DEVELOPMENT OF THE MRB 201/301

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ABSTRACT

The early history of navigation and hydrographic survey aids leading to the invention of the first Tellurometer and the MRB2 Hydrodist is briefly described.

The various operational and technical factors which influenced the design concept of the later MRB201 are discussed, together with actual field results obtained with the equipment. Some results of trials with the high speed MRB301 are also tabulated.

INTRODUCTION

Ever since man first ventured from the land upon the sea, he has been faced with the problem of navigation which for many centuries has taxed his ingenuity. Instead of the familiar land-marks such as valleys, rivers and mountains he was faced with a trackless expanse of water with little or no means of determining his whereabouts. In this hostile environment he had to rely on such dubious observations as the changing colour of the sea, the depth of water under his boat and the behaviour of the wind in order to have even an approximate idea of his geographical position.

There is little recorded knowledge of man's first ventures out of sight of land, but Egyptian hieroglyphic records do indicate the presence of foreign ships at Egyptian ports over 4000 years ago. The Phoenicians are credited with being the first to make use of astronomy in order to navigate their ships as early as 600 B.C. and their knowledge was later expanded by the Greeks and Romans. Little further progress was made until about 1000 A.D. when the rediscovery of the magnetic compass, previously known to the Chinese as early as 1600 B.C., heralded a new era of navigation and map-making. This was followed after the 13th century with the use of a crude form of sextant and Ptolemy's geography and maps were made known to the Western world at the beginning of the 15th century.

A satisfactory method of determining longitude was not devised until the invention of the chronometer and it was only in the 18th century that navigation became a reasonably exact science.

Apart from refinements in instrumentation there was little change in basic methods until the advent of radio. In 1880 Hertz produced radio waves and showed that they could be deflected by a metal object. This was later followed by telegraphy which enabled the accuracy of chronometers to be checked. The invention of radio direction finding during the first World War was the next significant step as it enabled position fixes to be obtained in all weather conditions. The development of radio detection and ranging (radar) during the second World War, was a further milestone and is still today one of the prime methods of in-shore navigation.

The rapid advance of electronic technology in recent years has resulted in the development of a host of electronic positioning and distance measuring aids. One of the first of these was the Decca Navigator which assisted in the 1944 D Day operations. The U.S. Navy Satellite Navigation System, developed between 1958 and 1963 was also a significant advancement.

The recent increase in hydrography throughout the world has generated the need for much greater accuracy, compatible with that of survey rather than navigational requirements. This in turn has resulted in the development of higher frequency systems capable of greater resolution and hence, accuracy. Many systems are available today, operating on frequencies of 1 or 2 megahertz and capable of giving positional fixes varying in accuracy from a few metres to a few hundred metres depending on their configuration and operation.

Reliable accuracies of better than a metre were first rendered possible with the invention of the microwave Tellurometer by Dr. WADLEY in 1956. Although this was first developed as a static instrument for land survey work, its potential in a dynamic role for hydrographic work was soon recognised. The first hydrographic Tellurometer, the MRB2, became available in 1960 and soon showed its capability for measuring distance to an accuracy of nearly ½ metre. This degree of accuracy was made possible by virtue of the relative freedom of microwaves from propagation anomalies which tended to limit the accuracy of lower frequency instruments. The Tellurometer MRB2 fulfilled the need for precise hydrographic surveying for many years until the rapid advance of technology dictated the need for a more modern instrument, simpler to use, and more directly compatible with data processing equipment.

The development of the MRB201 in 1970 was intended to fulfil this need and some of the factors which led to the final design concept are discussed in the next section.

MAJOR DESIGN PARAMETERS OF THE MRB201

There are many possible approaches to the design of an electronic position fixing system and the precise requirement must naturally determine the type of equipment to be used. The all important factor of cost must also weigh heavily in the final design of any such system.

FIG. 1. — A typical MRB 201 Master installation.

Most distance measuring or position-fixing systems available today suffer from one or more of the following disadvantages:

1. lack of instantaneous or continuous positional information;
2. loss of lane count in phase-type systems;
3. need to man Remote or Reference stations;
4. high power requirements for Remote or Reference stations;
5. lack of portability, particularly with land-based stations;
6. inaccuracies caused by reflections and propagation anomalies;
7. inadequate accuracy caused by inability to accurately determine transit times in pulse-type systems;
8. lack of multi-user capability;
9. excessively complex operation;
10. lack of compatibility with data recording and processing equipment;
11. inability to perform under all weather conditions;
12. lack of adequate range performance;
13. necessity to periodically direct antenna;
14. excessive cost.

Whilst it is neither technically nor economically possible to eliminate all these problems in any one equipment, the design concepts of the MRB201 were formulated with a view to overcoming most of the more serious disadvantages. The prime emphasis has been laid on accuracy as it was felt that there were many available systems capable of measuring to a few or a few hundred metres. The requirements of today's hydrographers, however, are dictating the need for measurements to better than ± one metre. Where this requirement has clashed with other operationally desirable features, such as ultra-long range, the latter have had to be sacrificed in the interests of obtaining this accuracy. Perhaps the most important decision which has to be made in the design of any new system is that of a choice of frequency and a few words about the effect of frequency on system performance would be appropriate.

FREQUENCY SELECTION

Most distance measuring or position-fixing systems can be classified into three different frequency groups.

1. Microwave (1 000 MHz to 10 000 MHz);
2. Medium frequency (1 MHz to 2 MHz);
3. Low frequency (30 to 300 kHz).

Depending on the frequency band selected, both range and accuracy performance are radically affected.

Basically the factors affecting propagation are so multifarious, and depend so much upon meteorological and extra terrestrial phenomena of which we cannot have complete knowledge, that no theories can give a precise answer to the problem of calculating the distribution of radiated field from a given transmitter. In general terms, however, it is possible to summarise and say that range performance is due primarily to the presence of three distinctly different methods of electromagnetic wave propagation.

(a) Groundwave propagation

This is one of the prime methods of propagation for frequencies in the 30 to 300 kHz band. Groundwave propagation is greatly dependent on the conductivity of the ground through which the radio wave travels. At very low frequencies the groundwave attenuation is slight and usable signal strengths are obtainable at distances of several thousand miles. This attenuation increases rapidly with frequency, however, and at the upper end of the frequency band usable signal strengths are only obtained at a few hundred miles. (Ref. Appendix A). The depth of penetration of the wave below the surface is also affected by both frequency and conductivity and can vary from a few metres to a few hundred metres. The depth of the groundwave at 1 megahertz is typically 20 metres.

Whilst low frequencies using groundwave propagation are ideal for ultra-long ranges, variations in conductivity and shape of the nearby terrain have a serious effect on the phase of the propagated wave and, as such, low frequency systems cannot be used for any accurate work. In addition the long wavelengths of 1 to 10 kilometres do not allow adequate resolution for survey type accuracies to be obtained. Special calibration can allow measurements to better than 50 metres to be obtained but the reliability of such measurements is often in doubt. A further disadvantage of low frequency systems is that antenna efficiency is directly related to the size of the antenna in terms of wavelength. A Hertzian dipole of length L carrying an alternating current of amplitude I radiates a power P given by $P = 40\pi^2 I^2 (L/\lambda)^2$. It can be seen from this that an efficient antenna has to be physically large in terms of wavelengths and this jeopardises the possibility of using low frequencies for a portable system.

(b) **Skywave propagation**

Skywave propagation is that caused by transmissions reflected from the ionosphere. This ionosphere is a region of ionised gases extending from altitudes of about 50 to 400 km above the earth's surface. It is a great natural phenomenon which makes long distance radio transmission possible at frequencies which would otherwise be very limited.

At frequencies below 500 kHz the ionosphere tends to act as an absorber and reliable skywave propagation is not possible. At frequencies between 500 kHz and about 30 MHz the ionosphere acts as a reflector, provided the angle of incidence of the radiation is within certain limits. Transmissions in this band can be effectively bounced around the earth. Above 30 MHz and particularly at microwaves electromagnetic radiation penetrates the ionosphere and this mode of propagation is no longer possible.

Whilst skywave propagation is of interest in that it affects medium frequency transmissions it is not of any real practical use for accurate position-fixing systems. The phase of the received signal is too variable as a result of the devious path by which it has been received.

Medium frequency systems still rely on groundwave propagation for their performance up to some 300 km and as such their accuracy is again limited by variations in conductivity and terrain. The shorter wavelengths of these systems allow high resolution to be obtained however, and with suitable calibration accuracies of a few metres can be obtained. Night-time range is generally limited to about 150 km by the increase in skywave propagation. The interference between skywave and groundwave causes both fading and phase inaccuracies which render these systems virtually inoperable at longer ranges.

(c) **Directwave propagation**

Directwave propagation, which is similar to that radiated by, say, a Hertzian dipole into free space, is the prime method of propagation for frequencies in the 1 000 to 10 000 MHz band. At these high frequencies propagation characteristics tend to a much greater extent to follow the classic free space law where the flux density S at a given distance d from an isotropic antenna is given by

$$S = \frac{Pt}{4\pi d^2}$$

Although the direct wave exists at lower frequencies of 1 to 2 MHz, it is effectively cancelled by the radiation reflected from the earth's surface which experiences phase shift of about 180° on reflection. At high frequencies the reflection coefficient of the surface is lower and the difference in path length, in terms of wavelength, much greater. Although this cancellation effect can still cause fading in the 1 000 to 10 000 MHz band its effect is generally less and decreases with increasing frequency. One major advantage of frequencies in this band is that it becomes possible to design directional antennae of reasonable size and this greatly reduces the effects of reflections from nearby objects. This in turn allows much greater accuracies to be obtained.

