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RECENT DEVELOPMENTS IN HIGH-ACCURACY MICROWAVE POSITIONING SYSTEMS

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SYNOPSIS

Most significant sources of position error are analysed. Techniques to reduce these errors are proposed and practical results compared with the theoretical analysis to demonstrate the improvement in accuracy over existing methods.

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Most microwave positioning systems are in one of two categories : frequency modulated continuous wave systems and pulse systems.

CW systems have mostly very narrow beam widths requiring careful physical alignment of the equipment and are intended for accurate surveying on land. Because they are CW systems, it is normally impossible to discriminate between wanted and reflected signals when there is multipath reception, and it is usual to make a number of range measurements at different frequencies and average out the unwanted signals. Achievable accuracy is high, better than 5 cm, but the systems are generally not suited to mobile applications, although some systems have been automated to make a degree of mobile use possible. The pulse systems are specifically designed for mobile use so that a number of mobile users can range to the same set of fixed transponders and track their positions frequently and regularly. Typically, 90° × 6° sector antennas are used on the fixed transponders and 360° × 30° omni antennas on the mobiles, which are normally ships and liable to roll. Multipath interference is only a problem if the unwanted signals are as strong, or stronger, than the wanted signals when special techniques are required

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to prevent loss of signal. Achievable accuracy is not so high as the CW systems and has typically been of the order of metres, rather than centimetres.

Obviously any attempt to design a pulse system of significantly higher accuracy must start with an analysis of all possible sources of error, and of how they combine to degrade the ultimate accuracy of the system. When compiling this list of error sources it quickly becomes apparent that the analysis is complex, not only because the number of error sources is significant, but also because some of them are interrelated. This appreciation of the complexity of the task was reinforced by the discovery of additional error sources during the development of the equipment, and by the realization that some systems use empirically derived numerical processing. While such processing may produce more attractive results, there is always a risk that they may actually increase errors and, under certain circumstances, go badly wrong. We therefore determined to provide the user with the choice between absolutely raw data and data processed in such a way that the results are totally predictable and understandable.

Let us now list the most significant of the error sources by following the process step by step. Refer to Figure 1.

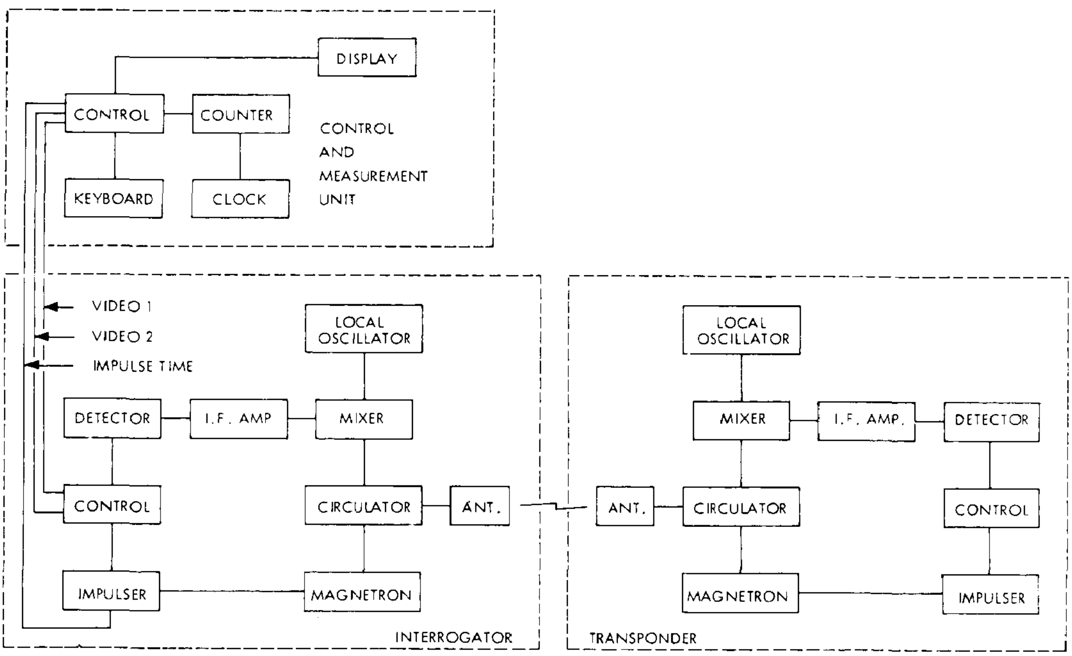


FIG. 1. — Simplified block diagram of typical magnetron system.

