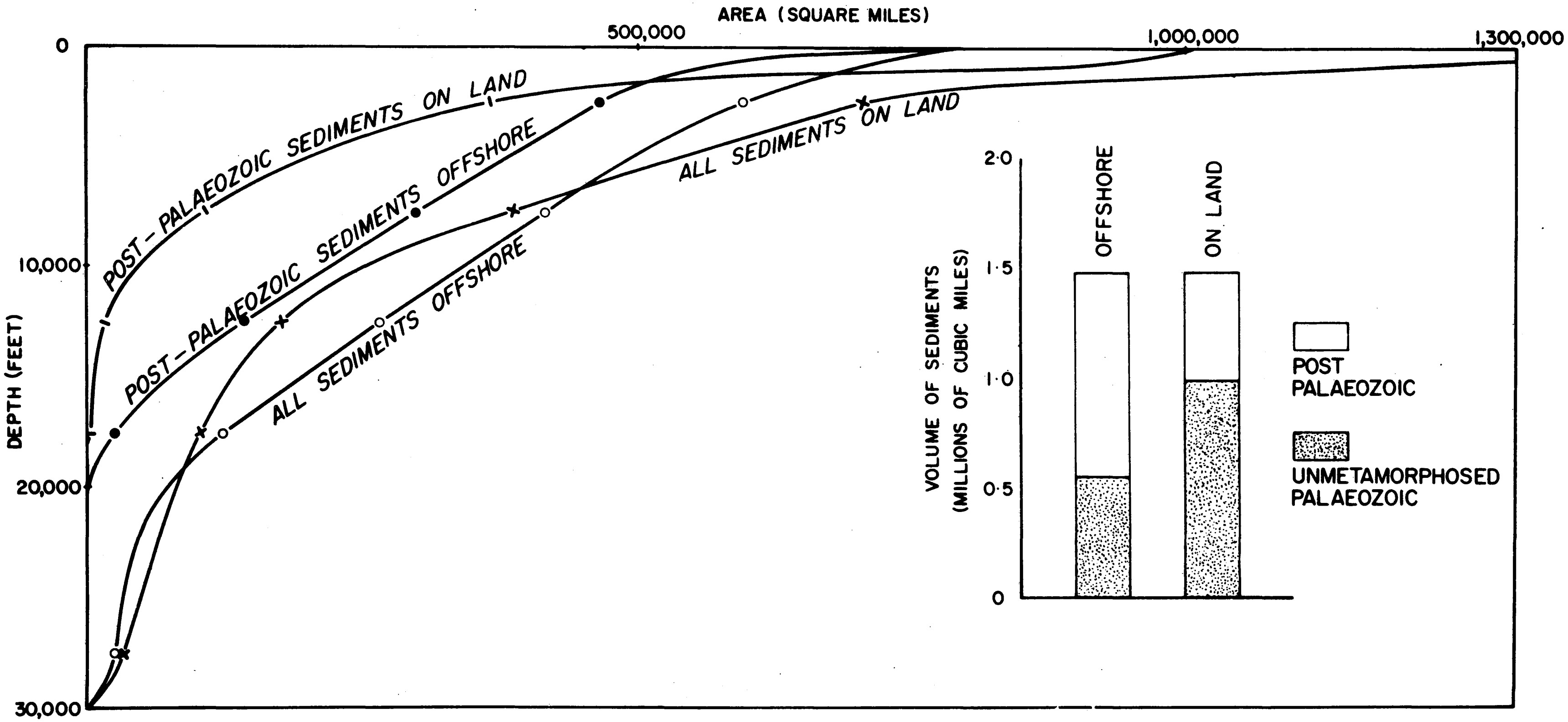
Magnetic. The onshore monitor must be made as reliable as the shipboard unit and expense and care must not be spared in achieving this end.

V.L.F. Digital recording of onboard data for a high sampling rate in preparation for post survey computer processing and reduction of human operation is essential. If other navigation systems work well the V.L.F. falls more into the category of a back-up system both for position and velocity.