The ionosphere has little effect on microwaves which penetrate right through and are, in fact, the frequencies used for deep space communication. The groundwave is so highly attenuated as to be virtually negligible.

One of the major disadvantages of the direct wave is the restriction of range to near line-of-sight conditions. Although this is a limiting factor in microwave ground-to-ground propagation the rays do partially tend to follow the curvature of the earth and this effect increases with decrease in frequency. There are two reasons for this effect—diffraction, and variation of atmospheric refractive index with altitude.

The surface of the earth can be considered as an obstacle in the passage of electromagnetic rays and diffraction effects can be explained on the basis of Huygen's principle which states that any elemental area of a wavefront can be considered to radiate in all directions. The intensity in any given direction being proportional to $(1 + \cos \theta)$ where θ is the angle between the wave motion and the direction chosen. This diffraction effect is inversely proportional to frequency and thus curvature, and hence range, of lower frequencies is marginally greater.

The refractive index of the atmosphere also has the effect of bending radio waves due to its variation with height. This refractive index can be approximately given by the formula

$$(n - 1)\, 10^6 = \frac{79}{T}\left(p - e + \frac{4800\, e}{T}\right)$$

where T = absolute temperature;
p = total atmospheric pressure in millibars;
e = partial water vapour pressure in millibars.

The value of n decreases linearly with height at a rate

$$\frac{dn}{dh} = 0.039 \times 10^{-6} \text{ units/metre.}$$

Since n decreases with height, the upper part of the wavefront travels faster than the lower and the rays will be bent downwards. The radius of curvature can be given by $R^{-1} = 0.039 \times 10^{-6}$ units/metre, i.e., $R = 25.5 \times 10^{6}$ metres which is approximately 4 earth's radii.

A simplified formula for calculating the distance to the radio horizon is given by $D = 4.13 \sqrt{h}$ where D is in kilometres and h in metres.

Meteorological Effects

One disadvantage of microwave transmissions which should not be overlooked is their inherent dependence on weather conditions. The presence of water in the amtosphere, either in the form of high humidity or fog and rain, can cause considerable attenuation, particularly at the high end of the band. From theoretical considerations it was predicted by van FLECK in the U.S. that both oxygen and uncondensed water vapour would have absorptions in the centimetre wave region. This is a molecular phenomenon which causes absorption of energy from the wave at certain wavelengths characteristic of the molecular structure. Typical attenuation figures due to water vapour and oxygen absorption are as follows:

1 000 MHz	0.004 dB/km
3 000 MHz	0.01 dB/km
10 000 MHz	0.02 dB/km

The attenuation due to rainfall also increases with frequency and typical figures for medium rainfall at a precipitation rate of 10 mm per hour are as follows:

1 000 MHz	negligible
3 000 MHz	0.002 dB/km
10 000 MHz	0.2 dB/km

It can be seen that if the range performance of an equipment is not to be seriously affected by weather, the operating frequency should be restricted to the lower end of the band.

In summarizing all the preceding factors the following picture emerges:

Low frequency

Very long range due to extensive groundwave propagation.
Large antenna and high power requirements.
Low accuracy due to poor resolution and effects of terrain and conductivity.

Medium frequency

Medium range performance utilizing groundwave propagation.
Night-time range limited to below 150 km by skywave interference.
Relatively large antenna and power requirements.
Improved accuracy due to higher resolution.

Microwave frequencies

High accuracy due to possibility of directional antennae and propagation free of terrain and ionospheric effects.
Low power requirements due to use of small sized high-gain antennae.
Range performance limited to near line-of-sight conditions.
Range performance affected by weather at upper end of frequency band.

It can be seen from a brief study of the above that where accuracy is required there is little choice other than the use of microwaves and limitations, such as line-of-sight range performance, have of necessity to be accepted.

Before making any final decisions on the use of a specific frequency within the microwave band it is as well to consider the propagation formula given in Appendix B. For direct wave propagation it can be stated that:

$$dm = \frac{\lambda}{\theta^2}\sqrt{\frac{Pt}{P_{Rm}}}$$

It is immediately apparent that, for the same antenna beamwidth and transmitted power, the maximum range *dm* is directly proportional to wavelength. It is reasonable to consider antenna beamwidth as a constant in this particular case as operational considerations will normally determine the minimum possible beamwidth which should be restricted in order to ensure the greatest possible accuracy.

From considerations of range performance and freedom from weather effects it is desirable to keep the operating frequency as low as possible within the microwave band. In addition, the cost of suitable microwave generators rises steeply with frequency. A delicate balance must be reached, however, between these factors and the requirements for high resolution and accuracy, coupled with antennae of reasonably small physical dimensions.

A careful consideration of all these facts together with an analysis of achievable accuracies has led, in the MRB201, to a frequency choice of 3 000 MHz. The results of some of these accuracy tests are tabulated later.

CHOICE BETWEEN PULSE, PHASE COMPARISON AND DIRECTION FINDING TECHNIQUES

There are three basic ways in which radio waves can be used for determining positional information.

(a) Relative bearings taken with radio direction-finding equipment;
(b) Range or range difference measurements from determination of pulse transit time;
(c) Range or range difference measurements from determination of phase delays of continuous wave transmissions.

The use of satellite transmissions for positional fixes should also not go without mention as it is almost unique at this time as an aid with world-wide capability of fixing to an accuracy of a few hundred metres. High precision fixes are not a routine matter however, and become impractical as speed of motion increases and becomes less certain. For this reason they have been left out of the discussion.

Doppler systems can also be considered as relatively low accuracy aids used primarily for navigation rather than precise hydrographic surveying. The cumulative error on most doppler systems is about 1 to 2% of distance travelled. They have a place, however, when used in conjunction with satellite navigation systems as they provide a velocity reference which greatly improves the accuracy of dead reckoning between usable satellite fixes.

(a) **Radio direction-finding**

This is still one of the prime methods of in-shore and even long-range navigation, due mainly to its low cost and ability to measure to virtually any radio beacon of suitable frequency. It is primarily a navigation aid, however, and has no place where accurate surveys are required. The beamwidths of antennae even in the microwave region are limited to a few degrees by considerations of physical size which has to be large in terms of wavelength, and at any reasonable range the resultant errors are unacceptable.

(b) **Pulse systems**

Systems which measure the transit time of radio pulses can be categorised into "passive target" and "active target" types.

Radar is an example of the former and is today one of the most useful aids for in-shore navigation. Passive targets can generally not be used for work where accuracies of a few metres are required, however, due to the difficulty of distinguishing the target from background clutter and the relatively weak signals returned. This is particularly applicable at long ranges.

Pulse systems using active transponders deserve serious consideration as high accuracy survey aids and there are today a number of these systems on the market. The principle of operation is similar to that of conventional radar except that the transmitted pulse, usually in the microwave region, is received by a transponder, frequency shifted by a small amount, and sent back to the Master unit where the delay time is measured by an accurate clock. With a knowledge of the velocity of propagation this delay time can be converted to an accurate distance.

There are many advantages to these systems not the least of which is their inherent simplicity and the small size of their transponders. Transponder power requirements are generally low due to their requirement for intermittent rather than continuous transmission. Most systems have the facility for semi multi-user operation in that a number of Master stations can in effect time-share the use of the transponders.

An inherent advantage, which is utilised in some systems, is that where multi-path problems exist the receiver can be designed to measure the first pulse received and discriminate against any further pulses which may have travelled by devious, and thus longer, routes. This can significantly reduce errors caused by terrain effect and the presence of large nearby objects which might act as reflectors.

There are two major drawbacks to any pulse system however, and for this reason the technique has not been considered for the MRB201. Both of these reasons are associated with the difficulty of obtaining high accuracy.

In any pulse system utilising pulse transit time measurements there are time delays which occur both at the Master unit and at the transponder. Provided these delays are constant they can be calibrated and thus have no effect on the final accuracy. In practice, however, it is technically extremely difficult to maintain constant delays with changes in temperature and the passage of time. Early systems had to be regularly calibrated for zero shifts and although modern techniques have virtually eliminated this requirement, pulse systems cannot compare with phase comparison systems where high resolution and accuracy are required.

The most serious limitation on the accuracy of any pulse system is the necessity for accurate measurement of pulse transit times. This, in turn, necessitates the use of pulses with extremely fast rise times which have to be measured to an accuracy of a few nanoseconds if accuracies of a few metres are to be obtained. Until recently the techniques for measuring nanosecond rise times did not exist. The rapid advance of the technology has now made this possible but even so, reliable and repeatable accuracies of better than 1 to 2 metres are nearly impossible to achieve.

The MRB201 was developed with the intention of achieving an accuracy of better than 1 metre and in view of this a phase comparison system similar to that used by other Tellurometers was the only choice.

(c) **Phase comparison systems**

Phase comparison systems rely on the determination of total phase delay between an outgoing and returned continuous wave signal. In effect a transmitted carrier or modulation frequency is received at a Remote unit and retransmitted back to the Master where a measurement of phase delay is made. Phase differences at high frequencies are extremely difficult to measure, however, and for this reason the frequency is shifted to the audio band before being processed. A more detailed explanation of the principle on which the Tellurometer operates, is given in Appendix C.

Due to the fact that virtually any modulation frequency can be used and phase can be measured to better than 1 in 10^3 the instrumental accuracy is theoretically almost unlimited. In practice, with narrow beamwidth antennae, accuracy of a few millimetres can be obtained and this limit is set by our inability to measure the true atmospheric refractive index, and hence velocity of propagation, rather than by any instrumental considerations.