1. The control and measurement unit (CMU) control sends a pulse down the video 1 wire to the interrogator control which commands the impulser to fire the magnetron.
2. Simultaneously the impulser sends a pulse up the impulse time wire to the CMU control which starts the counter. This is done to cancel out the delay in the video cable.

3. There will be a delay between the impulser firing the magnetron and the pulse leaving the antenna, but this will be small due to the wide bandwidth of the circuitry and variations will be negligible.
4. The pulse reaches the transponder antenna. The time of flight depends on the velocity of propagation (Vp) which will vary with temperature, humidity and pressure.
5. The pulse is amplified and detected. There will be a time delay which will vary with level, temperature, time and from unit to unit. There will also be a random component due to the finite signal to noise ratio (S/N).
6. On detection of the pulse the magnetron is fired. There is a delay before the pulse leaves the antenna which is small and of negligible variance.
7. The pulse reaches the interrogator antenna, time of flight again dependent on Vp.
8. The pulse is amplified and detected. Further time delay varying with level, temperature, time, and from unit to unit and S/N.
9. On detection of the pulse the control sends a pulse up the video 2 wire to the CMU control which stops the counter. The measured time is then processed and the range displayed. The calculation assumes that the clock frequency is accurate. Any error in clock frequency will cause an error in displayed range. In addition the counter can only measure time to the nearest whole number of clock cycles. The displayed range is therefore quantized.

The errors are therefore in four categories — long term, short term, quantization and propagation. The long term errors are the clock frequency error and the time delays in the interrogator and transponder which vary from unit to unit and with temperature, level and time. Traditionally, these errors are minimized by regular calibration of the interrogator against each one of its transponders on a known range, and this technique is successful providing the calibration is carried out regularly and when there is a significant change in ambient temperature. Because of the variation of range with temperature, it is also necessary to allow the equipment half an hour to warm up before commencing an operation. Variation with level (and hence with range) is best minimized by AGC (Automatic Gain Control), but this has proved difficult to realize for the interrogator, because it has to deal with a number of transponders in sequence which could be at very different ranges. There is an obvious conflict between the requirement for a long time constant (which works well at the transponders) to minimize the effect of spurious signals and reflections and for a short time constant (which is now necessary at the transponders) to allow switching between the transponders. The short term errors are random errors mainly caused by noise in the receivers — there can also be a random error in the transmit process but this is usually insignificant. Conceptually, these random errors are of less significance than the long term errors. They can be practically eliminated from a fixed range measurement by averaging, and reduced (in mobile ranging) by appropriate filtering. However, to the random error must be added the quantization errors. Quantization depends on clock frequencies which are in the range 60 MHz to 150 MHz resulting in resolutions from 2.5 to 1.0 metres. To improve the resolution a number of ranges are measured and averaged, but this process only works if a random variation is superimposed. In practice this is just what happens because, even ignoring the noise, the start time of the counter can be at any point of the clock cycle. The analysis is straightforward :

Consider a range $(n + f)r$
where r is the single shot resolution
n is an integer
and $0 < f < 1$.

Then the probability of measuring the range as nr is $1 - f$ and as $(n + 1)r$ is f.

Therefore, expected mean range is :

$$(1 - f)nr + f(n + 1)r = (n + f)r$$

and variance :

$$(1 - f)n^2r^2 + f(n + 1)^2r^2 - (n + f)^2r^2 = f(1 - f)r^2.$$

Hence maximum variance $= r^2/4$ and mean variance $= r^2/6$.

