Long Range Tracking of *Crocodylus porosus* in Arnhem Land, Northern Australia

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Abstract — This paper discusses progress to date with the University of Sydney's crocodile tracking program, which forms part of a detailed study of *Crocodylus porosus* in northern Australia. Following the development of a long range microwave, solar-powered tracking transmitter and a method of attachment to crocodiles, a pilot tracking program commenced towards the end of 1976. The aim of this program was to test the viability of a system operating at the chosen frequency of 1.25 GHz and involving three fixed, triangulating receiving stations located close to the Tomkinson River in Arnhem Land, Northern Territory, Australia. Some conclusions are presented and a new system, currently under development, is described in which spread spectrum and inverse hyperbolic navigation techniques are to be used.

INTRODUCTION

In 1971, the Environmental Physics Department of the School of Physics within the University of Sydney was established. An important part of the work of the Department since that time has been the longterm study of estuarine crocodile, *Crocodylus porosus*, which inhabits the northern coastal fringe of Australia. Many of this study's results have been published already (see selected list of references) and will not be reported here. Instead, this paper will describe a long range, radio tracking system under development by the Department's Telemetry Group which, in the past, has undertaken a variety of projects relating to the study of our environment.

The Group initially set about designing a radio transmitter and hand held receiver suitable for tracking *Crocodylus porosus* in its habitat. At that time very little was known about the life cycle of this animal and especially about the movements of mature individuals although some reports had been received of large crocodiles observed in the open sea hundreds of kilometers from land. Clearly, one requirement of the tracking system was a long range capability, another was a long operating lifetime, preferably in excess of one year. The original tracking system has been described by Brockelsby (1974) but since then, with increasing knowledge about the behavior of *Crocodylus porosus* and with advances in electronics technology, significant changes have been made to the original system and an entirely new approach is under development.

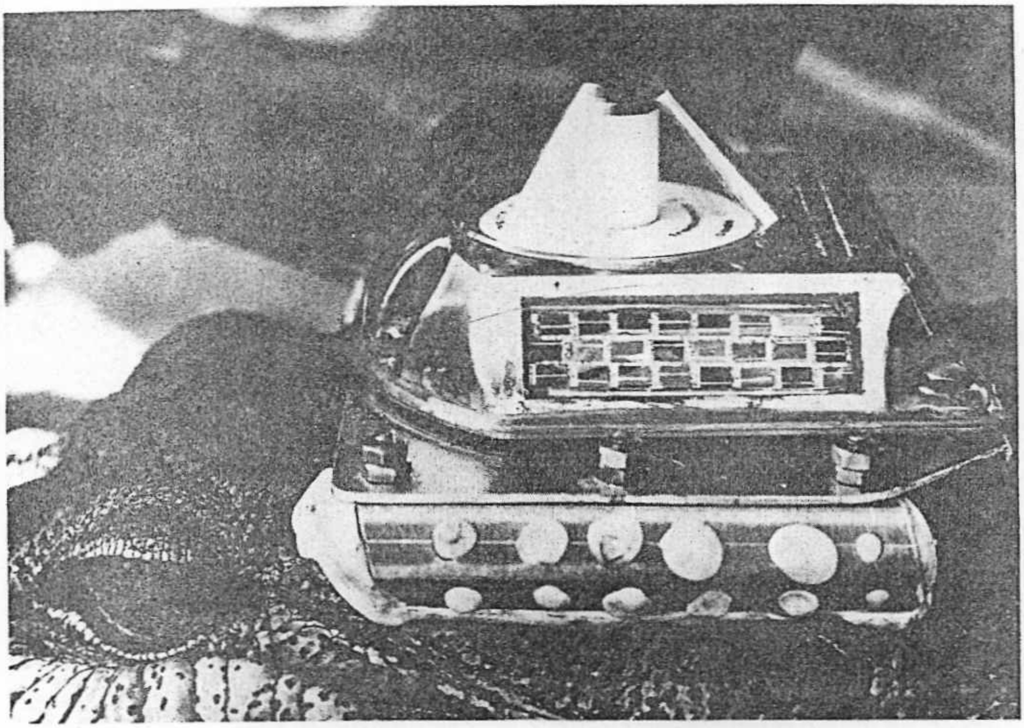

Fig. 2. A transmitter attached to the head of a 220 kg, male crocodile, 3.7 m long. The attachment method uses dental acrylic keyed to the sides of the skull platform.

