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DISTRESS BUOY SYSTEM ANALYSIS

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16. Abstract

This report presents a brief analysis and comparison of two candidate approaches to the implementation of a multiple access Emergency Position Indicating Radio Beacon (EPIRB) system for maritime use. One approach, implemented by the Federal Republic of Germany and tested by the European Space Agency (ESA) during the 1974-1975 ATS-6 tests, uses frequency-shift-keyed (FSK) audio tone pairs for user identification, with detection employing a bank of narrow-band filters. False alarm probabilities and other parameters are calculated for this approach. An alternative to this approach, promising improved performance in the presence of multiple interfering EPIRBs, is also described. This alternative uses orthogonal Pseudo-Noise (PN) spread-spectrum sequences to identify each EPIRB uniquely. These sequences are easily generated using linear shift registers, and the resulting receiver structure is comparable in complexity with that needed for the FSK approach. It is concluded that the acquisition and detection performance of the two approaches is about equal, but that the spread-spectrum method has advantages in a multiple-access environment.

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PREFACE

A signaling technique for Emergency Position Indicating Radio Beacons (EPIRBs) using FSK modulation, with detection employing a bank of narrow-band filters, was designed and implemented by the Federal Republic of Germany for ESA tests with the ATS-6 satellite. An alternative signaling scheme using spread-spectrum pseudo-noise (PN) modulation with phase-locked loop demodulation and correlation detection was felt to give improved performance in a multiple EPIRB environment. This report presents a description and comparative analysis of the two designs.

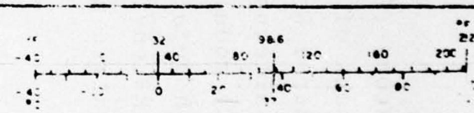
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

This report analyzes an existing L-band distress buoy design, and recommends alternative designs which should be considered.

2. ANALYSIS OF SYSTEM TESTED BY ESRO* WITH ATS-6

A current distress buoy system is described in "European Communications Experiments in L-Band with ATS-6," Vol. 6 Distress Buoy, System Design, Instrumentation and Experiment; European Space Research Organization, October 1975.(1) The disucssion of this section is based on the system description given in the document.

2.1 GENERAL DESCRIPTION

The system transmits a 64-bit message which is Miller (delay modulation) encoded. The bit rate is 64 bits/sec so that the message repeats once per second.

The data stream is used to deviate the transmitted L-band frequency. The separation between Mark and Space frequencies is either 240 or 480 Hz (480 Hz is used in only one mode of operation). Thus, the transmitted output is an L-band frequency shift keyed (FSK) signal with 64 bits/sec transmitted by deviating the carrier $\pm$ 120 or $\pm$ 240 Hz. The carrier center frequency is assumed stable to 1 part in 10^6. So an rms center-frequency error of roughly $\pm$1600 Hz should be anticipated.

The receiver converts the received L-band signal to baseband. Specifically, a band which is roughly 3000 Hz wide about the received carrier is translated down to the audio region. This band is analyzed by a bank of 48 bandpass filters. These are spaced every 60 Hz across the band, and each is 75 Hz wide.

Detection occurs when two of the bandpass filters indicate the presence of a signal. The two filters must be separated by the FSK deviation to indicate a valid signal. Thus, the probability of detection P_D of the distress message is given by

$$P_D = (P_d)^2,$$

---

*The name of the European Space Research Organization has been changed to European Space Agency (ESA).

where P_d is the probability of detection on one of the baseband filters. It should be noted that one filter sees only half of the received signal power assuming a reasonably balanced binary message as should be produced by the use of Miller encoding.

In order to create a false alarm due to noise, two filters with the appropriate spacing, say, 240 Hz, must erroneously indicate the presence of a pair of signals. Assuming 48 channels and a 4-channel separation between Mark and Space frequencies, the probability of false alarm, P_F, is approximately

$$P_F = 44 \, (P_f)^2 (1 - P_f)^{46},$$

where P_f is the probability of noise causing the threshold to be exceeded in a given channel filter. The expression above is approximate, in that it excludes the possibility that more than 1 pair of filters exceeds the threshold due to noise.

Now, the received carrier-to-noise density, C/N_o, worst case, is on the order of 20 dB Hz. This assumes the link budget given in Table 1.

The link budget of Table 1 does not include a multipath loss. This effect will be considered as part of the detection analysis.