Now $r = 150/f$ metres, f is the clock frequency in MHz.

Therefore, by the central limit theorem, taking p measurements,

$$\text{resolution} = \frac{150}{fp} \text{ metres} \qquad (1)$$

$$\text{standard deviation } \sigma = \frac{61.2}{f\sqrt{p}} \text{ metres} \qquad (2)$$

Figure 2 shows some actual examples.

Clock frequency (MHz)	No. of samples	Resolution (metres)	σ (metres)
60	32	0.08	0.18
150	5	0.2	0.18
150	10	0.1	0.13
150	20	0.05	0.09
100	50	0.03	0.09
100	100	0.015	0.06
100	160	0.009	0.05
100	220	0.007	0.04

FIG. 2. — Theoretical resolution and standard deviation due to averaging of quantized ranges in practical systems.

Propagation errors are normally assumed to be negligible. The Essen formula :

$$N = \frac{77.62P}{T} - \left(\frac{12.92}{T} - \frac{37.19 \times 10^4}{T^2}\right) e \qquad (3)$$

N = (retractive index − 1) × 10^6
T = Temperature °K
P = atmospheric pressure mbar
e = water vapour partial pressure mbar
("Electronic Surveying and Navigation", by Simo H. LAURILA, John Wiley & Sons, 1976)

predicts a 1 in 10^6 change in Vp for a change of :

0.8°C in temperature,
37 mbar in atmospheric pressure
0.23 mbar in water vapour partial pressure.

Vp is therefore not seen to be negligible. Obviously the calibration process will allow for Vp variation as well as equipment variation, but only until the weather changes. However, in practice any errors caused by Vp variation are swamped by equipment variations.

We conclude, therefore, that this type of system can only achieve accuracies of the order of 1 metre by careful calibration carried out regularly and when there is a significant change in atmospheric conditions. Without calibration, accuracy would be of the order of 10 metres, assuming that the units were originally set up according to specification. Additional random errors of the order of 1 metre are quite usual.

The system I shall now describe was designed primarily for accuracy, but ease of operation, rapid deployment and reliability were also important considerations. Refer to Figure 3.