Sonar Doppler. Instrumentally these units have proved very reliable in 1967 and 1968. Their problem has been in design deficiencies. In the last twelve months proven designs have appeared on the market and been used in the ECAFE Region. The Bureau's unit is being upgraded to the new standard.

E.M. Log. Back up ship's log devices including engine revolution recording monitors are mandatory.

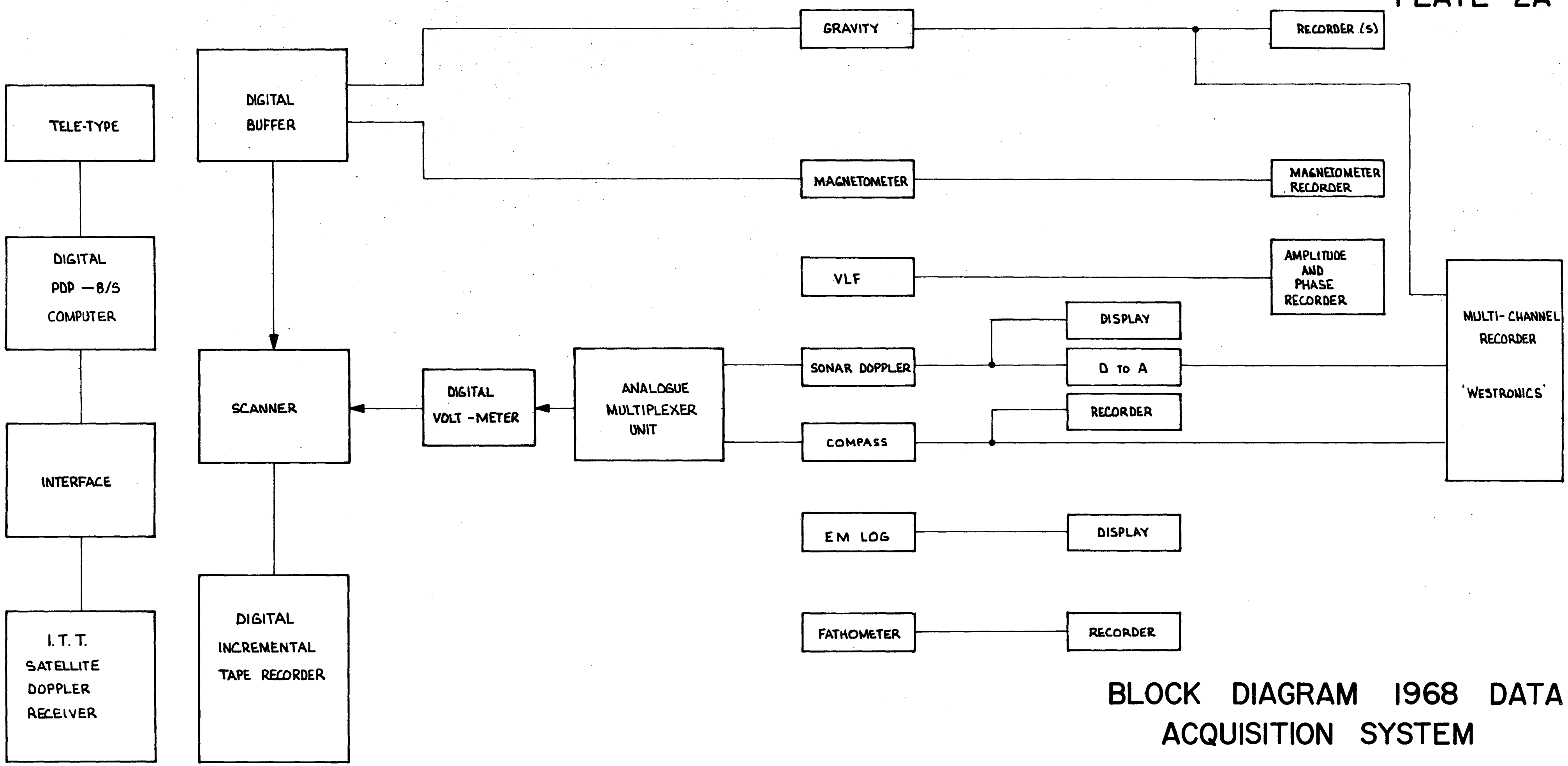
A block diagram of a system that it is hoped to have assembled for a survey of the Gulf of Papua and the Bismarck Sea in 1970 is shown on Plate 6.



