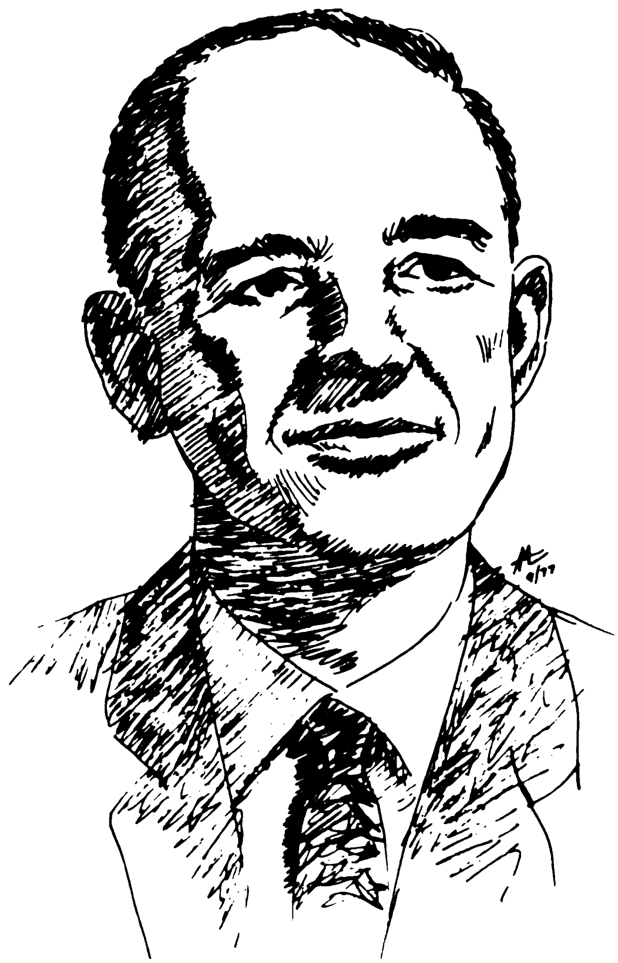
NAVAL RESEARCH REVIEWS

SEPTEMBER 1977

PROFILES IN SCIENCE



PROFESSOR ROBERT HELLIWELL

Dr. Robert Helliwell, who is Professor of Electrical Engineering at Stanford, has been an ONR contractor for twenty years. He is well known as a pioneer in research on whistlers and very low frequency (VLF) propagation in the earth ionosphere waveguide. Today he directs the Stanford VLF Group in a program of research on whistlers and related ionospheric phenomena, including a program of controlled experiments on the magnetosphere using a VLF transmitter at Siple Station, Antarctica. He is a member of the National Academy of Sciences and serves on its Polar Research Board and Space Science Board. The Royal Society of London recently awarded the Appelton Prize to Professor Helliwell for his contributions to the study of radio wave propagation in the magnetosphere and in particular his discoveries of wave-particle interactions including artifical triggering of FLF noise in the magnetosphere by ground-based transmitters.

Contaminants in the Navy Medium

Eric Shulenherger
Office of Naval Research

Introduction

What will the Navy need to know about biology in the ocean twenty years from now? That is basically the question facing the Oceanic Biology Program (Code 484) of the Office of Naval Research. After making the predictions, the Program looks for scientists who are capable of doing the basic research to provide answers and then funds their research. In addition the Oceanic Biology Program funds scientists working in problem areas that are already identified, such as fouling.

The Navy's operational medium is seawater. If seawater were pure, the Navy's job would be much simpler. Unfortunately, seawater is full of "contaminants." Most of these contaminants are organisms, and they affect every aspect of Naval operations. They interfere with active and passive sonar systems on all frequencies. They grow in unwanted places, reducing the efficiency of equipment and increasing downtime, maintenance, and replacement costs. They are responsible for almost all non-conservative properties of seawater. Over vast areas of the oceans their products or remains actually form the bottom into which some species then burrow, churning and recycling the material.

Oceanic Biology is not all negative, however. Research on marine mammals has helped the Navy understand problems of diving physiology and improve human diving abilities. Trained mammals are part of some fleet operational systems. In many areas such as sensory capabilities, marine organisms have already performed tens of millions of years of research and development for us, and the Oceanic Biology Program is trying to take advantage of this "free" information.

The Navy funds basic research in two main ways: (1) at naval research labs such as Naval Research Laboratory, Naval Underwater Systems Center, and Naval Ocean Research and Development Activity and (2) by issuing research contracts to highly qualified scientists at universities and research institutions. The Ocean Science and

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Technology Division (Code 480) of ONR handles many of these contract research programs, but it does not actually perform research or operate a laboratory. Each program area (marine geology, chemistry, biology, acoustics, physical oceanography, and technology) receives research proposals from scientists and funds those showing the highest promise of significant advances in areas of long-term Navy interests and needs.

The Oceanic Biology Program is divided into four broad areas, which will be discussed in turn: biodeterioration, sound in the ocean (volume reverberation and marine mammals), noxious and dangerous marine organisms, and special projects.

Biodeterioration
(The Growth of Fouling and Boring Organisms)

Biodeterioration costs the Navy over $500 million per year in identifiable, direct expenses: cleaning, maintaining, repairing, and replacing equipment damaged or fouled by organisms. Biodeterioration also reduces Navy operational efficiencies; these indirect costs are not readily quantified, but effects on operations may easily be much more important than direct dollar costs.

Fouling is a process that consists of identifiable steps. An outline of the process is shown in Figure 1.

ONR researchers have found that each step in the process appears to be a necessary precursor to the following step. Each arrow in the flowchart represents a potential control point or choke point for all steps following it. The biofouling program has researchers working on every arrow. We want to increase our understanding of the fouling process so that we can eventually improve the state of the art of fouling control techniques. Four thousand years ago the Phoenecians took their ships out of the water every year or two, hit the barnacles with a hammer, and put the ships back in the water. We are not very far advanced over that technique today.

The fouling process begins with a clean surface in seawater. Within minutes or hours it becomes coated with a slime film. The very first film to attach is non-living organic matter, always present in seawater, which physically sticks to the surface. Soon thereafter motile spores or reproductive cells of algae and fungi settle and grow, producing living films of fouling materials (Figure 2). This living film may damage the surface directly (as with acid-secreting bacteria)

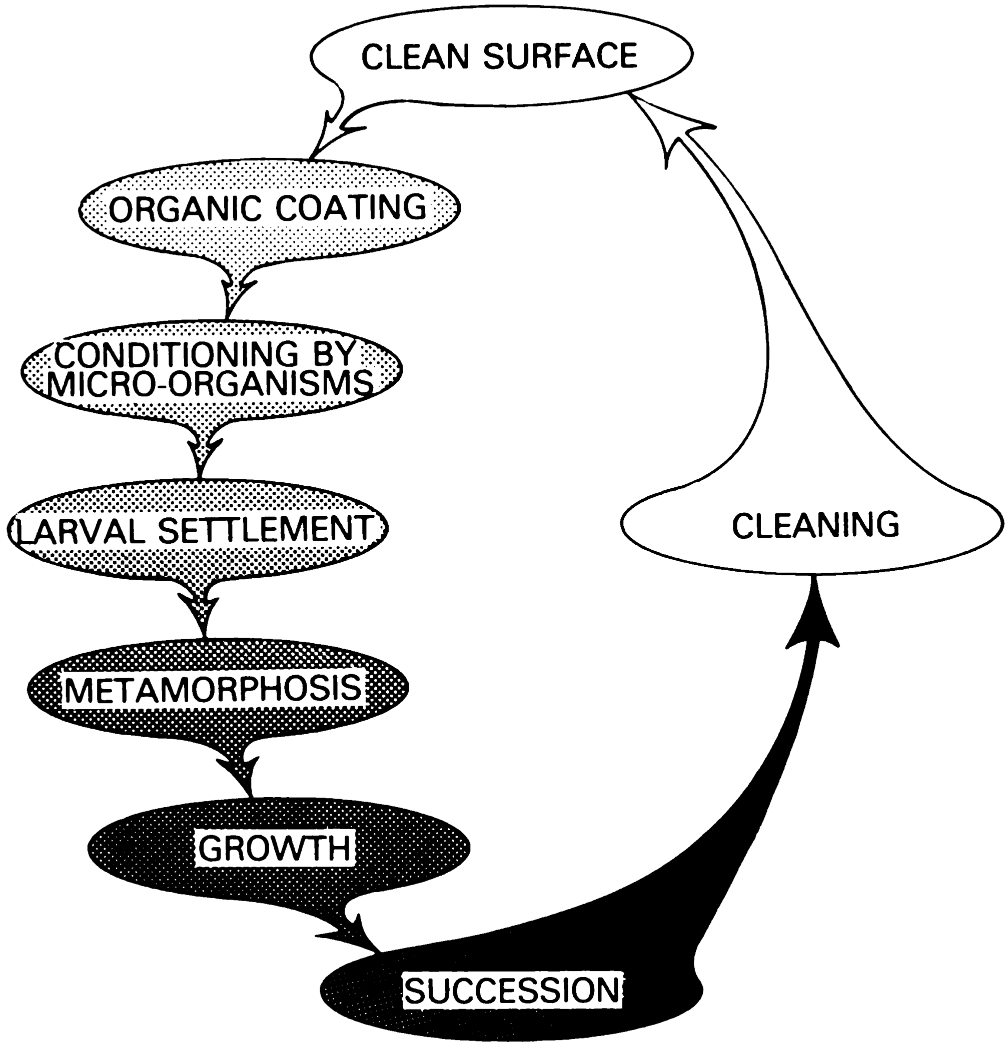
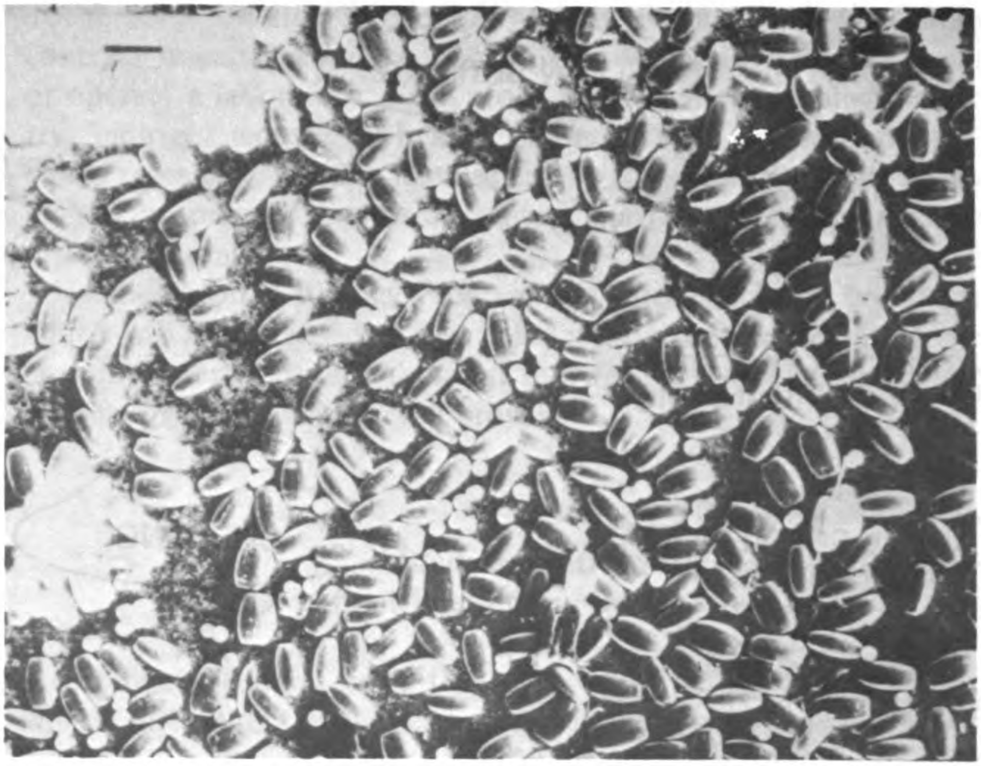


Figure 1 – Stylized representation on the general sequence of events in the overall cycle of biological fouling. Each arrow is a potential control point for the total process.

or indirectly (by providing chemical microhabitats wherein electrolysis increases by orders of magnitude). These organisms precondition surfaces, especially wood, for further attack. ONR researchers are asking questions that may ultimately lead to ways of slowing or preventing the attachment and growth of these films.