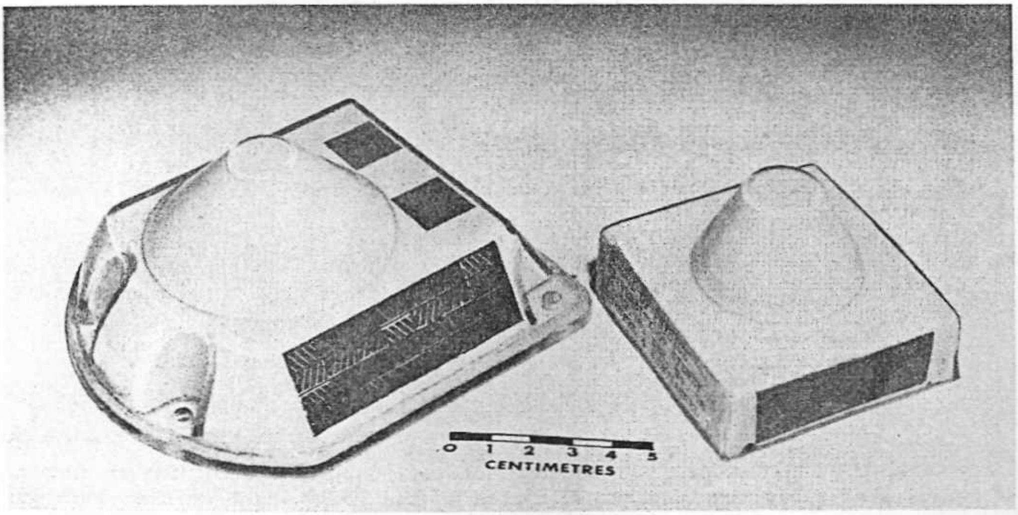

Fig. 3. For comparison with the earlier, solar-powered transmitter, a more recent design is shown on the right. Powered by lithium cells, this smaller transmitter has a greater power output and runs for about 500 days.

THE CURRENT TRACKING SYSTEM

Figure 1 shows a transmitter, now obsolescent, designed for tracking crocodiles longer than about 3 m. Figure 2 is a photograph of such a transmitter attached the head of a male crocodile 3.7 m long and weighing 220 kg.

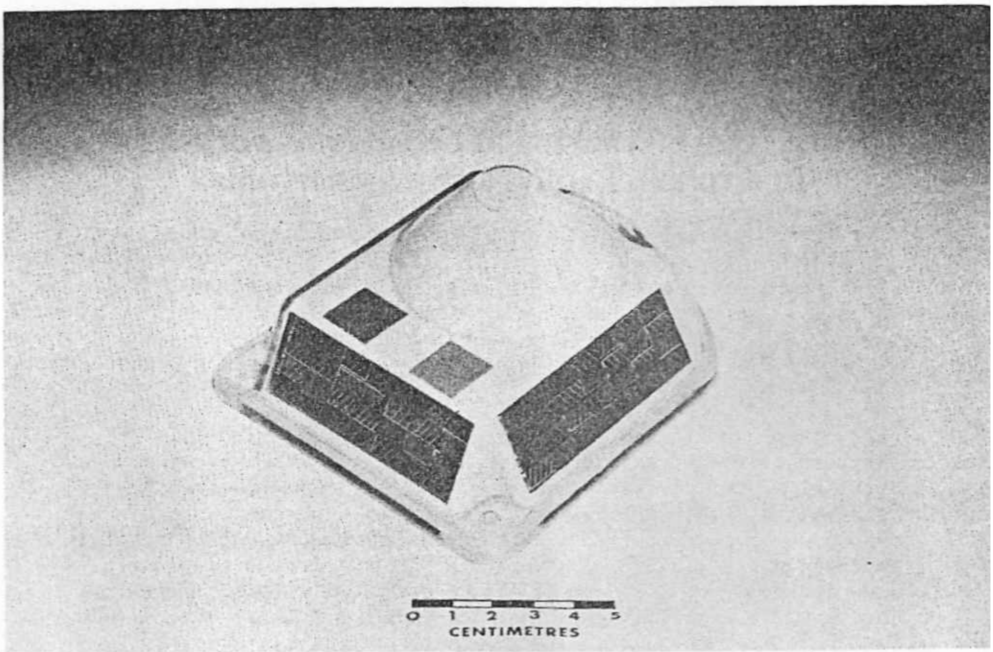

Fig. 1. Solar-powered tracking transmitter for crocodiles longer than about 3 m. Note the scale marked off in cm. A 3-color reflecting panel is used for visual identification also.

