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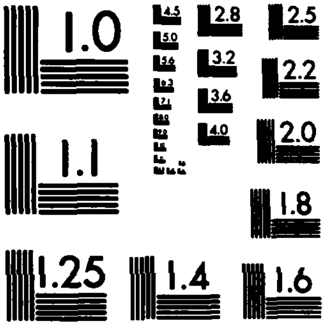

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RANGING AND CORRELATING SENSOR DEVELOPMENT PROGRAM

Interim Technical Report/Design Evaluation Report

SEI Reference 6038 ● November 1983

Prepared for:

U. S. Army Mobility Equipment Research and
Development Command
Fort Belvoir, Virginia 22060

Contract No.: DAAK70-82-C-0213
Data Item No.: A004

SCOPE ELECTRONICS INC. • A SUBSIDIARY OF SCOPE INCORPORATED
1860 MICHAEL FARADAY DR., RESTON, VA 22090 • 703-471-5600 • TWX 710-833-1178

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1. PREFACE

The work described in this document was performed under contract to the U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia by SCOPE Incorporated, Reston, Virginia. The contract number is DAAK70-82-C-0213, Ranging and Correlating Sensor Development.

The final goal of the program is to design and develop five Advanced Development Models (ADM) of an improved interior intrusion detection sensor. The program includes an investigation of new intrusion detection concepts, selection of techniques to be tested in brassboard form, followed by design, fabrication, and test of the ADM systems.

The improvement under development concerns the reduction of nuisance alarm sensitivity encountered using existing devices. The majority of existing devices are motion detectors, principally relying on a Doppler frequency as the basis for alarm. Nuisance alarms can potentially be generated from any environmental or man-made disturbance that imparts motion within the protected area. Examples include air turbulence, rotating or oscillating objects such as fans and curtains, and personnel/vehicular activity in adjacent areas. The thrust of this effort is to develop sensors with an inherent ranging capability, such that a disturbance can be localized and correlated to a specific location within the protected area. In this manner a significant reduction in nuisance alarm probability should be realized.

2. SUMMARY

The document ~~contained herein~~ reports the findings of the study phase of this contract, with conclusions and recommendations for advanced interior intrusion detection concepts to be tested in brassboard. The report discusses potential sources and properties of intrusion signals, measurement techniques, and signal processing methods to extract range and correlating data. It has been found that many techniques have the potential for ranging and correlation of intrusion signals, however few of these are accomplished in a straightforward, practical sense. Through the derivation and application of evaluation criteria, several candidates were selected for further study in breadboard experiments. The breadboard tests afforded a first hand opportunity to measure and compare the anticipated performance of these candidates. The outcome of the experiments then formed the basis for recommending concepts to be explored further in brassboard development.

3. TECHNICAL INVESTIGATION

3.1 INTRODUCTION

In general terms, the approach taken in this study was that of an optimization process in systems analysis. Optimization in this sense first involves a clear definition of the problem environment. Once having defined the problem, a set of initial solutions is proposed. From the proposed solutions, system design models are developed. These models further define the system design characteristics and the interaction of system variables and requirements. The models are then analyzed for their response to the intended environment. At this point the optimization process becomes recursive; knowing the behavior (response) of specific models in the environment, the set of initial solutions is re-examined for potential improvements. New models are developed and analyzed until a set of feasible solutions is obtained. The set of feasible solutions is then ranked according to their ability to meet the goals and objectives of the problem defined at the onset.

In the study described herein, the problem was initially defined through surveying literature reporting the experiences of others involved in intrusion detection and security technology. Appendix A contains a partial list of the references reviewed, with summaries of the pertinent facts obtained from each. The signal environments in which intrusion signatures could be measured were then identified. Identification of the environments involved analysis of the physical phenomenon associated with human intrusion, including both potential sources and properties of intrusion signals. An inseparable part of this analysis required determining if detectors and emitters were available to measure the intrusion signals. Given a signal environment and a set of transducers to measure the intrusion phenomenon, signal processing techniques pertaining to each environment were formulated. Both environments and target detection techniques were evaluated with a prescribed set of criteria from which highly ranked candidates were identified. These candidates were modeled and analyzed through breadboard circuit investigations. Representative system performance could be measured and weighed from the breadboard tests, thus providing a solid basis for identifying the candidates for brassboard development.

3.2 PHYSICAL PHENOMENON ASSOCIATED WITH HUMAN INTRUSION

The detection of human intruders must rely upon the sensing of environmental changes or effects caused by the presence and/or the actions of the intruder within the volume under surveillance. In order to seek out successful intruder detection system designs it is essential to review the options available. The process must begin with a summary of the physical phenomenon associated with human intrusion and the measurable effects that can be considered to implement a reliable detection system having the greatest possible immunity to extraneous nuisance signals.

3.2.1 Sources of Intrusion Signals

The penetration of a protected area by an intruder can be expressed in simple physical terms as a local biological mass in motion. The biological processes of the human body are unique sources of various chemical, radiant and thermal emanations not associated with inanimate physical objects. Additionally the presence and motion of the intruder have an effect on the electromagnetic and acoustic signal equilibria due to the absorption and reflection characteristics possessed by the intruder. These effects include transient phenomena associated with non-continuous motions of the intruder plus the permanent changes in the signal environment caused by intruder presence.

Table I. lists the major categories of physical phenomena which arise because of an intruder. They are divided into the three major categories of mass motion effects, emanations and effects on local signal equilibria.

3.2.1.1 Mass Motion

The effects of mass motion are seismic, acoustic and local gravitational effects. The movement of a mass from place to place subjects the ground or floor to a moving pressure equal to the intruder's weight on the order of 50 Kg. The transient effects produce seismic vibrations in the supporting medium which propagate through all continuous material in the structure. The steady state or presence effect results in pressure or stress in the supporting structure.

The motion of a mass results in air motion as well as induced motion of supporting structures. Acoustic signals in air are produced which range from very low (infrasonic) frequencies up into the very high (ultrasonic) frequency region of the acoustic spectrum. Finally, mass motion results in a change in the local mass distribution with the region under surveillance. This implies that a change in the local gravitational field takes place as the mass moves around.

1) MASS MOTION

  A) IMPARTS VIBRATION TO POINTS OF PHYSICAL CONTACT (PRESSURE AND SEISMIC).
  B) IMPARTS MOTION TO AIR (ACOUSTIC).
  C) CHANGES MASS DISTRIBUTION IN VOLUME UNDER SURVEILLANCE.

2) EMANATIONS

  A) ACOUSTIC
  B) ELECTROMAGNETIC (GRAY BODY RADIATION)
  C) CHEMICAL (CO_2, H_2O, PERSPIRATION)
  D) THERMAL CONVECTION AND CONDUCTION

3) CHANGE IN LOCAL SIGNAL EQUILIBRIUM

  A) ABSORPTION AND REFLECTION OF ELECTROMAGNETIC RADIATION.
  B) ABSORPTION AND REFLECTION OF ACOUSTIC OR SEISMIC SIGNALS.

TABLE I. PHYSICAL PHENOMENON ASSOCIATED WITH HUMAN INTRUSION

3.2.1.2 Emanation

The mere presence of an intruder results in emanation phenomena that are not normally present unless extreme measures are taken to prevent their escape. Respiration and cardiovascular activity produce acoustic energy which is transferred to air and matter in contact with the intruder. Physiological processes generate heat which raises surface temperatures above normal ambients and which have varying gradients throughout the limbs of the body. The resulting gray body radiation differs from that of most inanimate material.

Respiration processes of the lungs and pores issue quantities of water vapor, carbon dioxide and other chemicals into the surrounding air. Also, the thermal effects of conduction and convection locally affect the temperature of air and material in contact with the intruder. These induce thermal gradients which depart from those which prevail if no intruder is present.

3.2.1.3 Change in Local Signal Equilibrium

When an element of mass is introduced into an environment, the absorptive and reflective properties of the mass change the local state of equilibrium for both electromagnetic and acoustic signals. The intruder's presence causes changes in the amplitude, phase, frequency, direction and for electromagnetic radiation, the polarization of signals affected. In the absence of illuminants or radiators designed to provide a high level of ambient signal, only the gray body radiation from objects in the environment is available.

3.2.2 General Characteristics of the Intrusion Signals

Each of the phenomena listed above defines potential signal sources that can be used in an intrusion detection process. In later sections each of these signal environments will be discussed in some detail tying together the technology for sensing or transducing a particular signal, providing an illuminant when required and processing the resulting signals for the detection circuits. The following paragraphs offer a general description of the potential signal sources as an introduction to the more detailed material.

3.2.2.1 Signals Caused by Mass Motion

The accelerations and decelerations of the intruder will impart kinetic energy to any matter that is contacted. The pressures on supporting structures generate vibrations which propagate rapidly in material contiguous with points of contact. Material structures possess favored vibrational frequencies or resonances which depend on physical dimension and the types of materials from which they are made. The geometries of the object define points having either large or small signal amplitudes as well as points that strongly reflect incident acoustic energy. Signals may propagate either as transverse (violin string) or compressional waves, each traveling at different speeds.

A given physical environment will exhibit a wide range of frequency, speed, reflection and resonant characteristics because of the diversity of materials and their physical makeups. In many materials these seismic signals travel large distances with but small attenuation. Reflection and multipath signals will result at any point where there are discontinuities in the propagational speed.

The signals imparted by the intruder to the fluid medium of air are strictly compressional. The gross intruder motion predominantly generates very low frequency compressional waves in the air. Secondary acoustic signals can arise from movement of the supporting structure and any sliding contact between intruder and local material. Signals of this type can be found throughout the acoustic spectrum. The airborne acoustic signals radiate in a spherical wave from their source in all directions and exhibit strong reflection from rigid surfaces. Low frequencies propagate very well through air but higher frequencies are severely attenuated. Both temperature and humidity affect the speed of propagation and signal attenuation.

The remaining potential signal source due to mass motion is the actual mass distribution in the volume under surveillance. A redistribution of mass causes a slight change in the local gravitational field; this change is, of course, very slight and presents a severe challenge to a sensing system.

3.2.2.2 Signals Available from Intruder Emanations

Acoustic signals that may be available because of the presence (rather than the motion) of the intruder result from intrinsic motions associated with biological process. The cardiovascular and pulmonary actions within the human each produce low level acoustic signals. The pulsing of the heart, although a strong physical process, is well damped and transmits small signal levels to the surrounding air. The breathing process couples directly to the air, but the case of quiet breathing transmits predominantly very low frequency signals. Heavy breathing can generate turbulent air flow which is richer in high frequency content.

Moving to the electromagnetic domain, the human body must radiate or otherwise dissipate the nominal 100 watts of heat energy that are constantly generated internally. In general, this dissipation is reflected in warmer skin temperatures and breath exhalation warmer than the undisturbed surround. The warmer surfaces exhibit radiation levels higher than inanimate objects in the region. These radiations from bodies in the neighborhood of $300^{\circ}K$ are a maximum in the 8 to 20 micron region of the electromagnetic spectrum.

The chemical emanations from the human consist of rather large quantities of water and carbon dioxide vapor plus a number of trace chemicals which also appear in vapor forms. These vapors diffuse slowly into the surrounding air but leave a trail known to be trackable by the familiar bloodhound.

The body generated heat mentioned above not only radiates in the form of electromagnetic radiation, but is conducted to any material or air in contact with the body. This raises the temperature of the material being touched and, in the case of air, causes thermal convection currents moving up and away from the intruder. These columns of rising air are slightly higher in temperature than the ambient and slightly increase the air motion in the vicinity.

3.2.2.3 Signals Available from Changes in Local Signal Equilibrium

A volume under surveillance can in a general sense be considered a resonant chamber for both acoustic and electromagnetic radiation. Given a source or sources of either type of radiation anywhere in the volume, then the equilibrium condition for the volume will result in a fixed standing wave pattern if indeed no physical changes are taking place in the volume. The amplitude and relative phases of the radiant energy will be stable throughout the volume. In the real world this model must allow for signal penetration from outside the volume as well as controlled changes necessary for temperature control within the volume.

The penetration and subsequent motion of an intruder in the volume will disturb the signal equilibrium described above. The intruder will cause changes in signal amplitude, phase, polarization and frequency throughout the volume. These are caused by absorption and reflection of radiation by the intruder.

In typical environments, the only type of radiant energy that is present in any strength and stability is infrared electromagnetic radiation from gray body radiators. The exploitation of detection techniques using the principles of change in local signal equilibrium requires active illuminants or radiators for the acoustic domain and other regions of the electromagnetic spectrum. Transducers must then be selected and positioned in accordance with the type of system being implemented.

3.2.3 Detection System Design Criteria

Given the list of potential intrusion detection signals described above, the task of system design begins with a survey of the available emitters and detectors which can be used to sense the available intruder signals. In conjunction with these data, it is necessary to review all of the known methods for processing the transducer signals and accomplish reliable detection with a minimum of false alarms caused by nuisance signals.

The section to follow will present the current technology of emitters and detectors and the myriad of processing schemes that have been used in various target detection systems. The characteristics of these systems will be tabulated and ranked for suitability in the ranging and correlating system.

3.3 EMITTERS AND DETECTORS

A list of emitters and detectors available for use in intrusion detectors is given in Figures 3-1 through 3-6. The list is presented in flow chart form to show clearly the grouping of the transducers by signal environments. The emitters and detectors presented in the figures are generic rather than specific models. A list of specific representative transducers is given in Appendix B.

3.4 DETECTION AND PROCESSING TECHNIQUES

3.4.1. Passive Infrared Sensors

3.4.1.1 Physical Phenomenon of Intrusion

A passive infra-red detector alarms on the IR energy emitted by an intruder. No emitter is required to illuminate the area to be secured for the detector to operate. All objects radiate IR energy. The wavelength and amount of the energy is a function of an object's temperature, color and surface texture. IR energy is always present in a given area and changes very slowly with temperature. The passive IR detector responds to the abrupt change of IR energy with respect to the background level caused when an intruder enters its field of view.