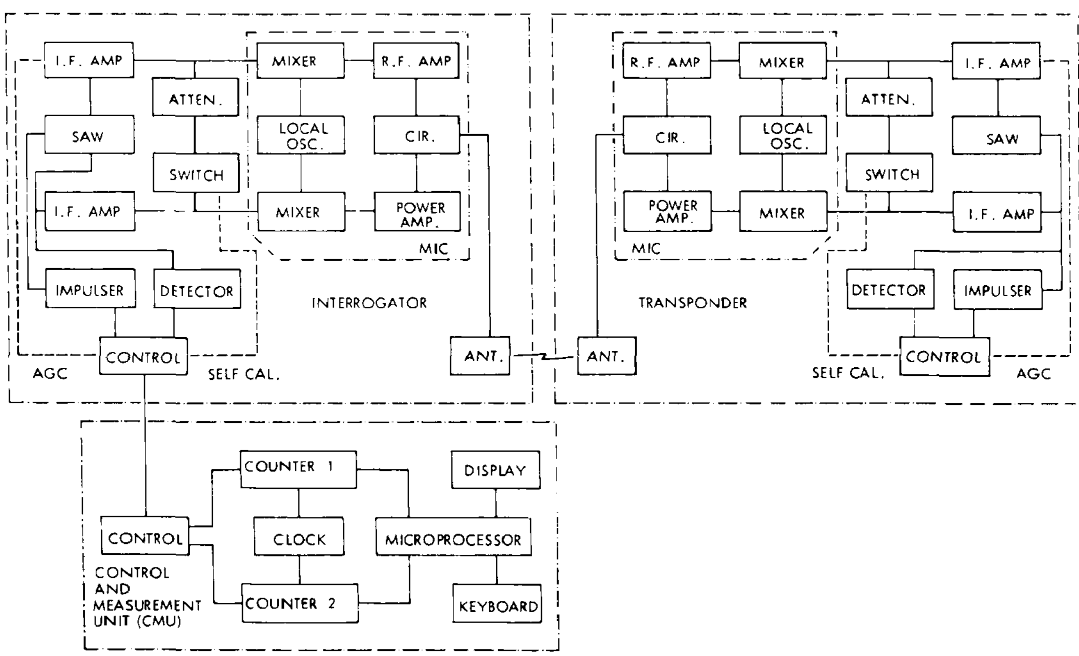


FIG. 3. — Simplified block diagram of new system.

The most obvious feature of the new system is the solid state transmitter which replaces the more usual magnetron. Peak output power is 0.5 watt compared with hundreds of watts from a magnetron. However, system gain is maintained at a sufficiently high level to produce 80 km range by pulse compression (chirp modulation). The improvement in signal (power) to noise ratio of a chirp filter is :

$$D = \Delta t \, \Delta f \qquad (4)$$

where Δf is the frequency sweep
and Δt is the time occupied by the sweep
(Spread Spectrum Techniques, by R.C. DIXON, John Wiley & Sons, 1976).

The filter is a specially designed SAW (Surface Acoustic Wave) consisting of a pair of matched filters on a single substrate and has a theoretical gain of 20 dB. In practice the gain is reduced to 19 dB by mismatch loss introduced to suppress the sidelobes. Overall system gain is 127 dB. The equipment therefore has the reliability of an all solid state system, lower power consumption (< 10 watts for the transponder) and also greatly reduced spectrum pollution. Peak spectral density is 0.05 μwatt/Hz compared with a typical figure of 100 μwatts/Hz for a magnetron system. Not so obvious are the ways in which the error sources described in the first part of this paper are tackled and the accuracy improved. Taking the long term errors first, the most significant of these are the effects of the time delays in the equipment. These have been almost entirely eliminated by the use of automatic calibration. Again this system is best understood by following the process step by step.

1. The CMU control sends a pulse to the interrogator control which commands the impulser to impulse the SAW. The SAW produces an IF (Intermediate Frequency) chirp which is amplified, converted to RF (Receiver Frequency) in the MIC (Microwave Integrated Circuit), amplified and transmitted. During this process the self calibration switch is on, allowing the chirp at IF to pass through the attenuator to the receiver IF where it is amplified, compressed in the SAW and detected. Only on detection of this pulse is counter 1 started. This means that when the return pulse is received, detected and the counter stopped, the time delays in the control cable, impulser, SAW, IF amplifiers and detector are cancelled out. The only delays not cancelled out are in the attenuator, MIC and antenna. Since these circuits are all wide bandwidth the delays are very small, and variations in the delays negligible.
2. The chirp reaches the transponder antenna. Vp variation as before.
3. The chirp is amplified, converted to IF, amplified, compressed in the SAW and detected. On detection of the pulse the control commands the impulser to impulse the SAW and a chirp is transmitted. This chirp is also passed through the attenuator by the self calibration switch to the receiver IF, amplified, compressed and detected, and a second chirp is produced and transmitted. The self calibration switch is set to off to prevent any more chirps from being transmitted, so the transponder replies with two chirps for every chirp sent by the interrogator. The time between these two chirps is equal to the turn around delay in the transponder, excluding the delays in the MIC and antenna but including the delay in the attenuator. As in the interrogator, the MIC, antenna and attenuator delays are small and variation in them negligible, but both chirps have random components due to finite S/N.
4. The two chirps then reach the interrogator antenna. Vp variation as before.
5. They are then amplified, converted to IF, amplified, compressed in the SAW and detected. As each pulse is detected, the interrogator control sends a pulse to the CMU control. The first pulse stops counter 1 and starts counter 2. The second pulse stops counter 2. Referring to Figure 4 :

   Counter 1 starts at $T_1 = 2a + b + j + k$.