The operating frequency of each transmitter is set to one of 10 'channels' cluster
at 24 KHz spacings around the center frequency of 1.254 GHz. One of five discrete tones is used to amplitude modulate the transmitted radio frequency carrier, makin
it possible to distinguish between as many as 50 transmitters operating simultaneo
A nickel-cadmium battery in the base of the transmitter stores energy supplied by three panels of photovoltaic cells arranged on the sloping sides of the outer case. Approximately two hours of direct sunlight each day are required to balance the transmitter's power consumption and, from the fully charged state, it will run for six days in complete darkness. Transmitter output consists of 10 mW, 50 ms tone burst emitted once every two seconds which is sufficient to enable the signal to be detected at a distance of up to 200 km with a receiver installed in a light aircraf
flying at a height of about 3,000 m. With the receiving antenna within a meter or so of the ground, however, the range is reduced to about 2 km.

The transmitter so far described is suitable for attachment to crocodiles longer than about 3 m. Crocodiles in this size range at present are not common in norther
Australia and are quite difficult to catch. Therefore, efforts were made to reduce the size and weight of the transmitter so as to enable smaller crocodiles to be tracked. The resulting transmitter can be seen in Fig. 3. Compared with the earlie
type which weighs 350 g, the new transmitter weighs 140 g, has a volume of 145 ml and therefore floats in fresh water. Its power output of 20 mW is greater and its efficiency of 20 percent is a factor of 2 or 3 times that of the earlier type. Although solar panels can be used, the transmitter shown employs two, size AA, 3.4 V
lithium cells capable of maintaining transmissions for approximately 500 days.

Figure 4 is a cross sectional diagram of this transmitter case and its antenna. electronics compartment is hermetic with glass/metal seals where wires pass thr its wall, and the entire device is enclosed in a shell of vacuum formed cellulos acetate-butyrate (Uvex). A hybrid microcircuit (Figs. 5 and 6) designed and ass in the Department's telemetry laboratory performs a number of functions at the t mitter. It maintains a low frequency quartz watch crystal in a state of oscilla and generates one of five discrete identification tones with which it amplitude-modulates the RF carrier for 50 ms every two seconds. Its power consumption tot 140 μW.

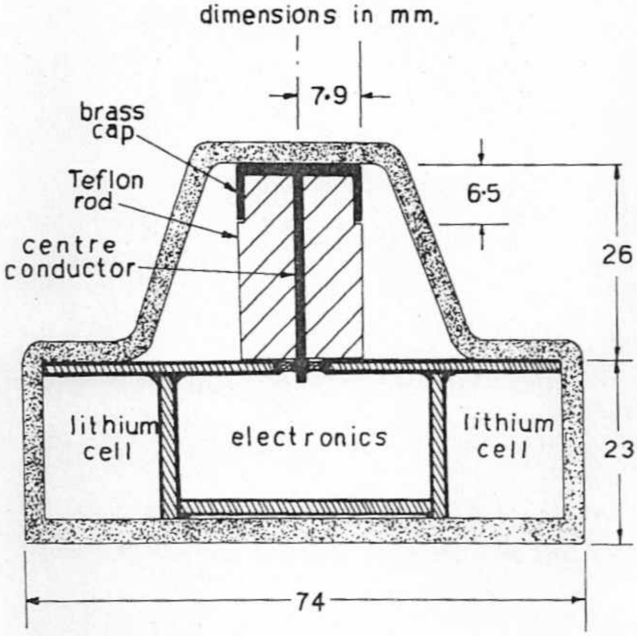

Fig. 4. Cross-section of the smaller tracking transmitter.

The transmitter is required to operate in a harsh environment. It must withstand continual immersion in saline water at depths of up to 30 m and, over a period of few minutes the temperature may cycle between 60 and 10°C; prolonged exposure to bright sunlight, frequent mechanical shocks, abrasion and vibration are to be expe The method of attachment to the animal also must be at least as reliable as the transmitter. For crocodiles longer than about 3 m, the bony platform on the top of the skull overhangs the earflaps sufficiently to allow a matching mould to be made and 'keyed' onto each side (Fig. 7). This process takes only a few minutes, and two sections with embedded bolts being held in position by a flat aluminum plate on which the transmitter is mounted. This procedure results in a rigid attachment requiring minimal pressure on living tissue. Also, the transmitter is positioned so that it receives the most exposure even when the animal is swimming at the surfa (Fig. 8).