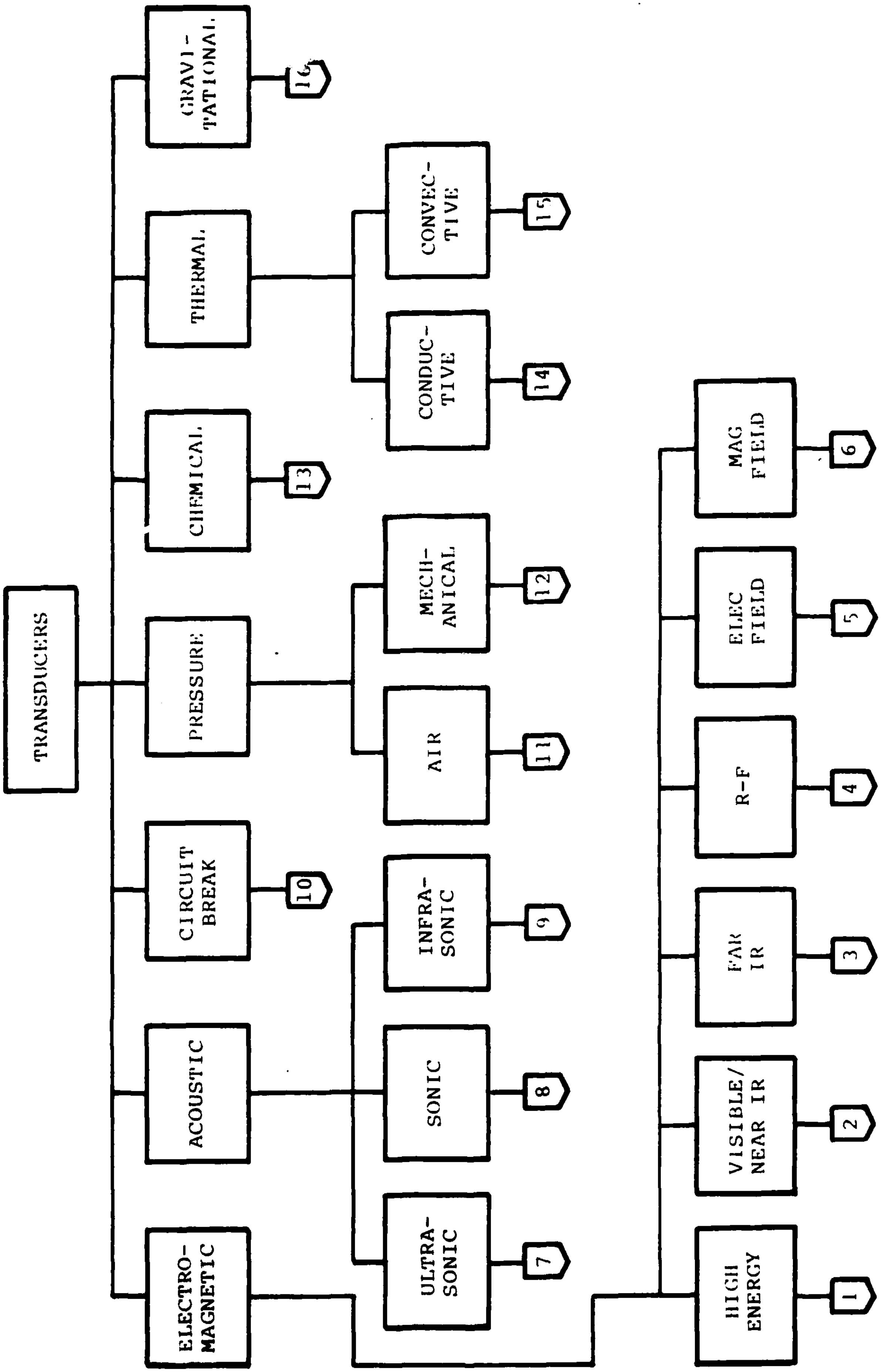

Figure 3-1. Available Transducers

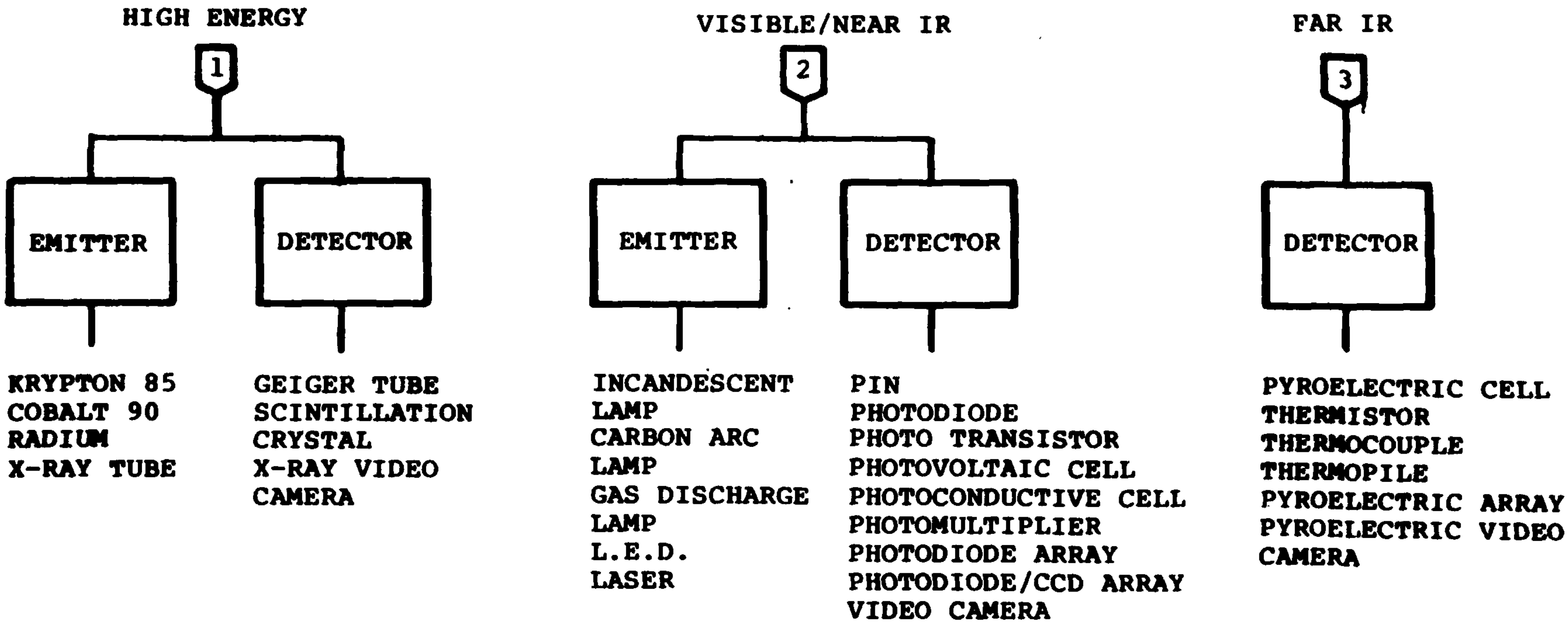

Figure 3-2. Available Transducers, Electromagnetic

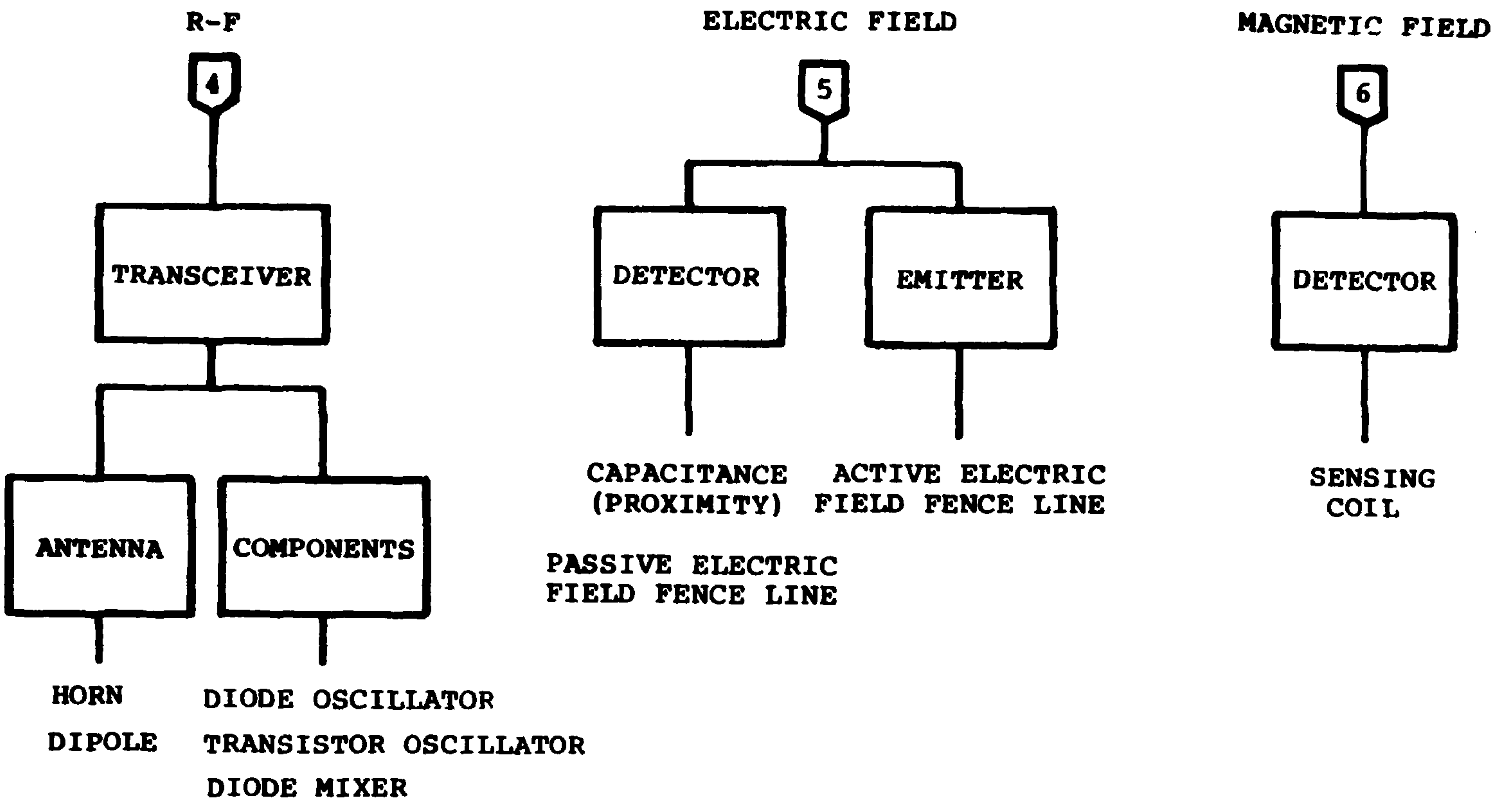

Figure 3-3. Available Transducers, Electromagnetic

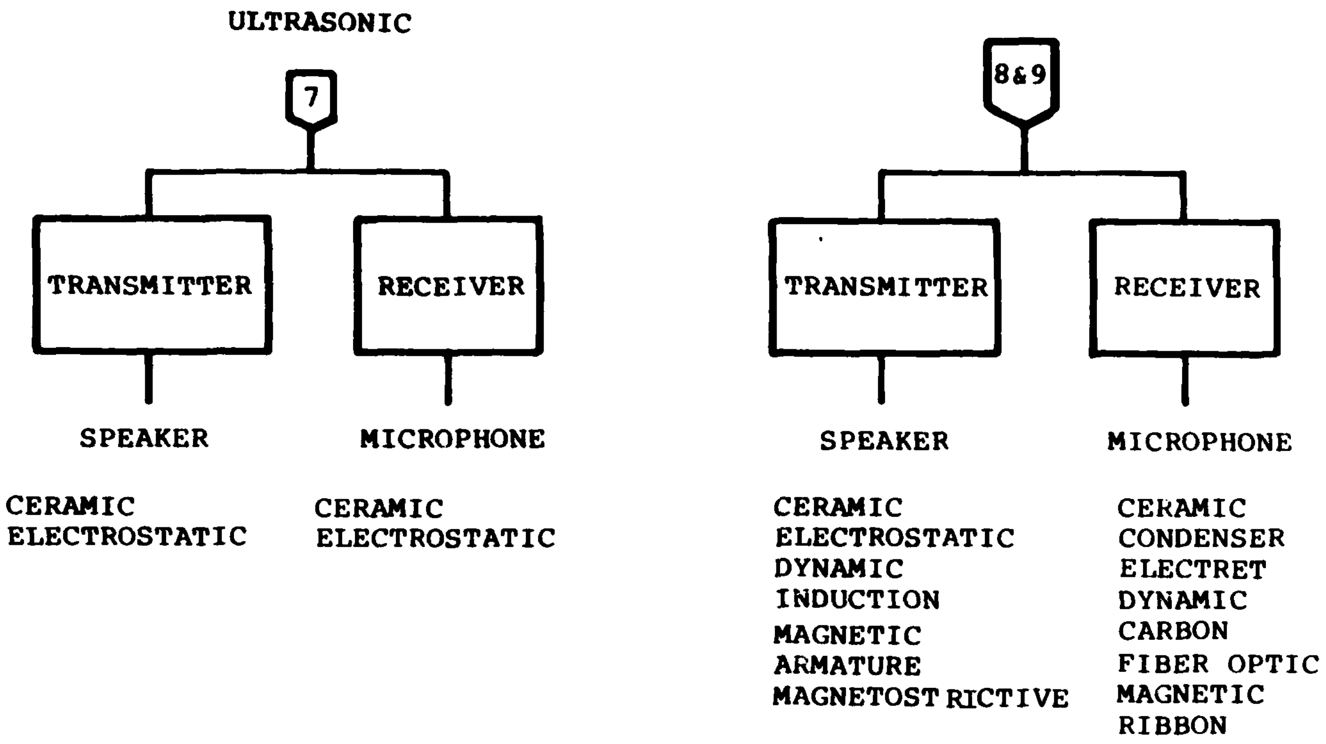

Figure 3-4. Available Transducers, Acoustic

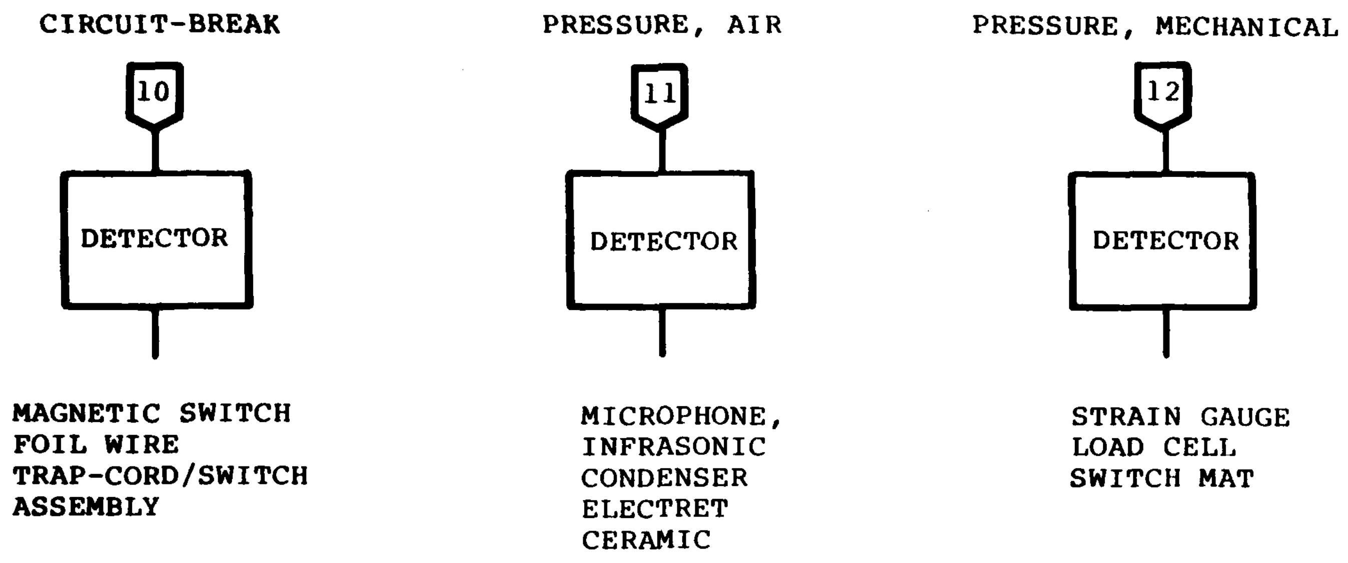

Figure 3-5. Available Transducers, Miscellaneous

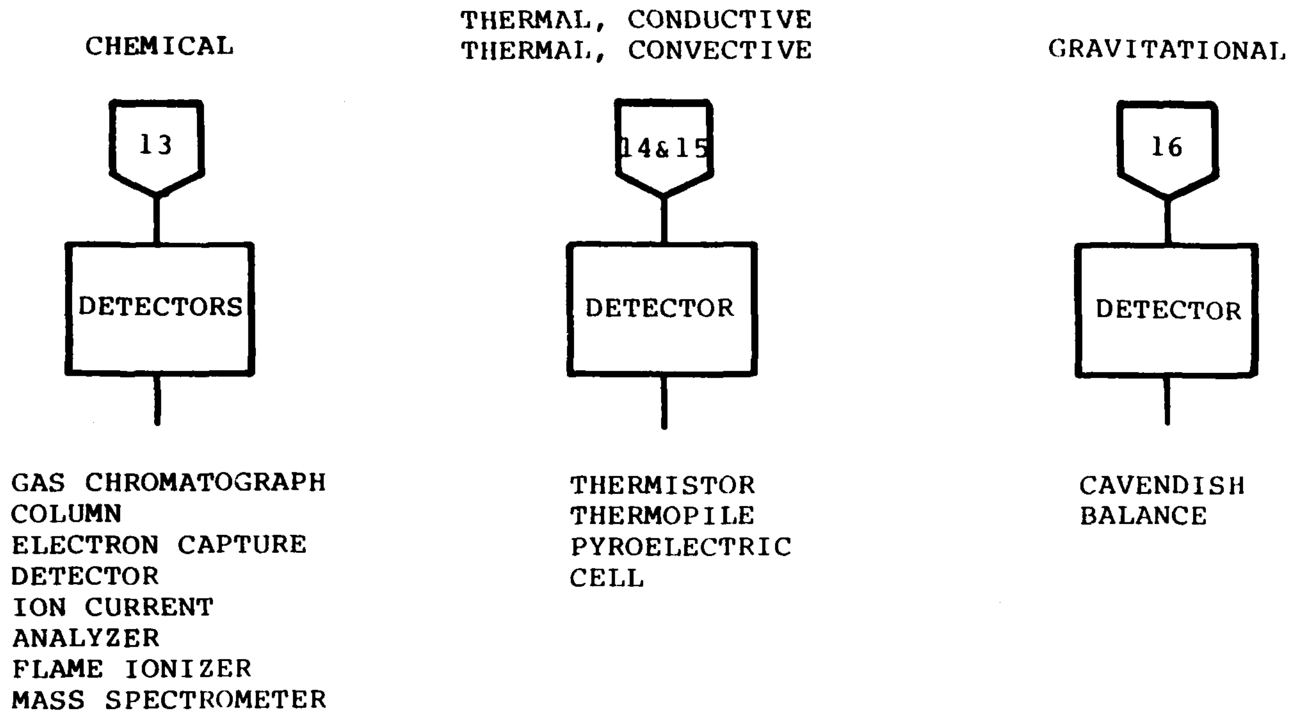

Figure 3-6. Transducers, Miscellaneous

3.4.1.2 Detectors

A human body at an average temperature of 98.6°F emits IR energy predominantly at wavelengths from 8 to 14 microns and radiates an amount of energy roughly equivalent to a 50 watt source. IR energy at these wavelengths is invisible to the human eye. An IR sensing element for energy at these wavelengths works upon the principle of responding to the change in its temperature due to being illuminated by IR energy received from its field of view. Three types of detectors are currently used in commercially available passive infra-red sensors. These are thermistors, thermopiles, and pyroelectric sensors. A thermistor changes resistance as its temperature changes. A thermopile is made up of several thermocouples connected in series and produces a change in generated voltage for a change in temperature of the element. The pyroelectric detector changes its polarization with a change in its temperature and is the most sensitive and quickest to respond of the three types. The pyroelectric detector is constructed from a crystal to which parallel electrode plates are attached. The crystal exhibits an internal electric field which results from the alignment of electric dipole moments. The electric field is directly proportional to crystal temperature because the degree of alignment can be disturbed by phonon vibration. If the temperature of the crystal varies, the electric field also changes and the change will produce an observable current when the electrodes are connected to external circuitry. The pyroelectric effect depends on the rate of change of temperature, and any steady radiation from stationary objects in thermal equilibrium will not be detected. Thus the detector inherently cancels out signals from stationary scene elements and responds to radiation that emanates from moving objects provided that the intensity of radiation of the moving objects differs from that of the background.

For increased signal and sensitivity, the scene under surveillance can be focused on the pyroelectric cell with a lens or with a curved mirror. The choice between the two may be based in part on the fact that a lens must be made from a material that passes IR energy from 8 to 14 microns. Glass cannot pass radiation much beyond one micron. Therefore the lens must be made of such costly materials as Germanium or Zinc Selenide. A mirror however is required only to reflect IR energy and can be made from any of a wide array of materials including silvered glass, and turns out to be much less expensive than the lens.

3.4.1.3 Dual Element Sensor

A type of passive IR sensor that is currently available and widely used for interior intrusion detection purposes contains a dual-element pyroelectric detector and a multisection mirror. The multisection mirror breaks the overall area of coverage into smaller separate fields-of-view. The number of fields-of-view equals the number of mirror sections. This arrangement provides more sensitivity than a continuous surface mirror because as an intruder moves in and out of the fields-of-view, the output of the detector is caused to vary between the background level and the intrusion level. The multisection mirror is thus particularly helpful for the situation of a uniform background of radiation.

A dual element detector is used to cancel out the effects of background and ambient temperature variations. The two elements are connected in series opposition such that their combined voltage is the difference between their individual voltages. As an intruder moves through one of the fields-of-view, the radiation emitted by him falls on one of the elements before the other. This causes a net signal out from the pair and forms a pre-alarm condition. By sensing the order in which the elements receive a stimulus, one can determine in which direction the intruder is moving. If the intruder continues to move across the fields-of-view, the differential signal fluctuates at a rate which is proportional to his speed. In order to distinguish between intrusion and nuisance phenomenon, the number of signal fluctuations may be counted, and a minimum count threshold of 2 or 3 can be set which must be exceeded for an alarm to be issued.

Although there are many equivalent beams of coverage with this sensor, one cannot obtain any bearing information on the intruder. This is so because no matter which beam is entered, the only indication is a signal level change from the detector. One cannot relate the signal level change to the exact beam entered because all beams are ultimately focused on the same detector.