DISTRIBUTION OF SEDIMENTS ON LAND AND OFFSHORE

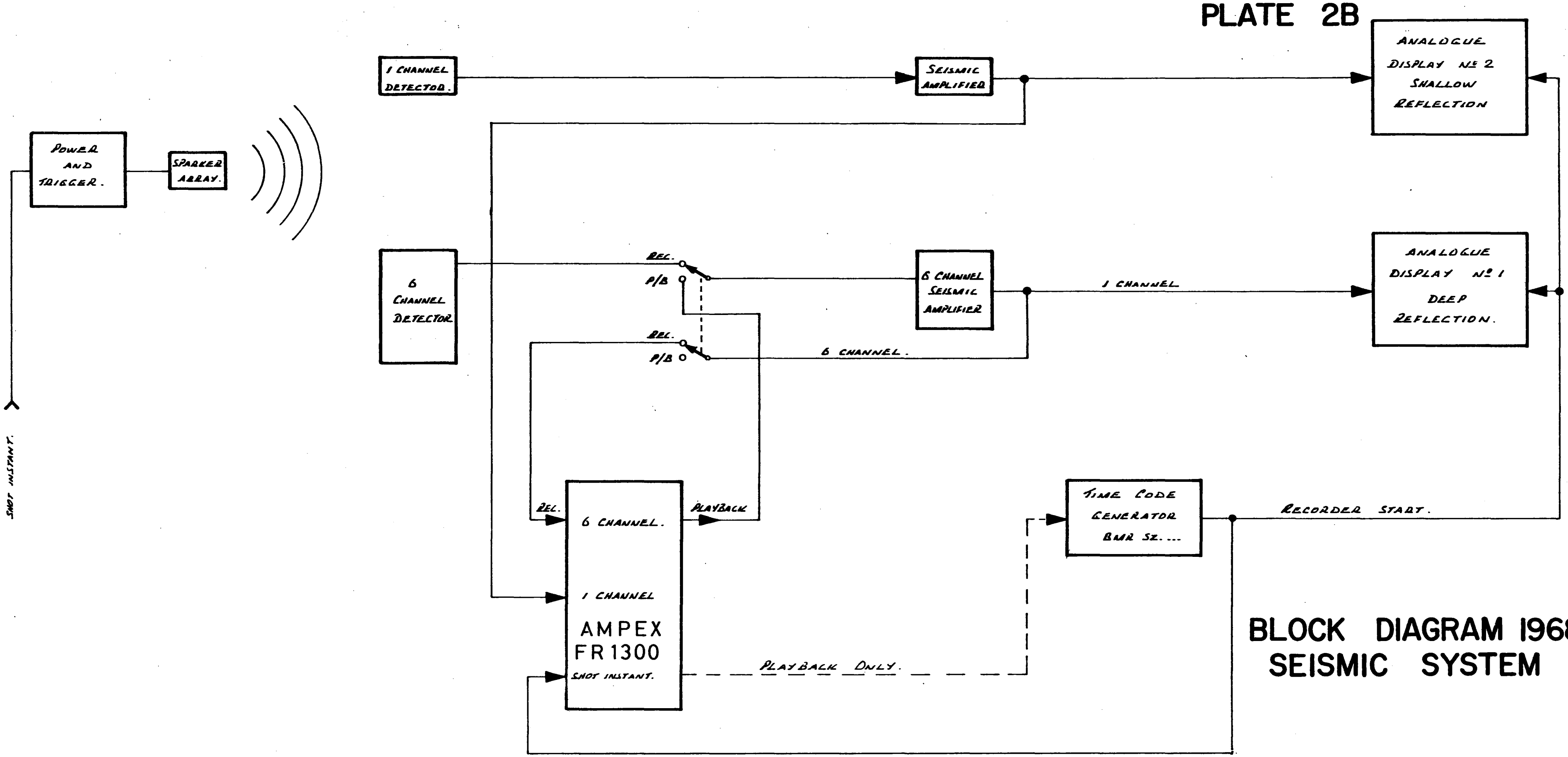
PLATE I

