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VHF-FM EMERGENCY POSITION INDICATING RADIO BEACON

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16. Abstract

This report describes the development and testing of an Emergency Position Indicating Radio Beacon (EPIRB) which operates on Channels 15 and 16 of the Maritime Mobile VHF Band. It provides functions necessary to ensure that distress alerting and locating can be quickly and reliably provided for small craft in distress, in coastal maritime regions. When energized by a person in distress, the EPIRB will emit a radio signal which alternates between Channels 15 and 16 using international distress tones for modulation. Between transmissions, the EPIRB will turn off so as to conserve battery power.

The EPIRB has been tested under actual distress conditions. It has been demonstrated to provide a reliable distress alert to Coast Guard stations within a range of 20 nautical miles.

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PREFACE

One of the earliest and most traditional of the Coast Guard's functions is Search and Rescue (SAR). The SAR program objective, stated simply, is to minimize loss of life, injury and property damage by rendering aid to persons and property in distress on, over and under the high seas and waters under the jurisdiction of the United States.

This report addresses the design, testing and demonstration of a VHF-FM EPIRB which provides the functions necessary to provide quick and reliable distress alerting and locating with a minimum interference to other communications in the coastal maritime region. The primary result of this program consists of a recommended set of operating parameters for a VHF-FM EPIRB. These are:

1. An EPIRB output power of one watt will provide highly reliable receiption at a range of 20 nautical miles.
2. The recommended EPIRB modulation consists of a two-tone FSK signal. The tones used are 1300 Hz and 2200 Hz. Each transmission consists of a short (1-2 second) burst of tones on Channel 16, followed by a longer (15 second) burst on Channel 15 after which the Channel 16 transmission repeats.
3. The EPIRB can be equipped to transmit low bit rate (eight bits per second) digital data on Channel 15. Such data transmission can be used to provide features such as user identification and nature of distress.

It is the author's belief that a VHF-FM EPIRB will be highly effective in reducing time of SAR alerting and location of recreational boats in distress. Further, evaluation of the available technology indicates that, the quantity of cost of such a device will be approximately $100.00, and possibly less. Widespread use of such an EPIRB will make the marine environment a safer place in which to operate.

The authors of this report are Peter D. Engels and Charles J. Murphy of TSC and Howard Salwen of Proteon Associates, Inc.

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1. INTRODUCTION

The U.S. Coast Guard in seeking improvements in search and rescue (SAR) capability seeks to (1) reduce the emergency notification (alerting) time for the commercial, military, and general boating public, and 2) provide the capability of detecting and locating the distress. Many areas addressing the SAR mission have been accomplished but insufficient detailed analysis has been done to provide a system approach integrating, in an inexpensive manner, distress alerting with position location. Presently the Coast Guard is actively pursuing the regulatory actions necessary to allow carriage of an Emergency Position Indicating Radio Beacon (EPIRB) compatible with the maritime VHF-FM system by ships and boats operating within the radio coverage of the National VHF-FM Distress System.

This report addresses the design, development and test of an EPIRB which provides the functions necessary to provide quick and reliable distress alerting with a minimum of interference to other VHF communications. In order to ensure this capability, the EPIRB possesses the following features:

1) Relatively high power output (1 watt) to ensure reception at shore stations within 20 nautical miles.
2) Transmission occuring sequentially on Channels 16 and 15. A short (1-2 second) burst of signal on Channel 16 is followed by a longer (10-15 second) burst on Channel 15.
3) A highly recognizable tone modulation consisting of the international distress tones at 1300 and 2200 hertz, alternating four times per second.
4) Provision for detection of simultaneous multiple EPIRBs. This capability is provided by terminating RF transmission following each sequence of Channel 16 and Channel 15 transmission, for a time equal to twice the total RF transmission time.
5) A flexible prototype design that allows for such desirable features as variable duty cycle, data transmission

2. DESIGN CONSIDERATIONS

Certain factors are critical to the design of this EPIRB. In the intended mode of operation, it may be floating at the surface of the ocean, and must transmit a signal which can be reliably received at a shore station up to 20 nautical miles distant, which may have an antenna height of 200 feet or less. The critical parameters then become:

a) Height of transmitting and receiving antennas
b) Propagation characteristics
c) Operating frequency and channel usage
d) Type of signal modulation (and its resultant reception technique)
e) The EPIRB antenna design

These will now be discussed in more detail.

2.1 ANTENNA HEIGHT

Since this system is essentially a line of sight communications system, reception range is primarily defined by geometric line of sight conditions. This condition is defined by the expression

$$d = (2h_t)^{1/2} + (2h_r)^{1/2} \quad (1) \qquad (2\text{-}1)$$

d = distance in statute miles
h_t = transmit antenna height (ft.)
h_r = receive antenna height (ft.)

In the proposed system, we assume that the transmitting (EPIRB) antenna is located on the surface of the earth (or ocean) so that $h_t = 0$. Then

$$d = (2h_r)^{1/2} \qquad (2\text{-}2)$$

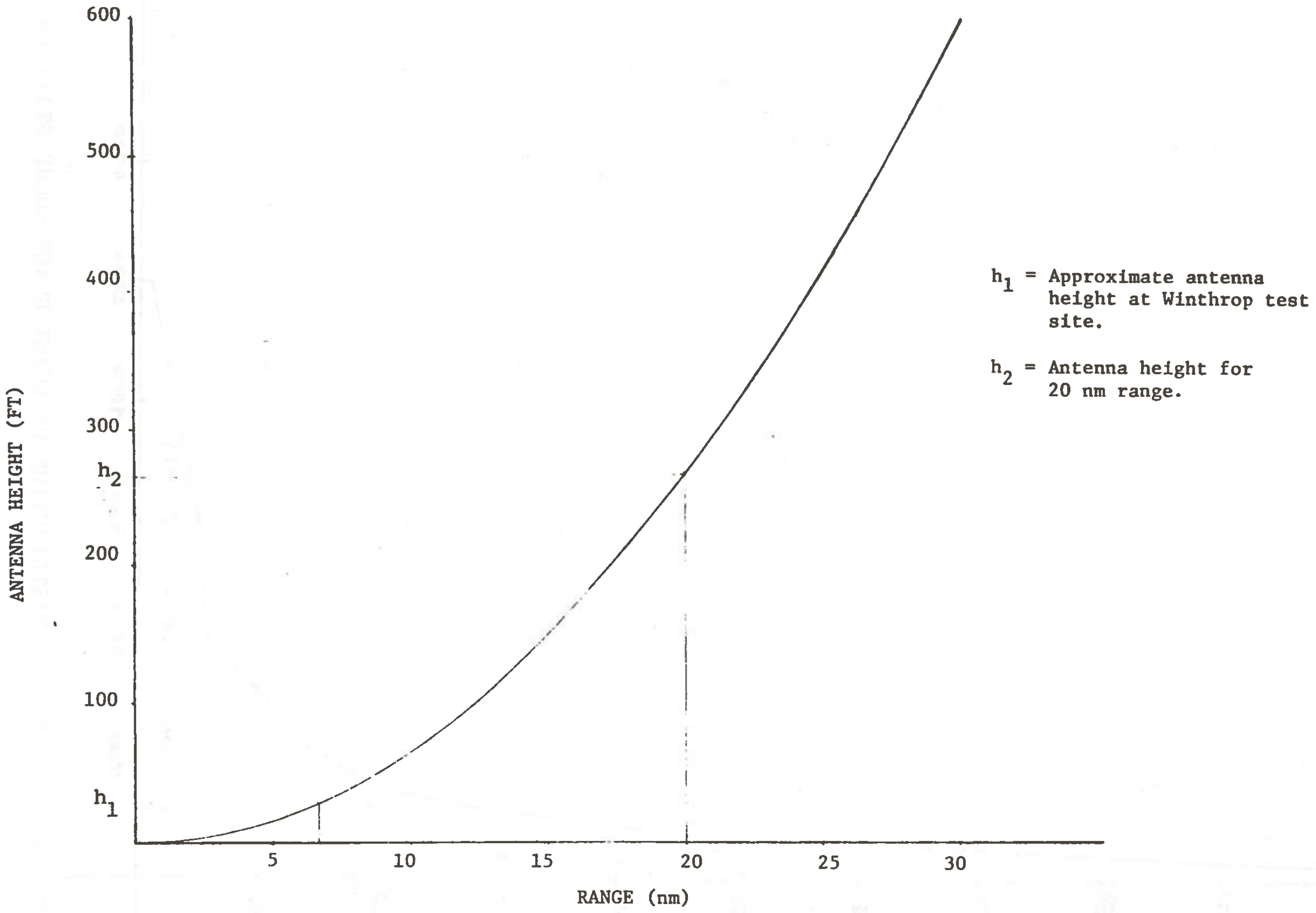

FIGURE 2-1. ANTENNA HEIGHT VS. RANGE FOR TRANSMITTING ANTENNA ON SURFACE

Groundwave propagation predominates when both antenna heights are less than ho, where ho is a parameter called the minimum effective antenna height, and is a function of the surface dielectric constant and conductivity. At the frequency of interest (156.8 MHz), ho is 21.55 ft. for a vertically polarized antenna over sea water. When the antenna height is greater than ho, attenuation decreases by 6 db for every 2 ho increase in antenna height, until free space propagation conditions are reached.

By examination of equations (2-3) & (2-5), we see that there are two important facts about groundwave propagation:

1) The attenuation is independent of frequency,
2) Attenuation varies as the fourth power of distance.

Furthermore, for a given distance, one can equate the two expressions so as to calculate the antenna heights necessary to ensure free-space propagation conditions. The results of such a calculation are summarized in table 2-1, which shows the receiving antenna height necessary for free space propagation, given a transmit antenna height much less than ho (EPIRB on the sea surface).

TABLE 2-1 RECEIVING ANTENNA HEIGHT NECESSARY FOR FREE SPACE PROPAGATION

DISTANCE (NAUT. MILES)	RECEIVE ANTENNA HEIGHT (FT)
0.1	14.1
0.3	42.25
0.5	70.4
1.0	140.8
3.0	422.5
5.0	704.2
10.0	1408.3
20.0	2816.6
30.0	5225.0

These calculations lead to the following conclusions:

1) For the typical case of the EPIRB in or near the water, and a small Coast Guard cutter homing on the EPIRB, the level of the received signal at the cutter is determined by ground wave propagation conditions.