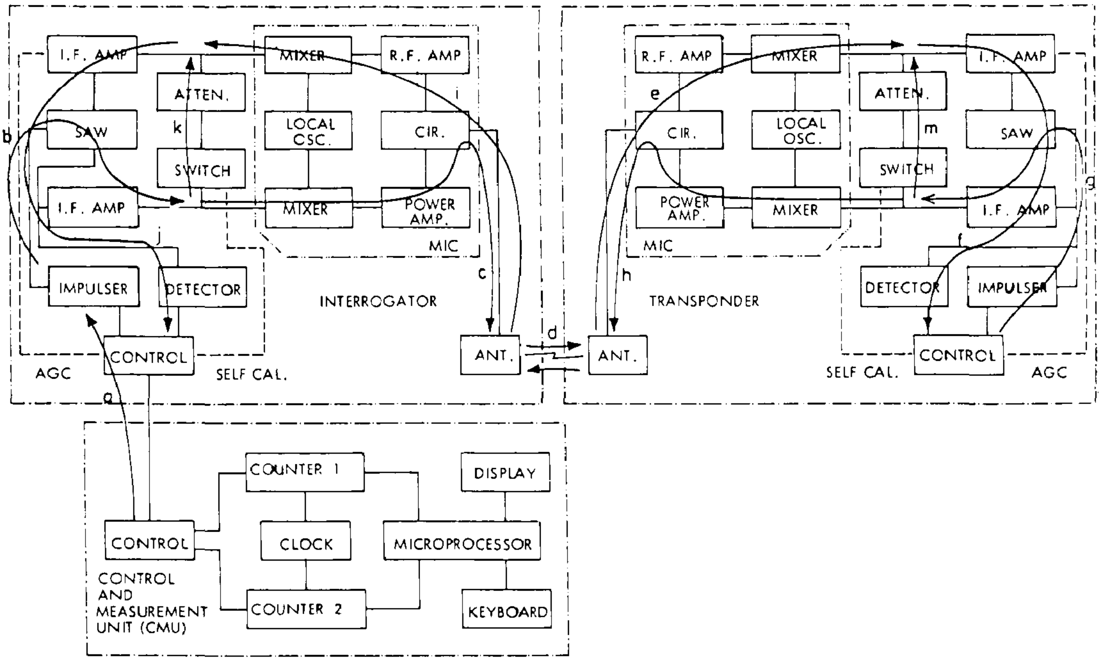


FIG. 4. — Signal paths.

Counter 1 stops and Counter 2 starts at :

$$T_2 = 2a + b + c + 2d + e + f + g + h + i + j$$

Counter 2 stops at $T_3 = 2a + b + c + 2d + e + 2f + 2g + h + i + j + m$.

Therefore, Counter 1 reading − Counter 2 reading

$$= 2T_2 - T_1 - T_3$$

$$= c + 2d + e + h + i - k - m$$

which is twice the time of flight only modified by RF and attenuator delays of negligible variation.

The importance of this is obvious. The system is effectively self calibrating. It is not necessary to carry out time consuming calibration exercises to take out variations from unit to unit, or with time, and variations with temperature are also cancelled out. So there are major benefits to both accuracy and operational efficiency. There is, for example, no warm-up period — accurate ranges are available from switch-on. This removal of the warm-up period would have been of great practical value with the existing systems, since our experience is that one of the most common mistakes is calibrating the equipment before it has reached equilibrium. Subsequent surveys are then carried out with miscalibrated equipment. However, having removed the warm-up period we have also removed the need for calibration.