3.4.1.4 Imaging, One-Dimension Scan

A passive IR sensor that uses a one-dimensional scanned imaging technique employs as a detector either a row of pyroelectric cells or a single pyroelectric cell and a mechanism such as an oscillating or vibrating mirror. The image of the area under surveillance is focused on the detector the output of which consists of a video signal similar to a single scanned line from a video camera. In order to alarm on a moving target when the mechanical scanning technique is used, scan-to-scan cancellation must be employed to subtract out the video information resulting from stationary elements of the scene.

With a non-mechanical scanning technique such as an electronically scanned row of cells, scan-to-scan cancellation is not necessary because the background radiation pattern does not sweep past each cell and is in fact constant. The signal out of each cell for stationary scene elements is close to zero because of the capacitive nature of the pyroelectric cells. The row of cells may be read out either by an on-chip CCD shift register if the assembly is integrated, or with the use of a separate analog multiplexer if it is not. For horizontal scanning, the azimuth of the target is proportional to the position along the scan at which it is detected. Anti-nuisance processing includes setting a requirement for a minimum indicated degree of movement along the row of cells and of determining that the response is continuous along the cells.

Ranging with a single detector assembly is not practical and can only be done to a crude approximation. If the width of all targets were a constant (far from true) the range of a target would be proportional to the width of the image. With the use of two detector assemblies, however, it is possible to calculate the target range by triangulation provided that the two assemblies are separated.

3.4.1.5 Imaging, Two Dimensional Scan

A passive IR imaging sensor that scans in two dimensions can use as a detector either a pyroelectric camera tube, a two-dimensional array of pyroelectric cells, or a row of pyroelectric cells in conjunction with an oscillating or vibrating mirror. Two dimensional arrays of pyroelectric cells may be mounted in IC packages with built-in CCD shift registers and clocking circuitry to shift the output of the array through a single video output port.

In order to cancel out stationary picture elements when a mechanical scanning technique is used, frame-to-frame cancellation must be employed. This is not required when an electronically scanned detector is used for the same reasons as given in the section on one-dimensional scanned passive IR imaging sensors.

Pyroelectric cameras, designed to provide standard TV type output (512 lines-per-frame, 60 frames-per-second) have been proposed for intrusion detection. They are not well suited for the task because of the high data rate. The only practical way to use them is in the "stare" mode where data is output only for pixels that have changed from one scan to the next. Even so the scan rate of 60 frames-per-second is much too fast for the intrusion sensor application.

When the orientation of the sensor is such that scanning is done in a vertical or near vertical plane, both azimuth and height information is obtained on the target. It is more difficult for an intruder to elude the two dimensionally scanned sensor by passing under or over its field-of-view than for the one-dimensionally scanned sensor since the field-of-view has height as well as width. The azimuth of the target is proportional to the position along the scan of the moving target image center with respect to the vertical edges of the scan. With a two dimension scanning technique the extreme edges of the target image in the horizontal direction can be determined more accurately than with the one-dimension scanning technique. The left-most edge can be found by vertically searching the stored matrix of pixels along each column starting with the left-most column to detect the first column which contains any target image video. The right-most boundary can be found in a similar fashion by searching right to left.

As in the case of a one-dimensional scan, ranging is not practical and can only be done to a crude approximation.

3.4.2 Passive, Electrostatic Sensors

3.4.2.1 Physical Phenomenon of Intrusion

A passive electrostatic sensor alarms on the electric field emitted by an intruder. To emit an electric field the intruder must first have accumulated an electrical charge on his body. He can do this by walking across a rug or brushing by a wall.

3.4.2.2 Detection

One way to detect the electric field is to employ a very high gain FET input operational amplifier to amplify the difference in potential that is electrically induced across the ends of a wire placed in the field. If the wire is oriented in line with the lines-of-force from the intruder, the free electrons in the wire will move along the wire in a direction opposite to that of the direction of the electric field and the ends of the wire will become oppositely charged. The operational amplifier amplifies the induced voltage. The output of the amplifier can be level detected to alarm on a minimum value of electrostatically induced voltage in the wire.

3.4.2.3 Problems of Implementation

The major weakness of this detection technique is the large degree of uncertainty that the intruder will accumulate a charge on his body. Even if a rug is installed in the room to cause the charge build-up, the intruder may discharge himself during normal movements in the room by touching grounded objects. Also the humidity would have to be kept low in the room.

The proposed sensor would be subject to a large degree of environmental noise in the form of stray electrical fields. A major contributor would be AC fields at multiples of the power line frequencies. The strength of the stray electrical AC fields would be much larger than the slowly varying electric field emitted by an intruder.

3.4.3 Active Electric Field Sensors

3.4.3.1 Physical Phenomenon of Human Intrusion

An active electric field sensor alarms on the effect of human presence on an electric field which is generated in a space to be protected. The most effective way to measure or detect this electric field disturbance is to measure or detect the change in capacitance caused by the dielectric and conductive properties of the human body. The capacitance of the object to be measured can be considered to be the detector portion of an active electric field sensor. The object must consist of two separate conductive pieces such as a wire and ground, two wires, two metal plates, or their equivalent.

3.4.3.2 Currently Available Sensors

Several commercially available sensors operate upon the active electric field principle though none can be considered to offer interior volumetric protection. One type is the proximity detector which offers point protection, e.g., it is designed to alarm when an intruder contacts or is in close proximity to a designated position in an area to be secured. It is used to protect metal objects such as safes or filing cabinets which form one portion of the capacitor. The object is placed on a grounded conducting plane but is insulated from it by thin insulating pads. The metal object is connected to one input terminal of the proximity sensor and forms part of a sharply tuned resonant circuit. The other input terminal of the proximity detector is connected to ground. An oscillator in the sensor generates an rf current which is passed through the resonant circuit and causes a given voltage drop across it. When an intruder touches or comes near the metal object he causes an effective change in the dielectric constant of the space in the vicinity of the object which changes the capacitance, detunes the resonant circuit, causes a change in amplitude of the voltage across it, and triggers the alarm indication.

Another type of active electric field sensor is the electric field fence sensor which is designed to provide exterior protection. Sensors of this type are made up of several parallel wires strung above ground either supported on a fence or parallel to it and supported on separate posts. One form of fence sensor uses active wires and passive wires. An AC generator excites the active wires with a voltage of 300 volts or more and the passive wires have a voltage induced into them by capacitive coupling with the active wires. An intruder attempting to crawl under the wires or trying to pass through the space between an active wire and a passive wire changes the capacitive coupling between the wires and therefore the amount of induced voltage in the passive wires which sets the alarm indication.

Another type of electric field fence sensor uses wires that are all active. Each pair of active wires is driven by the same AC voltage source. Both wires of the pair are balanced to ground with RC networks such that the voltage drops of both wires are the same in phase and amplitude. When an intruder approaches the pair of wires and is closer to one than the other he changes the capacitance to ground and upsets the balance between the voltages of the two wires which triggers the alarm condition.

3.4.3.3 Sensors for Interior Space Protection

Neither the proximity detector nor the electric field fence sensors as described above can be used directly to provide interior space protection with ranging capability. The main limitation of a proximity detector is the lack of sensitivity with distance of the intruder from the capacitive elements. Beyond a range of one meter the electric field intensity is considerably lower and the signal-to-noise ratio decreases to an extent that makes for unreliable alarming. Installing more than one proximity detector in a room and with a common processor would allow for fuller coverage of the area with some ranging capability. Existing metal objects distributed in a room could be wired separately to a multiple input proximity sensor processor. These objects might be filing cabinets, metal partitions, metal shelf units, etc. This method would be highly dependent upon the arrangement of the area to be secured and would not necessarily allow for uniform coverage of the area.

More uniform coverage could be obtained with an array of proximity detector elements installed in the floor distributed evenly throughout the area. These could consist of metal plates mounted flush with the surface of the floor and could be painted to resemble the floor. The plates could be alternately the signal plates and ground plates of the proximity detector array and each separate pair of plates would form the tuning capacitor of a separate resonant circuit. This type of multiple detector sensor would be difficult if not impractical to install because the wiring would have to be installed under the floor. Positional information on the intruder would be obtained from this system but it would be limited in resolution to the number of pairs of plates installed. Instead of mounting the plates directly into the floor they could be mounted in a mat with the wiring included in the mat. This would make installation easier, but the limitation on resolution of the positional intruder data would still exist.

Instead of an array of proximity detector elements in a floor mat, a grid of wires could be installed. The wires could be excited and sensed as described for the electric field fence sensors in the preceding section. This sensor would yield positional data on the intruder but would be limited in resolution by the density of wires in the grid. Also the signal pickup between the wires oriented in one direction with those oriented at right angles may present problems in balancing out the detection circuitry.

Merely placing arrays of capacitive elements in the floor does not provide total volumetric coverage of the room. The height above the floor in range of the array is one meter or less. Placing arrays of detectors in the ceiling in addition would increase the degree of coverage too, but it would not be totally volumetric. The size of the installation effort and the large number of detection elements needed to provide both floor and ceiling detectors makes this arrangement impractical. When the degree of uncertainty of the development of a successful and reliable sensor with the techniques described above is also taken into consideration, it becomes apparent that the idea of the use of an active electric field sensor as an interior motion detector should be ruled out.

3.4.4 Passive Magnetic Sensors

3.4.4.1 Physical Phenomenon of Human Intrusion

A passive magnetic sensor detects the magnetic field caused by the presence of a human intruder. The human body does not generate an appreciable magnetic field, i.e., one that can be easily measured at any distance from it. If the intruder carries an object made of magnetic material either in his hands or as part of his clothing the magnetic permeability of the space in his immediate vicinity will be increased over that of non-magnetic material. If the intruder is near a passive magnetic sensor, such as a coil of wire which does not have a current flowing in it, this change of permeability does not cause a response in the detector since no magnetic lines of force are generated by the coil. However, the Earth's magnetic field in the vicinity of the intruder will be distorted by the magnetic material carried by the intruder. As the intruder passes either through or by the coil, a number of magnetic lines near the coil will be shifted out of their normal equilibrium position and will be cut by the wire of the coil. This induces an EMF in the coil which is amplified and forms the basis for alarming.

3.4.4.2 Probability of Detection

The passive magnetic detector depends upon the intruder carrying a piece of magnetic material past the detector coil for detection. The probability that this will occur is so uncertain that this method of detection cannot be considered to provide adequate protection if used as the only intrusion sensor in an area. A further deficiency of this technique is that it does not lend itself to the requirements of providing volumetric coverage of a room and positional or ranging information on the target.

To meet these latter requirements a large array of sensing coils would have to be installed in the ceiling, walls, and floor of a room. The resolution would be limited by the area covered by each sensing coil. The large effort required to install the system makes it impractical for an interior motion sensor.

3.4.5 Active RF Sensors

3.4.5.1 Physical Phenomenon of Intrusion

An active RF sensor operates upon the principle of illuminating the area to be secured with electromagnetic waves at radio frequencies and of detecting disturbances in the radiated field produced by the presence or motion of a human intruder in the area. This principle is the same as that used in radar and the active RF sensor is in fact a radar. The lower limit of the frequency band of the radar is dictated by the resolution requirement for human targets. To reflect a detectable amount of energy from a human target, the wavelength of the incident signal should be comparable to or preferably smaller than the average dimension of a person in the beam measured at right angles to the beam. If for an average sized adult, the body width is estimated to be 0.5m, the wavelength of the signal used to illuminate the area should be .5m or less which corresponds to a frequency of 600 MHz or more. CW RF sensors operating at 60 MHz are presently being developed for exterior intrusion detection by Computing Devices Company, Ottawa, Canada for the U.S. Air Force. Computing Devices is also under contract with the U.S. Army BRADC to investigate similar sensors for interior use. While they have found frequencies as low as 30 MHz to be useful, in general, resolution of human radar targets improves with the use of higher frequencies.

The practical upper limit of the frequency band to be employed is limited by the state-of-the-art in microwave components available for operation at multi-GHz frequencies. The K-band (12.5 to 40 GHz) forms the current upper limit for most radar applications. At higher frequencies operation is made difficult by the design problems of higher noise, low receiver sensitivity and difficulty of obtaining sufficient transmitted power. Further limitation of the frequencies of operation is provided by the FCC which has set aside the following frequencies of operation for microwave intrusion detectors: 915 MHz plus or minus 13 MHz, 2450 MHz plus or minus 15 MHz, 5800 MHz plus or minus 15 MHz, 10525 MHz plus or minus 25 MHz, and 24125 MHz plus or minus 50 MHz.

The remaining sections on active RF sensors describe in detail and analyze four different radar techniques for application to interior intrusion detection which have the capability of providing range information on the target. The analysis shows that two of the techniques, the pulsed and modulated CW, exceed the FCC bandwidth limitations and cannot be used. One of the techniques, the interferometric, cannot be applied at the short ranges that exist indoors. It is concluded that the only technique that can be considered which meets FCC regulations and yields ranging information on the target is the multiple-frequency CW technique. Most of the equations and generalized systems described in the following sections were obtained from Reference 1.

3.4.5.2 Pulsed Sensors

The classical radar technique uses a narrow pulse of electromagnetic energy transmitted at a low duty factor and measures range by timing the round trip path to a reflecting object. The pulsed technique is simple and has several advantages with respect to false target discrimination. It can readily discriminate against targets outside of the range limits of interest. Stated differently, range can be measured unambiguously over arbitrary limits by choice of pulse repetition interval and the interval over which we choose to accept echo returns. Furthermore, we can adjust the receiver gain as a function of range so that targets of a given size produce the same level signal regardless of range.

Neither of these techniques is available with the CW radar, which is primarily a motion sensor rather than a range sensor. The pulsed ranging sensor has another advantage related to motion sensing that is particularly applicable to the intrusion detector. It can measure motion, or more properly the change of position of the targets observed, over arbitrarily long intervals. With the CW sensor, there is a practical lower limit to rate of motion that can be detected, since it is determined by the cut-off frequency of a high-pass filter.

While the pulsed technique is simple to apply for measuring range over intervals measured in miles, where pulses of several hundred nanoseconds duration are used, it presents difficulties for the intrusion sensor application. Here the maximum range is 10-20 meters and a resolution of no more than 1-2 meters is required. Since the range delay (round trip time) for electromagnetic radiation is about six nanoseconds/meter, very short pulses would be required - 10 nanoseconds or less. The interval of interest (for reception after the transmitted pulse) is no more than about 120 nanoseconds. The circuitry that produces the pulses and processes the echoes must be correspondly fast. While such high speed circuitry is not beyond the state of the art, it is in general more expensive and difficult to use and maintain than slower speed circuitry.

Another disadvantage is that the RF bandwidth required would preclude approval under the current FCC regulations. Part 15, Subparagraph F of the FCC Rules and Regulations governs devices of this type (intrusion sensors). Five nominal operating frequencies are set aside at 915, 2450, 5800, 10,525 and 24,125 MHz with band limits ranging from +/-13 MHz at the low end to +/-50 MHz at the high end. These limits include drift of the transmitter as well as modulation components. A rectangular pulse of 20 nanoseconds duration would have a spectral width to the first nulls of +/-50 MHz. To allow for transmitter drift and to include the modulation components outside of the first nulls, a pulse width of several times 20 nanoseconds would be required.

3.4.5.3 Pulsed System Design

This section presents the design of a pulsed radar for interior intrusion detection without regard to the FCC regulations mentioned above. This is done to illustrate whether development of a pulsed radar is feasible at all. The following design parameters must be chosen; radio frequency, pulse duration, and PRF.

In the case of RF, immunity to interference from other sources would favor choice of a higher frequency, while sensitivity considerations would favor lower frequencies. The latter is true since the path loss is proportional to frequency. It is also true that the target cross section increases with frequency also, but this effect does not offset the path loss increase. With lower frequencies then a system could operate with less transmitted power. With higher frequencies it is possible to get narrow antenna beam widths with physically smaller antennas. This, however, is not a consideration here, where relatively wide beamwidths are desireable. Before choosing an RF, we consider the other parameters.

The pulse width is determined by the resolution desired in the range dimension. A ten nanosecond pulse will provide a resolution of about 1.5 meters. This is also the minimum detectable range. Closer targets will return echoes while the transmitter is still on and will not be detectable.

The maximum PRF is determined by the desired unambiguous range interval. A PRF of 1 MHz will provide an interval of 150 meters, certainly enough for an interior intrusion sensor. Lower PRFs will decrease the likelihood of false indications but will provide less reflected power and hence less sensitivity. Lower PRFs will provide more time to process the data from each pulse. This may well determine the practical upper limit for the PRF.

3.4.5.4 Processing Schemes

The transmitter produces a pulse of 10 nanoseconds duration and the receiver looks for some period following this.

A 100 nanosecond period provides a range of 15 meters, a reasonable limit for the interior sensor. During this time echos from one or more targets will be received. The simplest processing scheme simply measures the distance to the nearest target above some threshold. We refer to this as a one-dimensional system since the measured data is a single quantity. Our decision could be based on the value of this quantity, but a more useful process considers the variation of this quantity with time.

Figure 3-7 shows the system, consisting of transmitter, antenna, receiver pulser and timer. The timer output is digital and provides data to a digital processor. The timer may be digital as shown in Figure 3-8 or analog as shown in 3-9. The digital timer requires a high speed counter and a clock rate of several hundred MHz to obtain resolution. The analog circuit can use a relatively slow analog to digital converter but requires a high speed operational amplifier for the integrator circuit. In either case it is possible to integrate the measurement process over a number of pulses by not resetting the counter or discharging the integrator.

This sensor is relatively simple and can be implemented easily in either the digital or analog version. Unfortunately, integration of the measurement interval over a number of pulses, while improving accuracy, does not contribute any improvement to sensitivity. We must still provide enough signal at the receiver relative to noise to provide reliable triggering with a threshold set so that no triggering occurs on noise alone. If this is not the case then the probability density function for the range measurement is as shown in Figure 3-10. With no target the curve would follow the dashed line.

For a uniform probability p that the threshold will be exceeded by noise alone (no STC applied), the probability that the range measurement will fall in the kth range bin is

$$P_k = p(1-p)^{k-1}$$

i.e. the probability of detection in the current bin times the probability that no detection has occurred in previous bins.