2) Although there are nearly 200 Coast Guard shore stations,

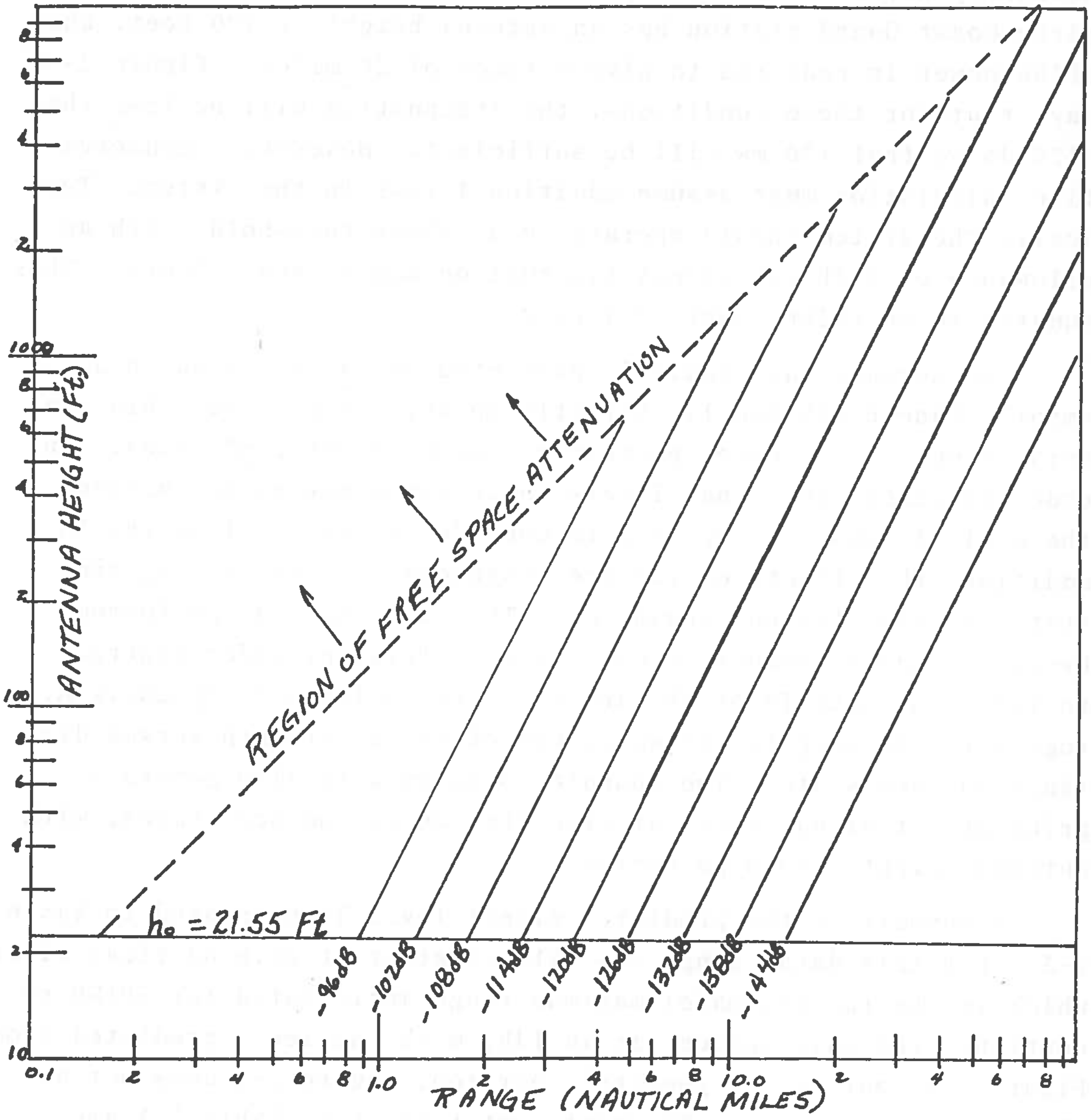

FIGURE 2-3. SURFACE WAVE PROPAGATION

TABLE 2-3. PREDICTED SIGNAL LEVEL AS A FUNCTION OF ANTENNA HEIGHT AND SEA STATE

Receiver Antenna Height	Sea State 0	Sea State 1	Sea State 2	Sea State 3	Sea State 6	Sea State 9	Fresh Water Sea State 0
0	-125dBm	-126.3 dBm	-127.6 dBm	-128.8 dBm	-131.8 dBm	-134.1 dBm	-140.5 dBm
100 meters (328 ft.)	-101 dBm	-101.7 dBm	-102.3 dBm	-102.8 dBm	-104.2 dBm	-105.3 dBm	-108.3 dBm
300 meters (984 ft.)	-83.4 dBm	-84.1 dBm	-84.6 dBm	-85.2 dBm	-88.0 dBm	-89.1 dBm	-95.0 dBm
3048 meters (10,000 ft)	-76.3 dBm	-76.3 dBm	-76.3 dBm	-76.3 dBm	-76.3 dBm	-76.3 dBm	-76.3 dBm

interference effects (such as spread spectrum). Such techniques result in complex and expensive receiver designs. On the other hand, given that the channel 16 EPIRB transmission is adequately heard by a number of vessels, the presence of the transmission would preempt the use of channel 16 for calling purposes and other distress and safety traffic. As will be discussed below, direction finding and homing equipment will require longer periods of transmission than those required for audible alerting purposes. Therefore, it is proposed that the EPIRB should transmit, alternately, first on channel 16 then automatically switch to channel 15 which would be reserved for EPIRB use. The transmission on channel 15 is proposed to be of longer duration than that on channel 16. The longer duration transmission on channel 15 allows time for the communication of status data, identification codes or a distress message, as desired.

2.4 SIGNAL MODULATION

A variety of modulation waveforms were considered for this system. These included the following:

1) Swept frequency tones, such as that used by 121.5/243 MHz EPIRBS.
2) Single-frequency tones
3) Multiple alternating tones
4) Spread spectrum

The criteria for selection were as follows:

1) Audibility to a human listener when detected by a conventional FM receiver.
2) Detectability in the presence of co-channel interference and background noise
3) Feasibility of automated detection.

All the tone modulation systems examined were found to be highly audible with simple discriminator-type demodulation. Both the swept-frequency tone and the multiple alternating tone system are clearly audible and quickly identifiable to the human listener.

and 2200 Hz, alternating four times per second. This waveform is simple to detect, is highly audible under all conditions, and minimizes spurious false alarm problems.

The choice of specific tone frequencies at 1300 Hz and 2200 Hz was made partly on the basis that this waveform is already in use as an international distress waveform--indeed, some ships already carry automated monitor equipment for this waveform. Therefore, this choice is quite rational, in that these frequencies are already used for distress alerting and the choice both maximizes system acceptability and minimizes the proliferation of different distress alerting systems.

2.5 EPIRB ANTENNA CONSIDERATIONS

The provision of a well-matched, efficient transmit antenna, with good radiation characteristics at very low elevation angles is critical to proper EPIRB signal reception. With these requirements, some form of vertically polarized antenna is essential. Thus, the classic antenna which has been used for this application is either a 1/2 wavelength dipole, or (to minimize length) a 1/4 wavelength antenna with a suitable ground plane. It should be noted that the presence of a ground plane, either as part of the antenna structure or in the form of sea water will inevitably tilt the radiation pattern up about 10° away from the local horizon; this can sometimes be alleviated by an angled ground plane.(7)

In addition to the requirements listed above, the present application imposes a new set of operating constraints: the EPIRB antenna must perform well under three separate conditions --

1) When floating free near a distress vessel - where the liquid medium is sea water.
2) Hand held, or otherwise mounted on the deck (or higher) of a distressed vessel.
3) When floating free in a fresh water medium - a situation typical of the Great Lakes. Although a 1/4 wavelength antenna will function well in condition (1), where sea

consists of a half-wavelength rod attached to a shorted quarterwave section of two-wire line. Fig. 2-4 illustrates the arrangement and shows the "J" shape of the conductors. The antenna is fed by tapping into the shorted quarter-wavelength section at the 50 ohm point. In commercial antennas the connection is made by attaching inner and outer conductors of a coaxial cable to the two-wire line; in an integrated EPIRB design a balanced (two-wire) feed could be preferable and even less expensive.

The operation of the antenna is straightforward, although a little unusual. The dipole is fed from the base at point "A" in figure 2-4 current flow down the antenna along the feed cable which could interact with water or surrounding structures and cause impedance and pattern variations is suppressed by the choke, which at point "A" presents an open-circuit to such currents. The resulting radiation pattern is that of a half-wave dipole.

The primary drawback of the J antenna is its physical length. An antenna length of 3/4 wavelength at 156 MHz is 1.4 meters or 4.7 feet. Although much of the matching section could be packaged inside the EPIRB, the antenna length is still over 3 feet, resulting in a rather cumbersome design. Further decrease in antenna length may be possible by loading the antenna, either with a disc-shaped hat, or with a small helical structure.(8) In both instances, the effect is to make a physically short antenna into one with greater electrical length. Further investigation of this technique was considered beyond the scope of this task and therefore was not pursued.

2.6 DURATION OF TRANSMISSION

As discussed in section 2.4, it was decided to adopt the 1300/2200 Hz two-frequency scheme for the EPIRB because 1) this audible tone scheme has international recognition as a distress call, 2) some vessels are currently equipped with automated detection equipment for this tone signaling pair, 3) the signal has good audible detection characteristics under high noise conditions, 4) the signal format is compatible with the requirements of automated detection systems.

The distress message code is substantially shorter. For example, the EPIRB could provide for the transmission of fire, sinking, medical emergency and disabled but not immediately in danger. The minimum number of bits for four possible distress codes is two. However, it is reasonable to employ redundancy in this portion of the distress message to enhance the reliability of detection. For this reason, it is assumed that 12 bits will be employed to transmit one of four possible distress messages.

Thus, it appears that 40 bits of data transmission capability is adequate for present and future system applications. The actual EPIRB transmission will consist of more than 40 bits because a preamble bit sequence is required in order to provide for reliable signal detection, bit synchronization, and start-of-message indication. The preamble bit sequence must be long enough to provide a high probability of detection and sufficiently accurate bit synchronization. The system design effort must determine the distress message bit rate and the required length of the preamble bit sequence. This, along with direction finding and homing constraints, will determine the duration of transmission on channel 15.

Communication with manufacturers of automatic direction finding equipment (ADF) and with USCG personnel who are familiar with the operation of ADF equipment indicates that the transmission of a signal for 2 or 3 seconds is adequate for direction finding purposes. However, when the signal is deeply buried in noise additional time should be provided to enhance distress message recognition by operating personnel. Thus, for the purpose of design analysis it is assumed that direction finding will require transmission on channel 15 for durations in excess of 5 seconds. Homing systems require much longer transmission durations. For example, it may take several minutes to orient a homer equipped vessel in the direction of a distress message when operating in rough seas and/or restricted channels. However, the EPIRB cannot transmit for such long durations and meet the constraints imposed by battery limitation and multiple EPIRB operational considerations. It is possible to operate the homing equipment while transmitting

3. OPERATIONAL CONSIDERATIONS

3.1 SUMMARY OF THE TRANSMISSION CYCLE

Figure 3-1 summarizes the transmission parameters discussed in this section. Each transmission cycle begins with transmission on channel 16 for 2 seconds. The modulation format used during the channel 16 transmission corresponds to the international distress tones at 1300 Hz and 2200 Hz. These tones are alternated every quarter second as described for the international distress call format. After a channel 16 transmission the EPIRB switches to channel 15 and continues to transmit using the same tone frequencies at 1300 Hz and 2200 Hz. However, the message is not a simple alternating pattern. For the first five seconds on channel 15 a preamble pattern is transmitted. This consists of 20 tone chips each of which is 0.25 seconds long. The code pattern used during this 20 chip preamble is selected to have good correlation properties for detection and sychronization of the channel 15 message. The latter 10 seconds of the channel 15 transmission consists of a 40 bit message which contains the vessel identification and distress codes. The 40 bits are transmitted using the same 1300 and 2200 Hz tone frequencies. Thus, the transmission duration on channel 15 is roughly 15 seconds. Following transmission on channel 15 the EPIRB switches back to channel 16 and repeats the first transmission pattern. Following the second transmission on channel 16 the EPIRB remains off for a variable length of time which is determined by the duty cycle logic. The exact duty cycle to be used will depend on the energy storage capabilities of the battery selected for the EPIRB. However, it is safe to say at this point that the selected duty cycle pattern will be similar to that shown in Fig. B-4.