PLATE 2A



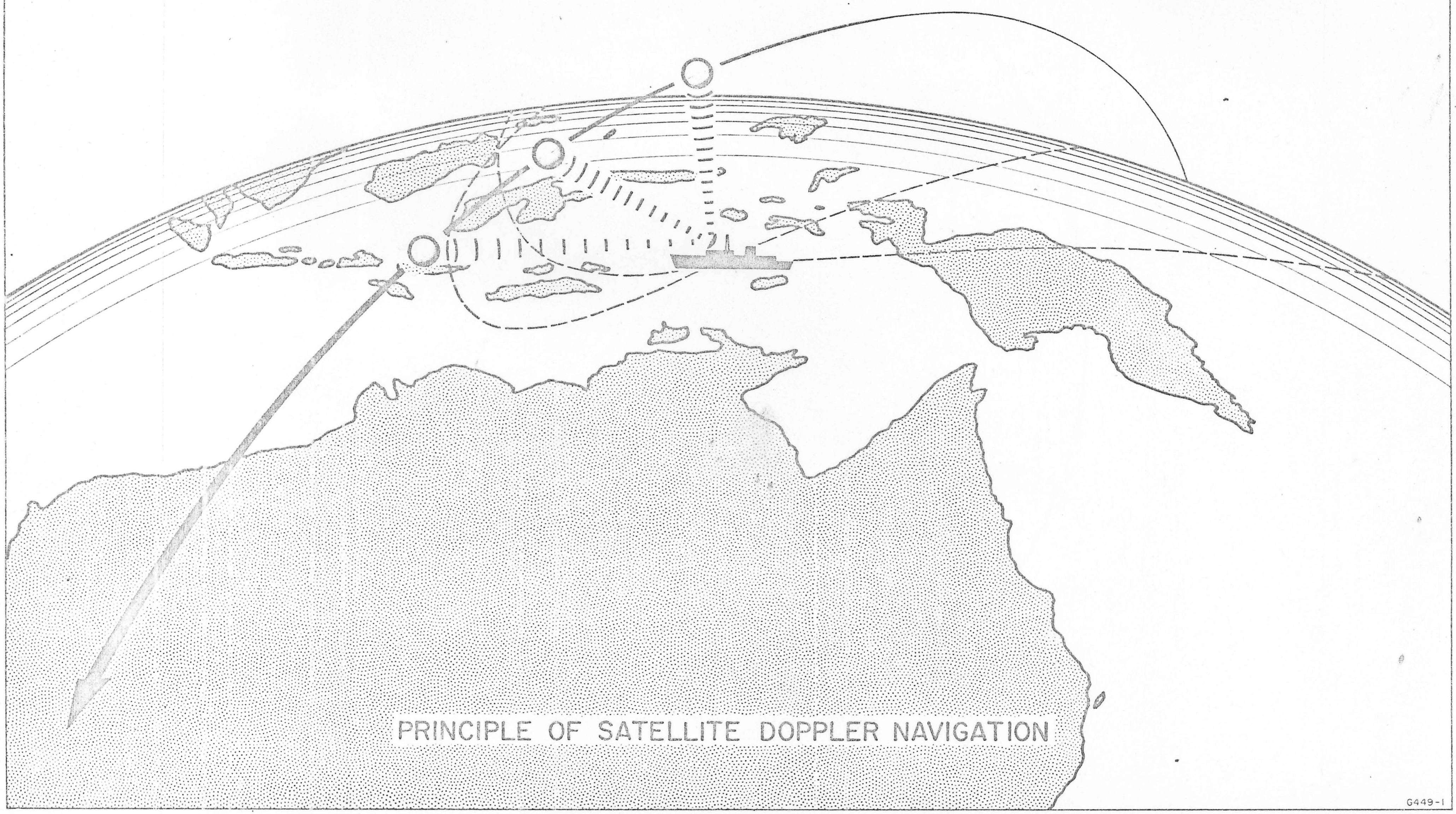
BLOCK DIAGRAM 1968 DATA ACQUISITION SYSTEM