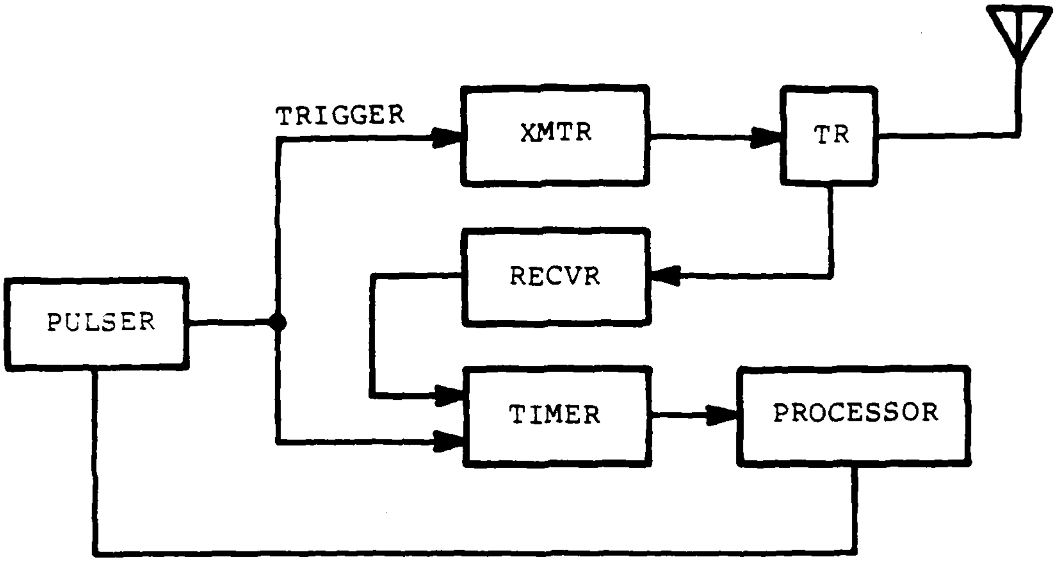

Figure 3-7. Pulsed Sensor

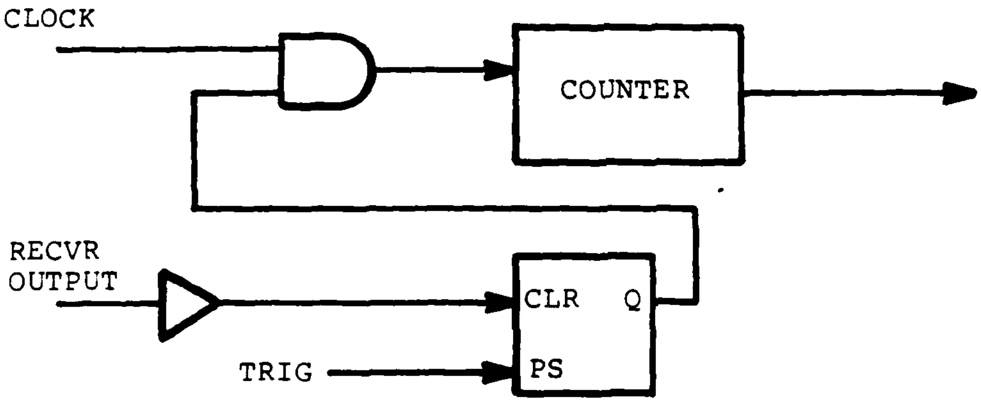

Figure 3-8. Digital Timer

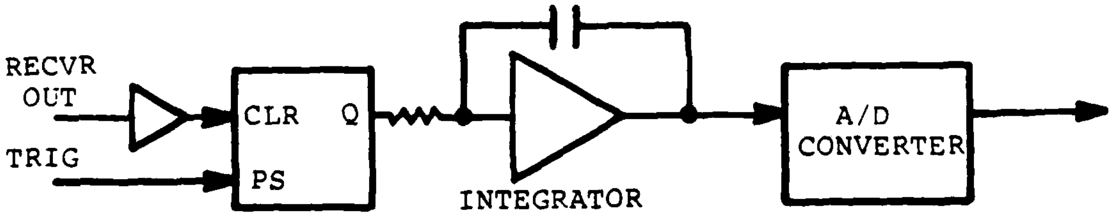

Figure 3-9. Analog Timer

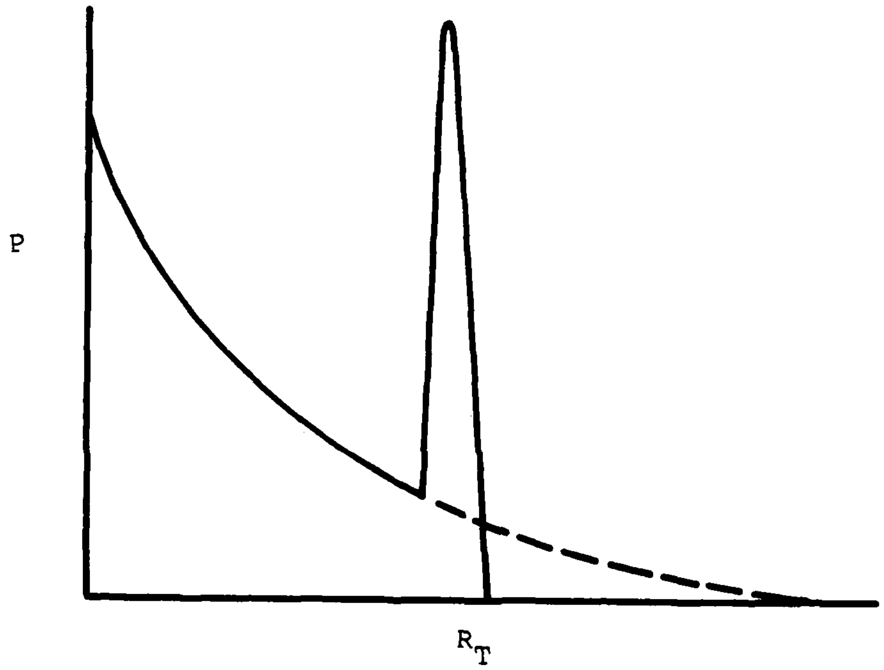

Figure 3-10 Probability Density Function for Pulsed Range Measurement

When a target is present at R_T (Figure 3-10) of sufficient size that detection is virtually certain, then the area remaining in the noise-only curve at ranges greater than R_T gets squeezed up into a peak centered on R_T. Obviously the distribution is not symmetrical about R_T except over a small range. Therefore, integration will not compensate for the lowered threshold. This would not be the case if we integrated the receiver output before applying it to the threshold detector. Then the signal-to-noise power ratio required for a given level of detection capability would be reduced by a factor between N and $\sqrt{N}$ where N is the number of pulses integrated.

Pre-threshold integration would add a measure of complexity to the system. It might be done as shown in Figure 3-11. The receiver output is combined with a delayed sample. If the delay is exactly equal to the pulse-repetition interval then successive outputs from the same range bin will "pile up". The delay can be incorporated in the frequency determining circuit of the pulser to ensure that the delay matches the PRI.

There is a serious problem with the delay line integrator in that a delay line with a large delay to rise-time ratio is required. If the feedback loop gain is close to unity as would be required for effective sensitivity improvement via post detection integration, then each pulse circulates through the delay line many times before its effect dies out. As far as the effect on the waveform of the signal is concerned this is equivalent to passing the signal through a number of delay lines in series.

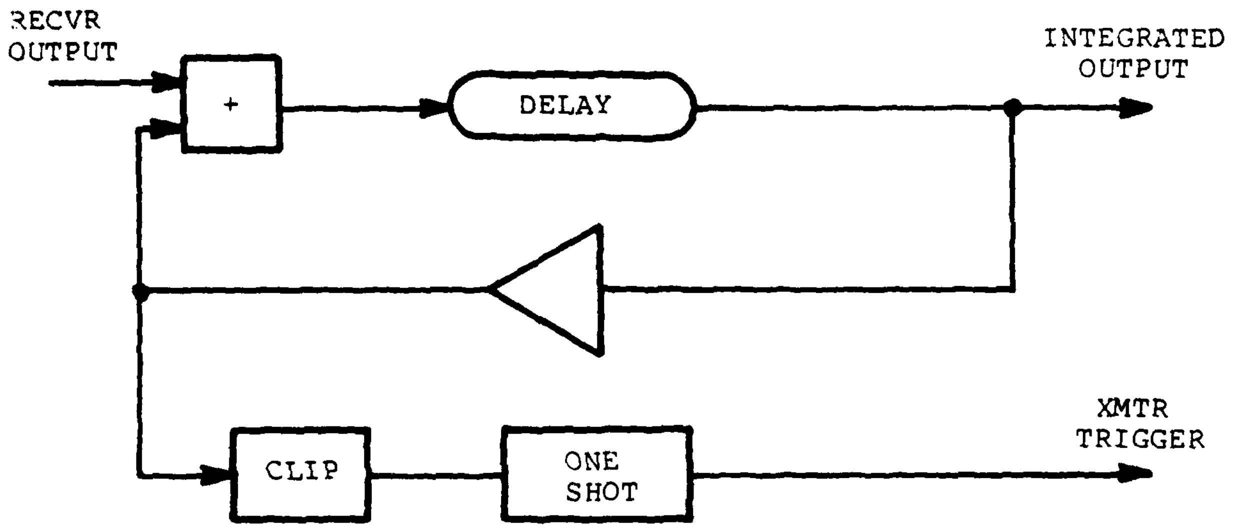

Figure 3-11. Video Integrator

Suppose we wish to integrate 100 pulses. If the range bin increment is 10 nanoseconds then we would like to keep the rise time of the processed pulse down to about 4 nanoseconds. Now the rise time is proportional to the reciprocal of the bandwidth and the bandwidth of n cascaded networks relative to the bandwidth of a single network is

$$B/B_1 = \sqrt{2^{1/n}-1}$$

and the rise time ratio is the reciprocal of this expression. For n = 100, B/Bl = .0833. The rise time for the delay line would have to be .0833 x 4 = .33 nanoseconds. If the delay is 1 microsecond a delay rise time ratio of 3,000 is required. This is certainly not feasible with lumped constant delay lines. It is possibly achievable with ultrasonic delay lines but at considerably greater cost.

A more sophisticated system measures the signal present in a number of range bins rather than simply the distance to the nearest target. This system is multi-dimensional with as many dimensions as there are separate range bins. Time variation of the multi-dimensional signal adds still another dimension. The system is somewhat more complex than the previous one.

Figure 3-12 shows a possible implementation. A high speed A/D converter samples the receiver output and provides a series of digitized outputs which are stored in a high speed buffer memory. To be compatible with the pulse width and range resolution, the converter has to run at a 100 MHz rate. This is feasible under the current state of the art. Analog-to-digital converters that operate at a 100 MHz rate are available and ECL memory can be used for the buffer.

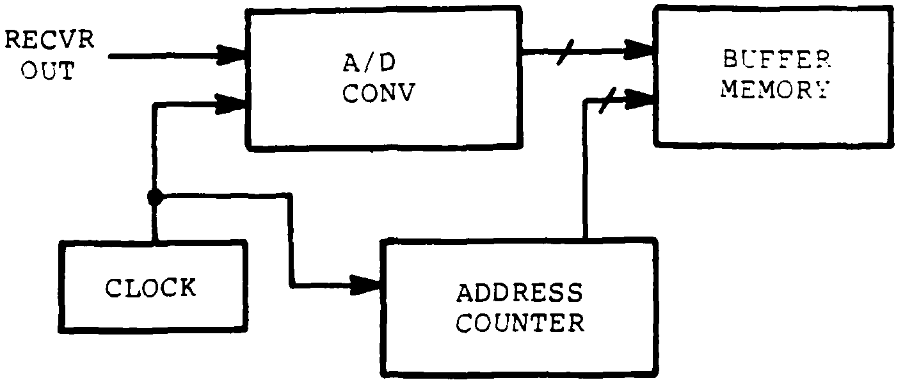

Figure 3-12. Multidimensional Range Processor

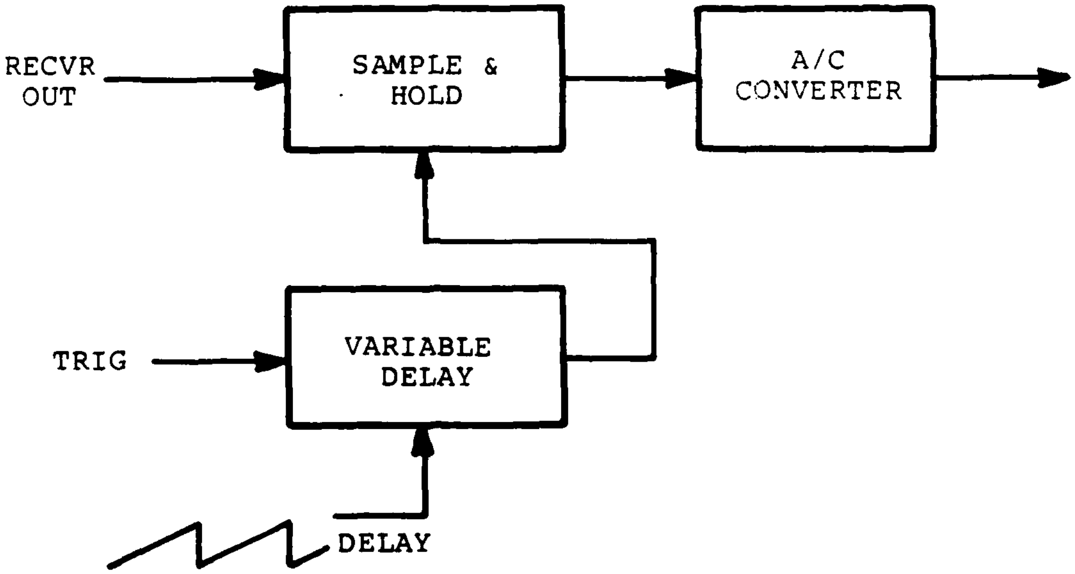

Figure 3-13. Alternate Multidimensional Range Processor

A system that does not require such ultra high speed components is shown in Figure 3-13. Instead of reading data for all range bins on every transmitted pulse, this system only reads one. The sample point is moved progressively further from the transmitted pulse for each measurement. A variable delay device generates the sampling delay with a sawtooth variation. A much slower A/D converter can now be used although a high speed sample and hold circuit is required.

A delay line integrator could be used with either of the multi-dimensional systems. The integration can be done digitally however, in the systems, although at some penalty in processing time.

3.4.5.5 Pulsed Sensor Range Calculation

In this section the transmitter power required for a pulsed sensor is calculated. The radar equation is

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}$$

where P_r is the received power, P_t the transmitted power, G the antenna gain, λ the wavelength, σ the target cross sectional area and R the range. The minimum received power is related to the receiver bandwidth and noise figure by

$$P_{rmin} = Fk\, T_o\, B(S/N)_{min}$$

where F is the receiver noise figure, k is Boltzmann's constant, $T_o = 290^oK$, B is the receiver bandwidth and S/N is the required signal-to-noise ratio.

The minimum required signal-to-noise ratio is determined by the probability of detection required, the permissable false alarm ratio and the number of pulses integrated. It is also a function of how the integration is done. For detection on a single pulse with 99% probability and negligible false alarm rate, a signal-to-noise ratio of about 16 dB is required. If the decision is based on n integrated pulses rather than a single pulse then the single pulse S/N ratio is reduced by a factor nE(n). E(n)= 1 for coherent (predetection integration). For post detection integration E(n) is a function of n, the probability of detection and the false alarm ratio. A lower limit is $\sqrt{n}$. For a human operator viewing a CRT display, E(n) approaches the lower limit.

The integration improvement factor nE is a slowly varying function of the false alarm and detection probabilities. A good approximation is

$$nE_1(n) \cong n^{.83} \quad n<20$$

$$\cong 2n^{.60} \quad n>20$$

These relationships assume that all pulses are weighted equally in the integration. With a delay line integrator this would require exact unity gain around the loop, impossible to achieve. In the digital scheme equal weighting is possible. With equal weighting it is necessary to periodically reset the accumulator. This presents no great problem. Another technique, however, is to add the latest value to a fraction α of the previous sum. Thus the contribution to the sum of a pulse received k intervals previous to the present is α^k relative to that of the latest pulse. This scheme further reduces the integration improvement factor by about .9.

The minimum transmitter power required can be written

$$P_{tmin} = \frac{(4\ )^{3} R^{4}{}_{max}\ k\ T_{o} BF(S/N)_{1min}}{G^{2} \lambda^{2} \sigma_{min}\ nE(n)}$$

where $(S/N)_{1min}$ is the single pulse minimum signal-to-noise ratio. σ_{min} is next estimated.

The radar cross section of a man is discussed in Reference 2. The authors measured values ranging from .2 to 1.75 M^2 for frequencies in the range 1120 MHz to 9375 MHz. Variations were functions of frequency, polarization and aspect angle. The measurements were made with a standing man. Precautions were taken to eliminate multipath via the ground reflection and distances were chosen where possible to assure a plane wavefront at the target. Ground reflections, posture other than standing and closer ranges where the wavefront would not be a plane could all tend to reduce the cross-section. We choose a value of 0.1 M^2 to provide some safety margin in the calculation.

Assume $R_{max} = 20$ m, $G = 3$ dB, $n = 100$, and $F = 10$ dB. A 10 ns pulse width requires an RF PRF of 200 MHz, and a video bandwidth B_{vid} of 100 MHz. The effective bandwidth, to be used in the calculation of the noise level is

$$B = (2B_{rf}B_{vid} - B_{vid}{}^{2})^{\frac{1}{2}}$$

in this case 173 MHz. The single pulse (S/N)min = 16 dB and the improvement factor for 100 pulse integration is 30. With these inputs the minimum peak transmitter power is approximately 8 watts.

This, of course, is the peak power. The average power is less by the duty factor, τf_p, where τ is the pulse width (10 ns) and f_p is the pulse repetition frequency. Suppose we wish to make the measurement in one ms. This means that we have to transmit 100 pulses in that period. The PRF is 100 kHz. The duty factor is $10^{-8}.10^{5} = 10^{-3}$. The average power is 8 mw.

An antenna gain of 2 was assumed. Hence the effective radiated power is 16 mw. Under FCC regulations an ERP of 75 mw is allowed (although not the bandwidth required for the pulsed system). There is margin therefore, for good performance with reasonable a transmitter design.

3.4.5.6 CW RF Ranging

The primary measurement available with CW radar is target velocity. This it can provide unambiguously by measurement of Doppler frequency. It is possible to measure range as well with a "CW" system by modulation of the CW carrier or by transmitting simultaneously on more than one frequency. This section shows why only the latter is potentially useful for the intrusion sensor application.

The transmitted signal in the general case can be expressed as

$$E(t) = A(t)\sin(\omega_c t + \phi(t))$$

where A(t) and $\phi(t)$ are the amplitude and phase modulation functions respectively. For a "CW" system only phase modulation is used and the receiver output is derived by mixing the received signal with the transmitted signal.