In any practical hydrographic operation reasonably wide beam antennae are required however, and the resultant multi-path errors are probably the overriding cause of any inaccuracies. Unlike pulse systems, signals reflected from nearby objects or the surface of the sea, combine to give a vector sum and the relative phase of this can be different from that of the true direct wave.

It can be seen from Appendix D that the phase error angle

$$\beta = \Sigma\, ai \cos \frac{2\pi \Delta d}{\lambda c} \sin \frac{2\pi \Delta d}{\lambda m}$$

and is thus dependent on the carrier frequency, modulation frequency, and path difference of the reflected ray. With changes in Δd the phase angle error will vary in a cyclic manner and can be smoothed out in any dynamic operation. In any event, provided that antenna heights are suitably chosen for the geometry of the system (see Appendix E) this error will usually be less than 1 metre.

One disadvantage of phase comparison systems is that although phase can be measured to an accuracy of 1 in 10^3 this measurement will be ambiguous for every complete wavelength that the wave has travelled, e.g., a system with 0.1 metre resolution will be ambiguous every 100 metres. Many systems rely on phase integration which has to be set up at a known point. This is a distinct disadvantage, however, as should the signal be lost at any time, there is no way of recovering the true reading other than by returning to a known point.

In the MRB201 a number of modulation frequencies are used in order to resolve these ambiguities and the system is thus independent of any other reference. Simultaneous transmission of these frequencies is unfortunately not possible but each of them is available on demand should there be any doubt as to the accuracy of a particular reading. This technique is generally known in position fixing systems as "lane identification". The comparison between the various readings taken with each of these pattern frequencies is a powerful tool in determining the validity and accuracy of any particular measurement.

HYPERBOLIC AND DIRECT RANGE MEASURING SYSTEMS

Having decided on a microwave phase comparison system for the MRB201, there remains a choice between two fundamentally different approaches—a hyperbolic system or a direct range measuring system.

A hyperbola can be defined as the locus of a point whose range difference from any two fixed points is a constant. It can be seen therefore, that if two transmitter stations radiate phase locked continuous wave carriers or carrier modulations, a family of confocal isophase hyperbolae is generated. Any receiver capable of measuring the phase difference between these radiated signals is automatically placed on its relevant hyperbolic position line. Two complete baselines are, of course, required for a complete positional fix.

One major advantage of hyperbolic systems is that the receiver is completely passive and as such the system is fully multi-user compatible. The number of receivers which can operate at any one time is virtually unlimited. Direct range measuring systems utilising continuous wave phase comparison techniques are usually only semi-multi-user on a time sharing basis. Another advantage of hyperbolic systems is that even at relatively low frequencies a small antenna can be used on the mobile receiver as there is no requirement for any transmission. The antenna need only be long enough to enable a reasonably good signal-to-noise ratio to be obtained.

One of the major drawbacks of the hyperbolic approach, however, is the problem of system geometry. In order to obtain a complete positional fix at least three, and probably four, stations are required. The angles of cut of the relative hyperbolae must also be as orthogonal as possible in order to obtain an accurate answer. On many coastlines, and in particular, a straight coastline, this is difficult to achieve. A comparison between the relative position lines and angles of cut of a hyperbolic and range measuring system is given in Appendix F. The geometric advantage of the direct range measuring system is immediately apparent. This is even more applicable on a straight coastline where 180° baselines are the only choice.

A further disadvantage of hyperbolic systems is the problem of lane expansion. It can be seen from Appendix F that the lanewidth of the hyperbolae increases with range and can, in fact, be approximated by the formula:

$$\text{lane expansion} = \frac{\text{range}}{\frac{1}{2}\,\text{baselength}}$$

In addition, this lane expansion increases when operating away from the centre line of the system. This problem can be the cause of considerable error at longer ranges and is one of the reasons why the MRB201 was designed as a direct ranging system.

A major inconvenience of hyperbolic systems is the necessity for special overlays or complex calculations in order to convert the co-ordinates to the more conventional rectangular system or even to plot a position on the map. With a direct ranging system such as the MRB201 this is, of course, straightforward.

FURTHER DETAILS OF THE MRB201 DESIGN

The various factors which have been discussed so far have led to the choice of a direct ranging system utilising phase comparison techniques and operating on a microwave carrier of 3 000 MHz. In discussing the major design parameters, there remains only the choice of antenna beamwidth, modulation frequency and the design of a suitable readout.

Apart from range considerations, the choice of a suitable antenna beamwidth is purely a function of accuracy versus operating convenience. Ideally, for maximum operating convenience, the Master unit should have an omni-directional antenna. Although this is possible, and indeed one has been designed, it is not adequate for operation in environments such as harbours where readings may have to be taken within one hundred metres of large ships or cranes. In these circumstances errors of many metres can be experienced and in some cases even the lane identification becomes completely erroneous. An optimum choice for accuracy and reliable operation has been found to be about 25°. It can be seen from the specification in Appendix H that the vertical beamwidth is slightly less. This has been done in order to reduce the effects of reflections from the surface of the sea. Despite what has been said about the omni-directional antenna it can, in open areas, give very good results. The next section contains a comparison of simultaneous readings taken with a standard directional antenna and an omni-directional antenna on a small boat in False Bay.

Where long range is required, high gain and hence a narrower beam antenna is required. Appendix G gives an indication of the line-of-sight range performance as a function of antenna gain.

The choice of a suitable modulation frequency is primarily a function of the resolution required. In the MRB201 a resolution of 0.1 metre has been chosen and with circuit techniques enabling phase to be measured to 1 in 10^3 a fine pattern wavelength of 100 metres is necessary. It can be seen from the basic measuring principle described in Appendix C that a pattern wavelength of 100 metres corresponds to a modulation frequency of approximately 1.5 MHz. In order to resolve ambiguities and eliminate errors a further 5 related frequencies are included.

The units have been designed with a dual Master/Remote facility which enables an additional check on the accuracy of any particular measurement. In addition this facility enables two remotes to measure their own baseline without the necessity of disturbing the master installation.

The readout has been specifically designed in digital form to enable a complete digital range presentation to be continuously available. This range presentation is actually an integrated fine pattern reading which is up-dated every millisecond and is thus virtually continuous. Lane identification can be achieved at any stage by means of a simple process of nulling a meter, arithmetical calculations being taken care of in the digital circuitry.

One of the problems with systems limited by line-of-sight is the loss of signal which can occur when the beam is temporarily interrupted by passing ships or other objects. In order to overcome this problem the MRB201 has been designed with a dynamic memory which, in effect, stores the slant range velocity. Whenever the true signal is lost the readout reverts to the remembered phase and continues as before giving range data. A front panel indicator is available to inform the operator as to whether the instrument is operating off the true signal or not. Provided no violent manoeuvres are made during the period of lost signal the readings are still extremely accurate as can be seen from the actual field results tabulated in the next section.

The operating speed of the readout has been limited to 30 knots in order to ensure that the integrated "fine pattern" reading is not affected by problems of noise or short term loss of signal.

In common with most modern position-fixing systems the readout has been designed with a digital data output that can be coupled to a printer, magnetic tape or punch tape recorder, on-line computer, track plotter or any other digital recording device.

MRB201 FIELD RESULTS

Accuracy trials with a dynamic hydrographic system capable of 0.1 metre resolution is not an easy matter. An alternative method of checking the equipment, more accurate than the equipment itself, must be available. The time honoured method of using theodolite fixes is probably the only answer and under practical conditions on a rolling boat, even this is not very reliable. In view of this, it was decided initially to use surveyed points positioned close to the water's edge along the coastline of False Bay. These points had previously been surveyed to an accuracy nearly one order better than that of the MRB201. The Remote unit was set up on a known point at the end of a pier and the Master moved to each of these points in turn. Measurements wre taken from both Master to Remote and vice versa in order to obtain an additional check on accuracy. Ranges varied from about 3.8 km to 38.1 km and these results are tabulated below.

Line	Surveyed distance (metres)	MRB 201 reading from A (metres)	Error (metres)	MRB 201 reading to A (metres)	Error (metres)
A – B	3 820.75	3 820.4	– 0.35	3 820.4	– 0.35
A – C	7 798.55	7 799.2	+ 0.65	7 799.3	+ 0.75
A – D	12 876.22	12 875.6	– 0.62	12 876.0	– 0.22
A – E	18 253.85	18 255.1	+ 1.25	18 254.4	+ 0.55
A – F	22 338.21	22 338.5	+ 0.29	22 338.5	+ 0.29
A – G	34 715.46	34 714.6	– 0.86	34 714.7	– 0.76
A H	38 163.23	38 162.2	– 1.03	38 162.5	– 0.73
	Standard deviation		0.79		0.56

It can be seen from the above that the standard errors were 0.79 metre and 0.56 metre respectively.

It is usually possible with static measurements to improve on this accuracy by varying the carrier frequency for each measurement. This has the effect of averaging, and thus reducing, the errors caused by ground reflections (see Appendix D). Under dynamic conditions this technique is not possible and for this reason it was not used in the above measurements.

In order to establish the accuracy under true dynamic conditions a number of points were established along a relatively straight road at a distance of some 5 to 8 kilometres from a Remote station. The Master unit was mounted in a light vehicle and readings were taken at various speeds as the vehicle passed these points.