3.2 MULTIPLE ACCESS

The EPIRB design described herein provides a relatively high power level (1 watt) in order to provide a usable signal with the propagation conditions described in Section 2.2. In order to minimize the battery requirements, it is reasonable to assume that the EPIRB will transmit bursts of signal, followed by periods of no transmission. This is shown graphically in Fig. 3-2. In addition, when more than one EPIRB is in operation at a given time the detection performance of the system will be degraded by the potential for overlap of the transmissions from two or more of the EPIRBs. It is likely that most EPIRB receiving systems will use frequency modulation detectors (i.e., ordinary FM receivers), in which case the strongest of the received signals will capture the receiver when overlap exists. This means that in order to detect the weaker (more distant) EPIRB signals there must be a high probability of reception without overlap. Appendix B analyzes this problem.

It should be noted here that there will always be a finite (but small) probability that several EPIRBs will turn on nearly simultaneously. In this eventuality, the receiving system will be incapable of distinguishing between EPIRBs, if they are in close proximity to one another. This event, however, will, in general, be quite rare, as the prime cause would be the sudden onslaught of violent weather (such as a line squall). Sudden, severe weather can (and has) caused severe distress to large numbers of small craft, and <u>no</u> communication system however complex, can accommodate such a situation, unless extremely large amounts of unused time are provided in the transmission format which in turn means that each EPIRB will transmit very infrequently. We have chosen instead to design an efficient communications system, with a high probability of reception and low probability of overlap. The primary consideration is that except for the highly unusual conditions mentioned above, the probability of multiple EPIRBs turning on nearly simultaneously, is extremely low.

3.3 BATTERY LIFETIME

The batter power requirements of the two schemes shown in Fig. B-4 were analyzed as typical designs. The results are shown in Table 3-4. The table assumes two possible patterns during each cycle: Channel 16 transmits preceding and following channel 15 transmissions. Channel 15 transmissions are always 15 seconds in duration while channel 16 transmissions are either 1 or 2 sec. long. The results of Section 2.2 indicate that 1 watt of transmitter RF power through a 0 dBi gain antenna should be adequate. For this reason, Table 3-4 assumes that the d.c. bus power required during transmission is around 3 watts. The battery capacity required for the various schemes is between 471 ma-hr. and 622 ma-hr. at 12 volts.

TABLE 3-1. BATTERY POWER REQUIREMENTS

	Cycle A		Cycle B	
	2 + 15 + 2	1 + 15 + 1	2 + 15 + 2	1 + 15 + 1
No. Trans. in 24 hrs.	472	472	399	399
Total Trans. Time	8968 sec.	8024 sec.	7581 sec.	6783 sec.
Energy Required for 3 watts d.c.	7.47 W-hr.	6.68 W-hr.	6.32 W-hr.	5.65 W-hr.
ma-hours at 12 volts	622 ma-hr.	556 ma-hr.	526 ma-hr.	471 ma-hr.

Batteries which are typically used in EPIRBs tend to lose their capacity at low temperatures. For this reason, it is necessary to derate the battery when consideration is given to low temperature operation. A derating by 50% is not unreasonable for this application. Table 3-5 summarizes the battery characteristics which are typical of what would be required by the EPIRB using the 2 + 15 + 2 version of Cycle "A."

TABLE 3-2. BATTERY CHARACTERISTICS

Voltage	12 volts
Energy Storage	7.5 W-hours
Low Temp. Design Point	-20°C
2.5 Hour Discharge Rate	250 milliamperes
Amp hours at 25°C	1.25 A-hours

4. PROTOTYPE EPIRB DESIGN

This section describes the design and construction of the prototype EPIRB. Five prototypes were built and tested during this program.

4.1 EPIRB DIGITAL DESIGN

The experimental EPIRBs implemented as part of this program were intended to provide maximum flexibility to the experimenters. The following parameters were controllable.

power output
antenna type
duty cycle variation
duration of channel 16 transmission
duration of channel 15 transmission

This was achieved using the system shown in Fig. 4-1 which shows the EPIRB block diagram.

Transmitter operation is controlled by the contents of a read only memory (ROM). In particular, the memory determines whether the transmitter is ON or OFF at a given time. If it is ON, the memory determines whether the transmitted frequency is on channel 15 or channel 16. The memory also determines which of the two FSK tones is used to modulate the output frequency.

The address of the ROM is determined by a counter which is incremented at a rate which is obtained by dividing down a stable reference frequency from the tone generator. Thus, as the counter counts up to its maximum and overflows, the entire content of the ROM is continuously scanned. Each cycle of the address counter corresponds to one transmission cycle.

In the absence of the divide ratio control, the system as described thus far is capable of constant duty cycle operation. A duty cycle counter is included which is incremented once each transmission cycle. This counter controls a divide ratio logic subsystem which reduces the address counter update rate during the OFF periods. As the number of executed transmitter cycles increases and the duty cycle counter content increases, the update rate of the address counter during the OFF periods becomes slower and slower. In this way the desired variable duty cycle is implemented. The system also includes a means for randomizing the OFF period from unit-to-unit. This is achieved by perturbing the divide ratio control subsystem by one of the ROM outputs. A unique ROM content would be implemented for each production unit.

4.2 TRANSMITTER DESIGN

The VHF transmitter portion of the system was implemented using a VHF Electronics Model TX144B commercial transmitter module. This unit provided the VCO, and power amplifier functions. It was necessary to modify the unit in order to provide Ch. 15/Ch. 16 capability and logic controlled ON/OFF functions, and to provide an output power of 1 watt.

Two types of antennas were used. A 5/8 wavelength whip antenna was mounted on one of the EPIRBS. Four other EPIRBS were implemented with a "J" antenna (Antenna Specialities Model ASM177).

The tone generator was implemented by a MC14410 integrated circuit (IC). For the purposes of experimentation, the read only memory was implemented using a 2101 random access memory with an attached battery pack. The rest of the logic was implemented in CMOS.

Tables 4-1 and 4-2 show two different duty cycle arrangements which were implemented for experiment purposes. Method "C" provides a 10 second Ch. 15 transmission. Method "D" provides a 15 second on Ch. 15.

4.3 MECHANICAL DESIGN

The prototype EPIRBs were all packaged in identical containers. The container consisted of a right circular cylinder, fabricated from 3 inch (inside diameter) PVC pipe, with suitable endcaps. The container is approximately 18 inches long. Two aluminum rails are fastened to the top cap, and the two printed circuit boards are fastened between these rails (see figures 4-2, 4-3 and 4-4). The antenna is a 50-inch whip, also fastened to the top cap with its matching section contained within the package. One circuit board (fig. 4-3) contains the VHF transmitter and its associated RF circuitry. The other circuit board (fig. 4-4) contains the digital circuitry. The batterys were mounted in the bottom of the container for ballast; rechargeable Gel cells were used. The container was sealed and pressurized (3 psi) to ensure watertight integrity. On the outside of the top cap were mounted the pressure valve and two switches--the on-off switch and another to choose the identification code.

The prototype floated with the antenna base about 3 inches above the surface. The output power was about 1 watt into the antenna.

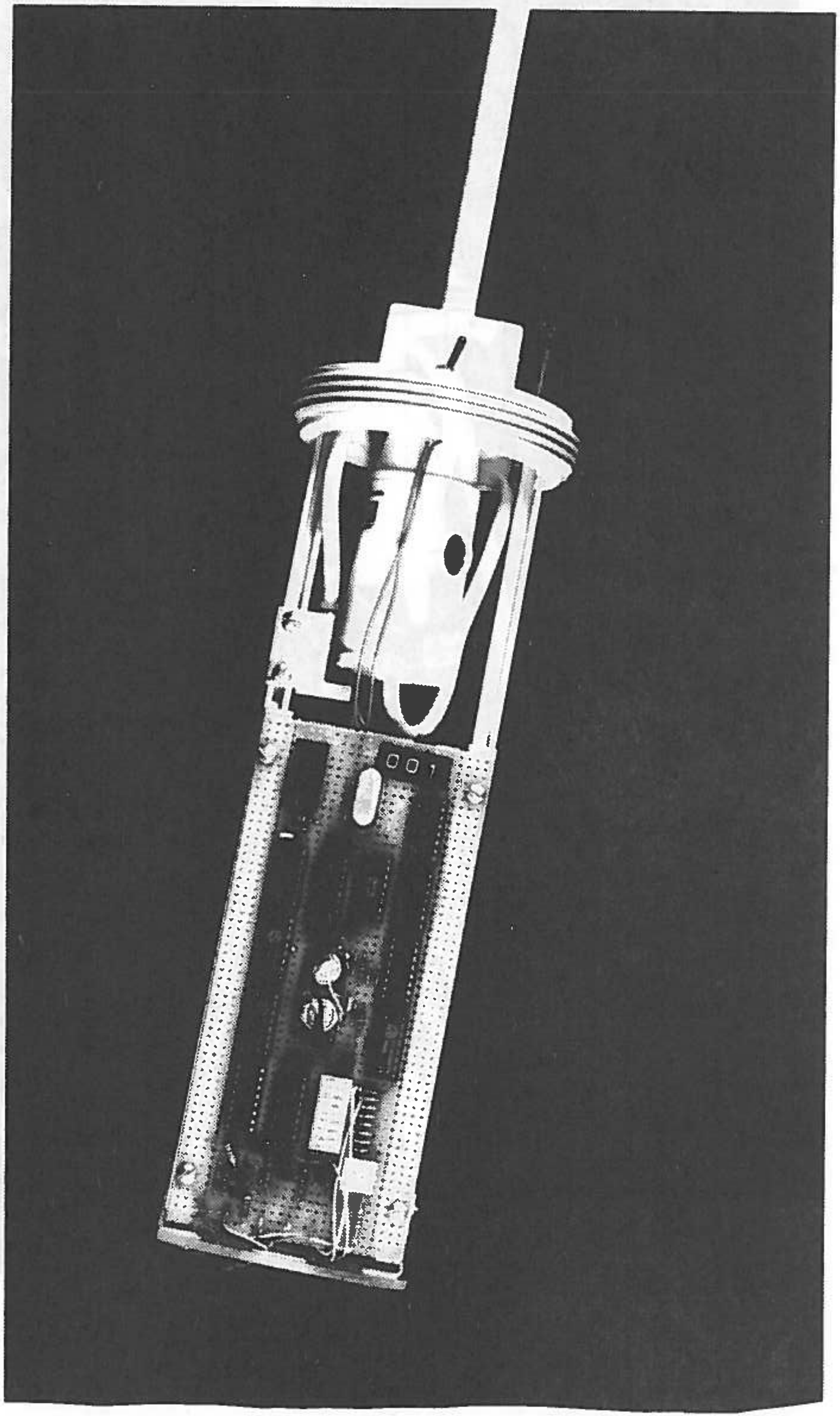

FIGURE 4-3. EPIRB DIGITAL ELECTRONICS

5. AUTOMATED EPIRB RECEIVER/PROCESSOR DESIGN ANALYSIS

This section considers the performance of the receiver to be used for high performance detection of the channel 15 message and for code processing to extract vehicle identification and distress level.