The next step involves the motile young (larvae) of larger fouling organisms such as barnacles and mussels. These free-swimming larvae (Figure 3) bump into potential substrates and after investigating the surface either accept it and settle down or reject it as unsuitable and swim off. If surfaces can be made distasteful to larvae, fouling problems could be reduced. Several Biology Program scientists are investigating the criteria and sensory apparatus these larvae use



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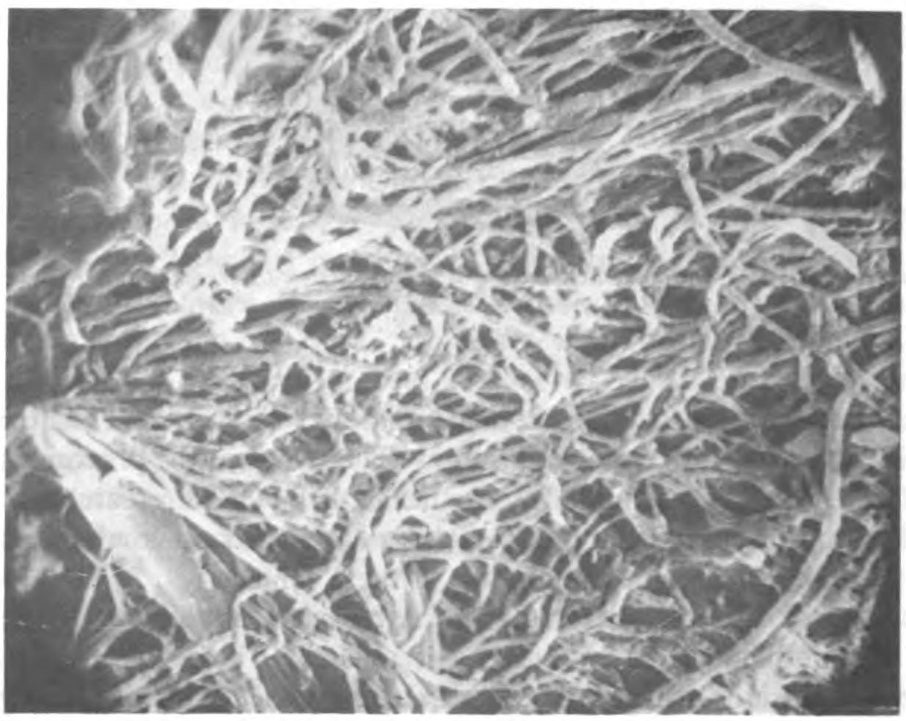


(b)

Figure 2 – Electron micrographs of initial "slime" films. (a) Coating of diatoms (single-celled plants), courtesy Dr. S. Gerchakov, Univ. of Miami, Fla. (b) Coating of fungus **(Penicillium)**, *courtesy of Dr. R. Mitchell, Harvard.*

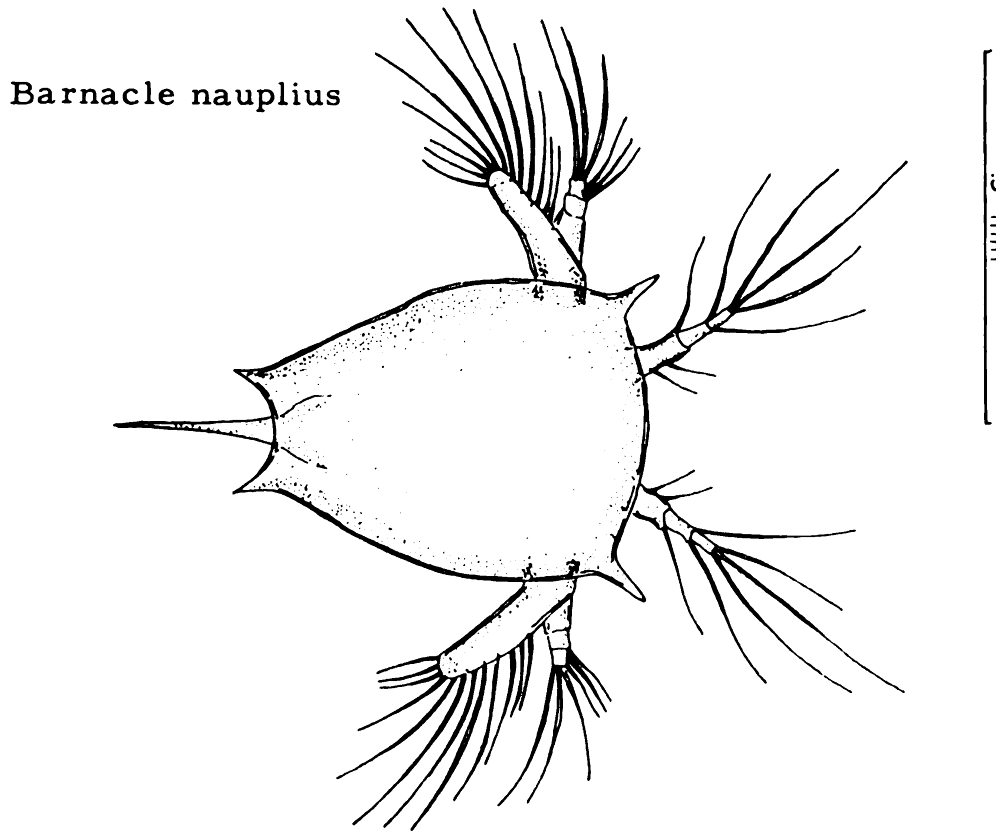


Figure 3 – Freeswimming microscopic nauplius larva of barnacle.

to evaluate surfaces. These scientists have discovered classes of chemicals which are repellent to some larvae but are not toxic. Such compounds may hopefully be better, longer-lasting, and cheaper than creosote, which is toxic and may soon be banned by the Environmental Protection Agency.

Larvae are microscopic, and their settling is not a serious problem except in special cases like optical surfaces and rapid-response thin-film sensors. A larva, once settled, must go through metamorphosis before growing to macroscopic size. Metamorphosis is a total restructuring of the animal's anatomy. It involves great metabolic activity of extreme chemical complexity, and may offer any number of potential interference points. To identify those points we must first understand the process of metamorphosis. Several investigators are working on metamorphosis in barnacles and boring molluscs ("shipworms").

Metamorphosis occurs at a very small size, and to become serious fouling problems the organisms must grow. Interference in the animals' growth is another potential control point in the fouling process. Scientists are looking into details of growth in several species, including digestion processes in teredo "shipworms" (really clams), calcium metabolism in barnacles, and calcium metabolism in boring clams. For barnacles, no metabolic control of calcium would mean no ability to grow by shedding the hard exoskeleton. For most boring clams the calcium carbonate shell is their drill, and no calcium deposition means no drill, which means no boring into wood or stone.

An established fouling community changes both species composition and areal coverage as time passes. Some such changes have been found to be cyclic, with a yearly high and low in percent of substrate area covered by organisms. Proper scheduling of maintenance procedures during a yearly low might yield significant savings in direct costs.

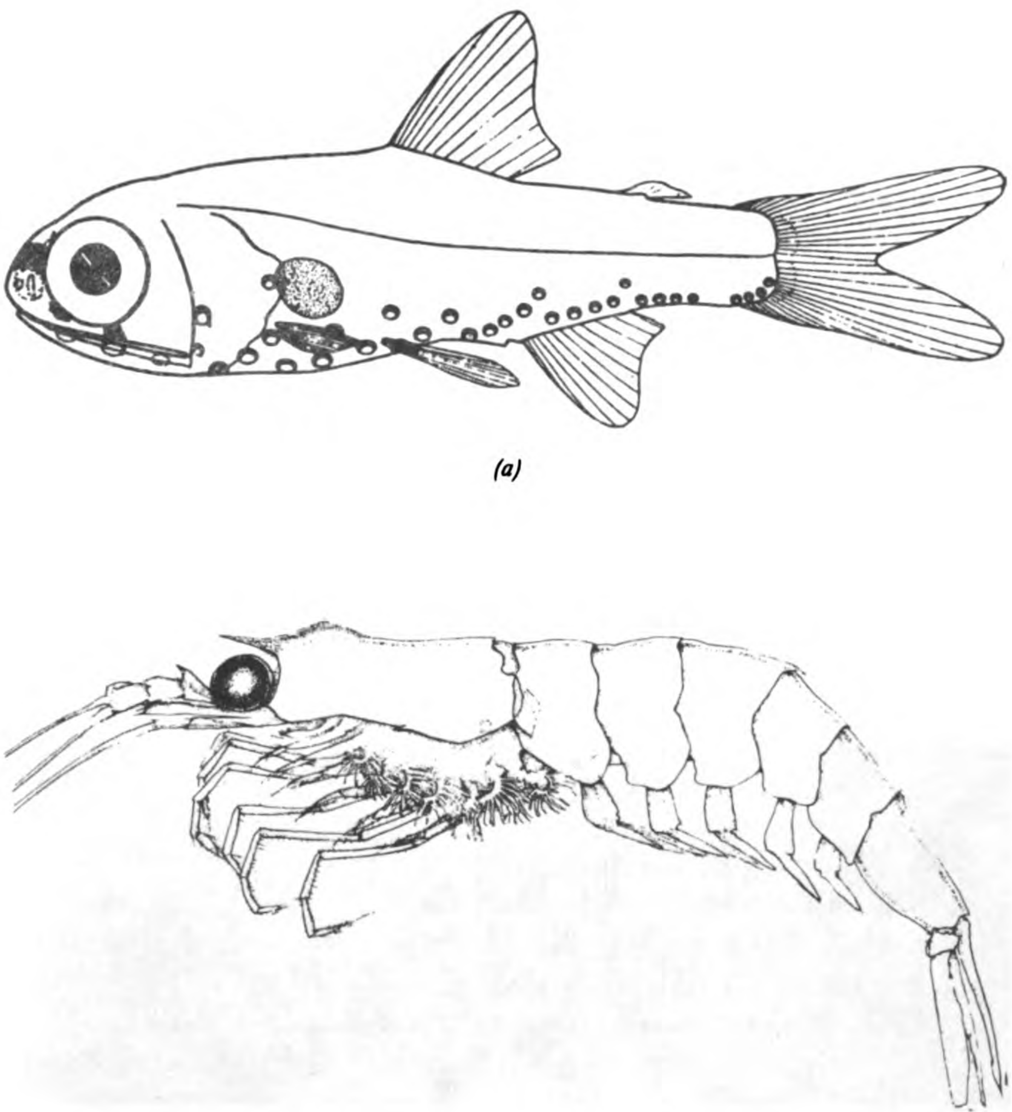
In short, the Oceanic Biology Program is operating a tightly integrated attack on all phases of the fouling program. This attack is aimed at understanding the process first, and then trying to control it.

Sound

Marine organisms absorb, diffuse, reflect, and produce sound. Sound in the sea is the second major research area within the Program. This work is divided into two areas, volume reverberation and marine mammals. Volume reverberation is the generalized, gradually decaying echo one gets from a transmitted sonar pulse. Essentially all volume reverberation is caused by organisms (Figure 4).

Several researchers are trying to find out precisely which organisms cause volume reverberation at various frequencies and various places. We need to know how these organisms are distributed in both time and space. Questions under investigation involve seasonality, daily vertical migration patterns, distribution of patches on scales from tens of meters to thousands of kilometers, and associations of various species with one another. Ultimately we want to know enough about volume reverberators to be able to tell Navy operators such things as what frequency would be best or worst at a given depth, season, location, and time of day. Such information bears directly upon both design and operation of Navy systems such as homing torpedoes, active sonars, and passive sonars.

To understand volume reverberation will be a long process involving development of acoustic sampling gear, improved nets to provide ground truth for the acoustical data, taxonomic expertise, laboratory experiments, and extensive seagoing investigations. All these tasks are now underway.