However, there are other error sources to consider. Level is also important. Figure 5 shows the form of the demodulated pulse. Timing is defined by the 6 dB point on the leading edge. At this point the gradient is about 1.2 % per nsec, so a 0.5 dB variation in peak amplitude causes a 5 nsec error in timing. It is therefore necessary to hold the peak pulse level to within 0.5 dB on both interrogator and transponder. This is done by digitizing the peak level, calculating the AGC voltage

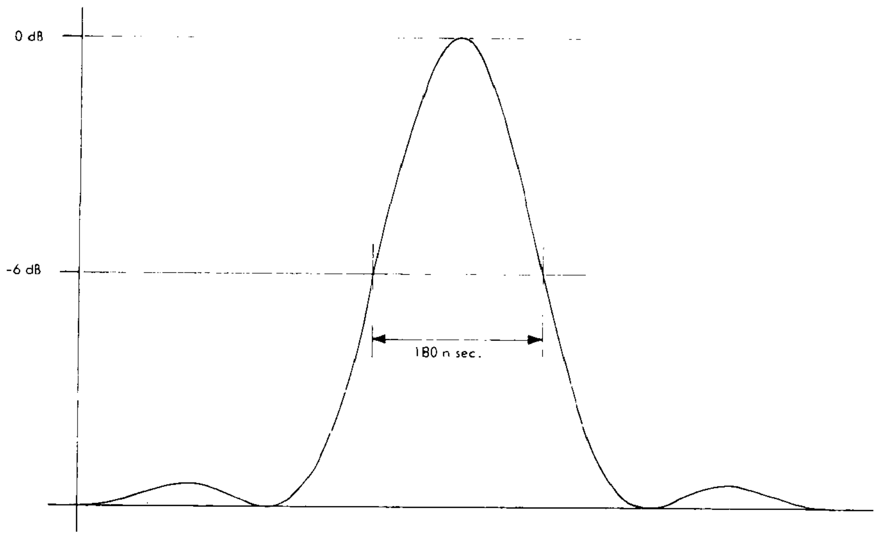


FIG. 5. — Demodulated pulse.

and applying it through a D to A converter. The interrogator then stores the AGC voltages for all transponders so that each time it interrogates a transponder it has a good estimate of the return signal strength. This application of AGC to both transponder and interrogator removes the variation of range with level and obviates the need for the production and use of calibration curves. Again we have improvement in both accuracy and simplicity of operation.

The relationship between peak amplitude and timing also determines the short term random variation of measured ranges.

For a signal to noise ratio of sdB the standard deviation of the time measurement is

$$\sigma = 83/10^{0.05s} \text{ nsec.} \quad (5)$$

Figure 6 shows the expected standard deviation at different ranges. The AGC operation prevents the S/N from increasing above around 30 dB, so no variation in σ is expected below 20 km. The single pulse σ is calculated from equation 5. There is one interrogator pulse which is answered by two transponder pulses, hence column 4, and the quantization is derived from equation 2. Respectable standard deviations are therefore predicted even at 80 km.

Range (kms)	Signal/Noise (dB)	σ (nsec) Single pulse	σ (metres) 3 pulses	Quantization (metres)	σ (metres) total	σ (metres) 100 pulse average
≤20	30	2.6	0.68	0.61	0.9	0.09
40	25	4.7	1.21	0.61	1.4	0.14
80	19	9.3	2.42	0.61	2.5	0.25

FIG. 6. — Predicted standard deviation vs. range.