5.1 SIGNAL CONSIDERATIONS

The EPIRB design described in this report is intended to provide coverage within 20 nautical miles of the coastline. Therefore, the system should provide coverage for slant ranges well in excess of 20 nautical miles. Table 5-1 shows the receiver power level for 1 watt transmitted EIRP at ranges of 24 nm and 30 nm. The transmitter height is assumed to be at sea level, and the receiver antenna height is assumed to be either 100 ft or 200 ft above sea level. Three wind conditions are given: no wind, 7.7 m/s, and 15.6 m/s. The latter two wind speeds correspond to sea-state 3 and sea-state 6, respectively. Also given in the table are the received power levels predicted by the classical smooth spherical earth propagation model.

Table 5-1 shows that the weakest signal strengths anticipated for this system should be about -126 dBm when the transmitted power is 1 watt and the receiving antenna has 3 dB of gain at the heights shown in the table. Of course, somewhat higher antenna gains are readily achieved and the transmitter may put out more than 1 watt especially at initial turn-on. In order to determine performance we must also have an estimate of the receiver noise characteristic. At frequencies in the vicinity of 150 MHz, the noise in the receiver is often the result of man-made ambient noise rather than receiver front-end noise. The level of man-made noise is a function of population density. For example, Fig. 1 of Section 29 of Ref. 1 shows that the equivalent noise figure of urban man-made noise at 150 MHz is approximately 36 dB. The equivalent noise figure of surburban man-made noise at 150 MHz is about 20 dB. For the purposes of analysis, we will assume the latter operational environment. Thus, with 1 Watt EIRP from the EPIRB, the worst-case received carrier-to-noise density will be approximately 29 dB-Hz. If it is assumed that the transmitted EIRP is 1.5 Watts then worst-case signal-to-noise density will be 30 dB-Hz. Such signal levels are well below the threshold of a conventional FM receiver designed for Maritime Mobile Service. Therefore, we must investigate the performance of FM receivers when operated below threshold.

The performance of an FM receiver above and below threshold was derived based on the work of Davis.(8) The derivation provided the signal-to-noise density at baseband as a function of signal-to-noise density at IF. The relationship used is given in Eq. (5-1).

$$\left(\frac{S}{N_o}\right)_{\substack{\text{base}\\ \text{band}}} = \frac{\rho\, B\, \delta^2}{2e^{-\pi f_m^2/B^2} + \dfrac{4B^2\, \rho e^{-\rho}}{\pi\, f_m^2\, (1-e^{-\rho})^2 [2(\rho+2.35)]^{1/2}}} \qquad (5\text{-}1)$$

where

$\rho = C/N_0B$, the IF SNR
B = the single-sided noise bandwidth of the IF
δ = modulation deviation (rads) = $\Delta f/f_m$
f_m = modulation rate (Hz)

Equation (5-1) is plotted in Fig. 5-1 for several choices of parameters. In particular, 2 IF bandwidths are assumed. One is the standard for typical VHF receivers--namely, 12 kHz. The other is 6 kHz. Two tone frequencies are assumed as before, 1300 Hz and 2200 Hz. In all cases analyzed the modulation deviation was assumed to be 2 radians. At 2 radians the best performance is achieved at 2200 Hz in a 7 kHz IF. However, note that a 1300 Hz tone in the same bandwidth could use a larger deviation. When the deviation is optimized, performance at 1300 Hz is similar to that shown for 2200 Hz in the 7 kHz bandwidth. The same argument pertains to the 12kHz IF bandwidth performances shown. Namely, in both cases, at 1300 Hz and at 2200 Hz, the 2 radian deviation assumed is smaller than that which would be allowable by the 12kHz filter. However, in this case, if the deviation were increased by 6 dB and a comparison made with the performances in the 6 kHz bandwidth, it is found that the relative performance of the wider bandwidth system below threshold is inferior to that of the narrower bandwidth system, so that the narrow bandwidth IF always provides the lowest threshold.

The propagation analysis of the previous section indicated that the worst-case received carrier-to-noise density is approximately 28 to 30 dB-Hz. Figure 5-1 indicates that the signal-to-noise density at baseband given this received carrier-to-noise density will be about 20 dB-Hz.

Fig. 5-1 also shows the performances of phase-locked receivers under a variety of operating conditions. The relationship between IF signal-to-noise density and baseband signal-to-noise density in a tone-modulated system with a high signal-to-noise ratio in the phase-lock loop tracking bandwidth is given by Eq. (5-2).

$$\left(\frac{S}{N_o}\right)_{\substack{\text{base}\\\text{band}}} = 2J_1^{\,2}(\delta)\,\frac{C}{N_0} \quad \text{for } (SNR)_\ell \text{ high} \tag{5-2}$$

where $J_1(\cdot)$ is the <u>1st</u> order Bessel function.

Figure 5-1 shows that given high signal-to-noise ratio in the loop bandwidth, the phase-locked receiver provides better performance than the FM receiver when the signal-to-noise density at IF is less than 30 dB. However, a separate set of points is given for the case in which the phase-locked loop noise becomes substantial, resulting in non-linear loop performance. In that case, the effective baseband signal-to-noise ratio is reduced by

$$\overline{\cos \phi_{rms}} = e^{-\phi_{rms}^2/2} \tag{5-3}$$

where ϕ_{rms} is the rms loop error. It is evident that the PLL demodulator performance will actually be little, if any, better than the conventional demodulator performance with a 6Khz IF bandwidth. The points which are included on Fig. 5-1 to show

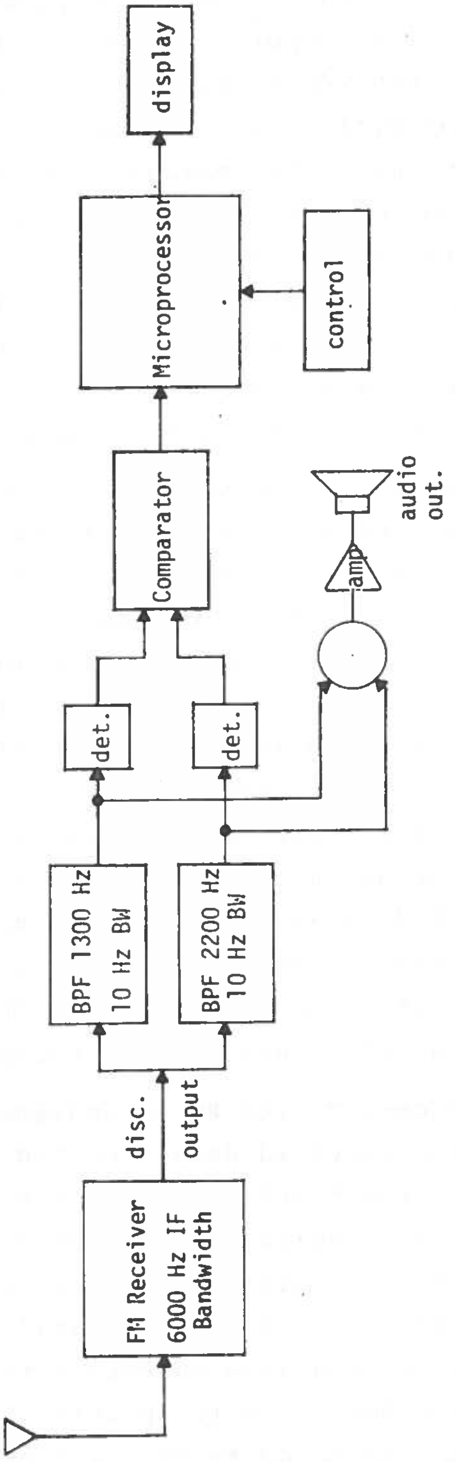

FIGURE 5-2. CODE RECEIVER SYSTEM

of 90% and probability of false alarm of 1 x 10^{-6} requires only an additional 8 dB. (Ref. 9)

In order to insure accurate data decoding, bit synchronization must be accurate to within 10% of a chip duration. At this level the loss in performance due to synchronization error is nominally 1 dB. The minimum energy-to-noise density per code chip in the preamble is approximately 12 dB given 20 dB-Hz at the output of the discriminator, 2 dB binary detection loss, and one-quarter second chip duration. A recent study of the type of system proposed for the EPIRB receiver has shown that a 10% rms error is achievable when the chip energy-to-noise density is approximately 6 dB.(Ref. 10) This means that the bit synchronization portion of the data detection and decoding operation has a 7 dB margin given the design parameters selected.

During the latter 10 seconds of the channel 15 transmission interval, the vessel identification number and distress code level are transmitted at a 5-bit per second rate. Thus, the energy-to-noise density per bit is 12 dB. This estimate includes the 2 dB binary detection loss. It is reasonable to assume that the performance achievable by this system will be comparable to that achieved by an incoherent FSK data link. Thus, it is estimated that the bit error rate given E/N_0 = 12 dB is approximately 1 x 10^{-4}.

It is possible to improve decoder performance by increasing the channel 15 ON time. This will accentuate the battery energy storage problem and will reduce the multiple EPIRB detection performance. Alternatively, it is possible to redistribute the 15 second channel 15 ON time between the prekey and data transmission intervals. This approach will reduce the distress message automated detection capability and will increase bit synchronization error. Such a trade seems hardly appropriate because the decoding process cannot begin unless detection has been achieved. All things considered, it would appear that the selected system parameters are in the desired ranges for this system. Further refinement should be carried out; for example, the design presented second bit duration, the bandpass filters should have 8 Hz bandwidths. In fact, the experimental system used commercially available filters which were somewhat wider, roughly 18 Hz. The outputs of the bandpass filters are detected to determine a measure of the amplitude in each of the bandpass filters. The detectors in the experimental system were implemented using analog multipliers, which provided nearly ideal square law detection characteristics. Under poor signal-to-noise ratio conditions, it can be shown that square law detection characteristics are optimum with respect to small signal suppression effects.

The envelopes of the two filters are compared in a comparator. The result of the comparison produces a high or low TTL level at the output of the comparator depending on whether the 1300 Hz filter output exceeds the 2200 Hz filter output or vice versa. The bandpass filter outputs are also summed in an analog fashion and applied to a front-panel mounted speaker for audio alerting purposes.

The logic output of the comparator is applied to a microprocessor system. The microprocessor was implemented using an Intel SBC80/10, which is a commercially available module using the Intel 8080 microprocessor chip. The microprocessor interfaces with front-panel control inputs, a Burroughs self-scanned display and in addition a teletype RS-232/C interface is provided on the rear panel.