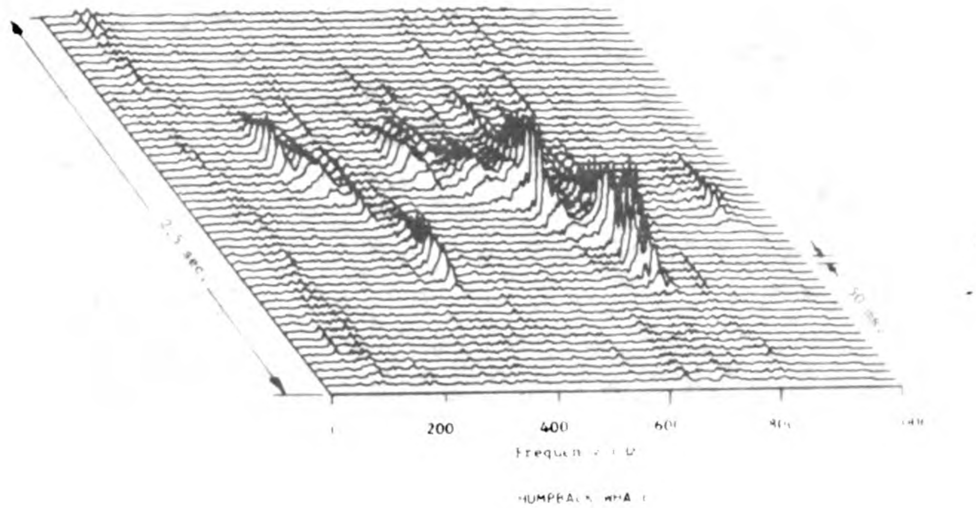
(a)

(b)

Figure 4 – Organisms such as these produce the phenomenon of volume reverberation, as well as causing discrete "targets" such as the Deep Scattering Layer. (a) Myctophid ("lantern") fish about 5-8 cm long. These animals have gas-filled swim bladders and are superb sound-scatters. (b) A species of euphausiid about 3-6 cm long. Some species of euphasiid are known as "krill," an important food for filter-feeding whales. Euphausiids are less efficient scatters than myctophids because they lack a swim bladder. They may occur in dense swarms and can be important scatterers at high frequencies.

The marine mammal program is centered about two major groups, whales and seals. Large whales are of Navy interest mostly because of their sound production abilities. Some species produce interesting patterns of vocalizations (Figure 5). Many vocal species can occur in dense concentrations at certain times and places and could interfere with or, perhaps, be of use in Navy operations. Oceanic Biology Program scientists are developing gear and techniques which will allow tracking of large whales. Radio transmitters can be implanted in the blubber of truly big whales such as blues, fins, and grays (Figure 6) or attached in various ways to smaller whales (Figure 7). In all cases the gear is carefully designed and fully tested to be harmless to the animals being tagged. Much of this work is being conducted in cooperation with other interested groups like the Marine Mammal Commission and the National Marine Fisheries Service. These transmitters operate only while the animal is surfaced to breathe, and can be tracked from boat, plane, land or the NIMBUS and TIROS satellites. This tracking ability is needed to answer many questions: do individuals or whole populations migrate, and if so, how far, how fast, and where? How many sub-populations are there in a species? Do groups of whales

Figure 5 – (a) Adult humpback whale leaping (purpose of this behavior is unknown).



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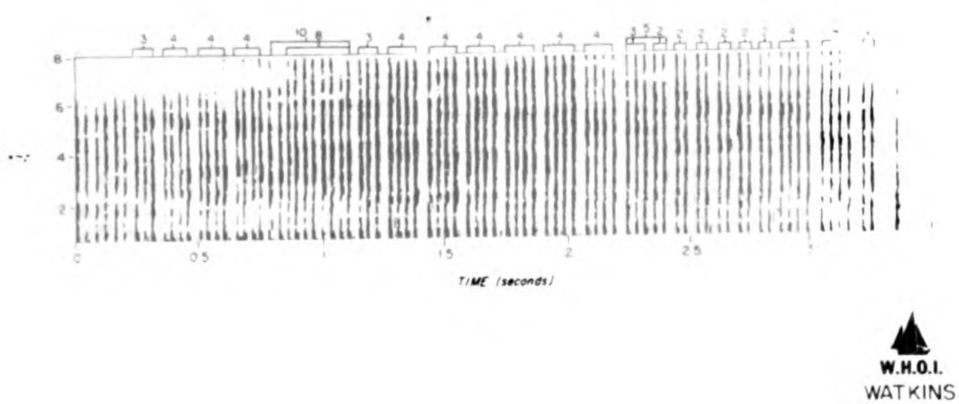
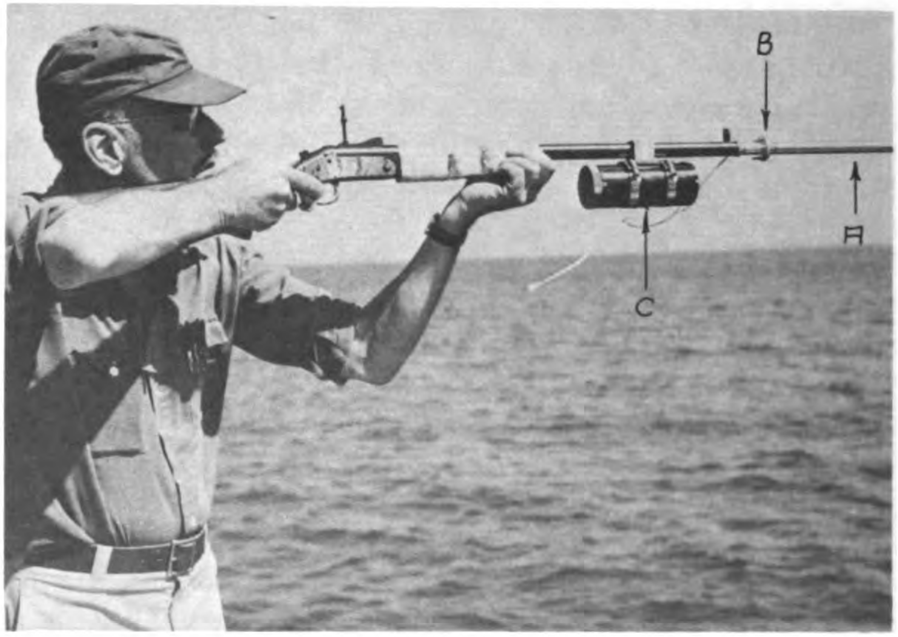


(c)

Figure 5 – (b) Humpback whale "song", intensity is represented by height of peaks, (c) Vocalization of sperm whale, consisting of a train of clicks. Courtesy Dr. William Watkins, Woods Hole Oceanographic Institution.



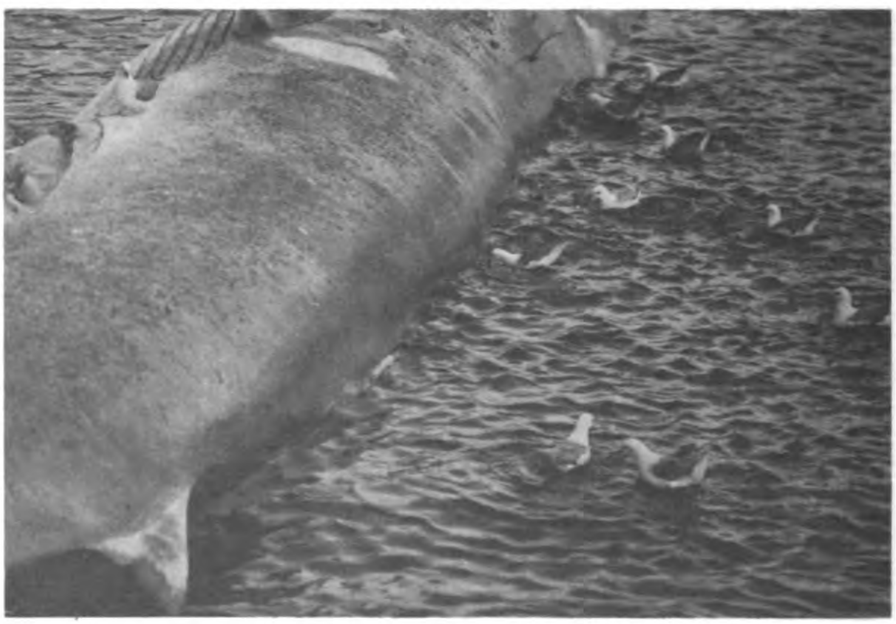
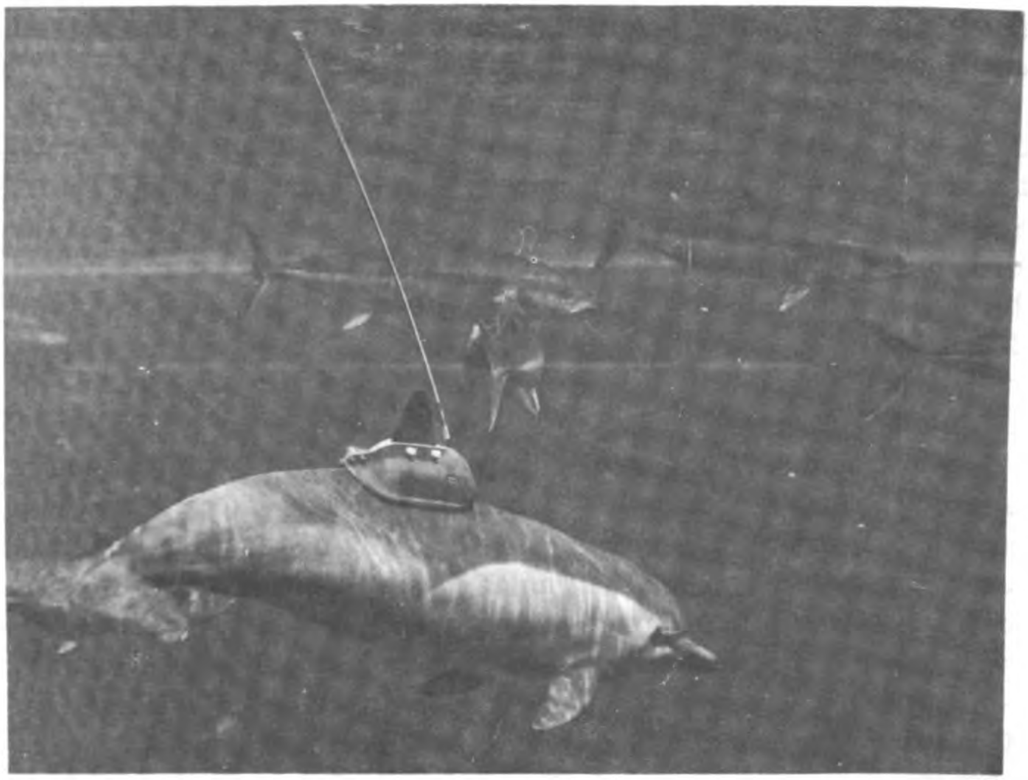
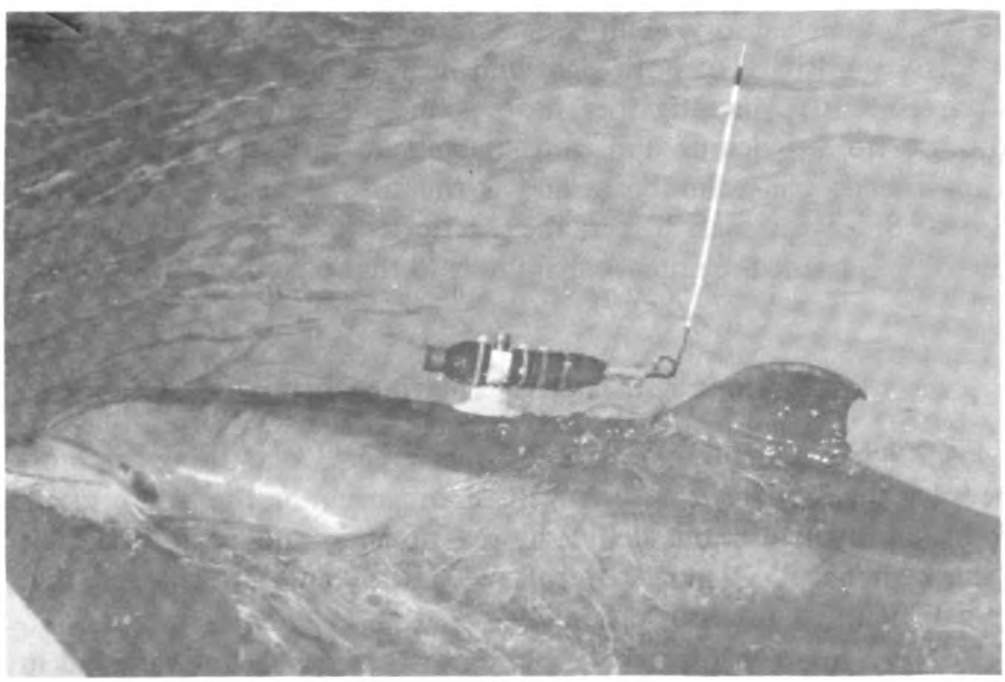


Figure 6 – Top: Dr. William Scheville of Woods Hole Oceanographic Institution with implantable radio transmitter for large whales. Transmitter and batteries are in point (A), ahead of stopper ring (B); stopper ring controls depth of penetration of tag. Whip antenna (visible in lower photo) extends down into barrel of modified single-shot 12-ga shotgun used as a launcher. Cannister (C) beneath barrel of shotgun contains retrieval cord in case of a miss: firing the transmitter into a 60-foot whale from a small outboard-powered boat in 8 or 10 foot seas is exciting, and both ricochets and clean misses are not unlikely.