Position	Surveyed Distance (Metres)	Dynamic readings obtained at speed of :							
		15 mph	error	20 mph	error	30 mph	error	40 mph	error
1	5 163.5	5 163.8	+ 0.3	5 164.2	+ 0.7	5 165.4	+ 1.9	5 165.2	+ 1.7
2	5 986.9	5 986.8	– 0.1	5 986.8	– 0.1	5 988.4	+ 1.5	5 990.4	+ 3.5
3	6 201.4	6 201.7	+ 0.3	6 201.6	+ 0.2	6 202.3*	+ 0.9	6 202.9	+ 1.5
4	6 500.7	6 501.1	+ 0.4	6 497.8	– 2.9	6 502.5	+ 1.8	6 506.9	+ 6.2
5	7 000.8	7 002.2*	+ 1.4	7 002.0	+ 1.2	7 002.6	+ 1.8	7 004.3	+ 3.5
6	7 655.6	7 656.6	+ 1.0	7 657.4	+ 1.8	7 658.1	+ 2.5	7 659.1	+ 3.5
7	7 843.7	7 843.3	– 0.4	7 843.8	+ 0.1	7 845.3*	+ 1.6	7 845.8	+ 2.1

(*) These readings were taken while the true signal was blocked by passing traffic and the readout was therefore working from its dynamic memory.

It can be seen from the above that the errors tend to increase with speed. Trials with the high-speed airborne version of the MRB201 have not shown this tendency and as a result the readout was carefully checked under laboratory conditions for any evidence of speed sensitivity. No evidence of this could be found and it can only be assumed that these errors were caused by the operator's inability to freeze the reading at the exact instant that the points were passed.

The Omni-directional Antenna

As has been mentioned earlier the use of an omni-directional antenna can considerably ease the burden of the Master operator.

In built up areas, such as harbours, however, considerable errors of many metres can be experienced due to the problem of multiple reflections. In open areas where the Master unit is several hundred metres or more away from any large objects the accuracies are considerably better.

In order to establish this fact two Master units were installed in a small boat — one with an omni-directional antenna and the other with a standard directional antenna. Tests were carried out in False Bay at ranges varying from about 800 metres to 15 km — the results of which are tabulated below.

Directional Antenna Range (Metres)	Omni Antenna Range (Metres)	Diff. (Metres)	Diff. Less 1.1 metre separation (Metres)
820.9	823.3	+ 2.4	+ 1.3
1 184.3	1 186.0	+ 1.7	+ 0.6
1 349.7	1 352.6	+ 2.9	+ 1.8
2 265.2	2 266.8	+ 1.6	+ 0.5
2 974.1	2 975.3	+ 1.2	+ 0.1
3 715.5	3 718.0	+ 2.5	+ 1.4
4 755.6	4 756.8	+ 1.2	+ 0.1
5 614.5	5 613.3	− 1.2	− 2.3
6 130.9	6 130.9	0.0	− 1.1
7 284.8	7 286.3	+ 1.5	+ 0.4
8 442.7	8 441.8	− 0.9	− 2.0
9 051.9	9 053.7	+ 1.8	+ 0.7
9 352.6	9 354.6	+ 2.0	+ 0.9
10 022.5	10 024.0	+ 1.5	+ 0.4
11 311.0	11 312.1	+ 1.1	0.0
11 627.8	11 630.0	+ 2.2	+ 1.1
13 829.8	13 831.3	+ 1.5	+ 0.4
14 517.2	14 517.9	+ 0.7	− 0.4
14 814.8	14 815.5	+ 0.7	− 0.4
15 131.2	15 131.0	− 0.2	− 1.3
15 471.4	15 471.0	− 0.4	− 1.5

Average = + 1.1   Standard deviation = 1.09

The omni-directional was mounted about 1 metre behind the directional antenna. The average error of 1.1 metre was therefore subtracted before the standard deviation was calculated.

It can be seen that reasonably good results are still achievable under these conditions although the range is normally limited to little more than 15 km.

THE MRB301

Although the MRB201 is ideal for normal hydrographic operations it has the disadvantage that the speed of operation is limited to little more than 30 knots. This limitation has been built into the readout in order to give the fine pattern integration a high noise immunity. This technique is no longer possible with airborne, or any other high-speed operations, and a new form of readout has been designed for this purpose. This readout has been referred to as the analogue to digital convertor (ADC) due to the fact that it effectively converts analogue phase information into digital form. The MRB301 is identical to the MRB201 with the exception of this new readout.

In any high-speed operation it is essential to have virtually continuous and unambiguous information and for this reason all the modulation, or pattern frequencies, should ideally be continuously transmitted. In practice this is extremely costly and difficult to achieve and these frequencies are therefore sequentially transmitted within a total period of two seconds. The Fine, or A+ Pattern, is interspaced between each coarse measurement in order to obtain the maximum resolution and is therefore available every alternate 250 millisecond period. This sequential switching is controlled by a unit referred to as the Programmer Interface Unit (PIU) which plugs into the socket normally occupied by the manual dial readout.

The ADC module plugs into the front panel of the basic MRB301 measuring unit at the Master station. Its primary function is to convert the pattern phase information to binary code decimal form and this is accomplished using a crystal controlled clock and other circuits which take into account the various dynamic factors involved. In addition, this clock is used to provide sequential readings on each pattern which are integrated over a 200 millisecond period. There is a dead period between patterns of 50 milliseconds. The patterns are switched in the following sequence: A, A—, A, D, A, C, A, B, which gives a total measuring time of two seconds, after which the next sequence automatically begins. A facility known as the "A Pattern Override" is also incorporated which enables continuous " Pattern readings" to be obtained. A further function of the clock is to time the Pattern Selection programme via the Programmer Interface Unit.

The MRB301 system is designed to operate at high speeds and this, combined with the fact that all pattern information is not simultaneously available means that the coarse pattern information has to be adjusted according to the rate of change of range, or slant range velocity, before being compared with the fine (A) information. The ADC is designed to operate with an on-line computer which can be programmed to obtain the slant range velocity from the rate of change of the A pattern. A forward-looking facility can be built into the computer programme to enable ranges to be predicted before they actually occur. In this way, readings which vary by more than, say, 2 standard deviations from the predicted range can be rejected thereby improving the noise performance of the system. The ADC has no readout of its own but can be operated directly with an on-line printer or magnetic tape recorder. In this way the phase information can later be processed into full range readings.

Other facilities built into the ADC include a cycle counter to indicate the time at which each range reading was taken and an event marker triggered by an external output, such as a camera shutter which can record the time of occurrence of an event such as an aerial photograph with an accuracy of nearly 1 millisecond. Four external 6-digit data inputs are also included to enable external data such as meteorological information to be included in the serial or parallel outputs of the ADC.

All information provided by the ADC is available either in parallel or 2-digit serial form. Typically the parallel data would feed a printer unit providing on-the-spot information and the serial output would feed either an on-line computer, paper tape punch or magnetic tape recorder. In its simplest form the system can operate with only a printer. The data can then be processed by hand or base computer in order to obtain full range information.

One potential source of error with this system is introduced by the fact that A pattern information is only available every 250 or 500 milliseconds and not continuously, whereas the event marker can be timed to the nearest millisecond. In practice, however, it has been found that interpolation between successive A readings is very accurate as can be seen from the following field results.

MRB301 Trials

One of the major uses of the MRB301 system is its use with line-crossing techniques. It is often a requirement to measure the distance between two points which are not intervisible or which are too far distant from one another to be within the range capability of one instrument pair. By means of this technique the distance is measured simultaneously in two parts. Two Master instruments are installed in an aircraft, the two Remotes being situated at the points to be measured.

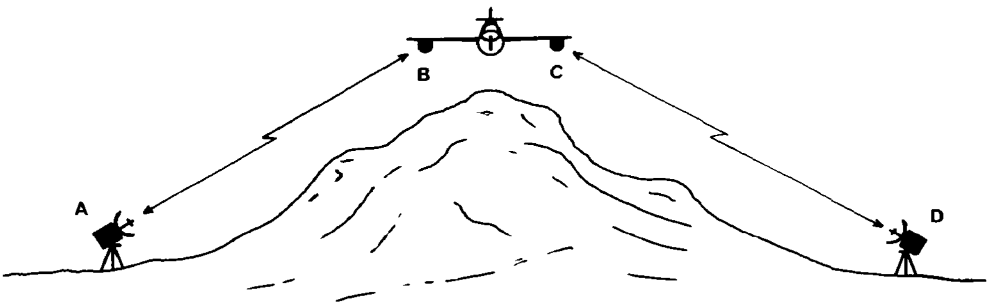


FIG. 2

The two individual ranges AB and CD are continuously measured and recorded while the aircraft flies a track which is approximately perpendicular to the line AD. When the sum of the two ranges is a minimum AB + CD is equated to the distance AD, after having taken account of meteorological corrections and aircraft altitude which can be determined from an accurate altimeter. This calculation can be performed by an on-line computer or by ground-based calculator using recorded results.

A number of trials have been carried out in Australia using this technique. The system consisted of a dual Master installation coupled to an on-line computer with printer and magnetic tape recorder. Automatic meteorological recording apparatus was used to obtain accurate on-line information.

A typical range sum plot obtained during these trials is given in figure 3. The following table is a summary of all the results obtained. It can be seen that several crossings were made in order to obtain an accurate value for each distance. All the points involved had been accurately surveyed over the past few years using a combination of astronomical observations, Tellurometer traverses, and triangulation. The MRB301 readings are compared with these results.