When the system is turned on, a front panel pushbutton resets the system, and the program is set to the monitor mode. In this mode, the program samples the output of the comparator and checks for correlation between the noisy bit pattern received from the comparator and a stored replica of the preamble sequence. If and when the correlation score exceeds a set threshold, the program leaves the monitoring mode and proceeds to search for the peak of the correlation function. Once the peak finder locates the correlation maximum, a simple manipulation determines the bit synchronization timing for the digital message which follows the preamble sequence. The program then proceeds to sample and store

6. TEST PROGRAM

6.1 TEST SUMMARY

Two prototype EPIRBs were constructed for the initial tests. The first unit was designed as a test bed and reference for comparison. It transmitted a continuous signal which alternated between modulated and CW transmissions. The second unit was the first prototype water-deployable unit with varying duty cycle. Using these two transmitters, a detailed field test was conducted during July and August, 1977. Table 6-1 summarizes the test results. The tests conducted were as follows:

a. A series of measurements were made at carefully calibrated distances. A 41 foot cutter served as a signal source, carrying the two test units to previously designated positions. The prototype EPIRB was deployed in the water, while the TSC test transmitter stayed on board the cutter. An instrumented TSC Van was used as a shore-based receiving site. At this site, measurements were made of signal level versus range during all tests. These measurements were then compared with two sets of analytical predictions. The measured signal level, in all cases, was the same as, or greater than the predicted level, thus validating the accuracy of the predicted level.

b. One Coast Guard cutter was equipped with a Dorne and Margolin homing direction finder. Tests of homing ability were then performed using this cutter, and a homer-equipped Coast Guard helicopter. The prototype EPIRB was deployed in the water, at various carefully located sites. The cutter and helicopter then attempted to home on the EPIRB from various distances. The 41 foot cutter consistently homed directly to the EPIRB from a range of 8 nautical miles. The helicopter homer could not home reliably at a range of more than 10-12 nautical miles, at altitudes of 500-1500 feet. However, when the helicopter receiver was switched out of the "homing" mode, the EPIRB signal could be received at ranges greater than 20 miles. Discussion with the helicopter pilots revealed that it was normal to experience a large loss of sensitivity when operating in the "homing" mode. This is not true of the homers used on cutters, and is believed to be due to a poor antenna design on the helicopter.

c. Three automatic read-out radio direction finders were then installed at the shore receiving site. These direction finders were selected as typical commercial units available for use in this frequency band. A series of tests were performed at different angles and ranges. These results demonstrated the ability of all three direction finders to make quick, accurate bearing measurements on the EPIRB signal. Typically, accuracies of 1 to 3 degrees were observed.

d. Four more prototype EPIRBs were designed and built. These units were carefully sealed and pressurized, because of leakage problems and resultant corrosion problems with the first unit. A special purpose EPIRB receiver was also designed and built. This receiver has the capability to receive and process the EPIRB signal, automatically generating an ALERT signal and providing a readout of the identification and situation data if encoded on the EPIRB transmission. This receiver was installed and tested at the shore site. The EPIRB signal was detected and the ALERT signal generated at a range of 30 miles from the shore site.

The van was equipped with a calibrated reference dipole whose output was fed to the receiving system through a known length of coaxial cable. The received signal was displayed on a Hewlett-Packard spectrum analyzer. Initial signal-level calibration was provided by feeding a known signal level into the antenna-end of the cable from antenna to the receiver.

For the initial tests, two transmitters were used. The first transmitter had an output power of 2 watts, using a dipole antenna and transmitted a signal which alternated between a two-tone modulation and a CW signal. The second transmitter was a prototype EPIRB. The EPIRB was watertight and designed for water deployment. This unit transmitted the chosen EPIRB modulation, as described in sections 2.4 and 4.1.

The test procedure was as follows:

1. The mobile van proceeded to the test site at Winthrop Highlands. When on site, antennas were erected and receiving equipment was calibrated.

2. The two test EPIRBs were placed aboard a Coast Guard 41 foot cutter. The cutter then proceeded to the first test location for the day. All tests were conducted in the vicinity of known navigational marks, principally buoys. Therefore, the distance from the test site to the EPIRB could be measured from the area chart.

3. Communication was established between the shore receiving site and the test cutter. Upon request, the cutter personnel would first energize the test transmitter at a known location aboard the cutter. Reception of this signal established a reference signal level for an unmodulated carrier and for a typical EPIRB modulation, transmitted from a fixed platform. When the reference level had been measured, the test transmitter was turned off; the EPIRB was then turned on and deployed in the water, 10 to 20 feet from the

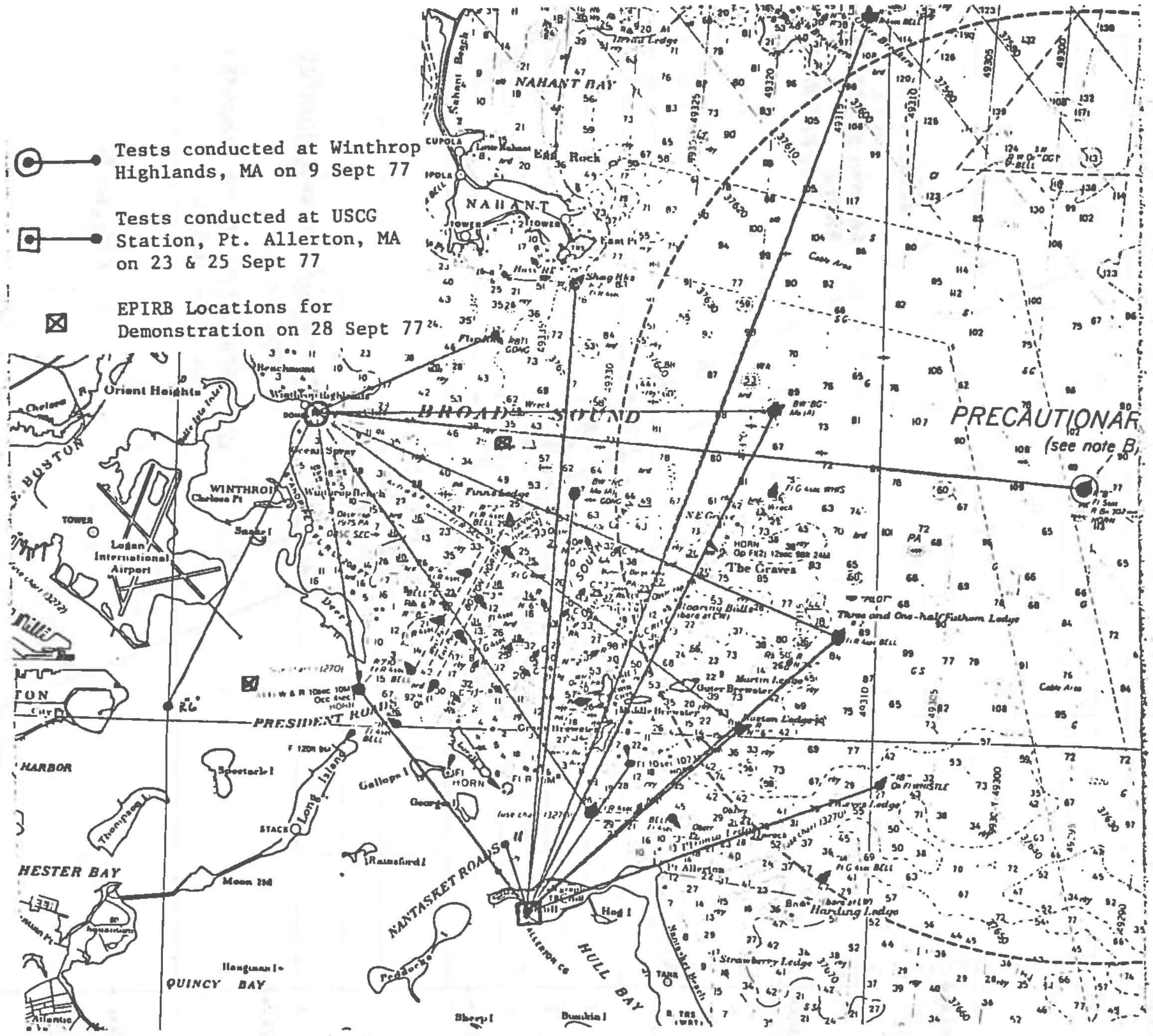

FIGURE 6-1 EPIRB TEST AREA CHART

6.4 EPIRB RECEIVER TESTS

The next set of tests was designed to verify reception range by the special EPIRB receiver described in section 5. In order to perform this test, the EPIRB was deployed by the cutter at a series of locations with gradually increasing range. Cutter location was determined by reception of Loran-C signals at the cutter with a commercial Loran-C receiver. At each test location, the EPIRB receiver verified correct reception by teletype printout of an identification number transmitted by the EPIRB.

This reception was perfect out to approximately 21 nautical miles. Beyond this range, signal reception was quite erratic, as deep fading was encountered. This was due to the relatively low height (30 feet) of the receiving antenna, plus substantial swells (3-6 feet) in the test location. Accordingly, a directional antenna with approximately 9 dB gain was substituted for the standard dipole receive antenna. This was equivalent to increasing the antenna height by a factor of 2.8 (to approximately 85 feet). With this antenna, the EPIRB receiver received and printed out the correct ID every time, out to a range of 33 nautical miles. This test verified the design range of the EPIRB receiver, as the unit was designed for reception to 30 miles.

6.5 SYSTEM DEMONSTRATION

Upon completion of the test program, the receiving test site was moved to the roof of the Pt. Allerton Coast Guard Station, Hull, Massachusetts in preparation for a system demonstration to be performed for personnel from the Coast Guard, FCC, & NASA. The demonstration included homing and location of EPIRBs from Coast Guard Cutters, and the use of shore-based direction finding as a Search and Rescue aid. Due to the presence of considerable land masses to the east and southeast of the station, which completely blocked line-of-sight paths from the ocean surface to the antenna locations, preliminary testing of DF reception from various azimuths was conducted. Two EPIRB test locations were selected which included significant close-in land blockage in the line of sight to the receiving antenna: 7.6 mi on a bearing of 119°M and approxi-

7. CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation are best summarized in the following conclusions and recommendations. The recommended EPIRB parameters are summarized in Table 7-1.

1. An EPIRB output power of one watt will provide highly reliable reception at a range of 20 nautical miles, provided that:
   a. The receiver antenna is located 100 feet or more above sea level.
   b. The EPIRB transmitting antenna design provides good radiation characteristics at low elevation angles. "Good" is here defined as equivalent to a true isotropic antenna; i.e., a net gain of no less than 2 dB below a dipole.

2. The EPIRB need not transmit continuously. Rather, the transmission should be for short (10-20 seconds) periods, with longer (30-60 seconds) periods of no transmission. This has been shown to provide efficient operation with substantial savings in battery power and no loss of information. Further, it is recommended that the EPIRB transmission should initially be relatively frequent, about once per minute; it should then gradually slow down, so that after approximately eight hours the transmissions will occur only 10-12 times per hour.

3. The EPIRB can be equipped to transmit low bit rate (eight bits per second) digital data on Channel 15. Such data transmission can be used to provide the following features:
   a. User identification. A 20 bit digital code, with a different code built into each unit at time of manufacture, will provide a unique identity for up to one million users. The number of unique

identities is easily increased; a 25 bit code will identify 33 million users and a 30 bit code will suffice for up to one billion users. At 8 bits per second, this will require less than four seconds of transmission time.

b. Situation encoding. A three bit code can generate information as to eight different situations or types of distress, entered by an external switch on the EPIRB. Some knowledge as to the nature of the distress situation would be extremely desirable; however, there is some evidence that most people will exaggerate the seriousness of the distress.