Bottom: Radio tag in position on a dead whale. Tag is carefully designed and tested to be non-injurious to the tagged animals, and is relatively no larger to them than a hypodermic needle is to a human. This whale was killed by commercial whalers off Iceland, and the photo taken during developmental testing of the tag. (Photos courtesy Dr. William Watkins, W.H.O.I.)





(b)

Figure 7 – Attachable radio transmitters for smaller whales. (a) Early model was attached to dorsal fin of porpoise; hydrodynamic problems are obvious. (b) Newer model is attached with suction cup and mounted on a swivel; rides in precisely the position occupied by a baby porpoise accompanying its parent. (Photos courtesy Dr. William Evans, Hubbs-Sea World Research Institute, San Diego)

exchange members? Where and when are various species found, and what are they doing at various times and places? (Figure 8)

Several scientists are busy matching recorded sounds with species, and they sometimes make truly startling discoveries. For example, the fundamental frequency of blue whale speech is 3.8 Hertz; as befits a big animal, it has a deep voice. Even more startling is the output or source power of one blue whale; it is the same as WW-II heavy cruiser at 26 kts (85 db re. 1 μbar at one meter). Such information, coupled with knowledge of where, when, and how many blue whales exist, may be of great interest to Navy operators and equipment designers.

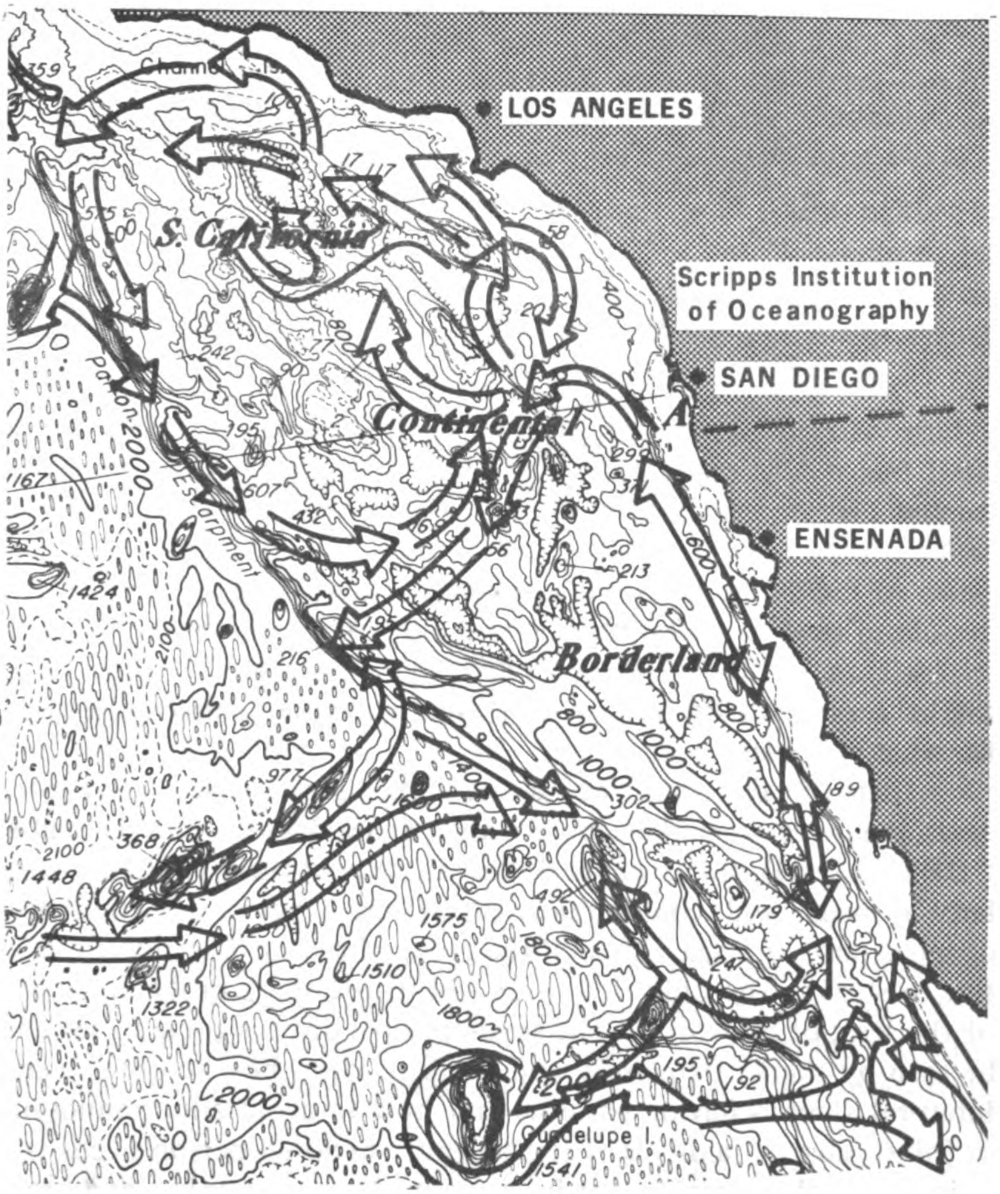
Seals and sea lions have sensory systems and physiology highly adapted to the submarine environment. Navy interest in these animals centers on two areas. First, the study of their unique physiology can help us understand human diving physiology. Experiments can be performed by or upon trained animals which would be impossible or impractical with human subjects. Secondly, these animals, when trained, are used as part of Navy operational systems like Quickfind. In Quickfind, a trained sea lion locates spent practice torpedoes or other gear and attaches a retrieval device to the gear.

Most of the Program's research on seals and sea lions has to do with their sensory abilities and trainability, their visual acuity, spectral sensitivity of both sight and hearing, and target discrimination. Recently, investigators have found that fur seals, formerly thought to be vicious and untrainable, are in fact tractable. The same species can echo-locate and is the first seal species known to do so. Since fur seals live in the Arctic ice pack, this may extend the Navy's trained-mammal capabilities to that environment.

Noxious and Dangerous Marine Organisms

Dangerous marine organisms means just one thing to most people, sharks. The most dangerous organism in the sea is man, followed by poisonous jellyfish, sea urchins, and rock fish. The "shark menace" is much overplayed and so emotion-charged that it is difficult to discuss it rationally.

Navy research into shark biology was recently re-evaluated in light of input from various segments of the Navy, such as divers and rescue workers. As a result, the Program has concentrated its limited shark-research money in the two areas most likely to yield good basic science of use to the Navy: (1) studies of the behavior of free-living sharks; what they do, where they do it, and why, and (2) studies on



(a)

Figure 8 – Porpoise tracking by radio.

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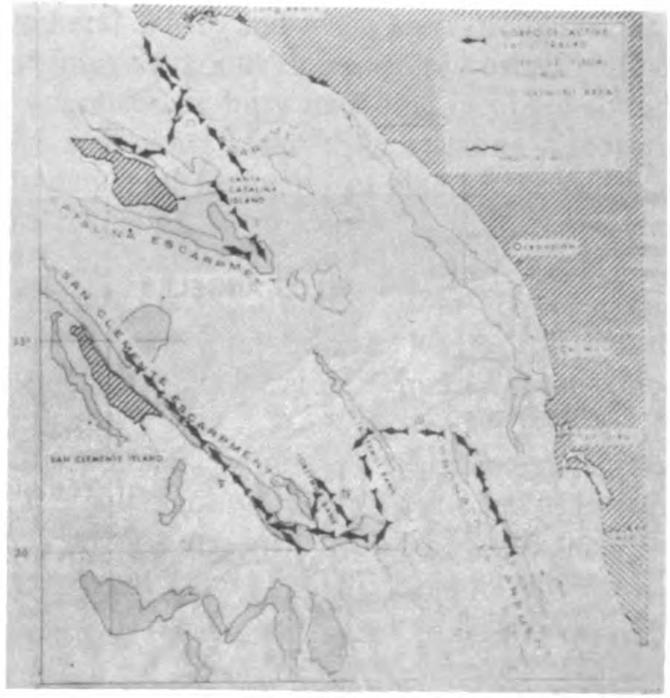


(b)

Figure 8 Tracks of specific individuals or groups can be used to produce charts showing a species' overall behavior in a region (Courtesy Dr. William Evans)

sharks' sensory abilities; how they investigate their surroundings and for what purposes.

There are three basic categories of men in the water. Those who enter the water regardless of possible shark dangers (SEAL teams, UDT personnel), those whose duties will expose them to sharks regularly (salvage and construction divers), and personnel accidently dropped into the sea. These three groups have different needs relative to sharks. The obligated diver will ignore shark problems as one of the least of his worries. The semi-optional diver is going to see and be seen by sharks frequently and needs to know how to observe and interpret their behavior patterns and how to avoid either annoying or interesting the animals. The accidently-exposed person needs isolation from the environment in as many ways as possible, and probably needs other things much more than shark protection (flotation, medical aid, protection from exposure).

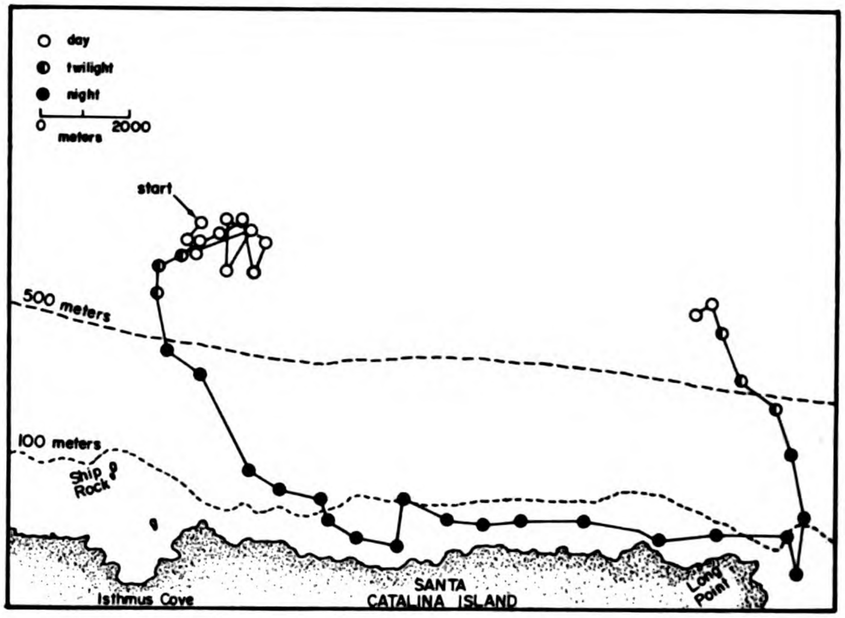
The Oceanic Biology Program's researchers are providing basic information which has radically changed our knowledge of the behavior of these so-called "unpredictable" animals. For instance, many species are now known to be highly territorial. Each animal has a personal space into which it is unsafe for anyone or anything to intrude since the intruder will be attacked. Like most territorial animals, sharks show their concern over intrusion by behavioral displays, much like a bull pawing the ground before charging. Shark territorial displays involve peculiar back-arched gymnastics, swimming in strange patterns, and holding the fins rigid in odd positions. These displays indicate the degree of irritation the animal is experiencing, and also indicate the likelihood of an attack upon the intruder. Once identified and studied, these behavioral patterns can be understood and interpreted; then the swimmer/diver community can be taught to recognize them and, hopefully, avoid provoking attacks.

Some species have daily activity rhythms and patterns of travel. Some species spend daylight hours in deep water and come in to shallow water at night to feed, travelling in predictable paths. Such information is of great interest to planners of amphibious or diving operations.

In addition to behavioral studies, various researchers are studying shark sensory abilities. In a fascinating series of lab and field experiments one scientist has shown that many sharks will indeed follow an odor trail upstream to bait. When they get within a few feet of the bait, they shift from using their sense of smell to using an ability to detect extremely low electric fields, such as produced by an animal's nervous system. When presented with a bait (fish) on the bottom and a very low current electrical device buried in the sand a foot from the bait, the animals oriented to the odor, swam to the vicinity of the bait, and then actually bit the electronic gadget (*not* the bait) every time. The experiment has been done over 200 times in the field on wild sharks. Some species detect electrical fields down to 0.01 microvolt/cm.