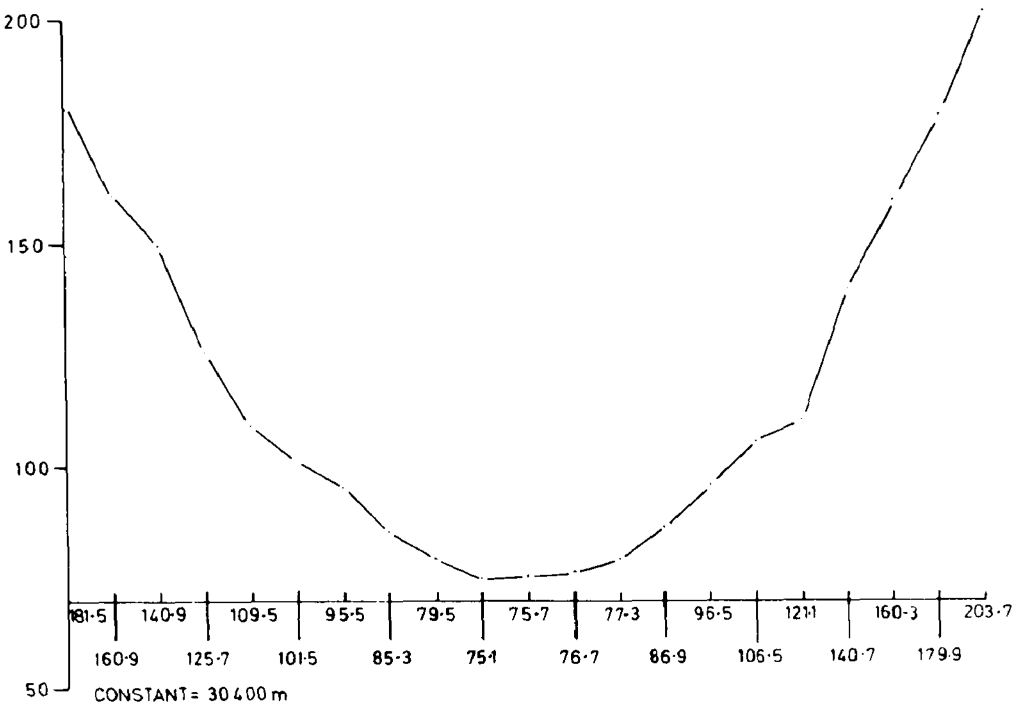


FIG. 3
Line 9 Stn 1, Kookaburra Stn 2, Loca Date 18.1.72

Figure 3 above refers to a single crossing performed on the Kookaburra/ Loca line. The vertical scale corresponds to slope distance added to the 30 400 m constant. The horizontal scale shows actual range readings taken at 2-second intervals during flight. The minimum slope distance from the graph is 30 475.1 m.

After the various corrections (least mean squares fit, refractive index, altitude and spheroidal reduction), the distance was calculated as 30 459.5 m. The surveyed distance was 30 458.3 m, representing a measurement error of + 1.2 m.

The results obtained from seven crossings on 1/12/71 are shown below.

Boomahnoomoona to Kookaburra Point, Bonegilla — surveyed distance 104 486.2 m

MRB 301 Measured Distance (m)	Error (m)
104485.8	– 0.4
487.8	+ 1.6
484.5	– 1.7
485.1	– 1.1
487.0	+ 0.8
483.7	– 2.5
488.6	+ 2.4

Mean of 7 crossings, 104 486.1 m

Error – 0.1 m

The following 5 sets of results were obtained on the same line, the first set being detailed above. Spreads refer to the peak/peak errors in the distance measured over the several crossings performed in any one series.

Date	No. of Crossings	Mean of Crossings (m)	Mean error (m)	Spread (m)
1/12/71	7	104486.1	– 0.1	4.9
2/12/71	3	104487.0	+ 0.8	2.2
3/12/71	7	104486.0	– 0.2	1.9
4/12/71	7	104486.8	+ 0.6	3.6
6/12/71	4	104487.5	+ 1.3	1.4

Final mean of 28 crossings 104486.5 m

Final error over 28 crossings + 0.3 m

The following three lines were also measured, the results being tabulated in the same form:

Loka to Kookaburra Point

Surveyed distance 30 458.3 m

Date	No. of Crossings	Mean of Crossings (m)	Mean error (m)	Spread (m)
11/12/71	10	30458.9	+ 0.6	4.6

Mt. Benambra to Kookaburra Point

Surveyed distance 63 675.5 m

Date	No. of Crossings	Mean of Crossings (m)	Mean error (m)	Spread (m)
13/12/71	8	63677.5	+ 2.0	9.0

Note: This range is over a lake, the Hume Weir, with subsequent high ground swing.

Loka to Benambra – surveyed distance 84 478. 1 m

Date	No. of Crossings	Mean of Crossings (m)	Mean error (m)	Spread (m)
13/12/71	12	84 478.6	+ 0.5	3.8

A distance of 203 km was also measured from Bendigo to Kookaburra Point with an error of 80 cm over 6 crossings.

APPENDIX A

Field strength at the earth's surface from a short ground-based vertical dipole radiating 1 kW over sea water with relative permittivity kr = 80 and conductivity σ = 5 mho/m.

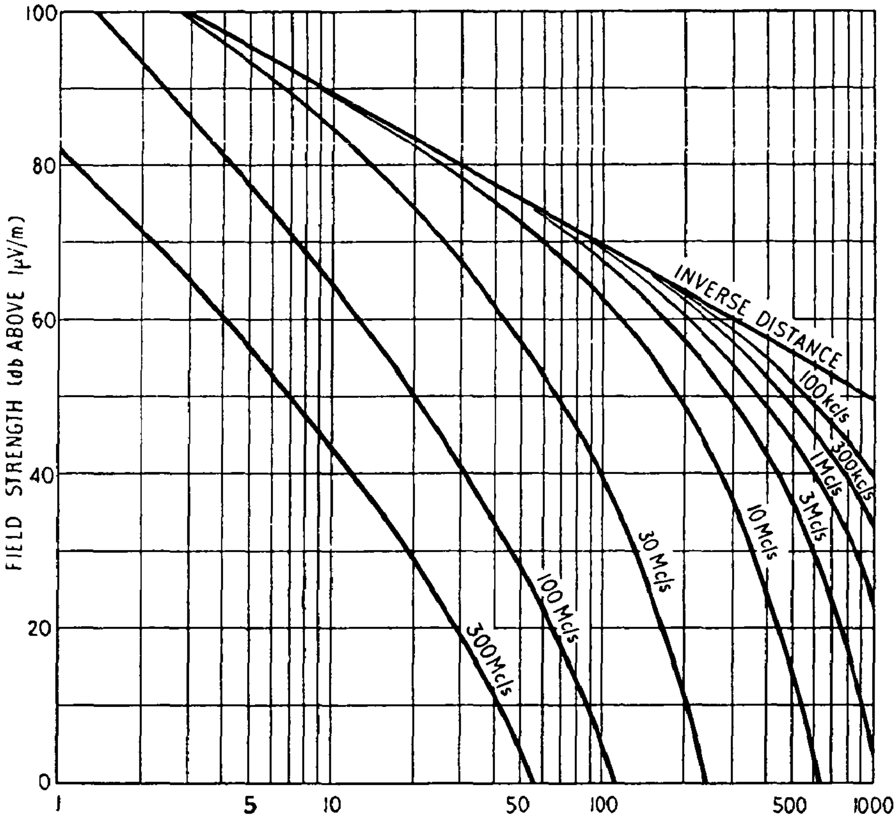


Fig. 4.
Field strength (db above 1 μV/m)

APPENDIX B

If an antenna is transmitting power P_T with a maximum directed gain G_T, the power flux density S at a distance d from the antenna, in the direction of maximum gain, is given by:

$$S = G_T P_T / 4\pi d^2 \qquad (1)$$

If the receiving antenna has an effective receiving cross-section A_R, the power received is:

$$P_R = A_R S \qquad (2)$$

Combining equations (1) and (2)

$$P_R = \frac{P_T G_T A_R}{4\pi d^2} \qquad (3)$$

If the gain of the receiving antenna, in the direction of the transmitter, is G_R and if λ is the wavelength of the transmitted signal:

$$A_R = G_R \lambda^2 / 4\pi \qquad (4)$$

Hence

$$P_R = \frac{P_T G_T G_R \lambda^2}{16\pi^2 d^2} \qquad (5)$$

If P_{Rm} is the minimum detectable signal for the receiver, the maximum operating range is:

$$d_M = \left(\frac{P_T}{P_{Rm}}\right)^{1/2} \frac{\lambda}{4\pi} (G_T G_R)^{1/2} \qquad (6)$$

If each unit has as its antenna a half-wave dipole backed by a paraboloidal reflector with a circular aperture of diameter D, the gain of each antenna is given by:

$$G_T = G_R = \frac{0.6\pi^2 D^2}{\lambda^2} \qquad (7)$$

where the factor 0.6 is representative for paraboloidal reflectors and feeds of the type generally used.

Substituting equation (7) in equation (6):

$$d_M = \frac{D^2}{2\lambda} \sqrt{\frac{P_T}{P_{Rm}}} \qquad (8)$$

Finally, since $D = 1.4\lambda/\theta$, where θ is the beam width between 3dB points and the factor 1.4 is typical of values for the size of reflector and type of feed generally used:

$$d_M = \frac{\lambda}{\theta^2} \sqrt{\frac{P_T}{P_{Rm}}} \qquad (9)$$

where d_M and λ are in metres, θ is in radians and P_T and P_{Rm} are in watts.