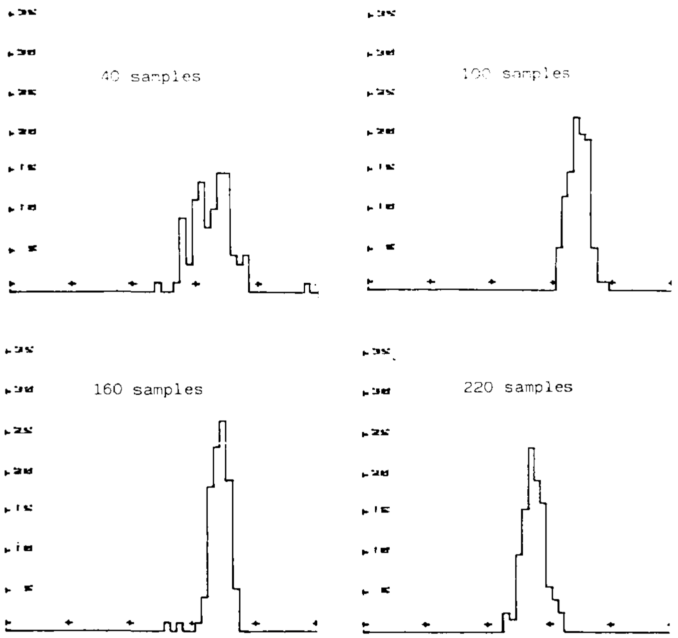
At the beginning of the development programme we aimed to design an equipment which could measure ranges of up to 80 km with errors of no more than 2 metres from all causes. Theory predicted we could — do the results confirm it ? Figure 7 shows the first set of systematic results we obtained, during a demonstration for a major customer. They show relative errors along a 100-metre stretch of runway, at a range of approximately 2 km from the transponder. The positions were not surveyed in, so the absolute errors are not available, but the relative errors have a standard deviation of 15 cm. Figure 8 shows the results of our first long range trial between surveyed positions across Lyme Bay. Readings were taken every 5 seconds at each of the sample average settings. The mean error of 1.29 metres is well within the 2 metres target, and subsequent trials have shown that our original figure for the delays outside the self calibration loop was 0.3 metres too low. We have now revised our maximum error figure from 2 metres to 1 metre. The agreement between predicted and actual standard deviation is evident, and all readings were included — there was no filtering of any kind.

In addition to the design for accuracy, attention has been paid to other problem areas, in particular nulls, processing and communications.

Nulls are caused by multipath propagation, mainly reflections off the sea surface, and space diversity is normally employed to overcome them. However, antenna and receiver switching are both expensive solutions so we decided to try

Reference (metres)	Mean (metres)	Error (metres)
0	2 487.19	0
5	2 482.44	+ 0.25
10	2 477.33	+ 0.14
15	2 472.06	− 0.13
20	2 467.20	+ 0.01
25	2 462.08	− 0.11
30	2 456.87	− 0.32
35	2 452.01	− 0.18
36	2 451.07	− 0.12
37	2 449.99	− 0.20
38	2 449.04	− 0.15
39	2 448.11	− 0.08
40	2 447.01	− 0.18
50	2 437.17	− 0.02
99	2 388.25	+ 0.06
99.5	2 387.82	+ 0.13
100	2 387.23	+ 0.04
OR	2 487.03	− 0.16
Mean Error : − 0.043 metre Standard Deviation : 0.139 metre		

FIG. 7



Sample Average	No. of Readings	Range Error Metres
40	89	1.07
100	95	1.23
160	94	1.23
220	124	0.55

Sample Average	Measured σ metres	Predicted σ metres
40	0.33	0.35
100	0.17	0.22
160	0.17	0.18
220	0.19	0.15

FIG. 8. — Berry Head, Hardy's Monument. Surveyed range : 73 542.2 metres. Mean error : 0.98 metres.

circularly polarized antennas to attenuate the reflections. The results have been most gratifying. Not only have we not found any nulls, but we have also been unable to detect any of the usual problems caused by reflection off ships, which augers well for system performance in ports and harbours.

The main processor in the system is an Intel 8088 with 8087 maths coprocessor. With this power available we have incorporated sophisticated processing to carry out a number of functions. Included in these are pulse correlation, to give further protection against reflections, full XY conversion to grid and Lat/Long using any spheroid selected by the user, track guidance, multi tracker, plotter drive and data communications. Data communication allows transmission of any data at 100 baud. It is normally used for monitoring transponder parameters including battery voltage and selected test parameters such as received signal strength, but is also available for external communications such as tide gauge monitoring. A filter option has also been included. It consists of a second-order zero-velocity error-predictive Kalman filter with user-selectable time constants in the range 10 to 100 seconds, using the proven algorithm from the Hyper-Fix system. The user has the option to switch out the filter and process the data in his own computer. Connection to external equipment is by either RS232 or IEEE488.