Scientists have now shown that sharks' senses are remarkably good; they have superb senses of smell and electrical detection, very good low-frequency hearing, and color vision of considerable acuity. They can sense pressure waves, and perhaps detect magnetic fields as well.

By learning about the sharks' sensory abilities and behavioral patterns, scientists are able to make sensible recommendations to Navy planners. For instance, the old standby Shark Chaser has been shown to be essentially useless as a repellent and procurement of it has been stopped. Probably the best candidate to replace it is the Johnson Shark Bag (Figure 9). This is a large black plastic bag with an inflatable ring around the mouth. The person in the water inflates the ring, then climbs inside the bag. He is then isolated from most of the shark's senses; he doesn't look like anything edible, odors don't trail off downstream, and he is electrically isolated since the



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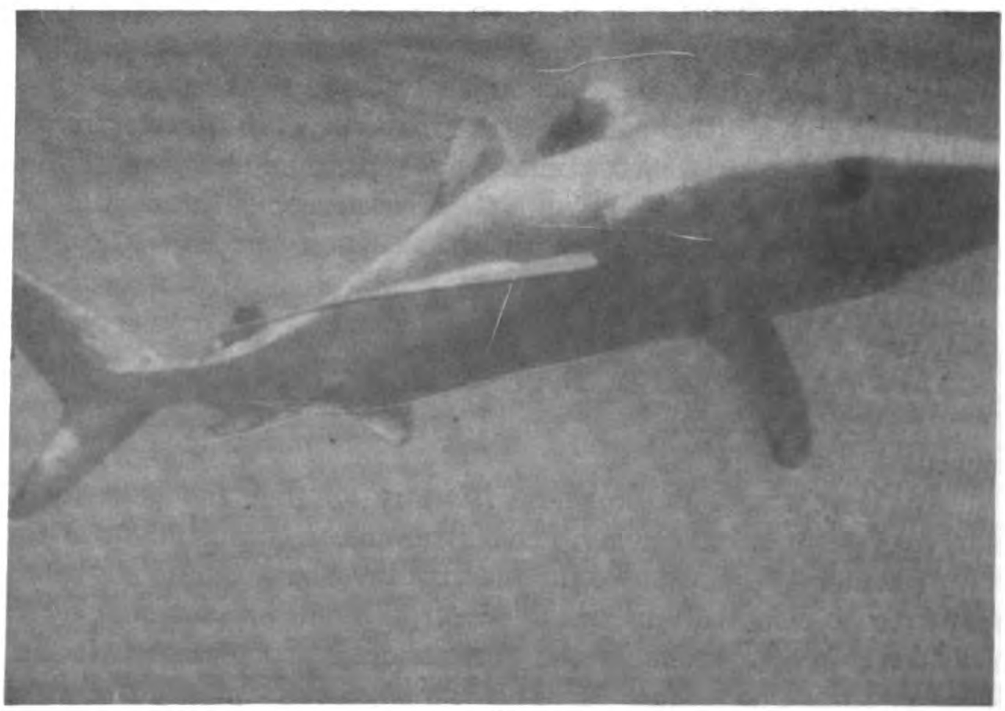

(b)

Figure 9 – *(a) Daily activity patterns of an individual blue shark near Santa Catalina Island, Calif. (b) Sharks are tagged with an acoustical transponder, seen just forward of the dorsal fin. Animals are followed by a diver carrying a hand-held interrogating unit. (Courtesy Dr. D. R. Nelson, Cal. State, Long Beach, Calif.)*

plastic film is an insulator. The collapsed bag fits neatly into the space formerly holding the package of Shark Chaser (Figure 10).

Special Projects

This category includes both very speculative work and some obviously practical projects. Work is beginning on bioturbation, the disturbance of bottom sediments by organisms. This information may well turn out to be vital to engineers a decade hence if the Navy begins to move into truly deep water. It is also of vital interest to marine geologists and chemists.

Work on bioluminescence is also underway: trying to understand it, map it, predict it, control it. Just how big a wake does an Enterprise-class carrier leave in a bioluminescent sea, and could it be spotted with image-intensification techniques from a satellite?

A couple of fish physiologists are building a prototype gadget to extract gaseous oxygen from seawater directly, by using fish-blood hemoglobin.

And finally, another Program scientist has recently shown that certain types of bacteria are sensitive to the magnetic field they

(a)

Figure 10 – The Johnson Shark Bag. (a) Collapsed next to the now-discontinued "shark repellent."

(b)

Figure 10 – (b) Deployed and manned during developmental testing.

live in; reverse the field, and they turn around and swim the other way. Fouling often starts with a bacterial slime film, and many of the most fouling-susceptible objects are made of magnetic materials. So perhaps in a few years the $5,000 that the Oceanic Biology Program spent to get this scientist a specially-modified nonmagnetic microscope with which to do his research will seem like the best investment ever made.

Spread Spectrum Technology Effecting Military Communication

Alan G. Cameron
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Introduction

Spread-spectrum technology is bringing about major changes in military communications. It can be used effectively to resist jamming, even when jamming signal level is far greater than that of the desired signal. Properly employed, it can also allow communication which is virtually undetectable. These properties result directly from the use in spread-spectrum systems of special wideband signals, of far greater bandwidth than the information being transmitted. Spread-spectrum is digital in nature, and thus is well matched to COMSEC (Communications Security) encryption/decryption processes; it can support voice, teletype, or virtually any form of digital data.

Spread-spectrum systems were first developed for classified applications almost twenty years ago. Since then, the techniques have found applications in the communications areas of jam-resistance, low-probability-of-intercept, and multiple access (where the problem is to resist the "jamming" caused by other users sharing a common repeater). At present, with the development of new digital components and devices, the economics of spread spectrum are changing rapidly; this once expensive technique is now competitive with many older methods of communication in many applications. It is therefore worthwhile for those involved in Naval Research and Development in communications and device development to gain an appreciation of what spread spectrum is, and how systems which employ it operate. This paper is intended to convey that appreciation (1). The Office of Naval Research has supported work in this field through the Joint Services Electronics Program at the University of Southern California and also through various projects at the Naval Research Laboratory.

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*Mr. Alan G. Cameron is a member of the staff at MIT, Lincoln Laboratory, Lexington Massachusetts. He is a member of the Office of Naval Research Reserve unit 101, Boston. His field of research is electronics, radar, and air traffic control.

Theory of Operation

One of the fundamental principles of digital communication theory (2) is that system performance (stated usually in terms of error rates) can be made to depend entirely on the parameter E_b/N_o, in which E_b is the received energy (joules) that is associated with each transmitted bit, and N_o is the noise power spectral density (watts per Hz) in the channel. Note that both parameters have the dimension watt-seconds (energy), and so their ratio is dimensionless.

Several relationships between performance and E_b/N_0 exist, applicable to various types of signalling; the two most common types used in spread-spectrum are known as orthogonal and antipodal signalling. In both cases, different waveforms are selected to represent binary 1 and binary zero; if we represent these waveforms by $S_1(t)$ and $S_0(t)$, assuming that each lies within the time interval $(0, T)$, and has unit energy,* and zero average value,† then the signals are orthogonal if:

$$\int_0^T S_0(t)\, S_1(t)\, dt = 0$$

and antipodal if: (1)

$$\int_0^T S_0(t)\, S_1(t)\, dt = -1$$

Orthogonality results if the signals do not resemble one another (i.e., they are uncorrelated); signals that are opposites (i.e., negatively correlated) are antipodal. The performance of orthogonal signalling is given by:

$$p(E) = \frac{1}{2}\ \mathrm{erfc}\ (E_b/2N_0)^{1/2} \tag{2a}$$

and of antipodal signalling by:

$$p(E) = \frac{1}{2}\ \mathrm{erfc}\ (E_b/N_0)^{1/2} \tag{2b}$$

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*i.e., $\int_0^T S_i^2(t)dt = 1, \quad (i = 0, 1)$

†i.e., $\int_0^T S_i(t)dt = 0, \quad (i = 0, 1)$

where $p(E)$ is error probability and "erfc" represents the complementary error function. Both relationships are shown in Figure 1.

Note that the above statements place relatively few constraints on what the signal waveforms must actually look like; they simply must look different from one another; the greater the difference, the better the system performance. Note further that there are no fundamental constraints on power, but only on energy; of course the two are related through the various bandwidths and rates employed.

To appreciate this relationship, which is at the heart of spread-spectrum theory, note that:

$$E_b \text{ (energy per bit)} = \frac{S \text{ (signal power, energy per second)}}{r_b \text{ (bit rate, bits per second)}} \tag{3a}$$

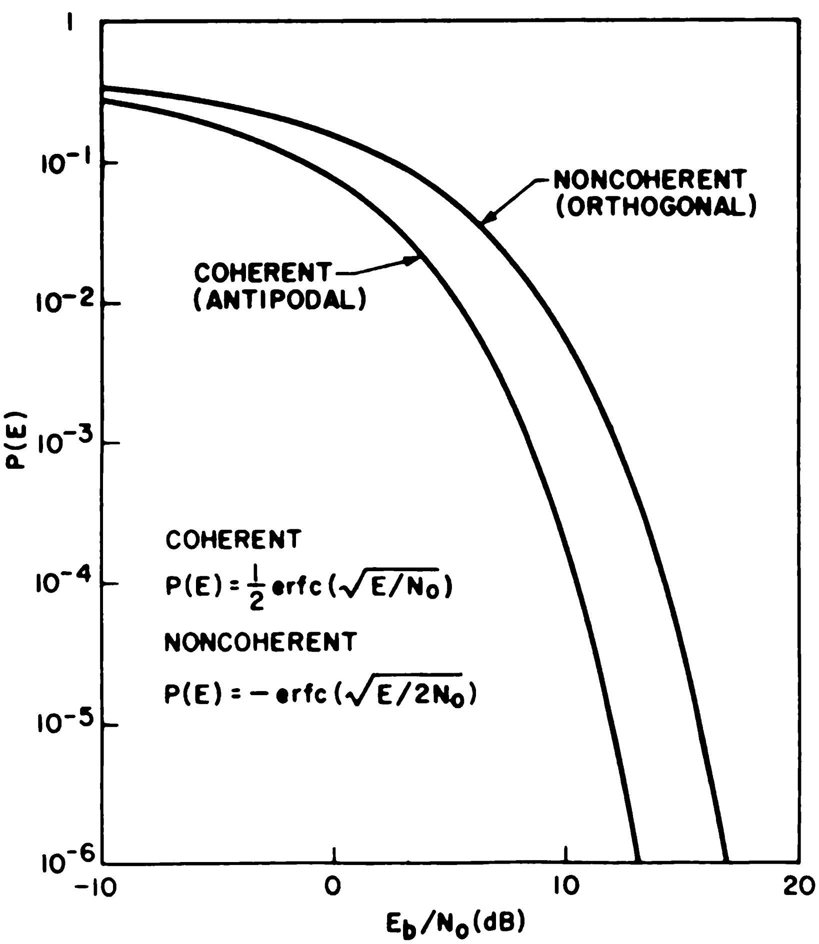


Figure 1 – Relationship between error probability and the parameter E_b/N_0 for binary orthogonal and antipodal signalling.

and:

$$N_0 \text{ (power per hertz)} = \frac{N \text{ (noise power, energy per second)}}{W \text{ (bandwidth, Hertz)}} \tag{3b}$$

In conventional digital radio transmission system design, spectrum availability is generally limited, and it is desirable to minimize the transmission bandwidth; it is practical to reduce it to a value comparable to the data rate. Thus:

$$\frac{E_b}{N_0} = \frac{S}{N} \times \frac{W}{r_b} \frac{S}{N}, \tag{4}$$

and reasonable performance, which necessitates a large positive value of E_b/N_0, requires that the signal-to-noise ratio (S/N or SNR) seen at the receiver must be similarly large and positive; for instance, from Figure 1, an error rate of 10^{-5} requires an input SNR of 9 dB, if antipodal waveforms are employed.

Spread-spectrum operation is based on the observation that sufficient E_b/N_0 can be obtained, even when SNR is quite small, if W is made large enough relative to r_b. Although such a large bandwidth appears wasteful of spectrum at first glance, in fact the increased resistance to interference which results allows common bandwidths to be shared; in addition, the spectrum spreading process decreases the power present in any narrow-band portion of the transmitted bandwidth, to the point where spread-spectrum signals are frequently unnoticeable to conventional receivers. The resulting spectral utilization efficiency is comparable to that of narrowband operation.