This may be expressed

$$R(t) = \sin\left(\omega_c \tau + \phi(t) - \phi(t-\tau)\right)$$

where τ is the range delay. If the target has a component of radial motion, τ is a function of time $\tau_o + \frac{2r't}{c}$. The receiver output then is

$$R(t) \cong \sin\left(\frac{2W_c r't}{c} + \phi(t) - \phi(t-\tau_o)\right)$$

when the constant phase term $\omega_c \tau_o$ and the time varying delay component in $\phi(t-\tau)$ have been dropped.

The first term in the phase function is the Doppler frequency component. The other two terms may be used to determine τ_o and hence the range with a suitable selection of $\phi(t)$. One choice is $\phi(t) = \phi_o \sin \omega_m t$. Then $\phi(t) - \phi(t-\tau_o) =$

$\phi_o \sqrt{2(1-\cos \omega_m \tau_o)} \cos(\omega_m t + \theta)$. $\theta = \tan^{-1}((1-\cos \omega_m \tau)$.

The receiver output then has the form of a sinusoidally phase modulated carrier with the Doppler frequency taking the role of carrier. Range information is contained in the amplitude of the modulation component, $\theta_0 (2-2\cos \omega_m \tau_0)^{\frac{1}{2}}$. For $\omega_m \tau_0$ small this is approximately $\theta_0 \omega_m \tau_0$.

ω_m has to be chosen large enough so that $\omega_m \tau_0$ will have some measureable value in the range interval of interest. If this interval is 20 meters and $\omega_m \tau_0$ is chosen at the maximum range = .003 (corresponding to about 1 degree) then the modulating frequency f_m is 6.8 kHz. This is at least a magnitude greater than any Doppler component that would be obtained from a moving human intruder even at the maximum RF (24 GHz). The received signal cannot be processed as a modulated carrier.

Another form of ranging modulation takes the form $\phi(t) = kt^2$. This produces a linear frequency modulation, the instantaneous frequency of the transmitted waveform being $_c + 2kt$. In this $\phi(t) - \phi(t-\tau_0) = 2k\tau_0 t - k\tau_0{}^2$. The first term represents a frequency that is added to the Doppler component. The second is a fixed phase term that can be neglected. The received signal is a sinusoid with frequency $f_d + k\tau/\pi$. There is no way, in this case, to separate the Doppler component from the range component. It is possible, however, to modulate the frequency of the transmitted signal in a sawtooth fashion so that the constant k alternates between positive and negative values. The receiver output then alternates between $f_d + k\tau_0/\pi$ and $f_d - k\tau_0/\pi$.

In order to separate returns from moving and fixed targets, k should be chosen small enough so that $k\tau_0/\pi$ for the maximum range for fixed targets is less than the minimum Doppler frequency. This unfortunately makes ranging modulation quite small for close in targets. Range differences must be detected, else the system is no more than a Doppler motion detector. Small components must be detected then at the scanning frequency rate. The returns from fixed targets, which will undoubtedly be large since these include the walls of the room, have phase discontinuities at the transitional points of the modulating waveform. These potentially will cause ample components at the modulating rate to occur in the output of the discriminator used to measure the ranging modulation.

Another means of processing is available for the linear sweep modulation system. The power density spectra of the received signal during the up and down sweeps can be measured and compared. Specifically one can be subtracted from the other. Stationary target echos will cancel, while moving ones will produce paired returns in frequency cells separated by an amount proportional to range.

The range resolution is determined by the scan rate and the frequency resolution in the measured spectrum. One still must keep the maximum offset less than the minimum Doppler to prevent fold-over frequency components for minimum velocity targets at the maximum range.

For a minimum Doppler of 20Hz (corresponding to a velocity of 12.5 cm/sec for a 24 GHz RF), and a maximum range of 20 meters,

$$k = \pi^{f}d/\ \tau = \pi f_d d/R_{max} = \pi.20.3\times10^8/20 = 942 \times 10^6 \text{ rad/sec}^2.$$

Now the minimum range measureable is determined by the frequency resolution in the measured spectra and this is $1/T_s$ where T_s is the scan period (upsweep or downsweep).

Now $T_s = \frac{\pi c}{4kR}$

for $R_{min} = 2$ meters $T_s = .125$ sec. The frequency scanned and hence the bandwidth of the transmitter is $.125 \times 942/2\pi = 75$ MHz which is far in excess of that allowable under FCC regulations.

It is concluded that neither the pulsed or modulated CW technique is particularly suited for the intrusion sensor application. Neither can be implemented in a satisfactory form under the existing FCC regulations. Even if this were set aside, they both require fairly complex and expensive circuitry to implement without promising any outstanding performance in terms of sensitivity or range resolution.

3.4.5.7 Multiple Carrier CW Sensors

Another means for making simultaneous range and Doppler measurements is by using multiple CW carriers. Consider the case of two carriers at ω_1 and ω_2. The transmitted signals are $\sin \omega_1 t$ and $\sin \omega_2 t$. The received signals are

$$\sin \omega_1 \left(t - \frac{2R_o}{c} - \frac{2r't}{c}\right)$$

and

$$\sin \omega_2 \left(t - \frac{2R_o}{c} - \frac{2r't}{c}\right)$$

These are mixed with the transmitted signals to produce

$$\sin \left(\frac{2\omega_1 r'}{c} t + \frac{2\omega_1 R_0}{c}\right)$$

and

$$\sin \left(2\frac{\omega_2 r'}{c} t + \frac{2\omega_2 R_0}{c}\right)$$

The phase difference between these two signals is

$$\Delta\theta = \frac{2\Delta\omega}{c} R_o + \frac{2\Delta\omega r'}{c} t$$

If one chooses $\Delta\omega$ such that the first term of this expression is less than 2π for the maximum range, then unambiguous range can be measured by measurement of the phase difference between the outputs. The second term of the expression is the Doppler associated with the difference frequency and is small. It expresses the change in phase shift associated with the change in range as the target moves.

Greater values of $\Delta\omega$ will provide more precise range measurements but at the expense of ambiguities since phase shifts modulo 2π are indistinguishable. To achieve precision without ambiguity more than two carriers can be used. The larger frequency spacings are used for precision with the smaller ones used to resolve ambiguities. The multiple frequencies can be transmitted simultaneously or sequentially in pairs.

Consider the simple, two frequency sensor shown in Figure 3-14. The receiver outputs are shown in Figure 3-15. The measurement of phase shift is accomplished by detecting the three zero crossings as shown at times t_0, t_1 and t_2. The phase difference is $2\pi(t_1-t_0)/(t_2-t_0)$, and the range is

$$R = \frac{c}{2\Delta f} \frac{t_1-t_0}{t_2-t_0} = R_{max} \frac{t_1-t_0}{t_2-t_0}$$

The measurement of the three times will be in error by an amount Δt as a result of noise in the system. First

$$\Delta R_{rms} = [(\frac{\delta R}{\delta t_0})^2 \Delta^2 t_{0_{rms}} + (\frac{\delta R}{\delta t_1})^2 \Delta^2 t_{1_{rms}} + (\frac{\delta R}{\delta t_2})^2 \Delta^2 t_{2_{rms}}]^{\frac{1}{2}}$$

$$= \Delta t_{rms} [(\frac{\delta R}{\delta t_0})^2 + (\frac{\delta R}{\delta t_1})^2 + (\frac{\delta R}{\delta t_2})^2]^{\frac{1}{2}}$$

since the rms error is the same for all three times.

Now

$$\frac{\delta R}{\delta t_1} = \frac{R_{max}}{t_2-t_0} = R_{max} f_d$$

$$\frac{\delta R}{\delta t_2} = -R_{max} (\frac{t_1-5_0}{t_2-t_0})^2 = -R f_d$$

$$\frac{\delta R}{\delta t_0} = -R_{max} (\frac{t_2-t_1}{t_2-t_0})2 = -R_{max} f_d (1-\frac{R}{R_{max}})$$

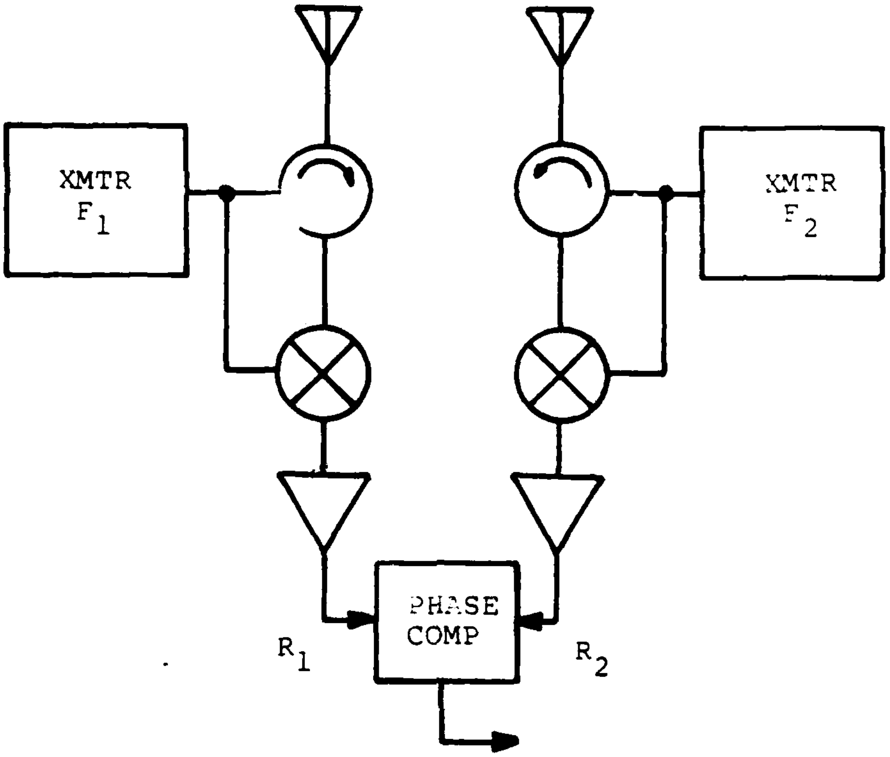

Figure 3-14. Dual Frequency Sensor

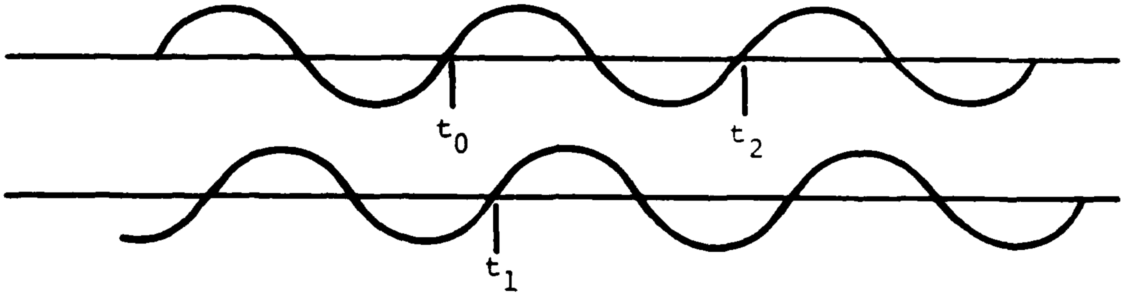

Figure 3-15. Output Signals

Therefore

$$\Delta R_{rms} = \Delta t_{rms} R_{max} f_d \; [\; 2(+\frac{R}{R_{max}})^{2-2} \frac{R}{R_{max}} + 2]^{\frac{1}{2}}$$

Now the slope of the signal at the zero crossing point is $2\pi f_d S$ where S is the amplitude. The rms time error is

$$\Delta t_{rms} = \frac{N_{rms}}{2\pi f_d S}$$

The signal to rms noise ratio is

$$\Gamma = \frac{S}{\sqrt{2}\; N_{rms}}$$

Thus

$$\Delta t_{rms} = \frac{1}{2\sqrt{2 f_d \Gamma}}$$

and

$$\Delta R_{rms} = \frac{R_{max}}{2\pi\Gamma} \; [(\frac{R}{R_{max}})^2 - \frac{R}{R_{max}} + 1]^{\frac{1}{2}}$$

This has the value $R_{max}/2^{\pi\Gamma}$ at $R = R_{max}$ and $R = 0$ and a minimum of $\sqrt{3/4}$ times this value at the midpoint $R = R_{max}/2$.

If $R_{max} = 20$ meters then Δf, the frequency difference between carriers, is $C/2R_{max} = 7.5$ MHz. Next is computed the signal to noise ratio and rms range error for representative designs at RF carriers of .915, 10.25 and 24.125 GHz. At these frequencies one is allowed a field strength of 50,000 microvolts/meter at 30 meters, per FCC regulations. This equates to an effective radiated power (ERP) of 75mw. One-half of this is available for each frequency. The radar equation is

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4}$$

Now $P_t G_t$ = 37.5 mw. Assume G_r = 3 dB; R = 20 m. As before the radar cross section of a man is assumed to be .1 m^2. Using the above figures the following received powers are calculated:

FREQ - GHz	Pr - dBm
.915	-86
10.25	-107
24.125	-114

To determine the signal-to-noise ratio it is necessary to calculate the noise power. Noise power is proportional to bandwidth, in the simple case the bandwidth required is twice the maximum Doppler frequency. If one uses about 12.5 m/sec as the maximum velocity, the bandwidths required are 160, 1800 and 4000 Hz respectively for .915, 10.25 and 24.125 GHz carrier frequencies. The noise is -174 dBm/Hz + F_{dB} where F is the noise figure.

With an assumed noise figure of 10 dB the following values for signal-to-noise ratio are calculated

FREQ - GHz	S/N dB	RMS Range Error - M
.915	57	.0045
10.25	24	.200
24.125	14	.635

At mid-range (10 m) the signal-to-noise ratios are better by 12 dB and the range errors smaller by a factor of 4.

It is concluded that a dual frequency system operating at either .915 or 10.25 GHz will operate with satisfactory sensitivity and range measurement accuracy at ranges up to 20 meters. The K-band frequency would also be satisfactory at a shorter maximum range. This can be achieved within the FCC Rules and Regulations.

There are problems with this approach, however. The sample system described works with only one target. With multiple targets present, it will provide data only for the strongest target, or, where the targets are at nearly the same level within about 3 dB, it will provide erroneous measurements. Even a single intruder might appear as multiple targets due to different rates of motion of different parts of the body. Multiple target discrimination on the basis of Doppler frequency may be possible, but would require a considerably more complex system.

3.4.5.8 Interferometer Technique

3.4.5.8.1 Functional Description - It is possible to locate a target by means of echoes and time difference measurements without ranging directly. This is done by measuring angle-of-arrival of echos at two spatially separated sites. The target is located at the intersections of the two lines of sight. As illustrated in Figure 3-16, angle-of-arrival can be determined by measuring the difference in time-of-arrival of echoes at two separated receivers. The time difference can be measured by the same techniques used for ranging, i.e. simple pulsing, pulse compression, CW swept FM, etc. It can also be measured by measuring the phase difference of the carriers of the received signals. In this case no modulation is necessary and the device is known as an interferometer.

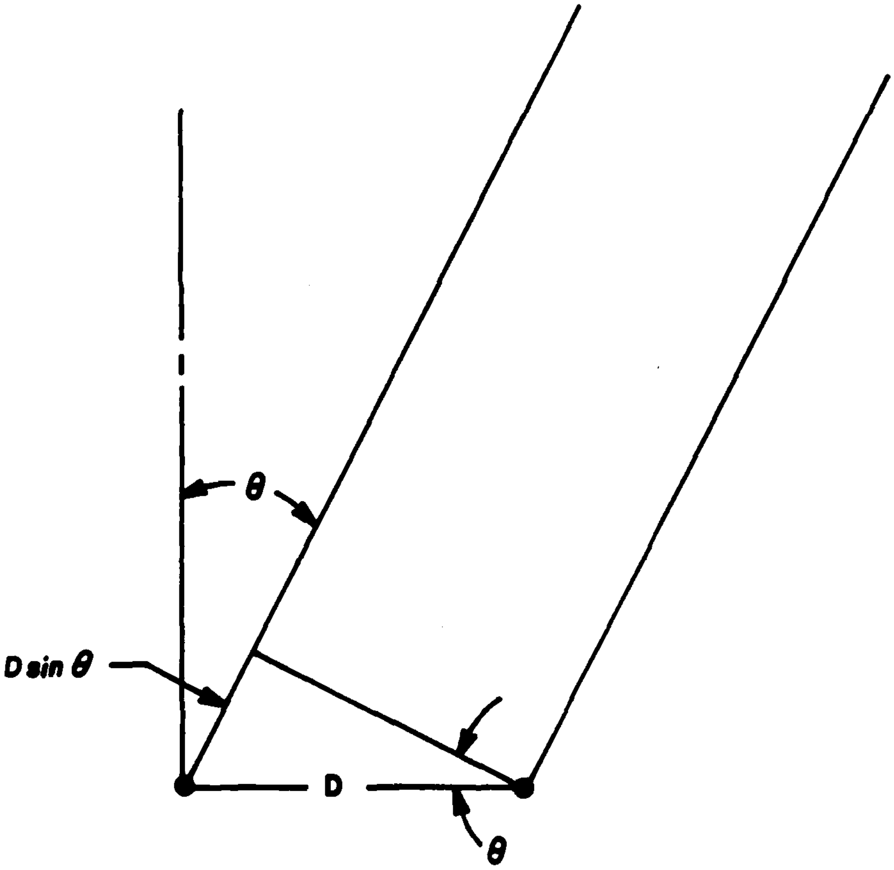

Figure 3-16. Angle-of-Arrival Measurement

An interferometer can measure angle unambiguously over a plus or minus 90° sector if the two receivers are separated by one-half wavelength at the carrier frequency. (The phase shift will be less than plus or minus 180° for any target.) It is clear that for an interior intrusion detector with ranging, motion detection is essential, else the receiver will be hopelessly cluttered with echoes from fixed targets - walls, floors, furniture, etc. Therefore, instead of measuring directly the phase difference between the carriers of the received signals, the phase difference between the extracted Doppler frequencies of the two received signals is measured. These signals are taken from the outputs of the coherent detectors in the two receivers.

The fixed target returns can be eliminated by high-pass filtering. The product of the two outputs is proportional to the cosine of the RF phase difference.