PLATE 2B



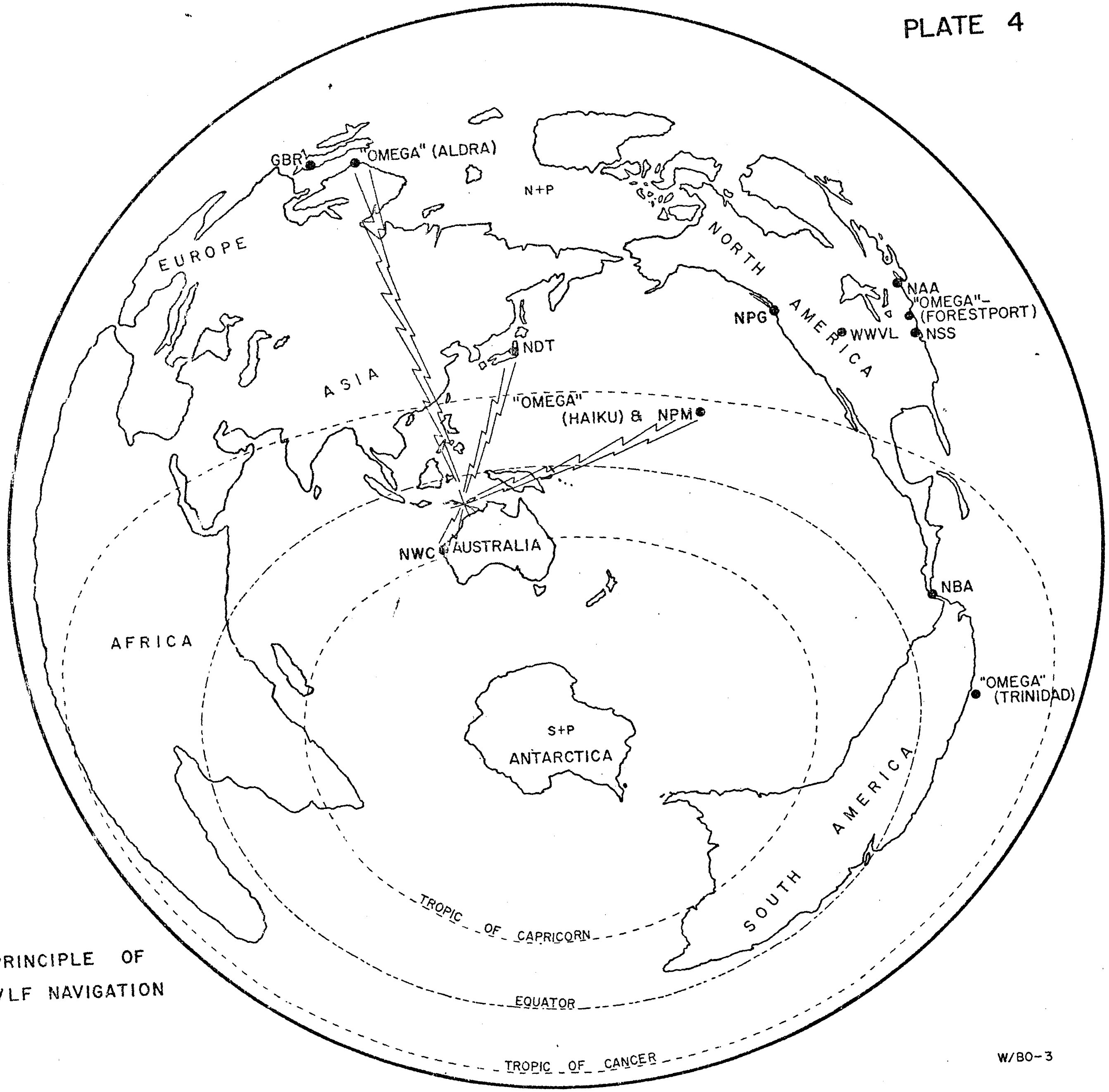
BLOCK DIAGRAM 1968
SEISMIC SYSTEM