From Equations 3 and 4, it can be seen that increasing the transmitted signal bandwidth relative to the information rate results in a direct reduction in the required SNR necessary to support a given level of performance. Transmitted bandwidths of the order of 10 MHz are practical in systems with information rates of the order of 1 KB/s; this results in a ratio W/r_b of 10^4, or 40 dB. Systems of this sort can perform well at input SNR as low as 10^{-3} (–30 dB). The factor W/r_b, which expresses the improvement in performance that results from bandspreading the transmitted signal, is known as the "processing gain."

This process can be viewed in a qualitative manner. The spread-spectrum receiver signal processing action effectively collapses the bandwidth of the received signal down to that of its information content. This process is accomplished in such a manner that the total power associated with any jamming signal is spread uniformly over the entire bandwidth of the received signal; all but that portion of it falling within the received signal information bandwidth can be removed by filtering (Figure 2).

Thus, to ensure a given jamming power density in the information bandwidth of the received signal, the jammer must increase his total power by the same amount as the bandwidth expansion of the signal.

Spread-Spectrum Techniques

Many varied techniques exist by which an increase in signal bandwidth results in improved performance. Several of these were employed routinely long before the principles of spread-spectrum were widely known. One very common example is ordinary frequency modulation (FM).

While FM lacks many of the desired attributes of a spread-spectrum system, such as resistance to intelligent jamming and the

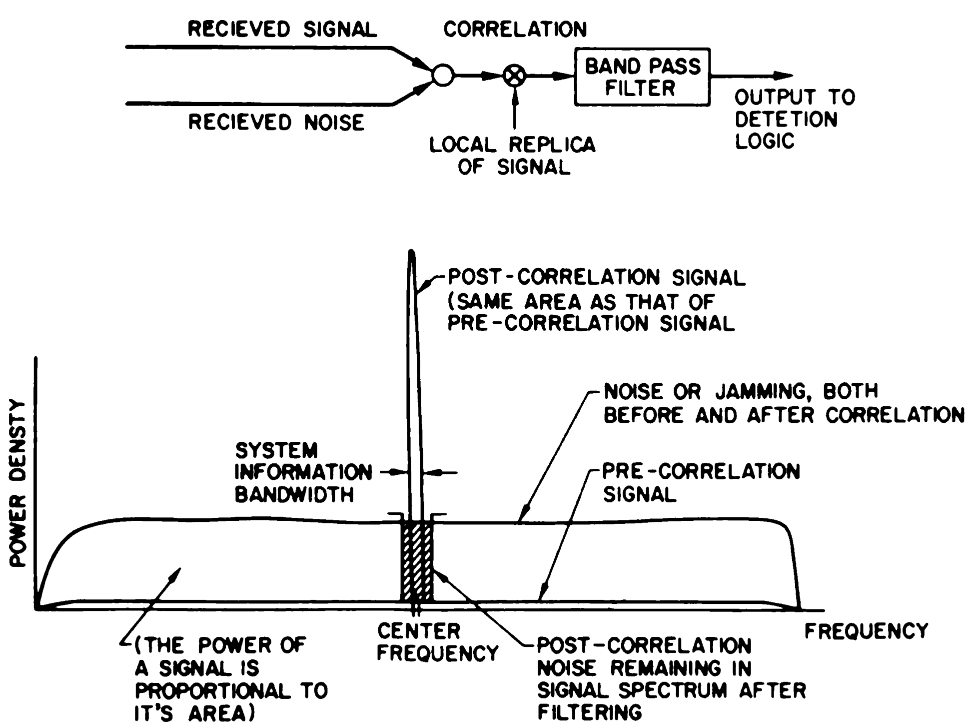


Figure 2 – Relationship between various spectra in a spread-spectrum system

inability to operate at negative received SNR,* the strong-signal SNR improvement that arises from bandwidth expansion in an FM system is a direct result of the same basic principles which allow spread-spectrum operation. Indeed, during the 1950's and 60's, much effort went into the development of analog FM systems that operate at reduced received SNR, for military anti-jamming applications. While these systems were never competitive with digital spread-spectrum approaches, they have found applications in commercial space communication (3).

Another system which has been in operation for many years, and which employs spread-spectrum principles to advantage is the military Identification Friend or Foe (IFF)/civil Air Traffic Control Radar Beacon System (ATCRBS) (4) system. In IFF/ATCRBS, many ground-based interrogators communicate with many aircraft on a common channel during a common time period. If we consider the timing, direction, and encoded data associated with the replies of a particular aircraft to one's own interrogations as desired signal, and all other replies (i.e., due to other interrogators and other aircraft) as undesired noise, we note that in relatively high-density regions, signal power can be quite a bit lower than noise power. (Undesired replies are called "fruit" in IFF/ATCRBS; fruit rates in excess of 1000/second are occasionally noted. A particular aircraft responds to an interrogator typically only four or five times per second, on a long-term average.)

The wide (10 MHz) signal bandwidth employed by ATCRBS allows the use of very short (20.75 μs overall) reply signals; as a result, even in high-density situations, examination of the signal seen by the interrogator reveals much "dead air," and relatively few instances in which two replies overlap. The receiver employs correlation techniques to enhance the desired replies and reduce the effects of the undesired replies. This is possible because the times at which desired replies occur are strongly correlated to interrogation times (i.e., they follow interrogations by a time related to aircraft range which is practically constant over the duration of an observation interval). Replies due to other interrogators are not correlated to one's own interrogation timing,† and so are rejected. Replies due to one's own interrogation of other aircraft are also strongly correlated with one another, but not with those of the

*Received SNR is often called CNR (for carrier-to-noise ratio) in analog systems to distinguish it from the SNR observed at the (audio) output.

†Interrogation rates are closely coordinated to ensure this.

desired aircraft, unless the two aircraft are in close proximity. The effect that occurs in those infrequent cases when aircraft are within one reply duration of one another in range (ΔR 1.65 nmi), and within an interrogator antenna beamwidth ($\Delta\Theta \leqslant 4°$) is known as "synchronous garbling," and is far more deleterious to system performance than is all asynchronous interference.

Still another military system that employs spread-spectrum concepts to advantage is the Navy-developed TACAN aeronautical radionavigation system (5). TACAN operation is quite similar to that of IFF/ATCRBS, although in TACAN, aircraft interrogate and ground stations reply. Again, synchronism of desired replies with interrogations is used to separate them from those replies due to interrogations by other aircraft.

Note that the systems just described were not specifically designed to reject intentional interference or jamming which is specifically formulated to disrupt them. Rather, they were designed to reject inadvertent jamming caused by other users or by natural background noise. And, with IFF/ATCRBS and TACAN, unless all parties involved cooperate to maintain the proper equipment parameters, severe degradations in system performance can result. An intelligent and concerted jamming attack, using to advantage the known signal structures of these systems, could substantially reduce their effectiveness. Communication systems designed specifically to reject intentional (and presumably intelligent) jamming generally employ cryptographic devices to randomize the structure of their signals in a manner which prevents a jammer without access to the cryptosystem from exploiting the signal structure. The friendly receiver, on the other hand, has access to the cryptosystem, and thus knows exactly what signal patterns to expect.

Two basic spread-spectrum concepts are employed in military communications applications: pseudonoise (PN) transmission, and frequency hopping (FH). Most systems developed to date employ variations of one or the other (or both) of these concepts.

Pseudonoise transmission can best be understood by analogy to conventional narrowband coherent communication systems. In such systems, the information is combined with, or "modulated onto" a continuous sinusoidal (CW) signal, the "carrier" (Figure 3), chosen such that the result is suitable for transmission over the channel. Typically, this combining action consists of simple multiplication. If the modulating signal is represented by $A(t)$ and the carrier by $\cos \omega_c t$, then the resulting signal is simply $A(t) \cos \omega_c t$. To recover the original modulating signal, the receiver in principle simply

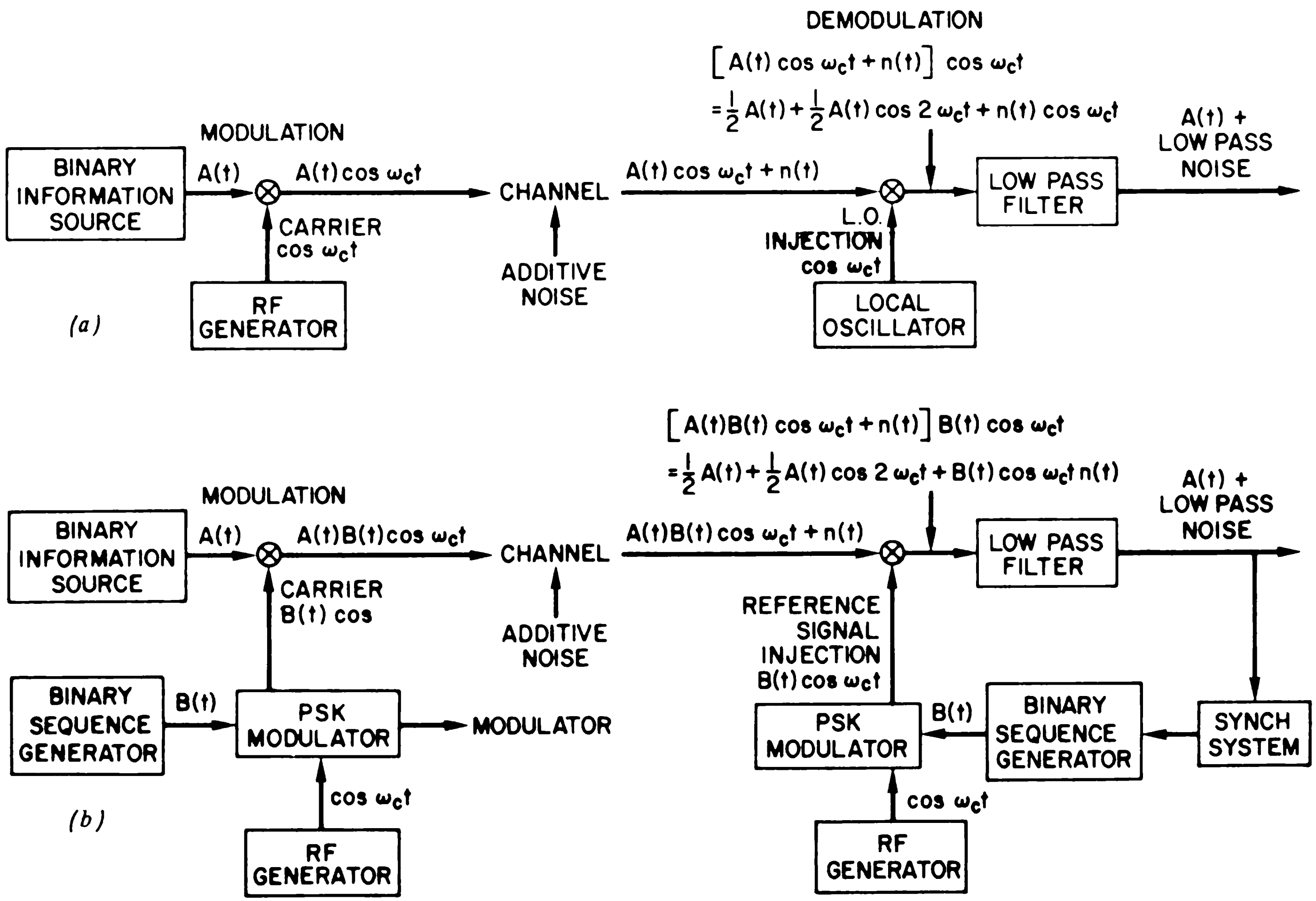


Figure 3 – Comparison between spread-spectrum and conventional signalling (a) conventional (cw) carrier, (b) wideband (pseudonoise spread-spectrum) carrier

multiplies the incoming signal by its own locally-generated replica of the carrier:

$$(A(t) \cos \omega_c t) \cos \omega_c t = A(t) \cos^2 \omega_c t$$

$$= \frac{1}{2} A(t) + \frac{1}{2} A(t) \cos 2\omega_c t \qquad (5)$$

Low pass filtering removes the second-harmonic term, and yields the original modulating signal.

In pseudonoise transmission, the carrier, instead of being a simple sinusoid, is a wideband noiselike signal, generally the result of very rapid phase-shift keyed (PSK) modulation of a continuous wave (CW) carrier by a random binary bitstream, with a rate far higher than the maximum bandwidth of the information, $A(t)$ (6). The sequence is usually generated by a cryptographic device.