Figure 3-17 is a block diagram of a microwave interferometer. The system transmits CW at about 1 GHz and the receiving antennas are spaced about six inches apart. A sample of the transmitted carrier is used to mix with the received signals and the resulting baseband output is high-pass filtered to remove all but returns from moving targets.

The carrier phase-angle difference is preserved in the Doppler returns. Accordingly, these are limited to standardize amplitude and the product taken. This should produce an output proportional to the cosine of the bearing angle. Two or more such systems would be required for location purposes.

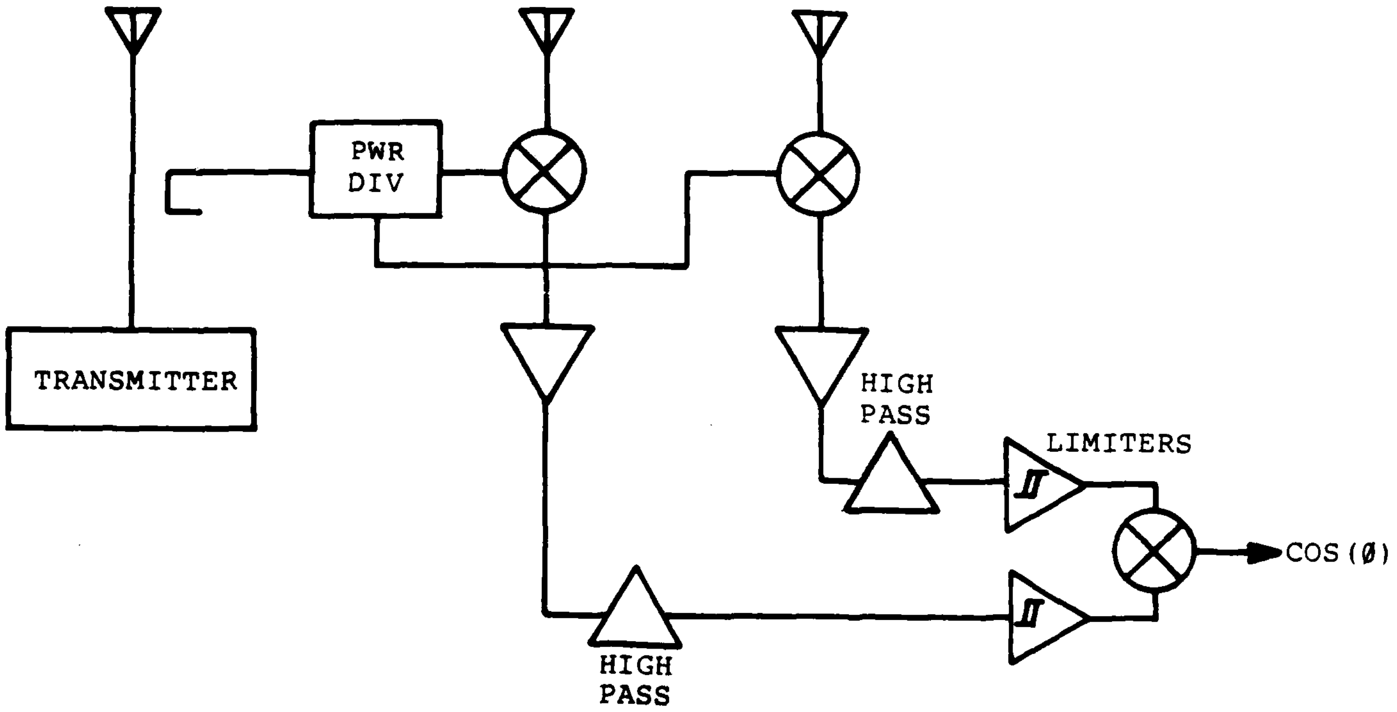

Figure 3-17. Microwave Interferometer

3.4.5.8.2 Limitations - The target bearing is given by the formula $\theta = \sin^{-1} \frac{\theta}{d}$ where θ is the phase shift between the two received Doppler signals and d is the spacing between the antennas. The phase difference between the two Doppler signals can be considered constant with respect to the direction of target motion only when the distance from the target to the receiving antennas is large enough that the two lines drawn from the target to the antennas are essentially parallel. Unfortunately this is seldom the case for the distances involved in most interior locations. A diagram showing the geometrical relationships between a pair of receiving antennas and a relatively close target is given in Figure 3-18. If the target bearing θ, the target velocity direction α and the target range R are as defined in the figure, the two components of the target velocity projected on the lines drawn from the antennas to target are V_1 and V_2. If V_1 is not equal to V_2, the Doppler frequencies received at the two antennas will be different, and the phase difference between the two received Doppler signals will be continuously changing and cannot be used to calculate the target bearing.

The difference between V_1 and V_2 will now be derived.

$$\tan \theta_1 = \frac{R\sin\theta - d/2}{R\cos\theta}$$

$$\tan \theta_2 = \frac{R\sin\theta + d/2}{R\cos\theta}$$

where θ_1 is the angle between the zero axis and the line from the target to antenna 1, θ_2 is the angle between the zero axis and the line from the target to antenna 2, and d is the distance between the antennas. The two velocities are:

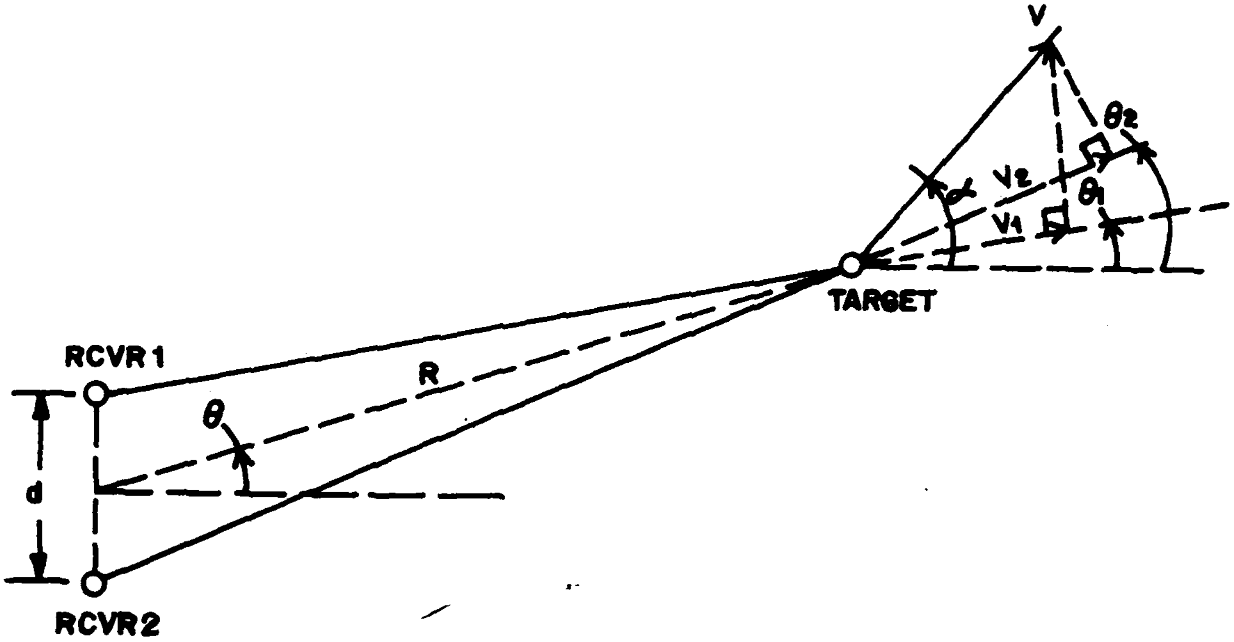

Figure 3-18 Interferometer, Near-Field Angles and Coordinate Projections Defined

$$V_1 = V \cos(\alpha - \theta_1)$$

$$V_2 = V \cos(\alpha - \theta_2)$$

Therefore:

$$V_1 = V \cos\left[\alpha - \tan^{-1}\left(\tan\theta - \frac{d}{2R_{\cos\theta}}\right)\right]$$

$$V_2 = V \cos\left[\alpha - \tan^{-1}\left(\tan\theta + \frac{d}{2R_{\cos\theta}}\right)\right]$$

The difference between the velocities V_1, and V_2 as a percentage of v_1 is given by:

$$\Delta V(\%) = 100 \times \frac{V_1 - V_2}{V_1}$$

$$\Delta V(\%) = 100 - 100\,\frac{\cos[\alpha - \tan^{-1}(\tan\theta + d/2R\cos\theta)]}{\cos[\alpha - \tan^{-1}(\tan\theta - D/2R\cos\theta)]}$$

Table II shows velocity differences which were calculated with the use of the above formula with respect to various target bearings and target directions of motion. These figures are calculated for a range R of 10 meters and a spacing between antennas suitable for operation at 915 MHz. For this frequency $\lambda = .328\text{m}$ and $d = \lambda/2 = .164\text{m}$. As may be seen from the table for the angles shown, the velocity differences range from 0 to 20%. These large velocity differences will result in proportionally large Doppler frequency differences between the signals received at the two antennas. Therefore the phase difference between the two received signals cannot be considered a constant and ought not be used to obtain the target bearing. Since, in general, an intruder is likely to be closer to a sensor than 10 meters, and a smaller range will cause even greater Doppler frequency differences, it is concluded that the interferometric technique cannot be applied to interior intrusion sensing for the purpose of obtaining target bearing and subsequent range determination.

TABLE II. PERCENT VELOCITY ERROR AS FUNCTION OF TARGET BEARING AND DIRECTION

Target Bearing	Target Direction	$\frac{V1-V2}{V1}$
Deg	Deg	%
0	0	0
0	45	-1.65
0	75	-6.31
0	85	-20.7
45	0	-1.14
45	45	0
45	75	-.667
45	85	-.97
80	0	1.6
80	45	.199
80	75	0
80	85	0

3.4.6 Active Visible/IR Sensors

3.4.6.1 General

Beam-breaking, imaging, optical radar, and fiber optic techniques can be used in both active visible light sensors and active infrared (IR) sensors. Visible light sensors employ photosensitive detector elements which respond to light wavelengths of from 500 to 1,000 nanometers. IR sensors use detector elements with optical filters which restrict and enhance sensitivity to light in the 800 to 1,100 nanometer range. Both types of sensors require external sources of artificial or natural illumination which may produce light distribution patterns ranging from narrow concentrated beams to even general lighting. Active IR sensors have the advantage of better concealability and may operate in totally darkened interiors. This section describes beam-breaking, imaging optical radar, and fiber optic techniques as applied to active visible/IR sensors.

3.4.6.2 Beam-Break

Beam-break sensors, also known as photoelectric sensors, direct a beam of light from an emitter, typically an IR LED, across an area to be protected at a photodetector. When an intruder enters the area and breaks the beam, he reflects all or a portion of the light. The reduced output of the photodetector forms the basis of an alarm. There are both bistatic and monostatic sensor types. The bistatic sensor is made up of two separate assemblies, one containing an emitter and the other a detector. The emitter assembly is placed in one location and the detector assembly in another. Placement is such that the beam from the emitter to the detector cuts across the expected path of an intruder. The beam can be extended around corners if required with the use of mirrors.

In a monostatic sensor, both the emitter and the detector are contained in one assembly. A separate assembly which contains a mirror is required to reflect the beam back from the emitter to the detector. The emitter/detector assembly is placed on one side of a protected path and the mirror assembly on the other side.

To reduce the nuisance affects of extraneous illumination, a pulsed emitter can be used with synchronous detection circuitry on the detector end. Pulsing also increases the maximum separation possible between the emitter and the detector because more power can be input into each pulse without exceeding the maximum average power dissipation of the emitter element. Another advantage is that an intruder cannot defeat the sensor with the use of a portable source of illumination.

The beam break technique does not yield any ranging information on a target. Alarm is given on loss of signal. If only one detector is used an alarm indicates that an intruder is somewhere along the line of a beam. If several emitter/detector pairs are located in a given area additional positional information on a target may be obtained, but no continuous volumetric protection is given.

3.4.6.3 Imaging, One-Dimension Scan

A sensor which uses a one-dimensionally scanned imaging technique employs as a detector either a row of photosensitive elements or a single photosensitive element and a mechanism such as an oscillating or vibrating mirror. The image of the area under surveillance is focused on the detector of which the output consists of a video signal similar to one scanned line output from a video camera. In order to alarm on a moving target, scan-to-scan cancellation can be employed to subtract out the video information resulting from stationary elements of the scene. For horizontal scanning the azimuth of the target is proportional to the position along the scan of the center of the image of the moving target with respect to the end of the scan.

For best contrast and highest signal-to-noise ratio, the lighting of the scene should be as uniform as possible. Care should be taken to prevent extraneous moving light such as from automobile headlights from falling on the scene since this can be a source of nuisance alarms.

Ranging with a single detector assembly is not practical and can only be done to a crude approximation. If the width of all targets were a constant the range of a target would be proportional to the width of the image. With the use of two detector assemblies however, it is possible to calculate the target range provided that the two detector assemblies are separated. The range can be calculated as a function of the known distance between the two detector assemblies and the target azimuths obtained from the two detector assemblies.

3.4.6.4 Imaging, Two-Dimensional Scan

An imaging sensor which scans in two dimensions can use as a detector either a video camera tube, a two-dimensional array of photodiodes, or a row of photodiodes in conjunction with an oscillating or vibrating mirror. Two-dimensional arrays of photodiodes are currently available which are mounted in

IC packages. Some contain built-in CCD shift registers and clocking circuitry to shift the output of the array through a single video output pin.

Video cameras or large photodiode arrays connected to standard TV video circuitry (512 lines per frame and 60 frames per second) can result in an information rate high enough to require large sophisticated array processors for real-time processing. If the resolution of the detector assembly exceeds the requirements of the intrusion detection sensor, some steps can be taken to reduce the information rate to a manageable degree. These include a lowering of the frame rate, integration of the video signal, and the lowering of the number of bits per video sample.

As with the one-dimensionally scanned imaging sensor, frame-to-frame cancellation can be used to eliminate or reduce the video output which results from stationary elements of a scanned scene. This leaves only video information caused by moving targets. For best contrast and highest signal-to-noise ratio, the lighting of the scene should be as uniform as possible. Care should be taken to prevent extraneous moving light such as from automobile headlights from falling on the scene since this can be a source of nuisance alarms.

When the orientation of the sensor is such that scanning is done in a vertical or near vertical plane, both azimuth and height information is obtained on the target. It is more difficult for an intruder to elude the two dimensionally scanned sensor by passing under or over its field-of-view than for the one-dimensionally scanned sensor since the field-of-view has height as well as width. The azimuth of the target is proportional to the position within the scan that it has detected. With a two dimension scanning technique the extreme edges of the target image in the horizontal direction can be determined more accurately than with the one-dimension scanning technique. The left-most edge can be found by vertically searching the stored matrix of pixels along each column starting with the left-most column to detect the first column which contains any target image video. The right-most boundary can be found in a similar fashion by searching right to left. As with a single detector assembly ranging is not practical and can only be done to a crude approximation.

3.4.6.5 Pulsed Radar

A visible/IR pulsed radar sensor uses a pulsed emitter, typically a laser, to illuminate a target. The range of the target is directly determined as a function of the measured round trip time of a reflected pulse which may be detected by a photodiode. In order to enhance returns from moving targets and cancel those of stationary targets, sweep-to-sweep cancellation or integration techniques can be employed.

Distance measuring devices which operate under the principles of pulsed optical radar are currently finding wide application in the surveying industry. These devices use a mirror reflector placed at the remote end of the dimension to be measured in order to ensure a large amplitude return.

Since the wavelengths of the illuminant is so short extremely narrow pulse widths are possible with optical radars. Pulses as narrow as one picosecond are possible with current laser modulation technology. For interior intrusion sensor requirements a wider pulse width can be used to reduce the bandwidth of the sensor circuitry. Assuming a minimum range requirement of two meters, the maximum pulse width is 2 x 2/3 x 10^8 or 13.3 nanoseconds. This is the pulse width necessary for the reflected pulse not to overlap the emitted pulse at a distance equal to the minimum range.

To measure the round trip time of a pulse, a binary counter can be used. The counter is enabled to count a high frequency clock from an external source by the transmit pulse and is inhibited from counting by the received pulse. The target range is proportional to the count indicated after the counter is inhibited. For a range measurement accuracy of +/-2m, a clock frequency of at least 1/13.3 x 10^{-9} or 75 MHz is needed. To increase the accuracy to +/-.5m, the frequency required is 4 x 75 or 300 MHz.

The beams emitted by lasers are extremely narrow and therefore angular measurement resolution is very high. For example, for a 1,000 nanometer emitted wavelength beamwidths on the order of 0.1 milliradians can be obtained. To locate a small moving target miles away over a wide angular purview by scanning techniques is a very time consuming process. For interior intrusion applications, however, the maximum target range is measured in feet rather than miles and a higher PRF can be used than for aircraft location and tracking. Therefore a scanning technique may be practical for interior applications with respect to time-to-detect.

A major factor to be considered in the use of a laser-based intrusion sensor is that a health hazard exists. Permanent eye damage is possible if a person stares directly at the emitted laser beam at close range. This is difficult to avoid since the beam is invisible, the sensor would be mounted inconspicuously on a wall, and indoor room layouts could allow a person to approach near to the sensor.

3.4.6.6 CW Radar

A visible/IR radar sensor which operates in the CW mode can detect the velocity of a target by measurement of the Doppler frequency shift of a laser beam reflected from the target. This can be done with coherent or non-coherent detection techniques. Coherent detection is done by mixing the return beam with a portion of the transmitted beam on a half-silvered mirror. The intensity of the mixed beam transmitted through the mirror at a photodetector varies at a rate equal to the Doppler frequency shift which is proportional to the velocity of the target.

The maximum Doppler frequency is much greater than that obtained from either an RF or acoustic radar which operates in the CW mode. For example, for a target moving at 6 m/s, the Doppler frequency shift for a 1 micron carrier wavelength is $2 \times 6 / 10^{-6}$ or 12 MHz. In order to reduce the maximum Doppler frequency, a non-coherent CW technique can be used. This entails amplitude modulation of the transmitted beam and non-coherent demodulation of the reflected beam. The demodulated signal is then mixed with the modulation signal to obtain the Doppler frequency shift. The Doppler frequency shift is equal to 2vfm/c where fm is the modulation frequency and v is the target velocity.

3.4.6.7 Fourier Transform Sensor

A visible/IR Fourier Transform Sensor may employ an acousto-optic camera to produce the spatial Fourier transform image of a scene under surveillance. One such camera is under development by Deft Laboratories, Inc., 7 Adler Drive, East Syracuse, New York. Much of the material presented in this section has been made available by Deft, Inc.