2.2 DETECTION ANALYSIS

In the absence of multipath fluctuations, the received signal-to-noise ratio (S/N) in a 75-Hz bandwidth filter is

$$S/N = 24 \text{ dB} - 3\text{dB} - 18.75 \text{ dB} = 2.25 \text{ dB}.$$

The 3-dB reduction is due to the fact that the signal is at each of the two FSK frequencies only half the time.

Now assuming a Rician fading signal with carrier-to-multipath ratio (C/M) of about 6 dB, and assuming that the fading is correlated over most of the detection integration, there is a loss due to signal fluctuation on the order of 2 dB.[2] This means that the available S/N per received bit is on the order of 2.25 dB-2.00 dB = 0.25 dB.

TABLE 1. DISTRESS BUOY LINK BUDGET*

Transmitted Power	+34.8 dBm
Transmitted Antenna Gain	0.0 dB
Pointing Loss	-4.0 dB
Cable and Coupling Loss	-0.8 dB
Effective Isotropic Radiated Power (EIRP)	+30.0 dBm
Space Loss	-189.0 dB
Receiver Antenna Gain	+18.0 dB
Polarization Loss	-1.0 dB
Pointing Loss	-1.0 dB
Cable and Coupling Loss	-1.0 dB
Total	-174.0 dB
Received Signal Level at Spacecraft (SC)	-144.0 dBm
Noise Density at S/C Receiver (Assuming 880° K)	-169.0 dBm/Hz
Received C/N_o at S/C	+25 dB Hz
Limiter Loss in S/C	-1 dB
Received C/N_o at Ground Station	+24 dB Hz

*This link budget is similar to that used by ESRO.

Next, the loss through the envelope detection process must be estimated. Given an 0.25 dB S/N at the input to the detector, the output S/N per bit is roughly -1.5 dB.[3] But 32 bits are integrated, on the average, over a 1-sec interval. Thus, the S/N at the output of the integrator is -1.5 dB + 15.0 dB = 13.5 dB where 15 dB expresses the enhancement provided by the 32 bit integration.

At that level, detection probabilities and false alarm rates on the order of those shown in Table 2 are achievable.[4]

TABLE 2. RECEIVER OPERATING CHARACTERISTICS

Probability of Detection (P_d)	Probability of False Alarm (P_f)
0.95	1×10^{-6}
0.995	1×10^{-4}

Using the second set of values in Table 2, it is found that the probability of detection, P_D, of the FSK distress signal is

$$P_D = (0.995)^2 = 0.99,$$

and the probability of false alarm, P_F, is approximately

$$P_F = 44(10^{-4})^2 \ (1 - 10^{-4})^{46} = 4.38 \times 10^{-7}.$$

At one detection decision per second, this implies a false-alarm rate of 1 per 264 days. Note that this detection performance is achieved at C/N_o = 24 dB Hz.

2.3 PERFORMANCE EVALUATION

The basic detection-false alarm performance of the system is quite satisfactory. Following detection; i.e., the determination that a distress signal is present, the outputs of the two baseband filters which indicated signal presence are amplitude-detected and subtracted to form a baseband bipolar data signal. This signal is then digitized and digitally integrated. The message is 64 bits long, and therefore, repeated every second. Thus, the integration is performed by superposing 1-sec repetitions of the received message until enough noise reduction is achieved to decode the message accurately.

Let us now consider the operation of this system when more than one distress buoy is energized at the same time. In that case, there will be two tone-pairs in the baseband. As long as these tone pairs do not overlap, there should be no problems because the satellite will pass the two FSK signals in quasi-linear fashion. However, each signal has a center-frequency uncertainty on the order of $\pm$ 1600 Hz. Thus, assuming a 240 Hz FSK deviation, there is a 7.5 percent chance that the two distress messages will overlap. When they overlap, and neither signal has been previously detected, it is likely that the detection algorithm will fail. Moreover, data demodulation will be seriously degraded when tones from different distress signals reside in the same channel filter unit.

The problem of signal overlap can be reduced by randomizing the transmission times of the buoys. For example, each buoy can be designed to transmit for 1 minute then remain off for, say, 10 minutes. In that case, the probability of overlap is reduced by a factor of more than 10. Thus, the probability of acquisition failure due to overlap will be less than 0.75 percent. Implementation of this approach implies that the mean time to first acquisition of the distress message is 5 minutes.

3. ALTERNATIVE DESIGN APPROACHES

Alternative design approaches were investigated to determine if high reliability distress buoy operation could be achieved when more than one buoy is in operation at the same time.