If biphase (0°-180°) PSK is employed, this wideband "carrier" is of the form $B(t) \cos \omega_c t$, where $B(t)$ is a random sequence with values of ± 1. The bandwidth of this signal is comparable to the rate of the random sequence. The information $A(t)$ is modulated onto this "carrier" to produce the signal $A(t)\ B(t) \cos \omega_c t$ for transmission. At the receiver, the signal is mixed with a local replica of the "carrier":

$$A(t)B(t) \cos \omega_c t \times (B(t) \cos \omega_c t) = A(t)B^2(t)$$

$$\times \ \frac{1}{2} + \frac{1}{2} \cos 2\omega_c t \ . \qquad (6)$$

If the locally-generated random sequence $B(t)$ is in perfect alignment with the received sequence, then $B^2(t) = (\pm 1)^2 = 1$, and upon low pass filtering, $A(t)$ results, as in the case of a sinusoidal carrier.

In the case of a sinusoidal carrier, alignment of the local carrier replica with that of the received signal amounts to a phase adjustment; any disagreement in the phases of the two results in a multiplicative term equal to the cosine of the phase difference.

In the pseudonoise case, not only must the carrier phases be aligned, but also the timing of the pseudorandom sequences. The synchronization techniques used to establish the proper time relationships will be discussed subsequently. Recalling the previous discussion on processing gain, note that any jamming signal not correlated with $B(t)$ will, when multiplied by $B(t)$ in the receiver, result in a signal whose spectrum, the convolution of $B(t)$ with the jamming signal, covers the entire spectrum of $B(t)$; thus it will be amenable to partial elimination by filtering.

In practice, most PN systems are mechanized somewhat differently from the above description. At the transmitter, the (generally binary) information is usually combined digitally with $B(t)$, and the resulting digital signal PSK modulates a CW carrier.

Frequency hopping accomplishes the same basic objective, and its mathematical analysis is similar to that of pseudonoise; its operation is shown in Figure 4. The transmitter employs a sinusoidal carrier whose frequency changes rapidly in an unpredictable manner. In general, the overall transmission bandwidth is broken into N uniform frequency slots, each with a bandwidth comparable to that of the information, and the carrier frequency is allowed to take on any of the N center frequency values. Since the jammer does not know and cannot anticipate which frequency slot will contain the signal at any instant, he is forced to jam them all. This requires N ($=W/r_b$) times the jamming power, and thus results in the same processing gain as for pseudonoise with comparable rate and bandwidth.

The success of a frequency-hopping concept depends on the jammer's inability to concentrate his power on the small fraction

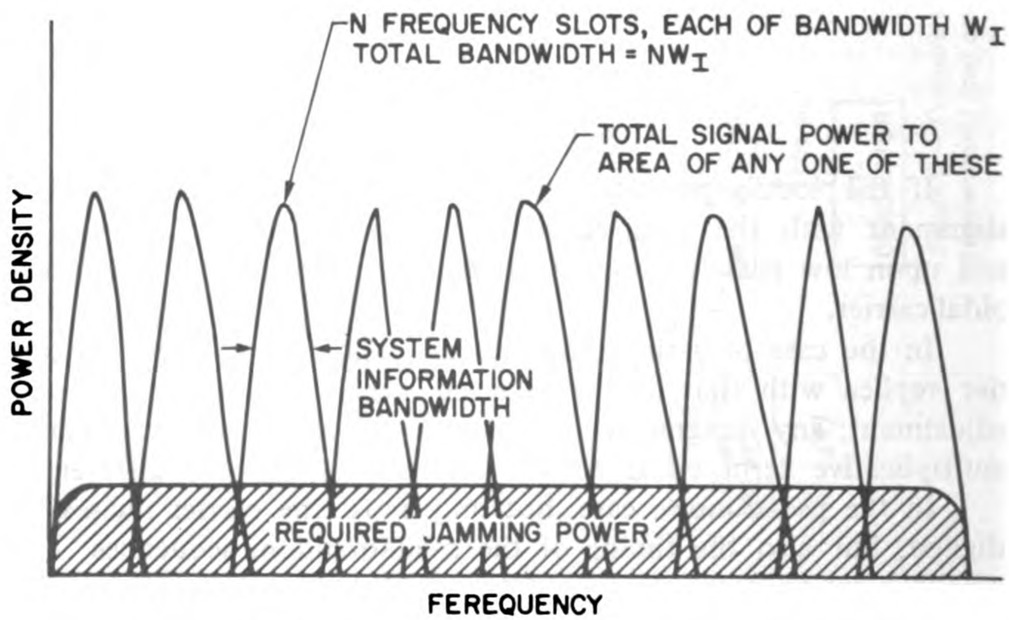


Figure 4 – Spectral relationships in a simple frequency-hopping system

of the bandwidth that contains the signal at any instant. This requires that the frequency-hopping pattern be unpredictable (which implies the use of cryptographic techniques), and that the hopping rate be sufficiently high that the jammer cannot sense where the signal is at any instant and jam it before it moves. In practice, frequency-hopping systems have been demonstrated with rates varying from a few hops per second to many thousand hops per second.

Systems which hop slowly, such that many bits of information are transmitted during a single hop can be vulnerable to narrowband jamming of a small number of slots; while resulting overall error rates will still be favorable, those errors that occur while the system is transmitting on the jammed slots will occur in bunches. In many applications this cannot be tolerated. The problem can be avoided through proper application of error-correcting coding. For example, in one scheme (7), information about each block of six information bits is spread over seven frequency hops in such a way that proper detection of any three hops suffices for correct detection.

A spread-spectrum system employing a given portion of the spectrum can accommodate many simultaneous transmissions. Just as many conventional radio sets would be assigned to different frequencies within the band to minimize interference, in this case, the different equipments would be assigned different code sequences. In PN, the sequences would be chosen orthogonal to one another; frequency-hopping patterns would be selected so that no two users transmit on the same frequency at the same time (or at least the probability of this occurrence is minimized).

Note that the jamming advantage which occrues to an individual radio set when it employs spread spectrum does not apply to an entire group of radios sharing a common spectrum. If the spectrum can be divided into M tightly-packed narrowband channels, all of which are occupied, and the jammer wishes to jam all of them, he must transmit M times the power required to jam any one of them. Now, if the M radios all employ spread-spectrum such that the entire spectrum remains utilized, processing-gain arguments still require that the jammer radiate M times the power required to jam a narrowband transmission in order to jam a wideband one. But now, since all occupy a common spectrum, once he has jammed one of them, he jams all of them. In a band containing large numbers of signals, use of spread-spectrum merely removes the jammer's capability to selectively interfere with a few transmissions, and forces him to jam them all, with the resulting increased requirement on jamming power.

Of course, the above reasoning neglects the effects of inter-user interference, which is often significant in both cases, and generally limits the extent to which a given portion of spectrum can be utilized.

Many variations of the basic pseudonoise and frequency-hopping techniques are seen in practice; some concepts employ low duty cycle, high peak power PN burst transmissions. When the timing of these PN bursts is controlled randomly, this process is sometimes called "time hopping," or "gated PN." If these bursts do not cause an increase in the transmitted signal bandwidth, this technique does not increase processing gain, since the increase in peak power is compensated for by a decrease in transmission time in such a manner that the energy per transmitted information bit remains constant. However, it does allow improved performance in certain tactical multiple-access situations employing PN, where signals from near users can jam those from more distant users. Even though the undesired signal employs a different code sequence, and is uncorrelated with the desired one, it can be seen that extreme differences in range (say 200 yards and 40 miles) can result in discrepancies in signal levels (in this case, the desired signal would be 46 dB below the undesired one) greater than typical processing gains (generally less than 40 dB) can overcome.

This so-called "near-far problem" does not occur in frequency-hopping systems, since different code sequences imply different hopping patterns, so at most times the undesired signal will be on a different frequency from the desired one. Time hopping, if properly designed, allows the receiver to recover sufficient information for satisfactory operation during those periods in which the interfering signal is switched off.

Many types of modulation can be employed in conjunction with frequency hopping; systems have been developed which use frequency-shift-keying, phase-shift keying, narrowband analog AM and FM, and PN. Designs involving the frequency-hopping of a PN signal can combine the relative simplicity of construction of PN with the relatively loose timing tolerances inherent in FH.

The chirp radar pulse-compression techniques of linear frequency sweeping and dispersive filtering (8) have occasionally been proposed for spread-spectrum communication applications, although they are inherently vulnerable to intelligent jamming, since waveforms can be easily duplicated.

Synchronization

As noted above, it is necessary for users of spread-spectrum equipments to remain in time synchronism with one another; in some systems, time accuracies of the order of 10-100 nanoseconds are required. Traditionally, synchronization circuitry has been the most complex portion of spread-spectrum equipments, and most performance short-comings have been associated with loss of synch.

Synchronization is generally less of a problem in frequency-hopping systems than in pseudonoise. In pseudonoise, time tracking accuracy of the order of a fraction of a bit of the keystream (ten to one hundred nanoseconds) is necessary; frequency hopping requires timing accuracy to a fraction of a hop (usually several microseconds). Thus timing in pseudonoise systems generally must compensate for vehicle motion, and short-term clock drift, while frequency-hopping systems are generally insensitive to these effects.

The synchronization process is generally separated into two phases: initial synch and tracking synch. The initial synchronization phase determines the timing of an incoming signal and brings the receiver into initial alignment; the tracking phase holds it in alignment.

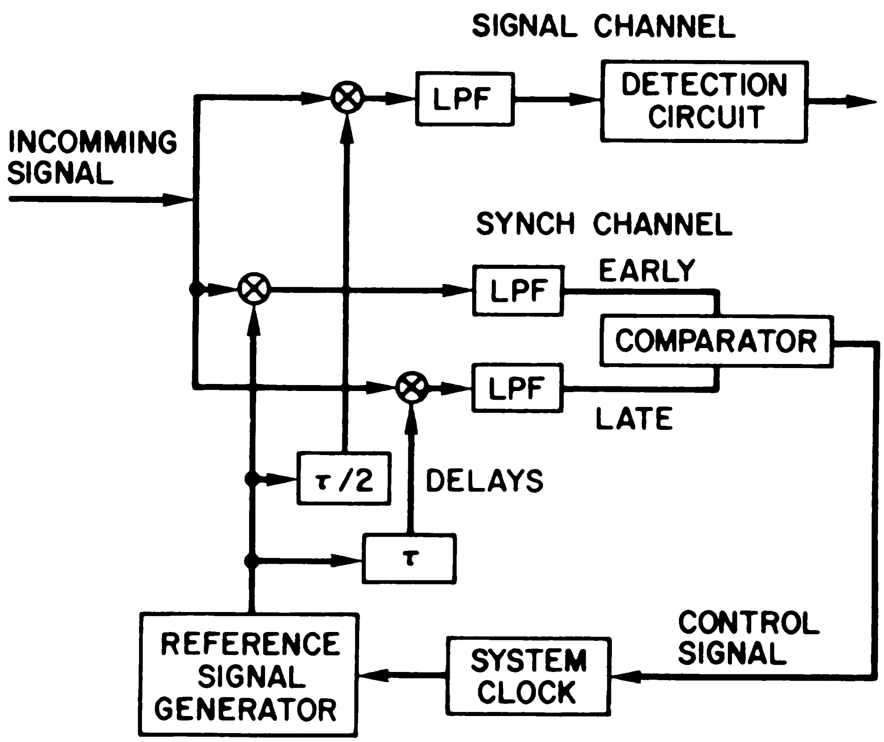
Initial synchronization usually involves the setup of receiver circuitry to recognize a particular synchronization waveform; when that waveform is received, the receiver establishes timing from it, and reverts to the tracking mode. For this process to be effective, it is essential that the probability of false declaration of synchronization be held to a minimum. At the same time the probability that the synchronizing waveform is recognized when it actually occurs must be maximized. These objectives can be accomplished simultaneously in a severe jamming environment only when the synchronizing waveform contains a large amount of energy, far more than is required for successful transmission of an information bit. For this reason, synchronizing signals are frequently fairly long, and comprise an appreciable portion of the transmitted signal.

Initial synchronization is frequently accomplished by means of a single synchronization preamble at the beginning of each transmission. The structure of the preamble is known to all users, and is usually fixed. An alternative is to intersperse synchronizing signals within the structure of the transmission, so that receipt of the beginning of the transmission is not necessary to achieve synchronization, and receivers which lose synchronization during the transmission can reacquire.