4. The recommended EPIRB modulation consists of a two-tone FSK signal. The tones used are 1300 Hz and 2200 Hz. Each transmission consists of a short (1-2 second) burst of tones on Channel 15, followed by a longer (15 second) burst on Channel 15 after which the Channel 16 transmission repeats. Each Channel 16 signal consists of the two tones alternating four times per second; the Channel 15 transmission utilizes the same two tones to transmit FSK data.

5. In areas of high boating activity and consequent high traffic density on Channel 16, reliable reception of the EPIRB transmission on Channel 16 can be very uncertain. Consequently, the Coast Guard should consider monitoring Channel 15 in high traffic density areas. It was demonstrated on this program that a receiver could be designed to correlate the Channel 15 data transmission so as to provide highly reliable alert detection at low signal reception. This receiver provided the following features.

a. Automated detection of an alert on Channel 15, thus minimizing the requirement for additional watch-standers.

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power is 1. watt. Reception at heights from 0. to 3048. meters is indicated. The resulting ground distances, dictated by the requirements of constant field of 30., 10., 3., 1., and .3 and .1 μV/m, extend to 300. km.

The computation is repeated for a fresh water path but only for "sea state" 0 (i.e., 0. wind velocity). The reason for this limitation is given below.

A.3 LIMITATIONS

The computer codes used in the present computation are based on the results of work done by van der Pol and Bremmer[1], Barrick[2] and Kaliszewski[3,4]. So far as their use at VHF and in a sea environment is concerned certain assumptions implied in the above analyses must be scrutinized and, in particular, those defining the limitations on the validity (and use) of the concepts of the surface impedance, of the apparent conductivity and of the roughness criteria.

A.3.1 Normalized Surface Impedance

The implied limitation on that parameter is

$$|\Delta| < 1$$

where

$$\Delta = \frac{1}{\sqrt{\varepsilon_r - i60\lambda\sigma}}$$

Here, ε_r is a relative dielectric constant of the ground, λ - is a wavelength, in free space, in meters and σ - is conductivity in mhos/m.

In our case we have:

I. Sea Path: $\varepsilon_r = 80$
$\sigma = 4.$ mhos/m
$f = 158.6$ MHz
$\lambda = 1.913$ meters

Consequently,

$$|\Delta| = 0.0463 << 1.$$

and ξ - is the surface height above a mean level.

For a wind driven sea surface we have the following theoretical relation:

$$\overline{h} = 4.345.10^{-3}\sqrt{U^5}$$

where U is the wind velocity in meters/sec.

By setting $(K_o\xi)^2 = 1$ we obtain the upper limit of applicability and, hence,

$$\overline{h} \simeq .3045 \text{ meters}$$

and

$$U \simeq 5.473 \text{ m/sec.}$$

corresponding, roughly, to sea state 2.

A little more relaxed criterion is obtained from the relation (implied in the program) derived from the Phillips model of the sea surface:

$$(K_o.\sigma)^2 \leq 1.$$

where

$$\sigma^2 = \frac{1}{2} BU^4/g^2$$

$$B = 0.005$$

$$g = 9.81 \text{ m/sec.}^2$$

Hence, at 158.6 MHz,

$$\sigma \simeq .3045 \text{ meters}$$

and

$$U \simeq 7.73 \text{ m/sec.}$$

or, roughly, corresponding to sea state 3.

We conclude, therefore, that the existing program can be used readily up to sea state 3. In fact we have exercised it also at sea states 6 and 9 and find the results to be quite agreeable although, as indicated above, we cannot justify the validity of the results at these high sea states.

TABLE A-1. COMPARISON OF CONTOURS AT VARIOUS SEA STATES

Sea State	Field Strength, μV/m	Difference, db
0	0.222	0
1	0.187	1.476
2	0.161	2.794
3	0.140	4.003
6	0.098	7.030
9	0.038	15.526

The comparison would indicate, at the specific heights and distance, a relative decrease in field strength of approximately 1.5 dB per sea state (or 5. knots in wind velocity). Surprisingly, this regularity extends well beyond the sea state which can be justified by the theoretical considerations.

The contours shown in Figs. A-1 to A-7 afford a quick appraisal of the permissible path geometry for a prescribed signal strength. Unfortunately, for low elevations the contours tend to be crowded and, in fact, obscure the intercept points at zero elevation. However, these can be recovered from the printouts. For example, the intercept point for SS = 0, .1 μV/m (zero elevation) can be read from the printout, at about 60. km.

It should be noted that most (but not all) data points were obtained at reception points below the horizon. This is quite fortunate for the computer fields are then truly radial (i.e., locally vertical). This is not the case with the line-of-sight paths where (1) further decomposition of the field strength may be necessary, and (2) the elevation pattern of the monopole must be considered. A modification of the program to enhance its LOS prediction capability is quite possible but must await a future opportunity.