PLATE 3



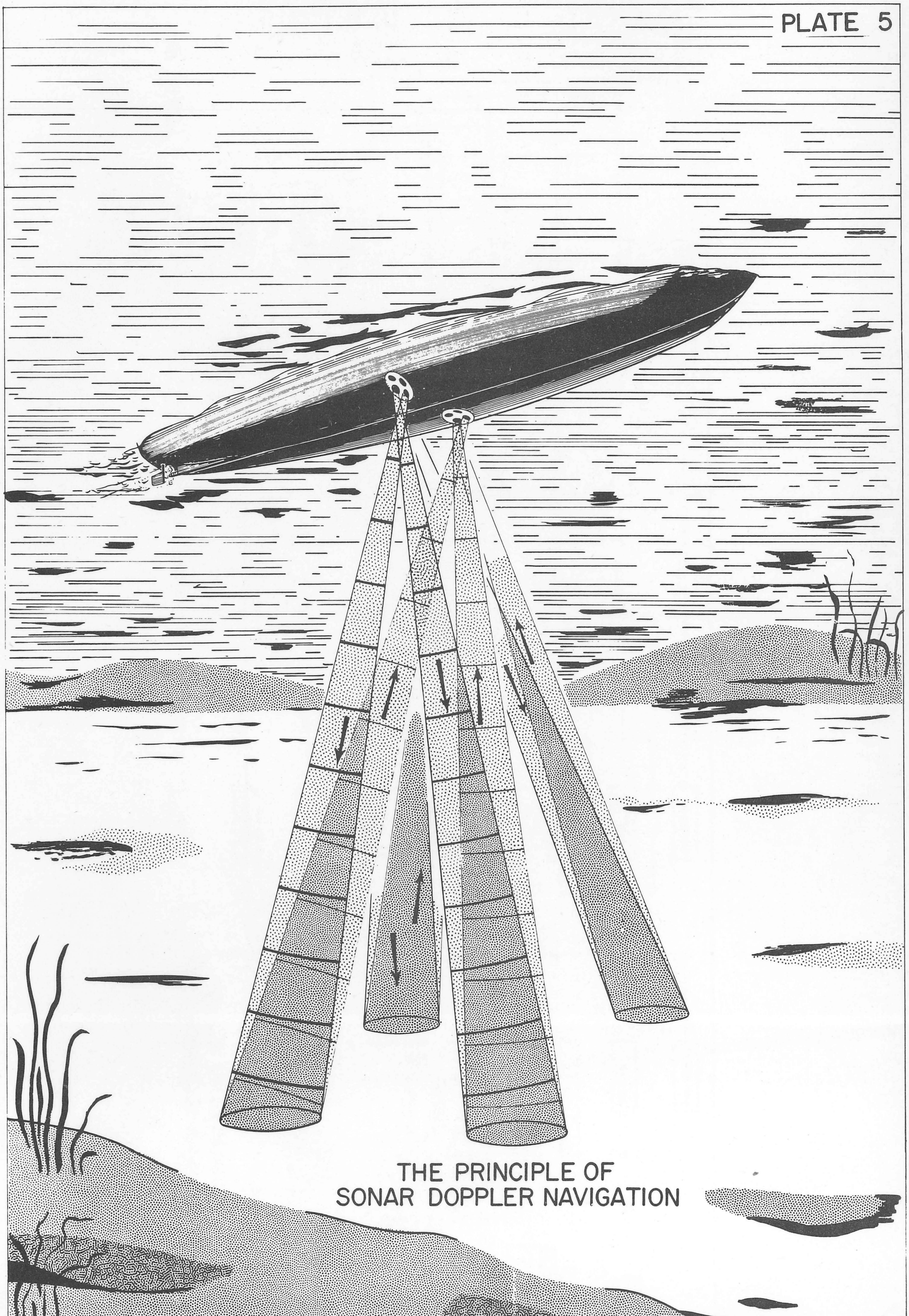
PRINCIPLE OF SATELLITE DOPPLER NAVIGATION