APPENDIX C

Basic measuring principle

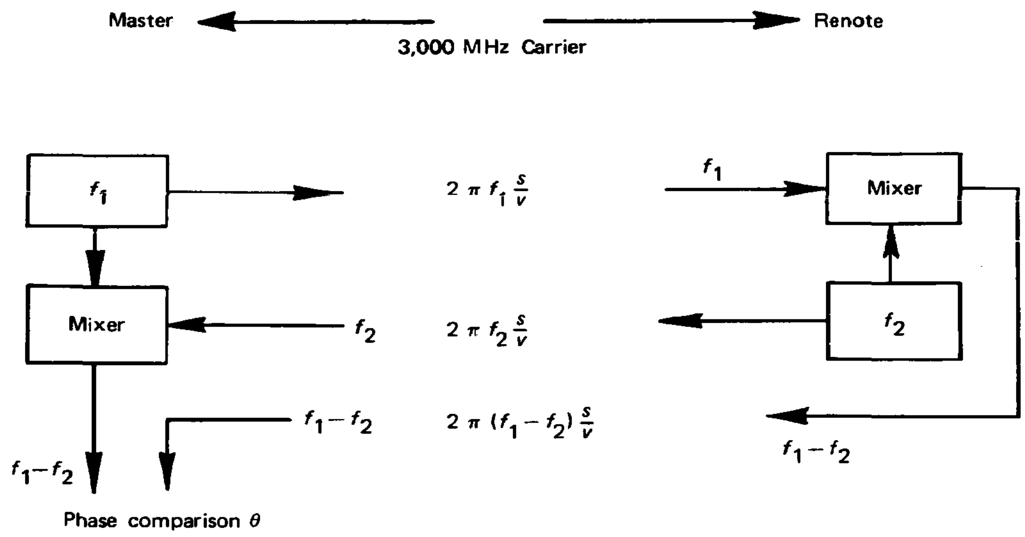


FIG. 5.

The above diagram explains the basic measuring principle where a modulation frequency f_1 is transmitted on a 3 000 MHz carrier from the master and f_2 from the remote. The master and remote are separated by a distance s. If the instantaneous phases of f_1 and f_2 are given by ϕ_1 and ϕ_2 respectively, then it can be seen that the final phase comparison θ will be given by:

$$\theta = \left[\phi_1 + 2\pi f_1 \frac{s}{v} - \phi_2 + 2\pi (f_1 - f_2) \frac{s}{v}\right] - \left[\phi_1 - \left(\phi_2 + 2\pi f_2 \frac{s}{v}\right)\right]$$

$$= \phi_1 + 2\pi f_1 \frac{s}{v} - \phi_2 + 2\pi f_1 \frac{s}{v} - 2\pi f_2 \frac{s}{v} - \phi_1 + \phi_2 + 2\pi f_2 \frac{s}{v}$$

$$= 2\pi f_1 \frac{2s}{v}$$

It can be seen that f_2 is eliminated from the equation and the system behaves in an identical manner to one where the double path phase delay is measured for f_1 transmitted from the master via the remote and back to the master. In practice this system of utilizing only one frequency would be complex due to the necessity of separating the outgoing and returned signals. The above system is a simpler approach which achieves the same nett result.

In addition the phase is measured at a low frequency of $f_1 - f_2$ (1 kHz) which enables greater instrumental accuracy to be obtained.

APPENDIX D

Phase angle errors caused by reflected rays

If Δd is the path difference between the direct and indirect (reflected) rays,

a_i is the ground reflection coefficient, i.e. the amplitude of a reflected ray relative to the direct ray,

λ_c is the carrier wavelength, and

λ_m is the modulation wavelength,

the angle error is given by:

$$\beta = \Sigma\, a_i \cos \frac{2\pi\,\Delta d}{\lambda_c} \sin \frac{2\pi\,\Delta d}{\lambda_m} \tag{1}$$

where the summation is over all the i reflected paths.

Since distance error is equal to

$$\frac{\lambda_m}{2\pi}$$

times the angle error, equation (1) can be written, considering any one reflected ray

$$\text{Distance error} = \frac{\lambda_m}{2\pi} a_i \cos 2\pi \frac{\Delta d}{\lambda_c} \sin 2\pi \frac{\Delta d}{\lambda_m} \tag{2}$$

The maximum possible value of the distance error (in either direction) is

$$\frac{\lambda_m}{2\pi}\, a_i.$$

This means that the maximum distance error is proportional to the modulation wavelength λ_m.

It is instructive to consider the effect of movement on errors due to ground reflection. From equation (2) above it will be seen, considering any one reflected ray that, if the path difference Δd changes steadily, the error will vary cyclically at two different rates. As Δd changes by an amount equal to the carrier wavelength λ_c, the error will be taken through one cycle; this will be the more rapid variation. The peak values of the error cycles will be determined by the value of

$$\sin \frac{2\pi\,\Delta d}{\lambda_m}$$

and will vary cyclically at a lower rate, since $\lambda_m > \lambda_c$.

For a line of length d and a centre clearance h the excess path length can be approximated by $2h^2/d$. Operationally it has been stated that for a line of some 30 km length, a centre clearance of 100 metres or less can give little error. In this case the excess length is approximately 2/3 metre and with a surface reflection of even 70% or $a_i = 0.7$, the peak error, putting

$$\cos \frac{2\pi \Delta d}{\lambda_c}$$

equal to unity becomes:

$$\text{error angle} = 0.7 \sin 2\pi \frac{0.67}{200}$$

which is about 1/4 metre in the indicated range.

APPENDIX E

Phase cancellation effects caused by direct and reflected ray interference

The direct ray and that reflected from the surface of the sea can combine to give both phase errors and amplitude fluctuations. These effects are dependent on the relative heights of both the master and remote antennae. The following set of graphs indicates the relative ranges (shaded areas) at which these effects occur. The relative signal strength is plotted vertically and the range is shown on the horizontal axis.

Within the shaded areas large variations in signal strength and phase errors of a few metres can be experienced. It is desirable for the remote antenna to be sited as low as possible, except where large ranges are required.

Phase cancellation effects caused by direct and reflected ray interference

Master height = 5 m

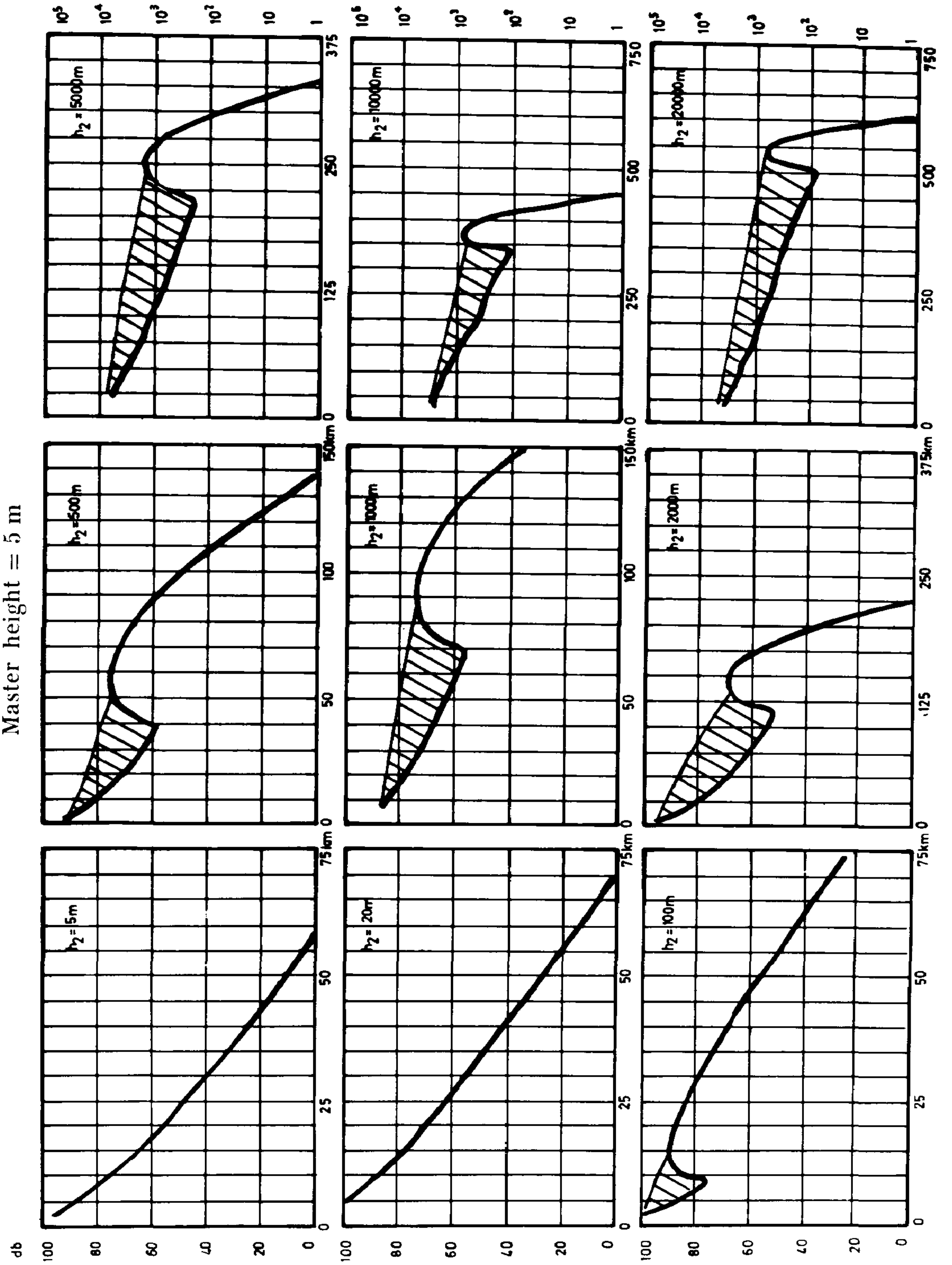
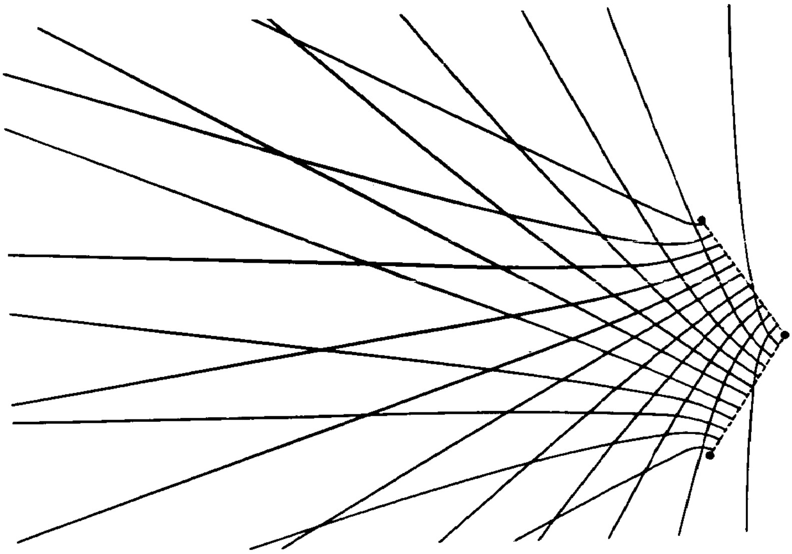
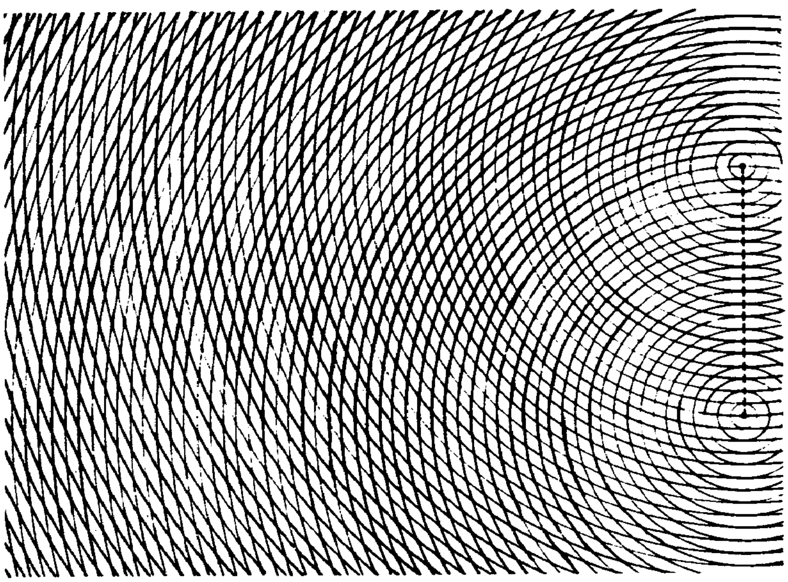