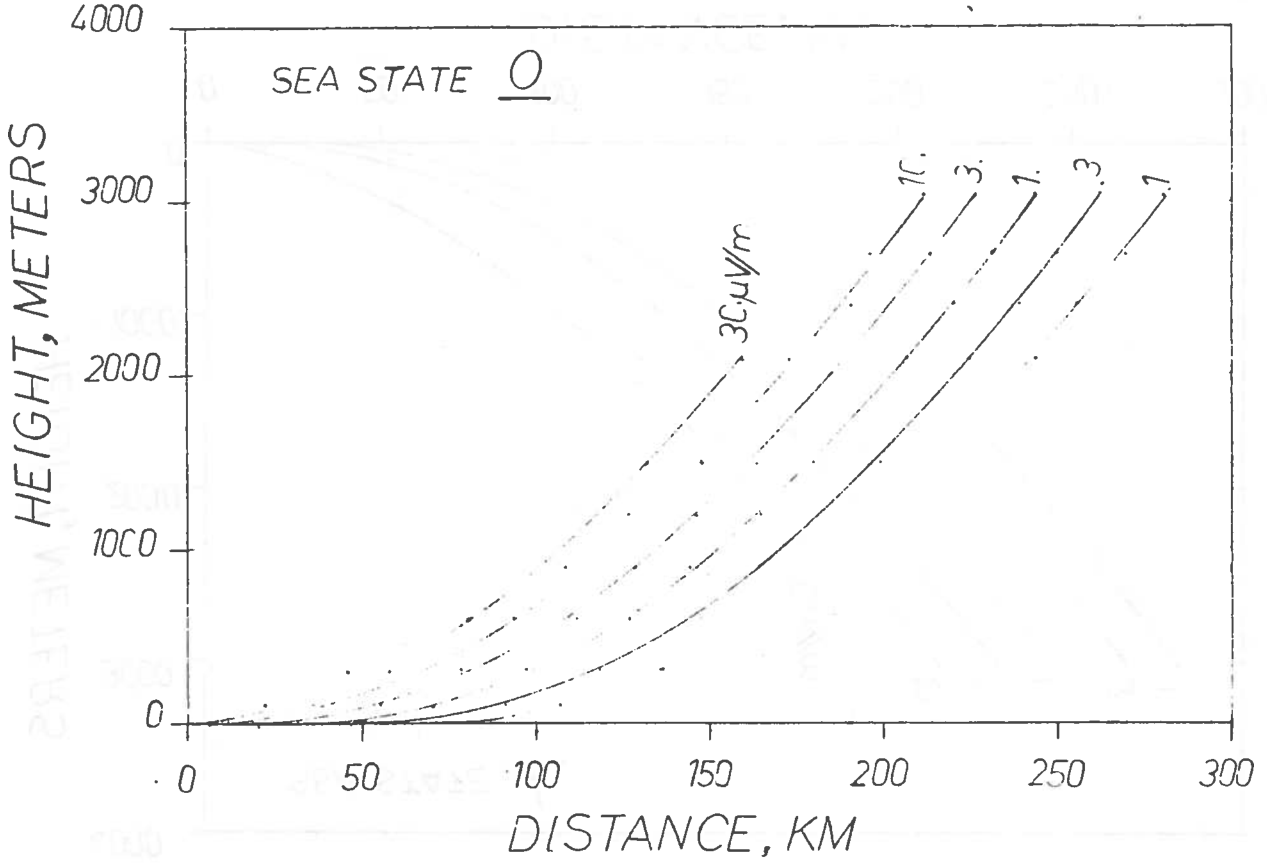

FIGURE A-1 CONTOURS OF CONSTANT FIELD STRENGTHS

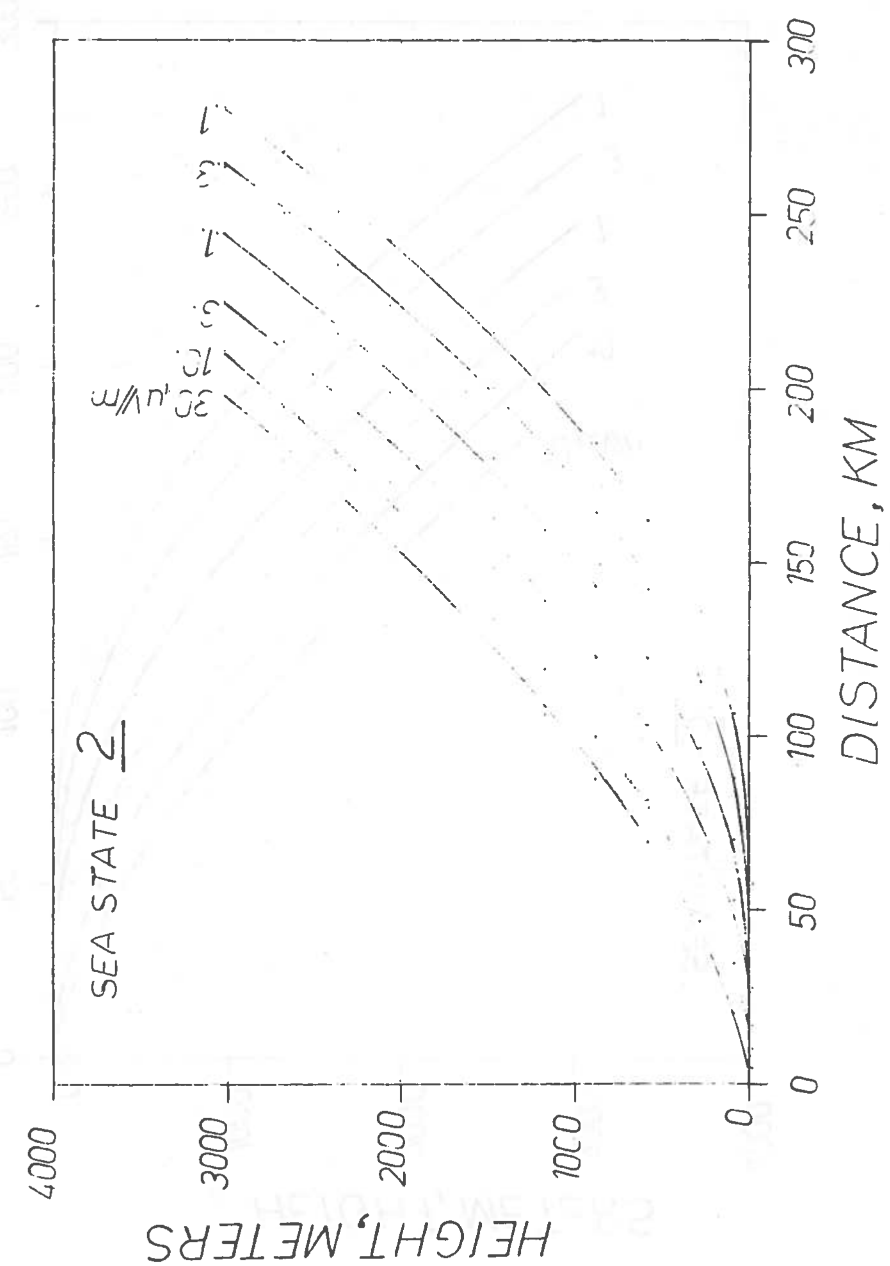

FIGURE A-3 CONTOURS OF CONSTANT FIELD STRENGTHS

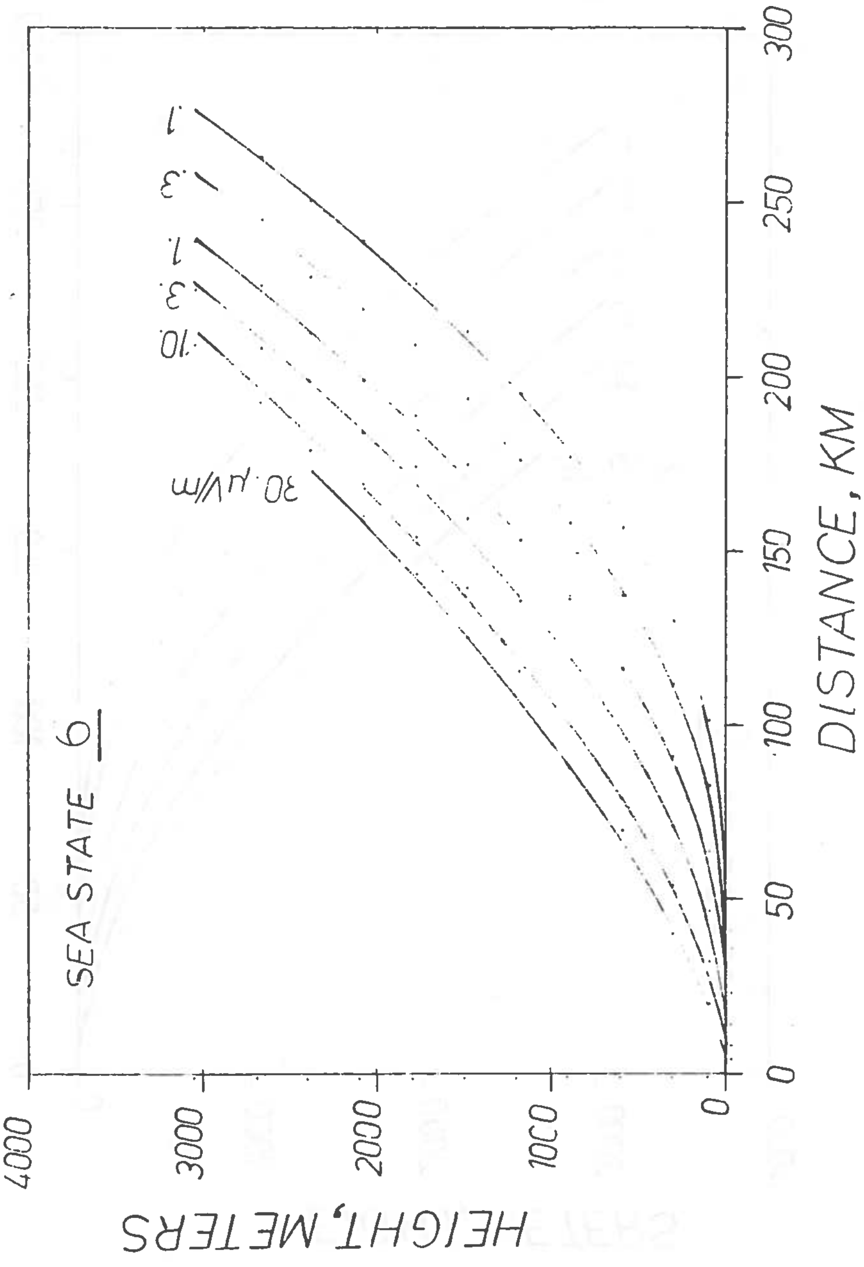

FIGURE A-5 CONTOURS OF CONSTANT FIELD STRENGTHS

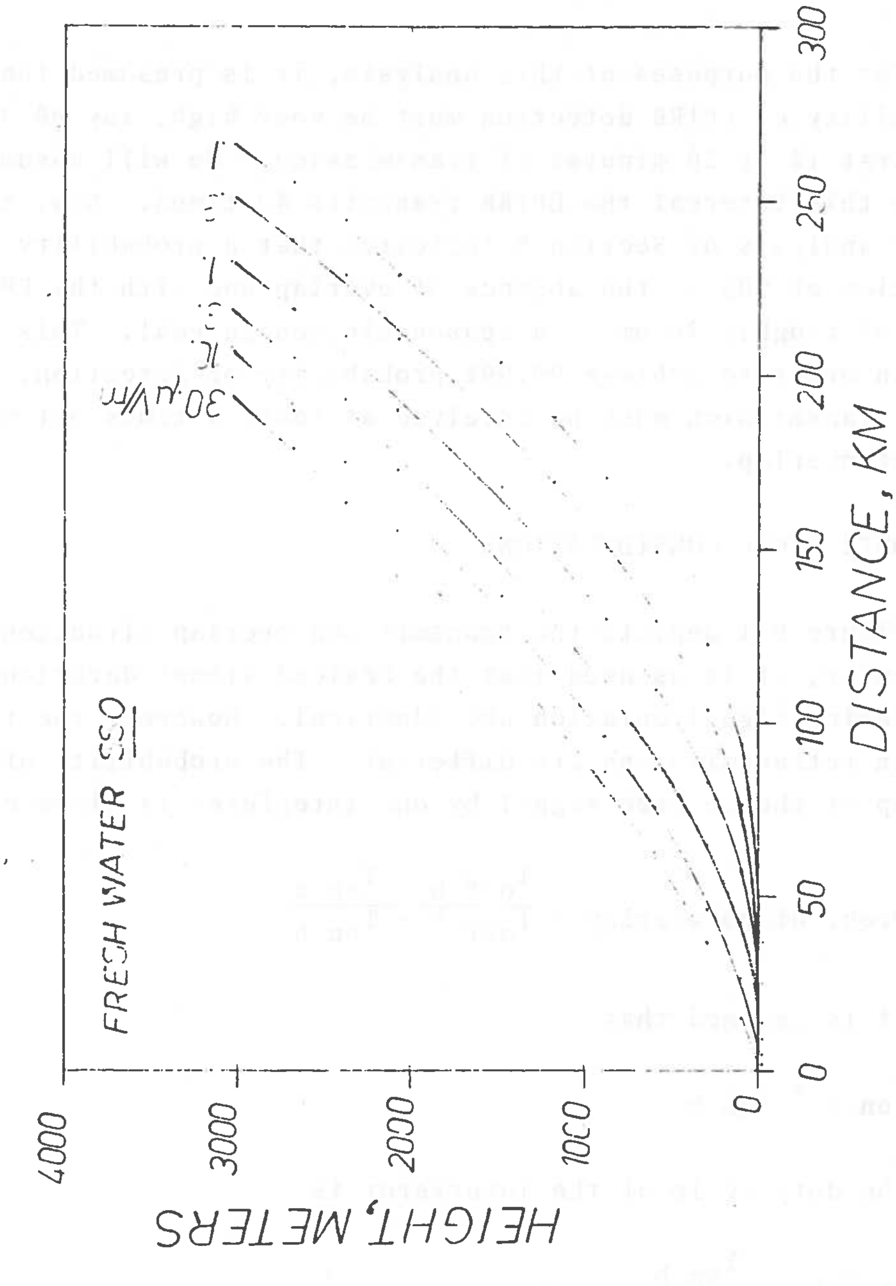

FIGURE A-7 CONTOURS OF CONSTANT FIELD STRENGTHS

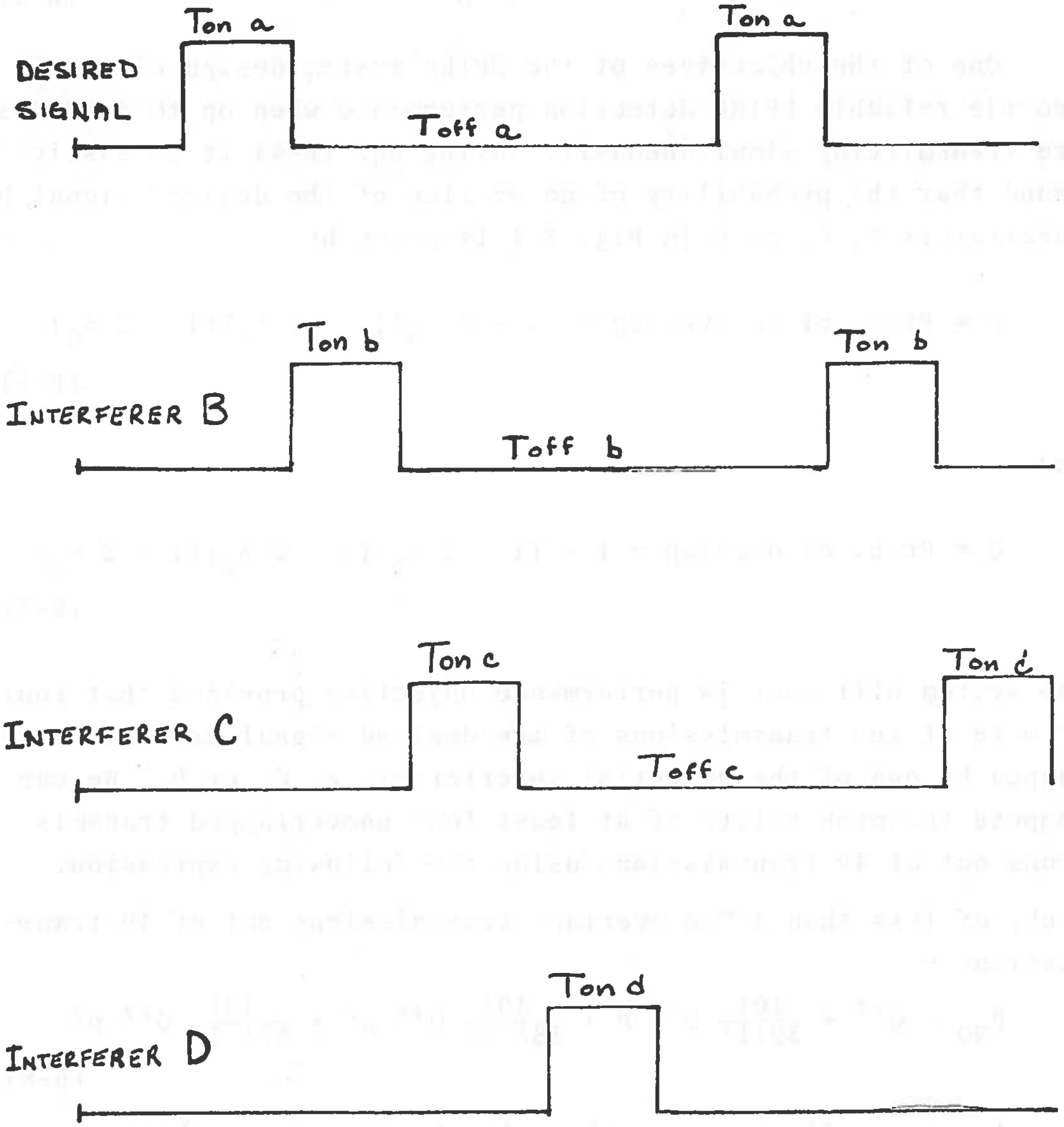

FIGURE B-1. THE OVERLAP PROBLEM

TABLE B-1. PROBABILITY OF SUBSTANDARD DETECTION PERFORMANCE VS. DUTY CYCLE

δ = Duty Cycle of Interferers	Prob. of Poor Performance
$\delta = 0.1$	4.24×10^{-9}
0.15	8.27×10^{-5}
0.2	1.64×10^{-2}
0.25	2.46×10^{-1}
0.3	7.48×10^{-1}
0.35	0.978
0.4	0.999
$\delta_b = 0.25,\ \delta_c = 0.15,\ \delta_d = 0.0625$	4.54×10^{-4}
$\delta_b = 0.25,\ \delta_c = 0.15,\ \delta_d = 0.15$	5.69×10^{-3}