A number of techniques were considered. The constraints on the design are that (a) the transmitter system remain as simple or simpler than the basic design discussed above, and, (b) high reliability detection and data demodulation performance are obtained when two or more buoys are operated simultaneously.

3.1 THE PN-PSK TECHNIQUE

The pseudo-noise phase shift key (PN-PSK) approach has achieved wide acceptance as a spread spectrum-multiple access technique for satellite communication systems. It should be considered for the distress buoy application because it has the potential for meeting the design constraints defined above.

3.1.1 PN-PSK Transmitter Design

A block diagram of one possible distress buoy-transmitter implementation is shown in Figure 1. The system is somewhat simpler than the basic FSK design, and will provide a more stable carrier frequency because it uses a fixed crystal oscillator rather than a Voltage Control Oscillator (VCO) as its frequency reference.

The operation of the device is as follows: The crystal oscillator output is multiplied up to L-band and mixed with the L-band VCO output in a phase detector. The output of the phase detector, with the PN-PSK baseband signal, is passed through a loop compensation network, and applied to the voltage control input of the L-band VCO to close the loop. The PN-PSK baseband signal is added to the phase error output, so that the L-band VCO output is phase-modulated by the PN-PSK data stream. Phase

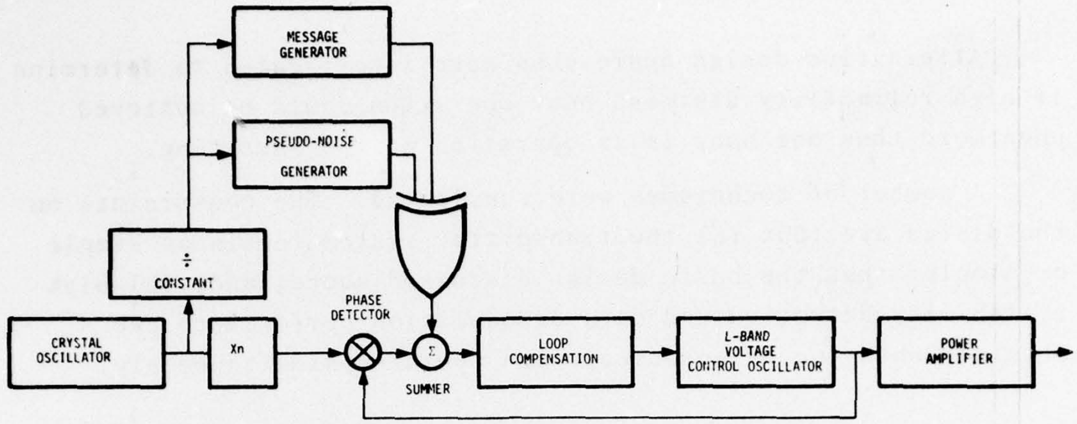

FIGURE 1. PN-PSK TRANSMITTER

deviation is controlled by adjusting the PN-PSK amplitude level at the phase error summing point. The PN-PSK encoded message is generated by digital logic which is clocked from the crystal oscillator.

3.1.2 Message Format

Typically, the PN-PSK approach is implemented so that one data bit is transmitted during each PN period. That is, a Mark is transmitted as one complete period of the PN sequence, and a Space is transmitted as the complement of the PN sequence. For ease of comparison, we will assume the same message format and data rate as were used by the ESA distress buoy. The message format for the PN system is defined in Table 3.

TABLE 3. MESSAGE FORMAT

Data Rate	64 bits/sec
Message Length	64 bits
Message Repetition Rate	1/sec
Number of Synchronization Bits	22
Number of Information Bits	42
Pseudo-Noise Sequence Length	127 bits

Each bit is represented by a 127-bit PN sequence, so that the actual transmitted bit rate is 64 X 127 = 8128 bits/sec. The phase modulation deviation is chosen so that there is considerable carrier power in the transmission. In particular, the deviation is set at ± 45 degrees. Thus, residual carrier power is 3 dB down from the total transmitted power output.

3.2 ACQUISITION PROCEDURE

The first step in acquiring the distress message is the detection of the presence of a carrier component at the receiver. Given that the worst-case C/N_o = 20 dB Hz as before, the residual carrier power-to-noise density will be 17 dB Hz, worst case.

Let us assume that the search for the residual carrier is accomplished by a phase-locked loop (PLL). The maximum sweep rate ω_{max} for a 90 percent probability of detection is approximately[5]

$$\omega_{max} = [1 - \sqrt{\frac{N_o B_n}{C}}]\ B_n^{\ 2} \ ,$$

where B_n is the double-sided noise bandwidth and C/N_o is the carrier-to-noise density.