During October and November, 1976 an experimental, 3-station receiving antenna arra was established along the eastern escarpment of the Tomkinson River near Maningrida, in Arnhem Land. Receivers were installed in towers overlooking the river at spacin of 5, 12 and 16 km and steerable paraboloids 1 m in diameter were used to obtain bearings on the maximum received signal strengths. The triangulating system was calibrated and tested during this period and it was found to be possible to locate transmitter to within about 50 m at a distance of 5 km. Concurrently with this work

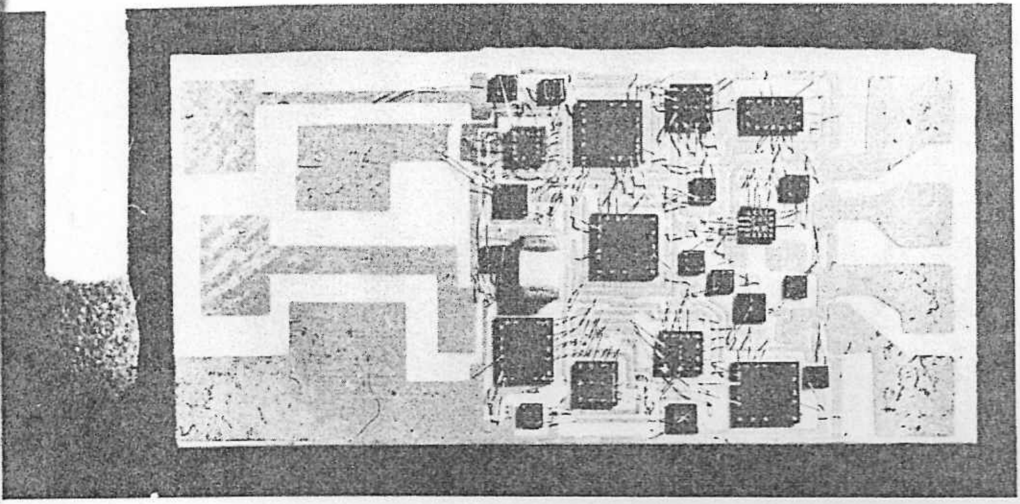

Fig. 5. Hybrid microcircuit used in the transmitter. A quartz watch-crystal (not shown) normally is mounted on the left hand section of the substrate after the rest of the circuit has been encapsulated in an epoxy resin.

n experimental and theoretical investigation was carried out over the same terrain n an attempt to determine the factors influencing the choice of an optimum radio tracking frequency. The results from this study (Horwitz, 1979) supported by experiental data from the triangulating array, suggest that a frequency closer to 500 MHz ould be more suitable for tracking crocodiles. It was found that for frequencies above about 300 MHz, path loss due to scattering by foliage increases radidly and that the superposition of all the scattered waves at the receiving antenna causes fluctuations in the signal strength due to relative motion of the transmitter and foliage. Long integration times are needed therefore to establish the average signal strength received from a particular direction and this is equivalent to reducing the overall system sensitivity. To offset this preference to select lower frequencies, there is the sensitivity of the transmitting antenna to detuning by changes in its local environment which increases as λ^6 at long wavelengths. Combining these factors leads to an optimum choice for crocodile tracking which is somewhere in the range 500-800 MHz.

Although some crocodiles have been tracked using these and earlier solar powered transmitters, as yet no full scale tracking program has been started. The intention is to obtain a very reliable and preferably automatic tracking system with the capacity to collect biological, behavioral and environmental data; it would be valuable also in other wildlife studies and could find application in monitoring human and vehicle movements as well as in search and rescue operations. One important advantage of an automatic tracking system is that it dispenses with the need for maintaining staff continuously at three remote stations in an area where communications are poor and cross country travel at times is almost impossible.