G449-1



PRINCIPLE OF
VLF NAVIGATION

W/BO-3



THE PRINCIPLE OF
SONAR DOPPLER NAVIGATION

PLATE 6A

BLOCK DIAGRAM PROPOSED 1970 DATA ACQUISITION SYSTEM

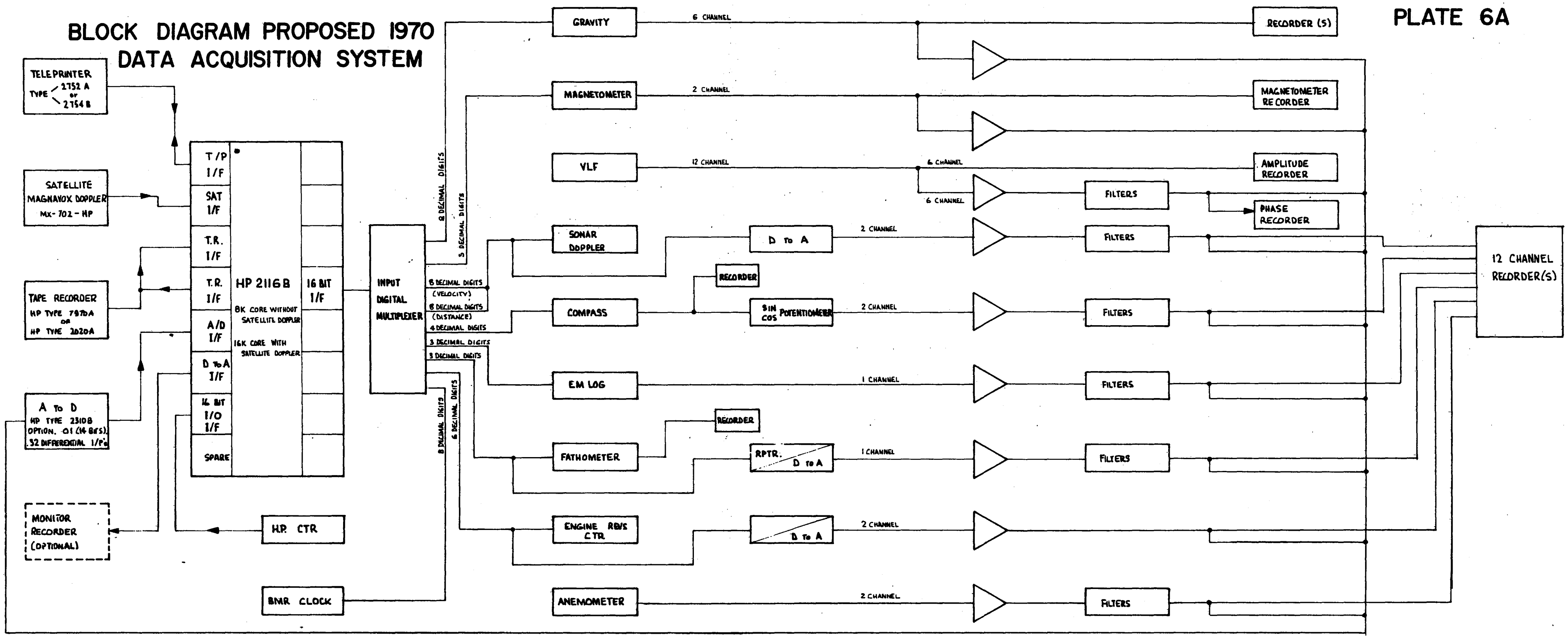
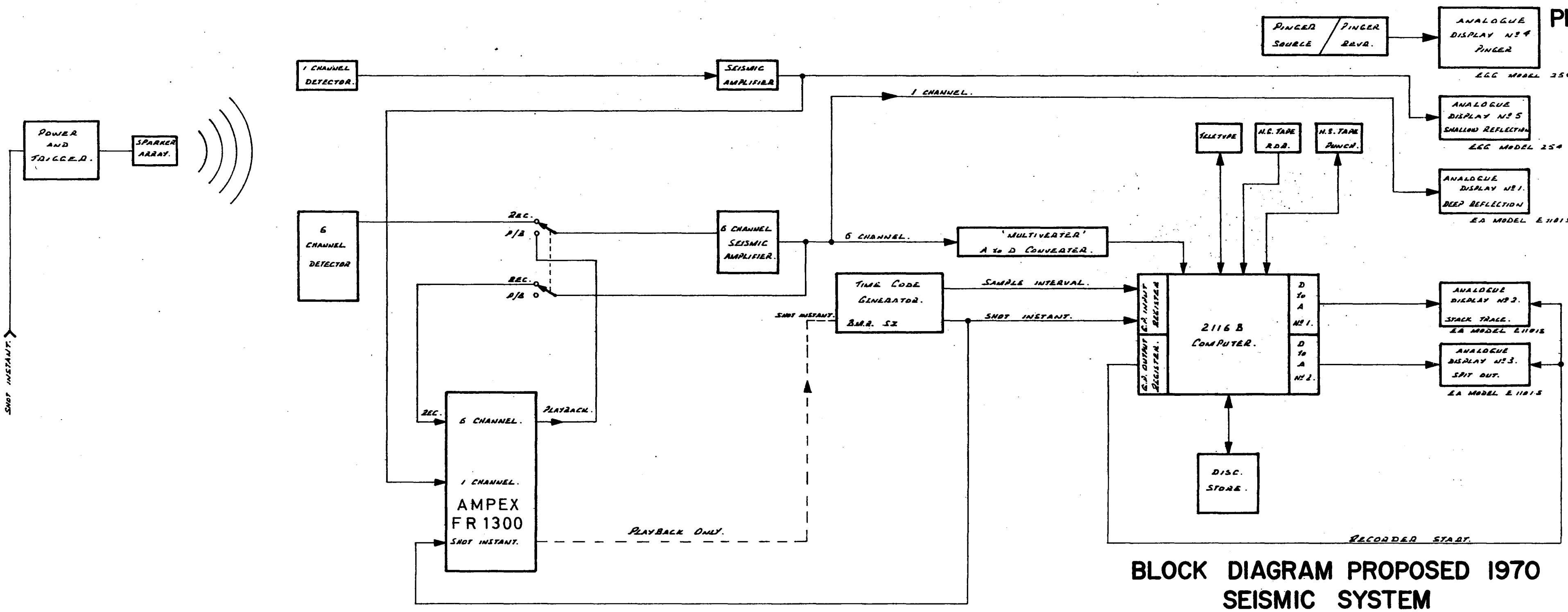


PLATE 6B



BLOCK DIAGRAM PROPOSED 1970
SEISMIC SYSTEM