FIG. 6.

APPENDIX F



Hyperbolic system geometry.



Range-range system geometry.

Fig. 7.

APPENDIX G

Range/attenuation chart for model MRB201

The range of both the MRB201 and the MRB301 system is dependent on the type of antenna used and the cable losses involved.

The range/attenuation chart shown overleaf indicates the achievable ranges under a variety of combinations.

This is based on:

(a) Lowest received power level of — 86 db/m.
(b) Power input to antenna of 200 mW = + 23 db/m.
(c) Strictly radio line-of-sight conditions.

To find the range capabilities of a given arrangement:

(a) Determine the gain of the antennae to be used (see list below) and add them.
(b) If cables are used to connect either the "Master" and/or the "Remote" to their antenna, the loss of each cable must be determined (see list below), and their sum subtracted from the figure obtained in (a). This is the Total Effective Antenna Gain.
(c) Using the chart, read off the range corresponding to this gain figure.

Antenna gain for:

(a) Rectangular reflector (or rotating antenna) .... 14 db
(b) Round 17″ diameter reflector .... 18 db
(c) Round 24″ diameter reflector with matching dipole ...... 22 db
(d) Omni-directional antenna ("doorknob") .... 3 to 4 db

Cable loss for (assuming RG5/BU cable):

(a) 11′6″ extension .... 2 db
(b) 23′0″ extension .... 4 db
(c) 35′6″ extension .... 6½ db
(d) Odd lengths calculated at 0.178 db/ft (0.585 db/metre).
(e) Type RG318/U (Andrew type HJ5-50) 0.024 db/ft (0.079 db/metre) ⅞″ "Heliax" cable should be used for the omni-directional antenna.

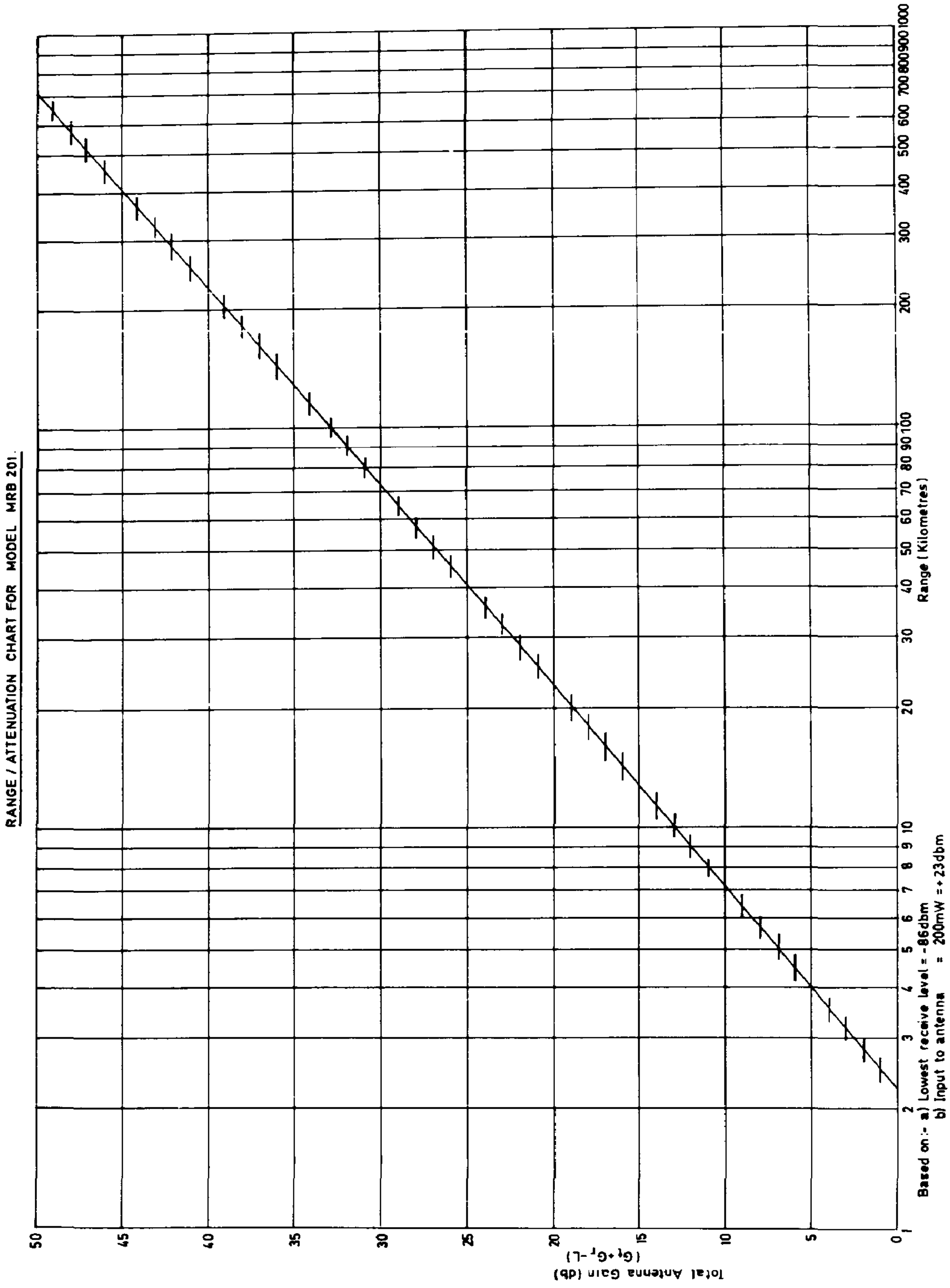

RANGE / ATTENUATION CHART FOR MODEL MRB 201.
Range (Kilometres)
1 2 3 4 5 6 7 8 9 10 20 30 40 50 60 70 80 90 100 200 300 400 500 600 700 800 900 1000
Total Antenna Gain (db)
(Gt+Gr-L)
0 5 10 15 20 25 30 35 40 45 50
Based on :- a) Lowest receive level = -86dbm
b) Input to antenna = 200mW = +23dbm

FIG. 8.

APPENDIX H

MRB201 specification

Range

1 to 50 kilometres assuming adequate line-of-sight conditions.

Accuracy

Under dynamic conditions better than: ± 1 metre
Under static conditions better than: ± 0.5 metre ± 3 p.p.m.

Resolution

0.1 metre

Beamwidth

Omni-directional antenna	Rotating antenna	Normal Antenna on instrument
Horizontal 360° Vertical 30°	Horizontal 27° Vertical 22°	Horizontal 24° Vertical 20°

Number of operators required

Two to three depending on installation and system.
Remote units can be left unattended after initial set up.

Display

DRI with a six-digit display (Nixie type tubes) giving integrated fine readings and provision for spot checks on coarse patterns.
or:
DRO with vernier dial allowing each pattern to be read three figures.

Measuring pattern frequencies

"Master" function	"Remote" function
A 1 498 470 Hz	A − 1 499 470 Hz
B 1 496 972 Hz	A + 1 497 470 Hz
C 1 483 485 Hz	B 1 495 972 Hz
D 1 348 623 Hz	C 1 482 485 Hz
	D 1 347 623 Hz

Note: These frequencies are calculated to give direct readout in metres assuming an average refractive index of 1.000330.