THE AUTOMATIC TRACKING SYSTEM

The automatic system now being developed is designed to identify, locate and collect data from more than 100 transmitters, the number depending upon the desired tracking and data rates. It embodies the principle of hyperbolic navigation (Van Etten, 1970;

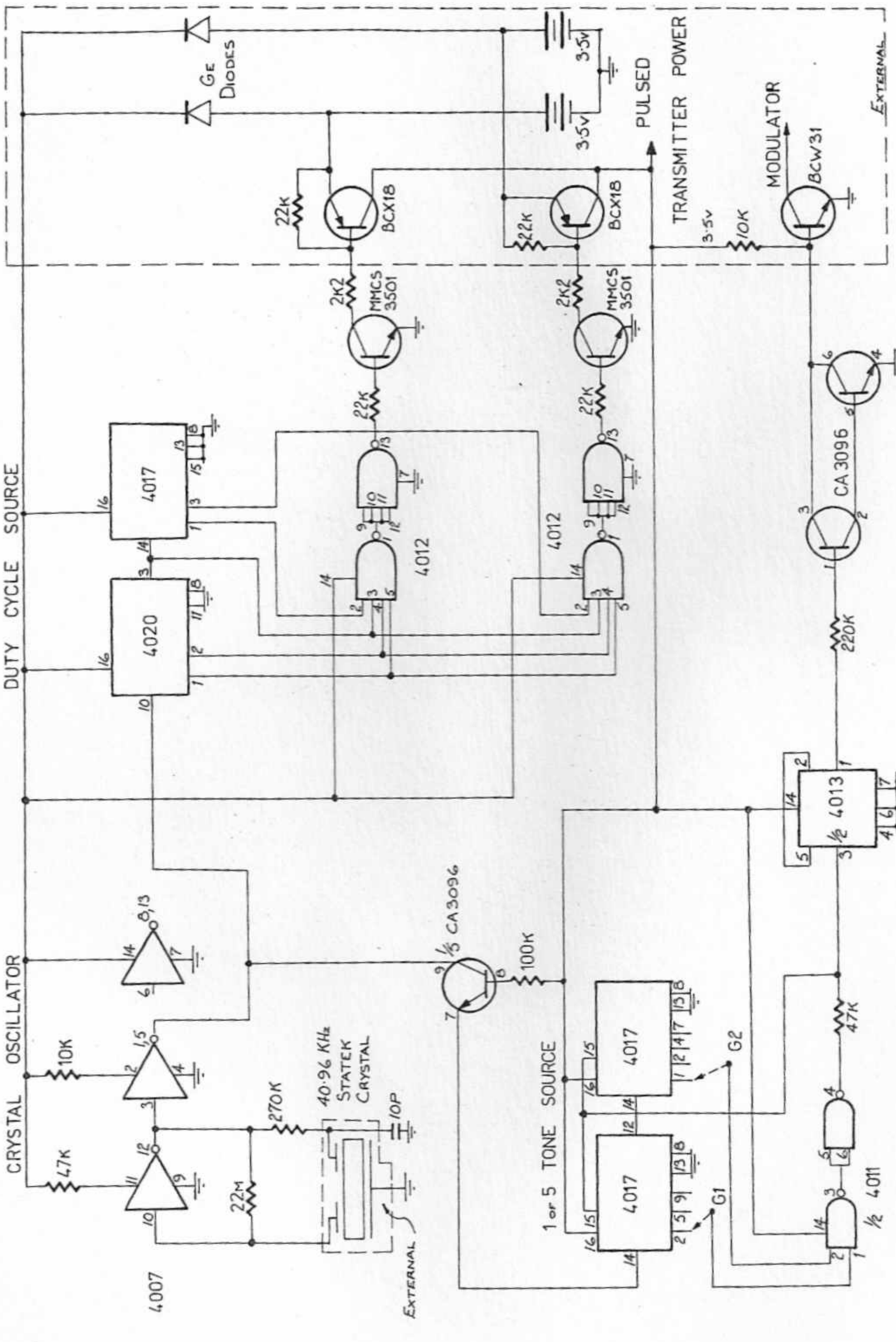

Fig. 6. Diagram of

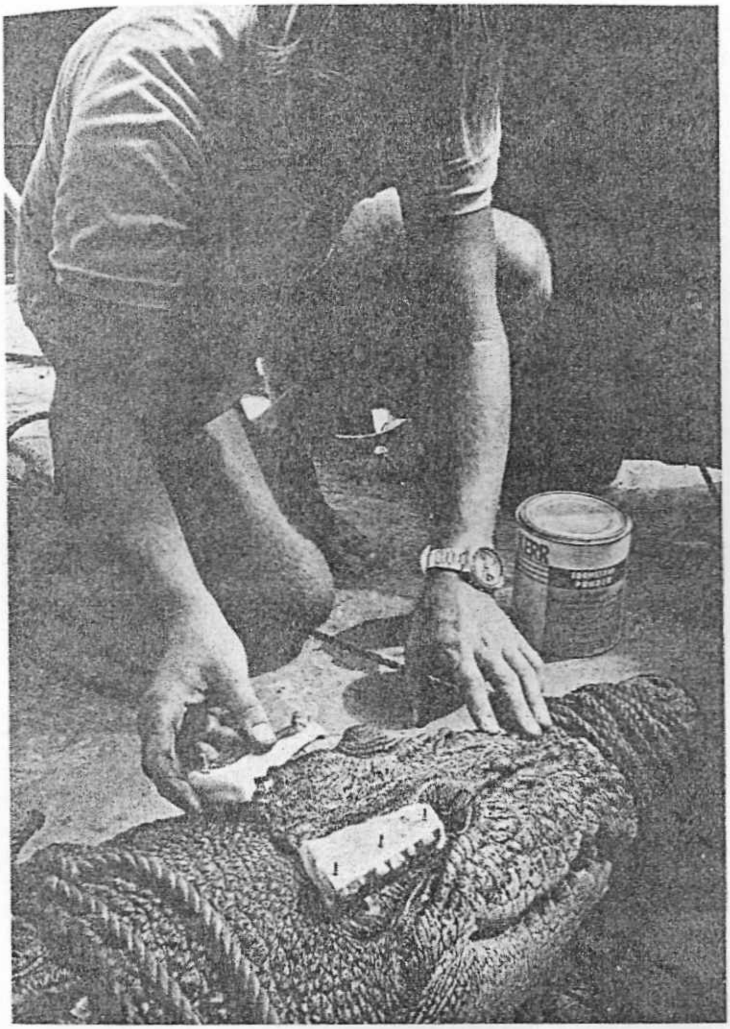

Fig. 7. Two moulds matching the bony protrusions above each ear take only a few minutes to form. The six bolts are used to secure an aluminum baseplate which supports the transmitter.

Beukers, 1974) applied in this case to the relatively short ranges required for tracking individual animals such as crocodiles in their habitat.

Worldwide, low frequency, hyperbolic navigation techniques have been in use since the 1940s; here a ship or aircraft equipped with a receiver, computes its own location from the differences in the times of arrival of signals from at least three widely spaced, fixed transmitting stations. The technique now being developed reverses the roles of transmitter and receiver. Instead, three, widely spaced and fixed receivers measure the differential arrival times of signals from transmitters attached to free ranging animals. Figure 9 shows the three receiving stations A, B and C with 'baselines' AB and BC of arbitrary length and orientation. Families of hyperbolas, known as lines of position, are associated with each pair of receivers.