Assuming a double-sided noise bandwidth of say 5 Hz the maximum search rate is 2.72 Hz/sec. The total frequency uncertainty region, 3000 Hz, can be swept in 1103 sec at this rate by a single PLL. A number of PLLs can be used in parallel to reduce the search time. In particular, let us assume that the ground station is equipped with 10 PLLs, each of which continuously monitors a 300 Hz portion of the total frequency uncertainty interval. Moreover, let us allow 5 minutes for each sweep; this corresponds to the mean acquisition time of the FSK system previously described. The sweep rate of the loops is 1 Hz/sec under these assumed conditions. The optimum loop noise bandwidth, assuming a second-order loop compensation, is 5.24 Hz. The worst-case noise error assuming a 17 dB residual carrier-to-noise density is roughly 13 degrees. At this level, the probability of acquisition will be well over 90 percent. In particular, if a synchronous amplitude detector and a low-pass filter with a 2 Hz 3 dB bandwidth are used for detection in conjunction with the PLL, the probability of detection will be 99 percent when the false-alarm rate is approximately 1×10^{-6}. This performance is better than that achieved with the FSK system previously described because C/N_o = 24 dB Hz was assumed for the FSK analysis while we have assumed C/N_o = 20 dB Hz.

3.3 DATA EXTRACTION

The indication that a signal is present in one of the PLL filters stops the sweep search procedure. At that point, the phase detector output of the indicating PLL will contain the coded distress message provided that a valid buoy signal was received.

A bank of code correlation detectors is used to determine whether or not the baseband output of the PLL which indicates signal presence is a valid distress message. A delay line correlation filter must be implemented for each possible 127-bit PN code format. The output of the correlation detector which is set up for the received PN code consists of positive and negative pulses at the distress message code rate, 64 bits/sec. These can be detected to produce the distress message. The message format given in Table 3 is such that there is insufficient energy-to-noise density per received distress message bit to ensure reliable detection of the message bits. In particular, the data power-to-noise density is equal to the residual carrier-to-noise density, assuming 45 degrees PSK deviation. Therefore, C_d/N_o = 17 dB, and the energy-to-noise density per bit is

$$E_b/N_o = C_dT/N_o = 17 \text{ dB} - 18.06 \text{ dB} = -1.06 \text{ dB}$$

where T is the bit duration.

Reliable bit detection requires E/N_o on the order of 10 to 12 dB. To achieve this level, the outputs of the correlation detectors can be integrated using digital techniques. For example, an 11 dB E/N_o can be achieved by integrating 30 received data bits each of which has E_b/N_o = -1.06 dB; i.e., there is an integration loss of roughly 2.5 dB.

3.4 DESIGN ALTERNATIVES

Thus far, we have assumed a basic message format similar to that of the FSK distress buoy system. However, by slowing the message bit rate down, we can gain two advantages. First, the 2.5 dB integration loss can, for the most part, be avoided. Second, the use of a slower data rate makes it easier to implement the entire data detection process (except for the PLLs) in digital computer software.

For example, a 2 bit/sec distress message data rate will provide E/N_o on the order of 17 dB - 3 dB = 14 dB, which is more than enough for reliable detection. The 2.5 dB integration loss will be avoided, provided that coherent detection is employed, and this can be done given a sufficiently low data rate.

The PN code bit rate is 2 X 127 = 254 bit/sec assuming a 2 bit/sec data rate and a 127 bit code. The PN encoded data signal must be digitized at a rate which provides roughly 5 samples per

PN code bit. Thus, a code correlation-shift register 5 X 127 = 635 bits long will be required. A correlation at each possible shift position requires 635 accumulation operations, and there are 635 shift positions. This means that roughly 40 msec are required to compute the correlation detector output at each shift position for each 0.5 sec interval of the input, assuming a 10 MHz computation rate. Clearly, ample time is available for this straightforward operation. Moreover, the digital hardware can be time-shared, so that several code patterns can be checked simultaneously with the same hardware. The correlation detector can also be implemented in digital software. In that case, a 1 MHz clock rate is assumed, and thus, 0.4 sec is required to process completely 0.5 sec of input.

Once the distress message is detected and the PN code identified and synchronized, a much simpler data demodulation procedure can be followed. Specifically, a local PN code generator can be used to "wipe off" the code. Then, an ordinary integrate-and-dump filter can be used to detect the data. This allows the shift register-correlation detector to continue its search for other possible distress messages if the PLL subsystem indicates that a potential distress message carrier is detected.