Antenna

Standard: Rectangular paraboloidal reflector with dipole.
Optional: Omni-directional type. Rotating twin aerial assembly with standard reflector and dipole.

Carrier frequency

2800 - 3200 MHz.

Note: An alternative frequency range of 3200 to 3600 MHz is available.

Carrier output power

Not less than 200 mW.

Current consumption

Basic Unit + DRI: 3½ Amps Nominal
Basic Unit + DRO: 2½ Amps Nominal } (operating voltage 10.5 - 14 V DC)

Weight

Basic Unit: 30 lb 9 oz (13.68 kg).
Basic Unit with standard antenna and DRI: 34 lb 9 oz (15.68 kg).
Basic Unit with standard antenna and DRO: 32 lb 12 oz (14.7 kg).

Dimensions of Basic Unit closed for transport

12″ width × 12¾″ height × 11¼″ depth (30 cm × 32.5 cm × 28.5 cm).

Unit function

Each basic unit has dual "Master/Remote" function. Units used as "Remotes" do not require the DRI since the DRO is normally used for baseline measurements.

Method of pattern selection

Master function: Front panel switch, or by remote control using a suitable interface unit.
Remote function: Pattern gates opened by tones in the range 39 kHz to 70 kHz radiated by the "Master" unit.

Speed of dynamic operation

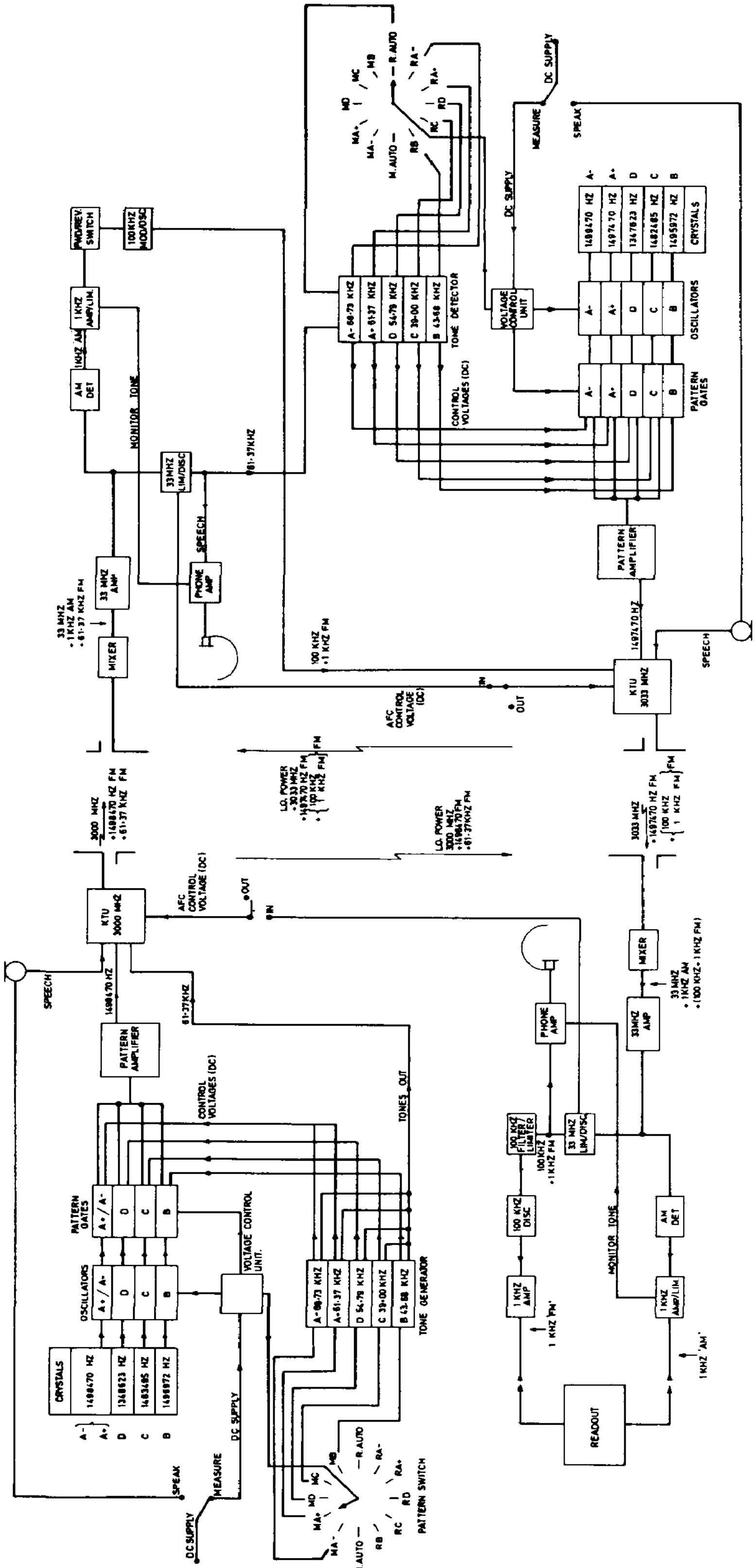
Up to 30 knots (approximately 15.5 metres/second) within rated accuracy.

Note: For readings within rated accuracy at full speed to be taken, automatic recording equipment (e.g., printout) is necessary. At maximum speed, accuracy will be impaired during rapid changes of direction.

Environmental conditions

Basic instruments operate within a temperature range of — 40° to + 50°C. If a rotating antenna or a DRI is used the lower limit is — 10°C.

APPENDIX J



MRB 201
BLOCK DIAGRAM

FIG. 9.

APPENDIX K

BLOCK DIAGRAM OF TYPICAL 2 CHANNEL MRB 301 SYSTEM.

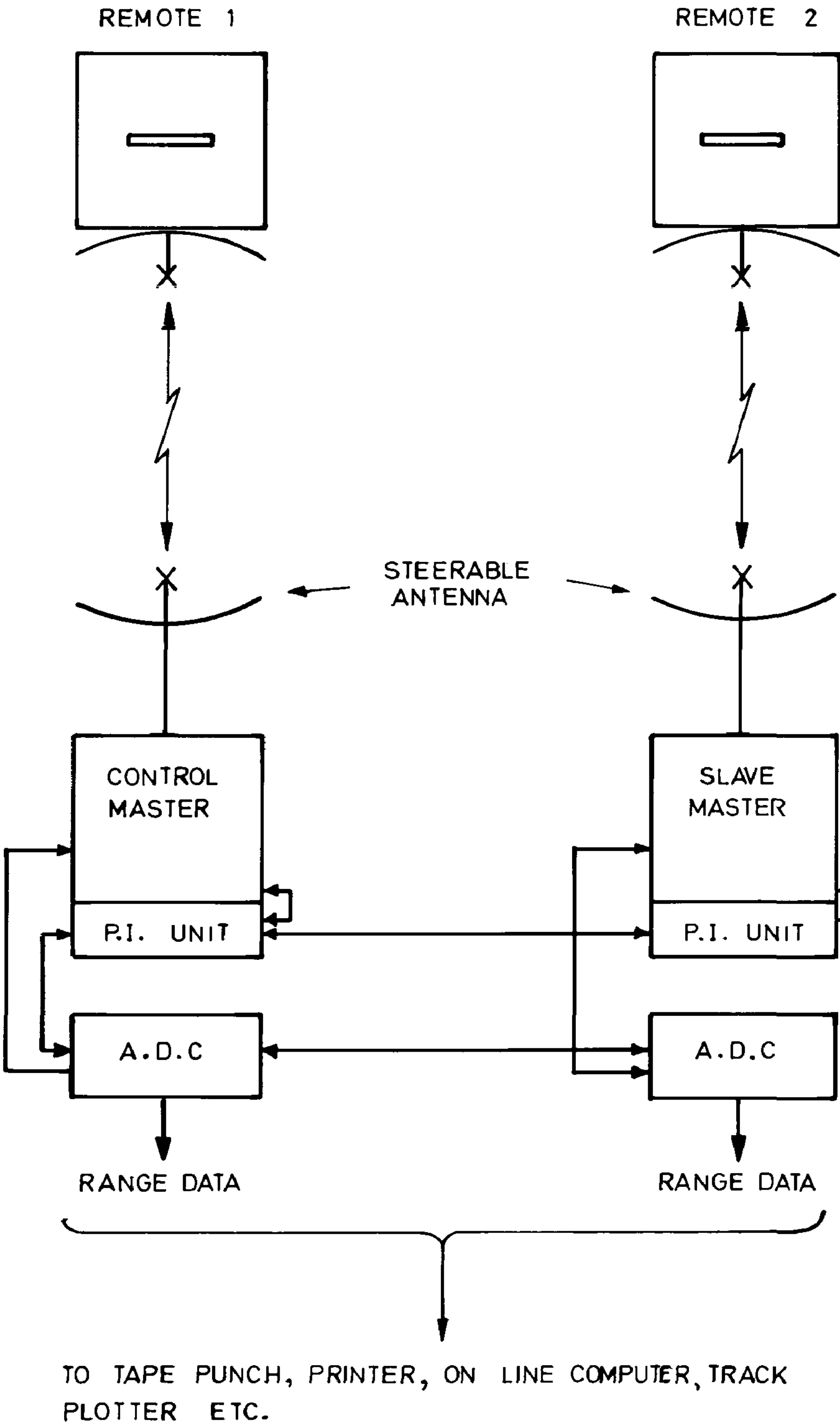


FIG. 10.