The major difficulty associated with initial synchronism is the protection of the synchronizing signals; they can only be scrambled to preclude deceptive jamming if the cryptographic devices at the transmitter and receiver are synchronized; if they were properly synchronized, there would be no need for initial synchronization. There are many ways around this apparent dilemma.

Synchronization tracking is generally accomplished by a relatively low-pass feedback loop which adjusts the receiver's timebase to track the incoming signal. In a PN system, tracking data is frequently obtained from an "early-late gate" (Figure 5). This circuitry collapses the incoming signal to two low-pass signals by combining it with two locally-generated reference signals differing in their timing by one bit of the random keystream. When the incoming signal is aligned with one of them (Figure 5b) its output will be a maximum, and that of the other will be zero. Proper alignment (Figure 5c) results when both are of equal amplitude; overall system timing is driven to maintain this condition.

Frequency-hopped signals can be tracked in some applications by simply varying receiver timing to maintain maximum level in the receiver after the signals have been dehopped. Other FH concepts



(a)

Figure 5 – Early-late gate operation (a) an early-late gate

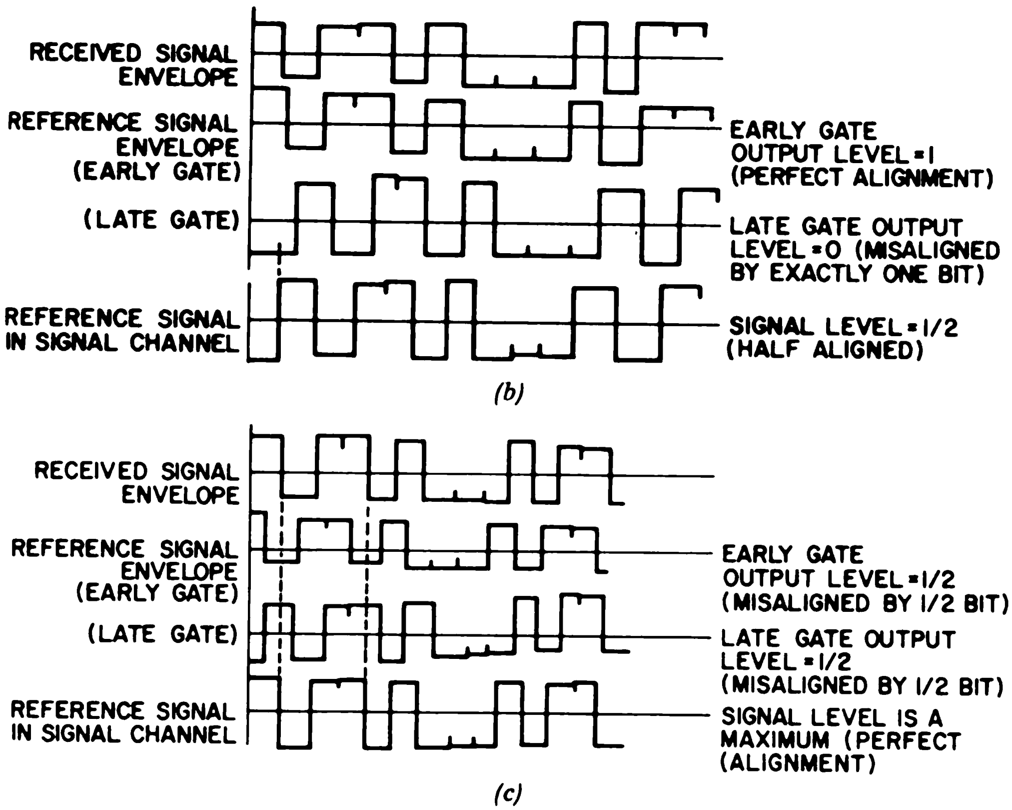


Figure 5 – (b) Clock misalligned by 1/2-bit-early gate reference aligned with signal, (c) Proper alignment-correlation equal with early and later reference signals.

involve the use of special synchronizing signals integral to the structure of each hop. Receivers employing these concepts can be mechanized using matched-filter concepts.

Spread-Spectrum Technology

The first spread-spectrum equipments employed conventional vacuum-tube technology, and wideband processing concepts similar to those developed for radar applications. More modern equipments continue to bear a resemblance to radar receivers, requiring relatively high linearity and large amounts of dynamic range. Fairly complex phase-linear wideband filters are often employed in spread-spectrum equipment designs, as are delay lines, correlators, and matched filters. Frequency synthesizers capable of rapid switching and settling on a new frequency are needed in frequency-hopping applications.

The increasing trend toward the use of digital processing circuitry to perform functions formerly done by analog elements is particularly pertinent to spread-spectrum system design. Digital techniques allow practical system designs today that would have been out of the question five years ago. A good example can be found in the area of matched filtering.

A matched filter (Figure 6) is a device which is "matched" to a particular waveform; its output at any instant is equal to the cross-correlation between the actual waveform being received and the waveform to which it is matched. Matched filters are well suited to PN system synchronization applications, in conjunction with waveforms which are PN sequences which possess good autocorrelation properties. Under these circumstances, in the absence of noise, the matched filter output is essentially zero until the instant at which the desired incoming waveform is exactly aligned with the replica stored within the matched filter; at that instant, a large impulse is output, and width of the order of one bit-width of the sequence, and total energy equal to that of the entire sequence. Since matched filter

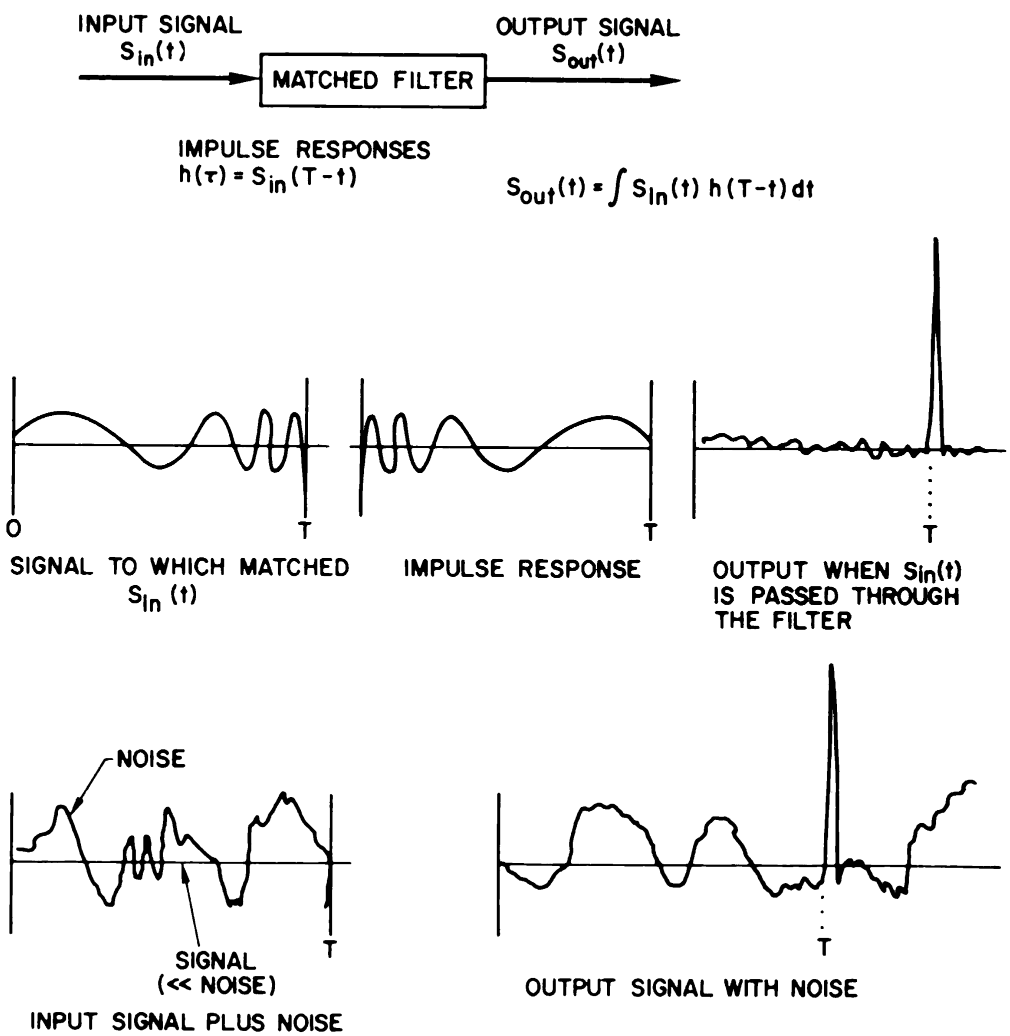


Figure 6 – Matched filter opaterion (a) the matched filter, (b) typical waveforms

operation is essentially linear, this action occurs in the presence of additive noise as well, and effectively boosts the desired signal energy up above the noise level to the point where it can be detected with high confidence.

These features are ideally suited to spread-spectrum applications; matched filters have been included in many spread-spectrum system designs over the past decade. However, until quite recently they have been impractical to implement, at least in tactical applications.

For example, one system developed in the late 1960's used a matched filter bank for preamble synchronization. The preamble was a PN sequence containing slightly more than 3000 bits. Due to limitations imposed by the matched-filter hardware, the particular sequence could not be changed arbitrarily, although the order of different portions of it could be rearranged. Discrete components were used, along with glass delay lines, and the bulk of the matched filter comprised the major portion of the entire radio set.

With today's large-scale-integration (LSI) techniques, charge-transfer-devices (CTD's) (9) will soon be available which will perform this entire function with fewer than a dozen integrated circuits. The inavailability of a single chip capable of performing the entire function is due largely to a lack of specific requirements for such a chip; such chips will very shortly be feasible. And CTD matched-filters can be serially loaded in a matter of microseconds with whatever reference sequence is desired.

Surface-acoustic-wave devices have similar applications to spread-spectrum technology, primarily in situations where extremely wide bandwidths are required, and shorter time durations are acceptable.

Microprocessors, which are currently finding many applications in tactical radio communication and navigation equipments (10), are similarly making fairly ambitious spread-spectrum system design concepts practical. They can replace hard-wired logic not only in system management and control applications, but also in the areas of digital sequence generation, received signal processing, and synchronization. Of equal import, when they are properly incorporated into system designs, the resulting system design will be capable of evolution to new and improved capabilities, simply by programming changes.

Conclusions

Spread-spectrum concepts have been well developed for many years. Fairly ambitious system designs have been built and demonstrated, but have never been widely implemented; those simple enough to be practical lacked sufficient processing gain, and those with the necessary processing gain and resistance to intelligent jamming were generally impractical and expensive. New electronic design concepts that are becoming practical today through LSI are removing most limitations and making practical many sophisticated designs. Applications are being found in tactical radio communication, satellite and space communication, navigation, radar and other areas. Needs have been established for some time; now that spread-spectrum concepts which satisfy these needs can be built reliably and inexpensively, we can anticipate the widespread use of this new technology in many military technology areas in the future.

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U. S. GOVERNMENT PRINTING OFFICE: 1977 O - 247-460

MORE EFFICIENT "TRAPATTs"

Scientists at the Naval Research Laboratory, have developed a high-power TRApped Plasma Avalanche Triggered Transit (TRAPATT) device, which yielded the most efficient results reported to date for operation with 50-microsecond pulse widths at a 1-percent duty factor. Power outputs up to 63W with 30-33-percent efficiency in the 2 GHz frequency range were obtained.

TRAPATTs compete with silicon bipolar transistors and gallium arsenide (GaAs) field effect transistors for use in a variety of military systems. While these transistors show great promise for future use in medium-power, wideband applications, there are still large areas of the microwave frequency-power spectrum where TRAPATTs or IMPact Avalanche Transit Time (IMPATT) devices are the best or only device choice.

Presently, nearly all TRAPATTs are fabricated from silicon, although originally some devices were made of germanium. Using the newly-developed NRL devices mounted on diamond heat sinks, markedly improved results were obtained in power and efficiency

TRAPATTs will be used in future microwave systems where high peak-power output with high efficiency is essential. However, they say a better understanding of the TRAPATT device-circuit interaction is still needed, as well as increased yield and reproducibility of devices capable of operating at wide pulse widths.

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NAVSO P-510

VOL. XXX, NO. 9

Cover Caption

Seen here is the gray reef shark. The peculiar arched-back posture and stiff, awkward extension of the pectoral fins indicate the shark is upset and is preparing to attack.

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