A generalized block diagram of a possible receiver configuration is shown in Figure 2.

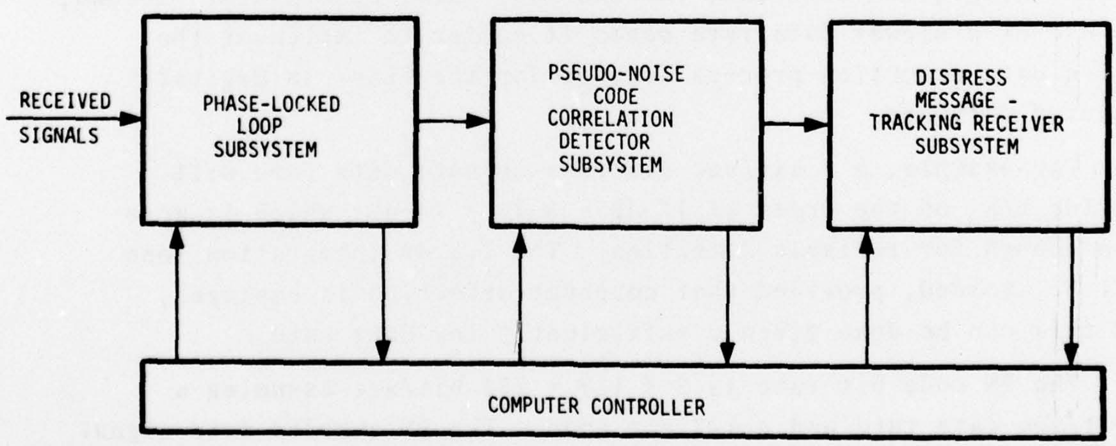

FIGURE 2. GENERALIZED PSEUDO-NOISE-PSK DISTRESS MESSAGE RECEIVER

4. SYSTEM COMPARISONS

The PN-PSK distress message system described here provides code division-multiple access capability. This added capability provides for a lower probability of mutual interference when two or more buoys are in operation simultaneously, relative to that achieved with the FSK apporach.

Of course, the added modulation complexity necessitates a more complicated receiver structure. However, the detection performance achievable with the PN-PSK technique is very similar to that achievable with the FSK approach.

The added complexity of the ground station is not considered a serious disadvantage because only a few ground stations are contemplated for the system. The additional costs of the electronics required are negligible compared with overall ground station costs. Moreover, the additional cost of the ground station electronics for the PN-PSK approach is certainly negligible compared with overall system costs.

Overall system costs are critically dependent on transmitter costs because many transmitters will be deployed in the system. The PN-PSK approach results in a transmitter configuration which is somewhat simpler than that of the FSK approach, given that crystal-stabilized frequency operation is required. In particular, it is relatively easy to phase modulate a fixed tuned crystal oscillator output, while frequency modulation requires either a voltage controlled oscillator which has poorer frequency stability or an additional up-conversion operation.

Table 4 shows a comparison of the performance factors of the FSK and PN-PSK approaches.

TABLE 4. SYSTEM COMPARISONS

PERFORMANCE FACTOR	FSK	PN-PSK
Transmitter Complexity	moderate	low
Receiver Complexity	moderate	high
Probability of Detection	0.99	0.99
Probability of False Alarm	0.4×10^{-6}	1×10^{-6}
Acquisition Time	5 min (mean)	5 min (max)
Simultaneous Transmitter Capability	good	very good
Time to Decode Message	30 sec	32 sec
Probability of Bit Error in 30 sec.	poor*	good
Assumed Carrier-to-Noise Density	24 dB Hz	20 dB Hz

*European Communications Experiments in L-Band with ATS-6, Volume 6--Distress Buoy, System Design, Instrumentation and Experiment ESRO, Oct. 1975, Fig. 7b.[6]

5. CONCLUSIONS AND RECOMMENDATIONS

The PN-PSK approach offers the potential for better data performance, better multiple transmitter capability, and slightly simpler transmitter configuration. These performance advantages were obtained by increasing the complexity of the transmitted waveform, and hence increasing ground station receiver processing complexity.

The PN-PSK system design presented here was tailored for ease of comparison with the existing FSK system design. It is recommended that further consideration be given to the PN-PSK approach in order to (a) optimize performance for the distress buoy mission, and (b) adapt the design for complete digital computer signal processing of the received distress messages.

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6. Ref. 1, Ibid., Fig. 7b.

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