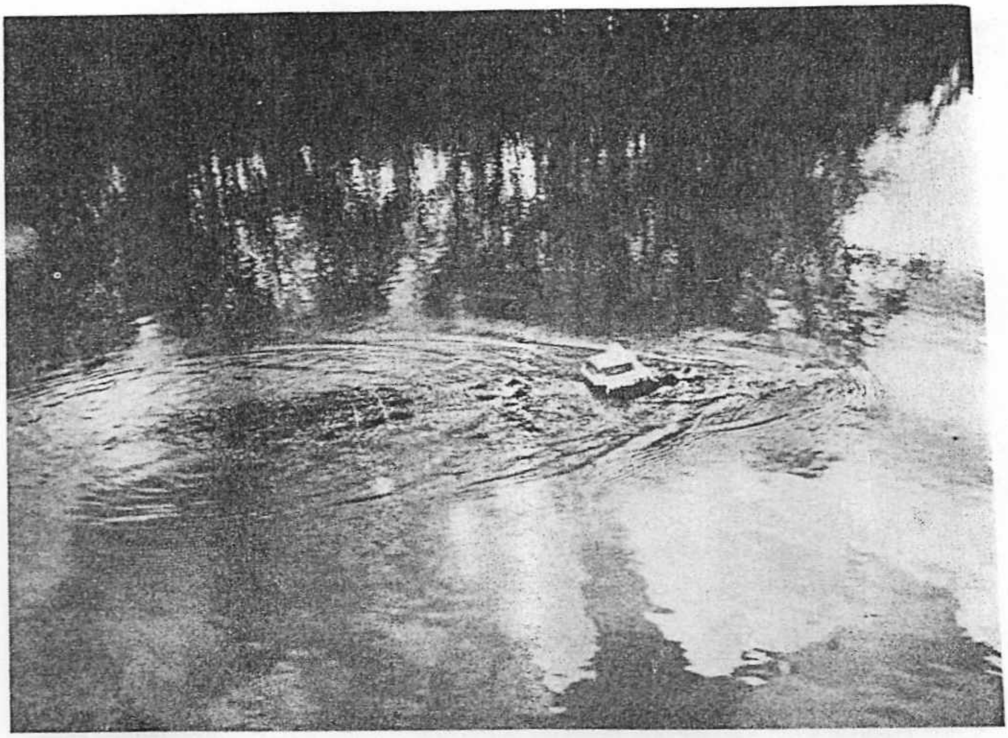

Fig. 8. A swimming crocodile showing how the attached transmitter is well exposed.

Each hyperbola represents a constant range, or time difference, of a signal arriv at two receivers from the transmitter T. If the times of arrival of a signal fro T at A, B and C are t_A, t_B and t_C, respectively, then the lines of position corresponding for example to the time differences $t_{AB} = (t_A - t_B)$ and $t_{BC} = (t_B - t_C)$ intersect at the location of the transmitter. In some cases a second, ambiguous intersection is possible but this can be resolved in a number of ways such as by reference to the previous position of the transmitter and its velocity.

One of the receiving stations is designated the 'master' and computes the transmi locations from the information provided by itself and the two 'slaves'. The iden position and other data associated with each transmitter are processed and stored for later retrieval and analysis.

In order to accommodate a large number of transmitters operating simultaneously, an effective means of separating the received signals is required. Also, since receiver sensitivity is optimized by using a coherent correlation detector, then local oscillator must be phase-locked to the incoming signal. Phase lock is diff cult to achieve if the transmissions take the form of low frequency trains of nar pulses, as each received pulse provides only one sample of the phase difference. This sample must be stored until the next arrives, the difference between the two being a measure of the phase *drift* in one pulse period. To avoid an ambiguous me ment of phase drift, the transmit frequency must not differ from the receive freq by more than half the pulse repetition rate and if, due to noise or interference, one or more pulses are lost, phase lock will be very difficult to acquire or main

If in addition to these requirements the system must be capable of handling data

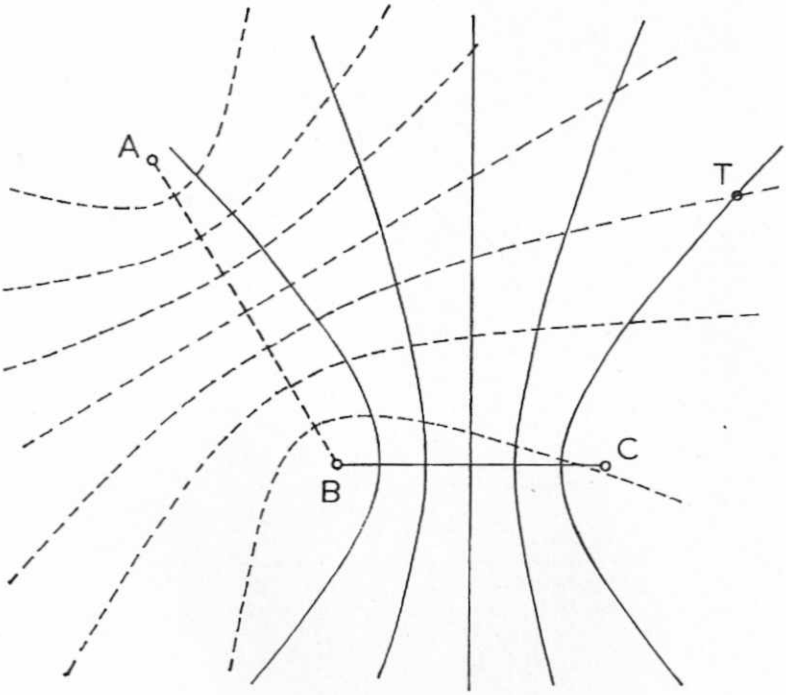

Fig. 9. Diagram showing three receivers, A, B and C and a transmitter, T. Hyperbolic lines of position associated with receiver pairs AB and BC enable the location of T to be determined at the intersection of the two appropriate hyperbolas.