In its current stage of development, the Deft camera is usable only with light in the visible range. Since a two dimensional representation of the spatial Fourier transform is output, this type of sensor can be loosely considered to be a special case of a two-dimensional imaging sensor. The transform image produced by the camera is position invariant and therefore any pattern recognition process applied to its output is simplified. Real time pattern recognition requires high speed processing of large amounts of data, however, and can be considered to exceed the requirements of intrusion detection.

The Fourier transformer can perform motion detection and ranging which are both applicable to intrusion detection requirements. Motion detection across the field of view of the camera can be accomplished by utilizing the spatial shifting theoreom of Fourier transforms. This theoreom states that a pure translation of a picture in real space leaves the magnitude of the Fourier components unchanged, but alters their phase by an amount proportional to the magnitude of translation. By monitoring the phase of a Fourier component, any motion in the picture can be detected. Since the Fourier transformer is a two-dimensional device, one can also determine the direction of motion with it.

Ranging on a target can be accomplished through the automatic focus detection capability for imaging systems. Focus detection is based on the property that most focused images contain abrupt changes in intensity due to object edges. As a result, a focused image will contain greater high-spatial-frequency content which is detected by the Fourier transformer. An automatic focus system can contain a mechanism to move the lens while sampling the amplitudes of several spatial frequencies. The position of the lens at which the maximum amplitude values of the sampled frequencies are obtained is proportional to the range of the target.

3.4.6.8 Fiber-Optic Sensors[3]

Fiber-optic transducers can be utilized in Intrusion Detection Sensors. Fiber-optic transducers are being developed that can respond to a multitude of physical perturbations including acoustic, magnetic, rotational, pressure, and temperature. These transducers are made from coated and wound optical fibers. The coating determines the type of physical perturbation to which the transducer will be sensitive. The winding pattern of the fiber determines the directivity of the transducer response, and the sensitivity is proportional to the total length of the fiber. All of transducers depend upon the transmission and detection of light through the fiber, but do not find application in active visible/IR intrusion detection sensors in the same manner as sensors described in the preceeding sections under the heading of visible/IR. The light in fiber-optic transducers is used only indirectly and the intrusion sensors constructed with them would fall under the headings of passive acoustic, passive magnetic, passive thermal, etc.

All fiber-optic transducers may be categorized into either amplitude or phase (interferometric) types. In an amplitude type transducer the physical perturbation interacts with the fiber or some device attached to the fiber to directly modulate the intensity of the light in the fiber. The advantage of this type of transducer is simplicity of construction and compatibility with multimode fiber technology. Amplitude type transducers include those that respond to pressure such as the fiber microbend transducer which utilizes induced bending loss in the fiber. Another amplitude type transducer is a moving fiber optic hydrophone in which two fibers are mounted such that the end surfaces are parallel, coaxial, and separated by 2-3 micrometers. Acoustic waves induce relative motion between a fixed fiber and a fiber which is free to move. Relative fiber motion varies the light coupled between the two fiber ends and thus modulates the transmitted light.

Phase (or interferometric type transducers) can be constructed for magnetic, acoustic, or rotation sensing. These theoretically offer orders of magnitude increased sensitivity over existing technologies. In the case of the acoustic transducer that is constructed with the use of an optical fiber interferometer, these theoretical predictions have been verified to the limit of the state of the art in acoustic measurement.

Fiber-optic technology has made possible the development of extremely sensitive transducers that may be utilized in intrusion detection sensors. Progress has been rapid and many transducer types have been demonstrated, but the technology is not fully developed nor exploited. Practical problems remain in the areas of noise sources and detection processes, in packaging and optimized fiber coatings. Transducer packaging to survive the stringent conditions encountered in operational deployment has not yet been developed.

3.4.7 Passive Thermal Sensors

3.4.7.1 Conductive

A conductive thermal sensor alarms on the heat emitted by an intruder that is transferred by conduction to a heat sensitive detector such as a thermistor or thermopile. The intruder must come in physical contact with the element or the surface in which the detector is mounted. The heat sensitive detector can be installed either in the floor or wall. To give wider coverage an array of detectors can be installed.

Since the intruder must come in physical contact with the protected surface to cause an alarm, the conductive thermal sensor provides at most only point or penetration protection. A major deficiency of this type of sensor is that if the intruder does not directly contact the detector, the time to alarm can be on the order of minutes. An intruder is not likely to remain in physical contact with one spot for a sufficient time to cause an alarm under this condition. No conductive thermal intrusion sensors are known from this study to be available from or produced by commercial security equipment manufacturers.

3.4.7.2 Convective

A convective thermal sensor alarms on heat emitted by an intruder that is transferred by convection to a heat sensitive detector such as a thermistor or thermopile. Since warmed air tends to rise, the most reasonable location for the installation of the detector element is in a ceiling. To increase the area of coverage an array of detectors can be installed. Some measure of positional information would be gathered on an intruder with the use of this approach. However, with the superposition of natural room air currents on the rising air current from an intruder, the position information can be obscured. Also, the high false alarm rate caused by a forced hot air heating system, or any heating system for that matter, with this type of sensor can make it extremely unattractive.

3.4.7.3 Passive Circuit Break Sensors

A circuit break sensor alarms on the interruption of an electrical current which is caused by the direct breaking by an intruder of the circuit associated with the current. One such type of sensor uses foil-wire installed in windows or doors which carries the sensing current. When the surface containing the foil is broken, the foil rips, thus interrupting the current. Another sensor employs magnetic switches mounted on doors or windows. Opening the portal magnetically causes a switch to open which is in series with the sensing circuit. A trap cord/switch assembly is another circuit break sensor. This sensor uses a cord that is attached to a lever on a tripping mechanism associated with a switch. To arm the sensor, the cord is stretched across the path to be secured. When an intruder inadvertently bumps the cord, the switch is tripped open which breaks the sensing circuit.

Circuit break sensors are simple and reliable but are basically penetration sensors and offer no volumetric protection or ranging capability.

3.4.8 Active Magnetic Field Sensor

An active magnetic field sensor can use a sensing coil to detect an intruder. The sensing coil acts as part of a resonant circuit associated with the detection circuitry of the sensor. The sensor alarms on the change of inductance of the coil which can be caused by an intruder who passes by the coil with an object on his person which contains magnetic material. The change of inductance of the coil can be detected either as a voltage change across the coil or as a frequency change if the coil is part of the frequency determining circuit of an oscillator.

To increase the area of coverage an array of sensing coils can be installed in floors or walls. Some measure of positional information can be obtained on the intruder this way. This sensor does not provide volumetric coverage or range information on the intruder. The fact that the sensor depends upon the intruder's carrying some magnetic material gives it a poor probability of detection.

3.4.9 Active High Energy Radiation Sensor

A sensor can be developed that uses a form of high energy radiation such as gamma rays, x-rays, or ultra-violet rays as an illuminant. Techniques similar to those described in the Active Visible/IR section can be applied for intrusion sensing. These include beam-breaking and one and two-dimensional imaging. The invisible nature of the radiations can make the sensor inconspicuous and enables operation in darkened interiors. The penetrating quality of both gamma and x-rays can make possible the detection of an intruder when hidden behind partitions or furniture. The obvious health hazards associated with the use of these radiations for interior intrusion applications form an over-riding objection to their use as illuminants.

3.4.10 Passive Acoustic

3.4.10.1 Single Element

The goal of signal processing of single element, passive acoustic detectors is to detect and identify the characteristic "sounds" of an intruder. The "sounds" of an intruder can manifest themselves in different forms. One can consider the intruder from a biological point of view. There are many bodily processes which can produce acoustic vibrations including respiration, pulmonary activity, speech, digestive functions, and joint motion. An intruder also interacts with his environment to produce acoustic disturbances. His motion through the air, the rustling of clothing, the impact of feet upon a floor, and the turning of a door knob are all interactions with the environment which can in principle be detected acoustically.

The "sounds" of an intruder can manifest themselves in multiple spectra. For example, consider a person wearing hard soled shoes walking on a tiled floor. The impact of the shoes against the floor produces the <u>audible</u> clicking sounds that are so familiar. The impact may also excite <u>infrasonic</u> structural resonances depending on the floor and foundation characteristics. <u>Ultrasonic</u> frequencies may be generated by the crushing of microscopic particulates (dirt, cleaning abrasives) under the force of his weight.

It is evident there are numerous potential acoustic signals associated with human intrusion. Just as important however, is the fact that there are perhaps more everyday phenomenon which produce acoustic disturbances <u>not</u> directly associated with human intrusion. These other disturbances fall into the broad classification of nuisances. An inherent task in accomplishing the goal of passive acoustic signal processing is then to develop a set of criteria which discriminates the range of potential intruder emanations from those of nuisance phenomenon.

A threshold-crossing detector is conventionally the first step in passive acoustic signal processing. The threshold establishes a decision level whereby signals below the threshold are considered noise and those exceeding the threshold are considered significant. The occurence of a threshold crossing is defined as an "event."

The threshold is set based upon the expected upper limit of noise; electronic and/or ambient acoustic. Under certain conditions, a floating threshold may be used to provide a dynamic discrimination level for changing background noise. If a floating threshold can be used, relative sensitivity and S/N are maximized at all times. Otherwise, the threshold must be set above the maximum noise level expected, even if it occurs infrequently.

Additional levels of processing are invoked only after an event is defined by a threshold crossing. Additional processing is required to identify the source of the event, since it could be the result of either a nuisance or an intruder. The event is characterized by a number of measured parameters such as its frequency content, energy, auto-correlation, pulse shape, rise time, duration, etc. Each of these parameters will represent a quality or quantity concerning the event which, ideally, will be unique to the event's source.

In the context of a FIDS there are primarily two sources or classes of events of interest: nuisance and intruders. By appropriate selection of signal parameters to measure, one can in theory produce a predictive relationship between the values of those parameters and the true classification of the source. This type of signal processing is referred to as pattern recognition. In practice, however, it is difficult to obtain a one to one correspondence between a given unknown signal and its true classification. There is always some error involved due to the real limitations imposed by signal attenuation, the detector's electromechanical transfer characteristics, finite bandwidth in signal conditioning circuits, sample rate, resolution, etc. Therefore, rather than predicting a response theoretically, an empirically derived data base is formed from signals representative of all classes of interest. This data base or training set is used to evaluate the various signal parameters' ability to determine an event's classification, and to derive the predictive function. It is evident then that an unknown signal whose measured characteristics do not fall within the bounds of the training set will be given an ambiguous classification.

At the onset, the binary classification of nuisance vs. intruder seems simple enough. As was mentioned earlier, however, further examination reveals that the classes of nuisance and intruder encompass a vast range of potential signals, each of which must be considered as distinct signal sources. Consider for example, the class containing intrusion signatures. An intruder might crawl, walk, run, or scurry from point to point. Each of these actions produces acoustic responses in a slightly different manner. Now consider that each of these responses will vary depending upon the clothing and shoes he may be wearing as well as any equipment he may be carrying. Now consider his proximity to the detector, the room geometry, floor type, ceiling type, wall construction, floor covering and other factors related to the FIDS environment that affect the intruder's acoustic signature. Similar arguments concerning the unpredictability of nuisance acoustic signatures unveils a virtually unbounded problem. Bounds can be placed on the problem by examining the likelihood of a given mode of intrusion and nuisance, however, any attempt will be by necessity subjective.

To be of practical use, the training set must be large enough to cover a very wide range of measured intruder and nuisance conditions. For the best results, the measurements should be made in the actual facility to be monitored with the detectors placed in their anticipated final positions. These requirements are to ensure that any "coloring" of the nuisance and intruder signatures by the environment will be considered in the training set. Since the predictive function is derived from the training set, any alteration of the detector system or the facility's configuration may degrade the performance of the sensor. If the degradation is severe enough, it may be necessary to retrain the sensor for the modified configuration.

In general, the trade-offs in passive acoustic signal processing based upon a pattern recognition scheme will be the probability of error (P.O.E.), the number of signal parameters to be measured, and the diversity of signals to be identified under a single classification. P.O.E. is the probability that an unknown signal will be classified incorrectly. It is the measure of success for the processing scheme and is to be minimized. The P.O.E. can usually be improved by increasing the number of signal parameters measured. Increasing the number of measurements to be performed on each event however, introduces additional computation time and/or additional hardware complexity and cost. The evaluation of each event requires more time, therefore the sensor will be inactive for a larger percentage of time. P.O.E. increases proportionally with the diversity of signals under the same classification. As the set of signals broadens for a given class, the distribution of values for the selected parameters will also increase. As the parametric bounds increase to encompass more diversity, overlaps occur between the bounds for other classes, and the P.O.E. correspondingly increases.

3.4.10.2 Multiple Elements

The addition of multiple elements in a passive acoustic detection system affords considerably more discrimination capability than single element systems.

Multiple elements can be utilized to discriminate between nuisance and intruders in several ways. The first method is the use of time-of-arrival information to compute the location of an acoustic source. The first detector to sense an acoustic event starts timers which measure the time delay (Δt) for the remaining detectors to sense the event. Using the known coordinates of all detectors and the velocity of sound in the propagating medium, the source location of the event may be computed by triangulation techniques.

Source location through passive detection can be used for correlation with other ranging techniques. By comparing previous locations over a set time interval, the location method may also be used to monitor the path taken by an intruder and to approximate his velocity. These aspects of passive source location permit discrimination between intruders and nuisance by:

1) Allowing rejection of signals with nonsense locations. An example of a nonsense location would be one computed outside the area of interest; i.e., outside the facility.

2) Adding weight to range information obtained through a complementary technique such as pulsed radar. It is unlikely that a nuisance event would produce a disturbance at the same location for techniques based upon separate phenomenon and measured in unique manners.

3) Graphically tracking the movements of the intruder to determine if they exhibit the behavior of a human.

Multiple passive acoustic detectors may be used in processing schemes simpler than source location to provide nuisance discrimination. One of these alternate methods requires a Δt measurement, but it does not use a triangulation algorithm to compute a finite location. This method simply rejects all signals which appear simultaneously on all detectors, i.e., $\Delta t = 0$. The rationale behind this technique is that few real acoustic disturbances will occur equidistant from all detectors. On the other hand, intermittant electrical transients tend to appear simultaneously on all detector channels, and therefore can be rejected as nuisance in this manner. Transient electrical noise interference can be a significant source of nuisance for solid-coupled ultrasonic vibration monitors because of their broad frequency response (0.1 -1 MHz) and high amplifier gains (60 - 100 dB).

Another alternative to source triangulation is the use of guard detectors. Guard detectors provide a simple means to determine whether a particular event originates from inside or outside the area of interest. Guard detectors are positioned on the outermost perimeter of the area of interest, paired with other detectors to be used for conventional signal processing on the interior. Rather than a Δt timer, sequential logic is used to determine the order in which a particular event is detected by the sensing elements. An event originating outside the area of interest will trigger the guard elements first, then the inner detectors. By assuming that events occuring outside this acceptance zone are nuisance, the sensor will ignore these events without further processing. Likewise, if the sequence of detection indicates an event occured within the acceptance region, then the event signature is analyzed for source characterization.

Source location, coincidence rejection, and "guarding" through multiple element signal processing provides a means to screen out many events without the need for extensive analysis of their signatures. The underlying assumption is that it is reasonable to expect nuisance and intrusion events will exhibit some degree of localization. These methods reduce the overall numbers of events to characterize by pattern recognition, thus saving processing time and therefore maintaining the sensor in an active state for a greater percentage of time. These techniques do not make the task of source classification any easier for those signals which do pass the initial levels of screening.

There are other assumptions which require consideration when evaluating these methods for a FIDS application. First of all, it is assumed that both the radiators (nuisance and intruders) and the detectors have omni-directional transmission and receiving characteristics. That is, the source of acoustic radiation should not display any preferred directivity pattern. Likewise, the detectors are required to have uniform sensitivity independent of the incidence angle, at least in one plane.

The use of a triangulation algorithm assumes known constant acoustic velocities in the materials propagating the signals. For airborne signals, this does not present a great problem. However, if detectors are used which are intended to detect vibrations in solids, then some difficulties arise. Since different materials have different acoustic velocities, care needs to be exercised in the placement of detectors. Detectors must be placed on one type of material to avoid velocity transitions that would upset the Δt relationship between elements. Velocity is not only dependent upon the elastic properties of a material, but also upon the mode of vibration. Longitudinal waves propagate with approximately twice the velocity of shear waves in the same material. Surface waves' velocities are less than shear waves by a fraction proportional to Poisson's Ratio for the material.

Source location methods as described also assume line of sight propagation from the source to each of the detectors. Reflecting surfaces in the vicinity of the detectors will allow multipath signals to exist from a single source, creating confusion in the measured Δt relationships.

The final gross assumption is that each event is an isolated, discreet phenomenon in time such that no confusion arises in the Δt measurements. Accurate location measurements cannot be calculated if the next event occurs before the previous event has been detected by all elements.

3.4.11 Active Acoustic

3.4.11.1 Single Element

There are two phenomena that can be utilized in single element active acoustic signal processing for the detection of human intruders. These phenomena are the absorption and reflection of acoustic energy. In restricting consideration at this point to single element devices, by definition the elements must behave as both emitter and detector. This implies a pulsed mode of operation whereby the element is alternately stimulated (pulsed) to emit acoustic energy and for a regular time interval following the pulse, the element is passively waiting for an echo return. The pulse interval repeats on a regular basis whether or not an echo is returned. The pulse repetition interval may be intentionally varied for some applications to permit distinction between first time echos and multiple-time-around echos.

Before addressing particular absorption and reflection techniques, it is worthwhile at this point to further establish the framework of these discussions around the FIDS application. The first point to consider is the medium of acoustic propagation to be used. Acoustic disturbances can be propagated in any medium with elastic properties including solids, liquids, and gases. For FIDS, one has two choices for active acoustic propagation media; the structural members of the facility (walls, floors, ceiling, etc.) for wave propagation in solids, or the atmosphere contained within the facility for gaseous conduction of acoustic waves. Since active acoustic detection requires the interaction of the energy field with a target (either through absorption or reflection), it stands to reason that the magnitude of the interaction will determine the effectiveness of a given technique. If the acoustic energy for the FIDS device is propagated through the structure of the facility, then little interaction can be expected. For example, if a surface wave pulse is transmitted through the floor, an intruder standing in its path will cause some damping of the wave and possibly some reflection. Under good conditions, the effect will be measurable and might be useful for FIDS. However, the interaction is largely dependent upon the surface area of the intruder's contact with the floor. On the other hand, if the acoustic energy is propagated through the air to strike the target, then the magnitude of the interaction is much greater because a greater amount of absorption or reflection can occur. Further discussions therefore will assume airborne acoustic propagation because the potential interaction will be much greater. Airborne acoustics also has the advantage of constant velocity of propagation over solids. Range and location measurements will therefore be more predictable and reliable.