The table clearly shows that there is a rapid onset of poor performance when the duty cycle of the interferer is in the vicinity of 20%. Moreover, the table shows that if the duty cycle of the interferers is less than 10% there is no chance that less than 4 transmissions out of 40 from a given EPIRB will be overlapped by any of the other three EPIRB transmissions. Table B-1 also shows the more complicated case in which the duty cycles of the 3 potential interferers is not the same. Here again, good performance will be achieved as long as the duty cycles of the potential interferers is less than 20% on the average.

The discussion of this section shows that the system can provide adequate performance with 4 EPIRBs operating simultaneously provided that the duty cycles of the 3 interfering EPIRBs is roughly 20% or lower and that the duty cycle of the desired EPIRB signal is high, i.e. roughly 50%. Figures B-2 and B-3 show candidate duty cycle patterns for the EPIRB system. These patterns are easily generated using low cost digital logic in the EPIRB system. The pattern of Fig. B-2 begins with a duty cycle of 40%. This duty cycle remains for the first 400 seconds (6.66 minutes). Then the duty cycle is reduced to 25% and this persists for the next 640 seconds. The duty cycle is reduced at regular intervals

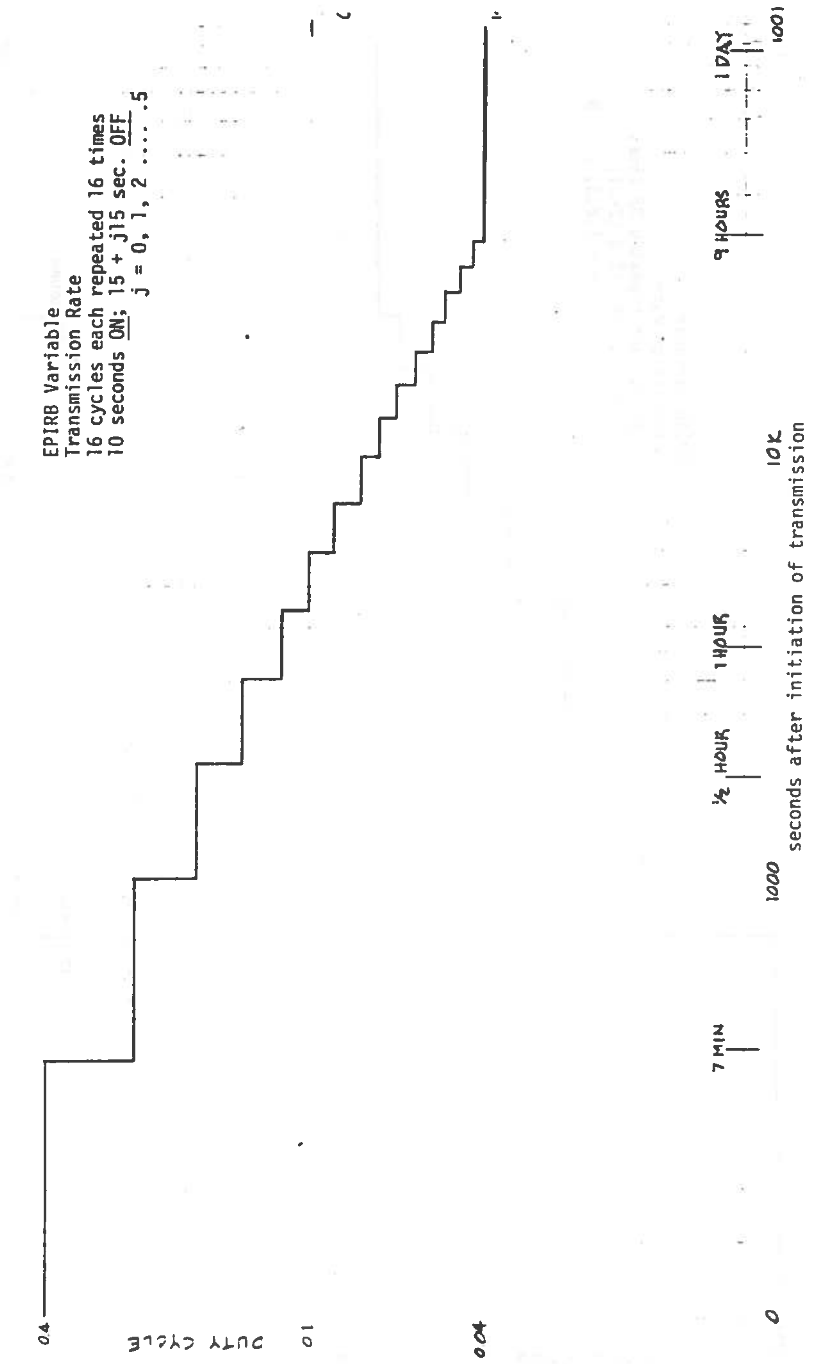

FIGURE B-2. EPIRB VARIABLE TRANSMISSION RATE
16 CYCLES EACH REPEATED 16 TIMES
10 SECONDS ON; 15 + j15 SEC. OFF
j = 0, 1, 2 5

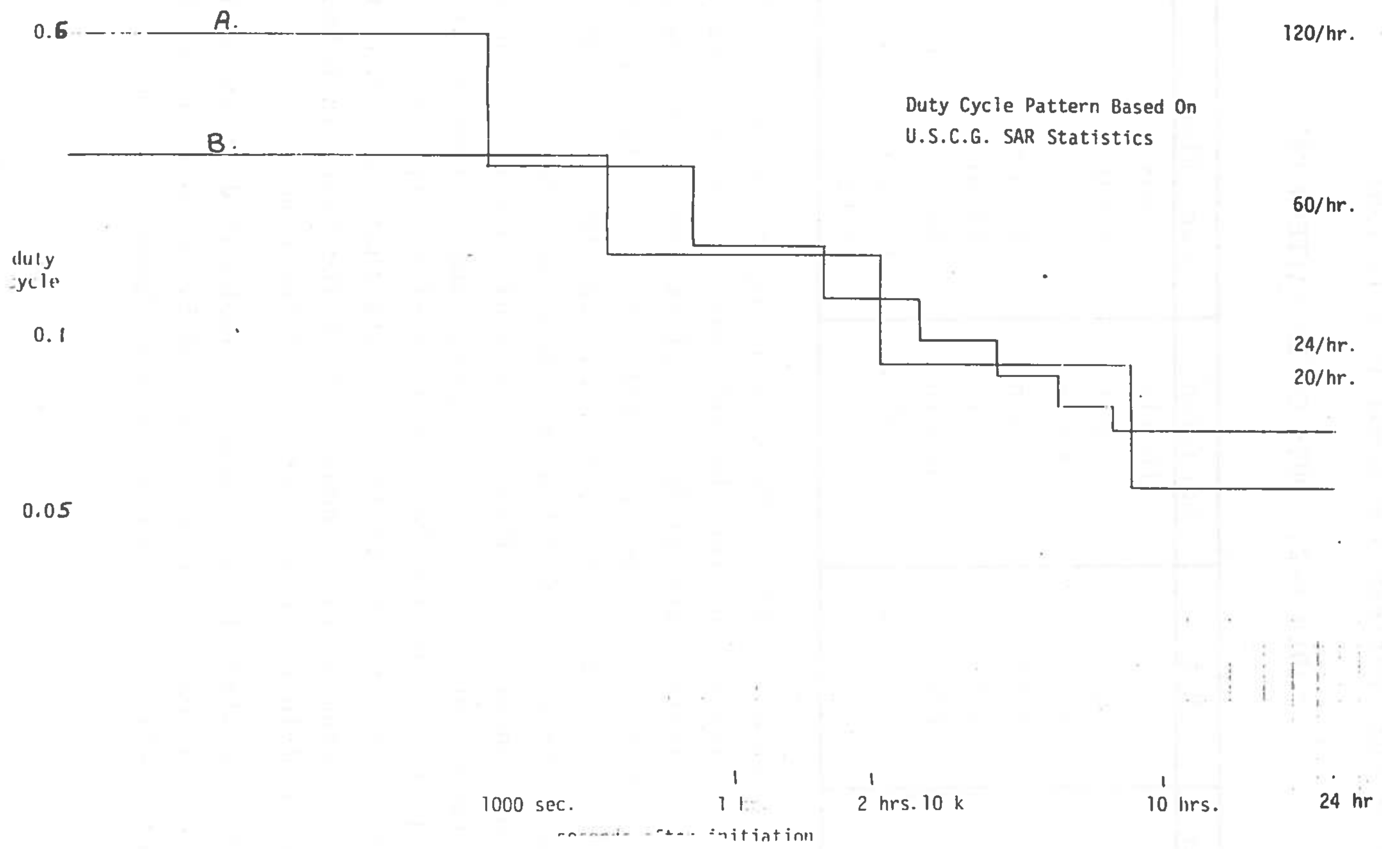

FIGURE B-4. DUTY CYCLE PATTERN BASED ON U.S.C.G. SAR STATISTICS

TABLE B-3. DUTY CYCLE PATTERN "B"

Duty Cycle	Rate	Duration	Cum. Time
26.3%	1.05/min.	30.4 min.	30.4 min.
15.8%	37.9/hr.	101.3 min.	131.7 min. (2.2 hrs.)
8.8%	21.1/hr.	364.8 min.	
4.6%	11.1/hr.	-	24 hrs.

Patterns "A" and "B" are quite similar in the region from 1000 sec. to 30000 secs. (8.27 hrs.). The differences between the two patterns occur at the beginning and the end of the duty cycle patterns. Both satisfy the general constraints of the EPIRB multiple access requirement. Namely, the duty cycles are less than 20% most of the time. However, the duty cycle pattern of Table B-3 is the one recommended for implementation. It is the simplest of all those considered, and the changes in the pattern correspond most closely to the available statistics on time to rescue.

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