e the ability to provide high range-resolution, it becomes clear that a short
ation, low duty-cycle, pulse-transmission format is unsuitable.

of the specifications can be met and the above mentioned difficulties overcome
transmitting continuously, at a low power level, while phase modulating the car-
r with a very long, pseudorandom code. The resulting radio frequency transmission
known as 'spread spectrum' (Dixon, 1976) because most of the transmitted energy
dispersed into a band of frequencies about twice as wide as the code bit rate.
ypical example might be a 1023-bit Gold code (Gold, 1967) in which 0 and 1 corre-
ond to carrier phase angles of 0 and Π radians, respectively. If the code bit rate
1 megabit s^{-1} the code repeats itself every 1.023 ms and most of the transmitted
ergy is contained in a 2 MHz bandwidth centered on the carrier frequency.

order to detect such a spread-spectrum signal, the reciever generates the same
de with which it phase modulates its oscillator. This is crosscorrelated with
e incoming signal as the local code epoch is slowly advanced or retarded until it
incides with that of the received code. When this happens, the spectrum of the
gnal at the correlator output collapses to a very small bandwidth enabling a narrow
nd, phase-lock loop to acquire the signal.

ere are many advantages to be had from this technique. In the first instance, all
ansmitters operate on about the same center frequency, identification being achieved
mply by using a different code. Since this eliminates the need for separate

frequency channels, it is not necessary to control each transmitter's frequen with great accuracy. When many transmissions are received simultaneously, th tion of crosscorrelations between the locally selected code and undesired cod arises. Gold (1967) has devised a method of generating code sets containing separate codes each of length 2^n-1 bits. The crosscorrelation between members set is $|R(\tau)| \leq 2^{(n+1)/2}+1$ bits where τ is the delay between the codes and n is tive, non-zero integer. For example, if $n = 10$ there are 1023 codes in a set having a peak autocorrelation of 1023 bits and a maximum crosscorrelation bet any two bounded by $|R(\tau)| \leq 47$. There are many other code types with different perties having advantages and disadvantages, depending on the application.

Range resolution is a function of the code bit-rate and the ability of the re to track the autocorrelation peak closely. If the bit rate is 1 megabit s^{-1} f example, and the receiver tracks the peak to within ± 10 percent of one bit, t range resolution is ± 30 m. For a code length of 1023 bits, the range *ambigui* is approximately ± 150 km. Further, if the transmitted and received codes are aligned by as little as one bit, then the output of the correlation detector d to a very low level. In this way, multipath signals delayed by more than one interval are almost completely rejected by the receiver. For instance, with a rate of 10 megabits s^{-1}, those multipath signals traversing a route exceeding direct path by 30 m or more are essentially undetected.

The spread spectrum technique is also highly effective in suppressing the effe of interference. The worst kind of interference likely to be encountered in p is a continuous wave (CW) at a frequency lying in the receiver passband. The of this undesired signal is spread by the crosscorrelation process at the recei so that only a small portion of its energy is accepted by the narrow postcorrel filter; wideband interference is dispersed still further and is even less effec

Data can be transmitted digitally by phase-shift keying (PSK), in which each *co* *block* is assigned a 0 or Π phase. Thus, in the previous example, one data bit be conveyed by 1023 code bits at a maximum rate of 9775 bits s^{-1} with a code ra 10 megabits s^{-1}.

An experimental transmitter now under construction uses an erasable, permanent only memory (EPROM) to store the code which can be up to 4096 bits long. The bi rate is 1 megabit s^{-1} and the radiated power is approximately 2 mW centered on a frequency close to 500 MHz. Five AA size, nickel-cadmium cells designed for hig temperature operation and recharged by a solar panel provide the energy needed. There is sufficient reserve to run the transmitter for up to six days without ad tional charge.

At this stage of the program, there is still much to be done. The problem of ac ing the desired direct path signals at the three receiving stations, as quickly possible and in the presence of multipath propagation, has to be tackled. Most ably this will involve an acquisition strategy developed in the software and usi as much present and past information about the particular transmitter as can be available. A minicomputer installed at the master station is required to handle this problem. Also it will solve the hyperbolic equations giving the various tra mitters' positions, resolve any ambiguities which may arise, compute position err process and store data and make available a graphic display and hardcopy output t the operator.

The many applications of such a system justify the effort going into its develop As digital speeds increase and power consumption, size and cost of components fal the technique presented here will become increasingly attractive.

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