Another point to consider before discussing particular techniques is the selection of acoustic frequency. Acoustic waves can be generated over a wide range of frequencies using conventional technology. Since the FIDS device is intended to be used in environments where authorized persons may be present, the audio range (20 Hz - 20 kHz) should be excluded because of the annoyance and distraction such a device would present. The infrasonic range (<20 Hz) would not present any problems as an annoyance, however the detectability of a human target is poor at these frequencies. Poor detection is a consequence of the long wavelengths of infra-sound in air. Wavelengths range from 56.5 feet at 20 Hz to 1130 feet at 1.0 Hz. To act as an efficient reflector of acoustic energy, the target dimensions should be on the order of one wavelength or more. Even at 20 Hz, a human target is only about 1/10 of a wavelength and therefore would be "invisible" to infrasonic frequencies.

On the basis of the preceeding arguments, the following discussions will be focused around pulsed techniques that use ultrasonic frequencies propagated in air.

3.4.11.1.1 Pulse Echo Absorption - Pulse echo absorption is limited to the detection of target presence. The method may be used for FIDS in the following manner. A pulse emitted by an acoustic transducer will propagate through the volume of the facility until it strikes a large reflecting surface such as a backwall. Most of the pulse energy will be reflected and subsequently a portion will be intercepted by the transducer. The reflection appears at the transducer at time t = (2) x (Range)/ Velocity in air. (The factor of two appears because it is the round trip path that determines the time delay.) The backwall reflection will not change its position in time, regardless of the pulse repetition frequency. It is therefore possible to gate this signal in time so that it may be distinguished from reflections that might appear due to other objects in the facility. The presence of a target is detected by monitoring the backwall reflection. An intruding target that intercepts the acoustic pulse will absorb and reflect some of its energy before it reaches the rear boundary. The backwall is not illuminated with as much energy and therefore its reflection will not contain as much energy as prior to the intrusion. Hence, the time-gated output of the reflected energy will exhibit a corresponding reduction in amplitude.

An estimate of target size is not possible based upon the amplitude of the gated signal. If the range of the target is known, then a first order approximation can be made based upon beam shape and attenuation losses. Not knowing the range however, one cannot ascertain whether a change in amplitude is due to a large target at a distance, or a small target at close range which intercepts most of the beam cross section. Single element pulse echo absorption has other limitations. For targets close to the backwall, it may not be possible to separate the target and backwall reflections in time because they will smear together. The range gate must also be tailored for the distance between the transducer and the backwall reflector, therefore adjustment is required from one installation to the next. This method may be impractical for coverage of large facilities because the pulse energy may be attenuated into the noise region before the round trip has been completed. Facilities containing many stationary reflectors (furniture, equipment, etc) in the propagation path may not permit enough of the initial pulse energy to reach a backwall to obtain a good signal to noise ratio. The technique is subject to false alarm if the transmitted pulse energy drops for any reason. When this occurs, the reflected energy will be dropped a proportionate amount and may fall below the alarm threshold. Momentary pulse losses and long term degradation can be accommodated by setting the alarm threshold relative to the energy of the transmitted pulse (as opposed to fixed thresholding). Changes in the environment such as furniture rearrangement will demand resetting of the threshold criteria if these changes alter the amplitude of the backwall return.

3.4.11.1.2 Pulse Echo Reflection - Techniques that process the acoustic energy reflected by a target can provide indications of the target's size, range, motion, and velocity.

Of all the measurements that can be obtained, sizing is perhaps the least accurate. To a first approximation, the amplitude of a return is proportional to the "size" of a target. There are many factors, however, that influence the amplitude of a return other than the size or area of a target. The first of these is the distance between the target and the transducer. Distance has an influence because of beam divergence and attenuation. As a beam (or pulse) of acoustic energy propagates further from its source, its energy density decreases over a constant cross-sectional area due to beam spreading. Targets at distant range are not illuminated by the same energy density as those at close range, and therefore do not return as much. In addition, attenuation of the pulse occurs as it loses energy to the propagating medium (viscoelastic losses); the further the signal has to travel, the more its energy is lost to the medium. Distance-amplitude correction can be applied if the range of

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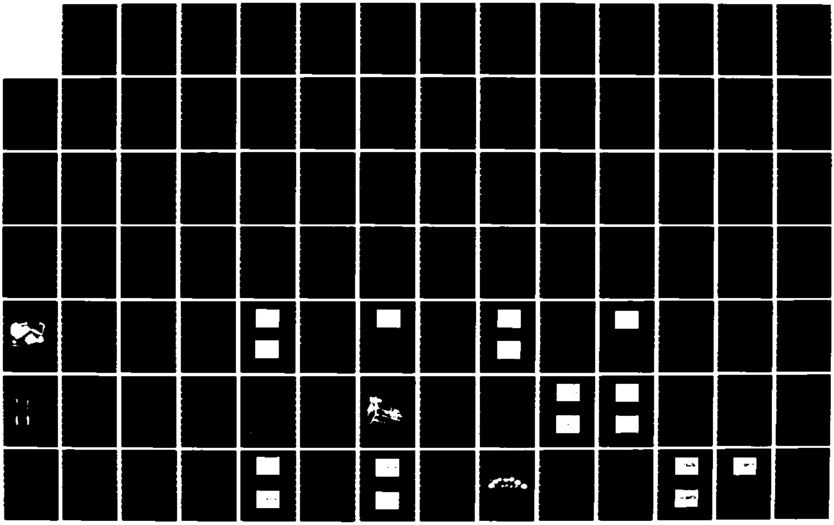

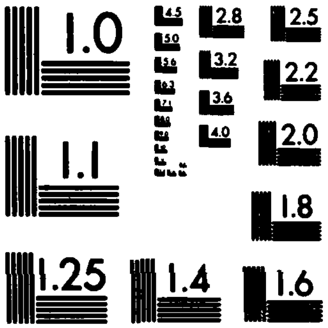

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the target is known and the beam profile is well characterized. Amplitude correction, however, will not improve the signal to noise ratio.

Another factor influencing the amplitude of a target's return echo is its orientation relative to the direction of pulse propagation. Acoustic target detection relies predominantly upon the reflection of the pulse back in the direction of the transducer. Therefore, the largest returns that can be detected are those from the fractional area normal to the direction of pulse propagation. Fortunately, human targets are complex geometries and as a result the probability of a reflecting surface normal to the beam axis is large at any on-axis rotation. However, a person directly facing the transducer will present a larger area normal to the beam than the same person standing sideways or lying flat relative to the beam's main axis. Again, although the actual size of the target has not changed, the amplitude of the return changes with respect to target orientation.

Another factor affecting a target's return amplitude is its position relative to the beam's main axis. Just as with electromagnetic antennas, acoustic transducers emit a characteristic radiation pattern that is a function of the shape of the vibrating element, its dimensions, and the wavelength of waves generated. If the emitter has a narrow radiation pattern (highly directional), a target will produce a maximum return when centered on the beam axis but will rapidly diminish if located a few degrees off-axis. Conversly, the emitter can be designed such that it produces a very broad, diffuse radiation pattern.

Off-axis returns will not decrease in amplitude as rapidly as narrow beam emitters, however the energy density is more diffuse and therefore the same target would not yield as energetic a return as it would in a narrow beam. A trade-off then exists between the maximum range desired and the volume or area covered within that range for a given transducer output level and beam profile.

The pulse echo technique can be used to determine the range of a target by measuring the time-of-flight between transmission of the pulse and reception of the target's return echo. By assuming a known constant velocity of propagation (in air), a direct relationship exists between the time-of-flight and the distance traveled. The maximum unambiguous range is determined primarily by the pulse repetition frequency selected. The presence of a target within the unambiguous range is detected by the reception of its echo before the next pulse transmission occurs. Targets beyond the unambiguous range will return echos which will be detected in subsequent pulse repetition intervals. If this should happen, targets may interpreted as having close-in ranges when in fact they do not. In the nomenclature of radar technology, these ambiguous target indications are referred to as multiple-time-around echos.

The easiest way to avoid interference from multiple-time-around echos is to ignore all returns except the first following pulse transmission (up to the maximum range). The sensor will then wait for a predetermined amount of time before transmitting another pulse. This time lag between pulse transmissions allows multiple-time-around echos to attenuate below the detection threshold so that no interference results in the next pulse interval. This approach is highly feasible for ultrasonic ranging devices due to the rapid attenuation of ultrasonic frequencies in air. To contrast with radar, attenuation of electromagnetic radiation by the atmosphere is negligible below 1 GHz and only becomes significant above 10 GHz. At 10 GHz, the attenuation is approximately 0.01 dB/Km (Reference 4). An ultrasonic wave at a frequency of 63 kHz in air (50% relative humidity) experiences absorption losses at a rate of 2147 dB/Km (Reference 5). The magnitudes of the attenuation differ by a factor exceeding 2×10^5. It is then reasonable to conclude that by appropriate selection of ultrasonic frequency, transmitter output level, detection threshold, and pulse repetition interval that multiple-time-around echos will not be a major concern for ultrasonic ranging systems. The principle limitation of an ultrasonic device which looks only for the first return following pulse transmission is that it requires an unobstructed clear space ahead of the sensor. That is, if stationary objects such as furniture are immediately in the path of the pulse, their echos will lock out returns from more distant ranges. Returns from stationary objects ahead of the sensor (clutter) are also a potential source of false alarms.

A method to overcome stationary clutter interference is to detect Doppler frequency shifts induced by moving targets such as intruders. When a pulse is reflected by a moving target, the carrier frequency will change in proportion to the target velocity according to the relationship $f_d = 2\ V_r\ f_o/C$ where f_d = Doppler or difference frequency, V_r = component of target velocity along the line of pulse propagation, f_o = carrier frequency, and C = carrier wave velocity.

If Doppler detection is used, stationary targets will produce no frequency deviation whereas moving targets will. If the anticipated range of target velocities is known, then by selectively passing only the corresponding Doppler frequencies within the return echos, indications will occur only when a moving target is present. This technique is especially attractive because when large amplitude clutter signals are present, a moving target signature is detectable even though its amplitude is significantly below that of the clutter. Measurement of the Doppler frequency also allows estimation of target velocity.

The conventional method to extract the Doppler frequency component is to mix (heterodyne) the transmitted carrier with the received echos. If a frequency shift has resulted due to target motion, the two signals will "beat" against each other. The beat frequency is the difference frequency or the Doppler shift.

In a pulsed Doppler system, the Doppler waveform is sampled at the pulse repetition frequency. Unless this frequency exceeds twice the maximum Doppler frequency ambiguous Doppler frequencies will occur. Furthermore, there exists a set of Doppler frequencies at which the samples from one pulse to the next will exhibit the same output from the mixer. These frequencies occur at integer multiples of the pulse repetition frequency and the corresponding target velocities are termed the blind speeds. Several blind speeds may occur within the range of intruder velocities but these should not pose a major limitation due to the composite set of velocities presented by human limb motion.

Range information can be extracted from a pulsed Doppler system using either hardware or software based signal processing techniques. Delay line cancellation is a prevalent hardware technique used in radar systems, whereby the current and preceeding returns are subtracted, leaving only the dynamic portion of the return as a residue (i.e. the moving target). The residue will appear only at the time within the pulse repetition interval which corresponds to the moving target's range.

Simple delay lines are easily implemented but suffer from practical limitations. One limitation is the need to maintain nearly perfect gain balance between the delayed and undelayed channels. If the gains are not properly matched, then a residue will occur after subtraction even when no moving target is present. Gain control can be made less critical if a frequency modulated delay line is used rather than an amplitude dependent delay line. That is, rather than subtracting amplitudes directly, the FM delay line technique outputs difference frequencies upon subtraction. The difference frequencies correspond to the amplitude change between the delayed and undelayed channels and therefore provides the moving target indication.

Neither the amplitude modulated nor the frequency modulated delay line techniques will provide adequate cancellation if the time delay is not exactly one pulse repetition interval. Delay lines are not stable devices because their characteristic delay time is temperature dependent. In addition, other circuitry involved in the processing can introduce variable delay factors due to their own temperature dependencies. There are various techniques which can compensate for non-constant delay, but the complexity of the circuitry increases accordingly[6].

Extracting the range of a moving target in a pulsed Doppler system can alternatively be performed by digital processing and a software-based algorithm. The results are analogous to delay line cancellation, however digital memory is utilized rather than a delay circuit. For these techniques the mixer output is sampled and digitized during each pulse repetition interval. The digitized samples within each pulse repetition interval are stored in a one-dimensional array; each element of the array corresponds to a range bin. If another one-dimensional array is used to store digitized samples from the next pulse interval, the two arrays can be subtracted element by element (range bin by range bin) to produce the resultant. Ideally, the resultant will be zero in each range bin if no moving target is present, even in the presence of large clutter returns from stationary targets. On the other hand, a moving target will produce some finite magnitude of difference, provided the target moves a sufficient amount between pulses. The non-zero difference will appear in the array element(s) corresponding to the target's range.

Digital pulse to pulse cancellation produces a much cleaner residue upon subtraction and with greater ease than hardware delay lines. One reason is that the need for two hardware channels is eliminated. The signals to be subtracted are obtained on one channel, therefore the problem with gain balancing is avoided. There is also an inherent immunity to gain drift because the drift between any two adjacent pulses will be negligible. The problem associated with maintaining precisely one pulse interval delay in the hardware-based design is also eliminated using digital memory subtraction. In the digital scheme, the pulse transmission represents a positive timing reference. By keying the data storage with the start of pulse transmission, one is always assured of proper range bin alignment during the subtraction process. Even if the pulse repetition interval randomly varies from pulse to pulse, the residue upon subtraction still will be accurate up to the maximum range defined by the shortest pulse repetition interval.

3.4.11.2 Multi-Element

The benefits of multi-element active acoustic signal processing can be realized in two respects. The first is that it permits multiple usage (ganging) of the single element methods described in Sections 3.4.11.1.1 and 3.4.11.1.2. Ganging single element devices as previously discussed can provide multi-dimensional ranging and target location, coincidence detection, and absolute target velocity. Secondly, multiple elements enable the separation of transmitting and receiving elements so that continuous wave (CW) and other related methods may be used as well as pulsed. The same arguments brought up in Section 3.4.11.1 apply concerning the choice of solid vs airborne acoustic propagation and in the selection of frequency. Therefore, the following discussions assume airborne propagation at ultrasonic frequencies unless otherwise noted.

3.4.11.2.1 Ganged Single Element Devices - Multi-dimensional ranging/location can be provided by placing two or more single element devices at different orientations in the facility. For instance, simple pulsed ranging devices may be placed at "n" locations in the facility. Range measured by each device defines a circular perimeter about the device. Therefore, if n = 2, a location calculation can be made based upon the intersection of the two circles. The solution for n = 2 will not be ambiguous if the devices are mounted in the corners of the room.

Multi-sensor location not only provides detailed information on target position but also leads to other correlating data. First of all, multisensor range determination for location calculation is a form of coincidence detection unto itself. If a real target is present (as opposed to random nuisances), a carefully installed multi-element pulsed ranging system will detect target presence on all three channels and give range values that coincide at one point (within the error bounds). Consistency in the measurements will also be maintained over numerous pulse repetition intervals, if the target is "real". This configuration then has gained both spatial and temporal consistency checks not possible with a single element pulsed ranging device.

Other correlating information obtainable from multi-dimensional ranging includes absolute target velocity and the path traversed. Velocity, bearing, and path determination are direct results of position calculations. If the position values are computed and stored with each pulse repetition interval, then velocity (and path) are obtained by the rate of distance (position) change between samples. The time base for rate determination is the pulse repetition interval. Velocity calculated in this fashion is a vector quantity, therefore bearing is known inherently. This contrasts with single element Doppler techniques which only give the component of target velocity in the direction of the transmitter/receiver (radial velocity). If the target's velocity is entirely tangent to the direction of wave propagation, a single element Doppler system will provide no indication. A properly oriented multi-element ranging system however, will provide position, velocity and bearing regardless of a target's direction of motion.

Multi-element data such as the amplitude of various pulse-echo returns at different orientations can be used to better approximate the size of a target. As mentioned in the discussions of Section 3.4.11.1.1, the orientation of a target will affect the relative amplitude of its return. By illuminating the target from several directions simultaneously, the orientation dependance can more easily be characterized and factored out.

Ganged systems consisting of pulsed ranging single element devices can be implemented by multiplexing their respective pulse transmission intervals. While one element is active (either transmitting or receiving), others would be momentarily disabled until the previous transmit/receive interval was completed <u>and</u> any multiple echos were given time enough to attenuate.

3.4.11.2.2 Multi-Element Absorption Techniques - As discussed in Section 3.4.11.1.1, a system may be configured to detect a loss in amplitude of a reference pulse to sense the presence of an intruder. The method described, however, was severely limited because of the need for a large reflecting area (backwall) to provide the reference signal. The technique can be improved by using separated transmit and receive elements at opposite ends of the facility. Now through-transmission of a pulse or CW may be used, rather than a pulse-echo mode only. In this sense, the through-transmission absorption may be viewed as an acoustic beam break technique.

The advantages over a single transmit/receive element are clear. The receiver need only be positioned in the path of the acoustic wave. There is no requirement for a reference reflector and thus more flexibility is afforded in the positioning of the device. Greater sensitivity and signal to noise ratio are achieved because the necessity of the round trip path is eliminated. Therefore a larger distance can be covered by the same amount of transmit energy without sacrificing signal to noise ratio.

It is probably advantageous to use a focused beam transmitting element rather than a broad beam in order to keep sensitivity high. A widely dispersed field may have multiple paths to the receiver. Therefore, a target's affect on the received signal will not be as pronounced because of contributions from other parts of the field.

A focused beam is more a necessity with a CW system than for a pulsed device. Pulsed systems can take advantage of the time-of-flight relationship to disregard multipath signals arriving at later times than the line-of-sight path. A pulsed system which gates the received signal based upon the line-of-sight path however, will require range gate adjustment for each application and periodic calibration.

In spite of the improvements gained by separating the transmit and receive elements, the absorption method is still limited compared to other candidate sensor techniques. If thought of as a beam-break device, one can see that detection is wholly dependent upon interception of the acoustic "beam" by an intruder directly in the path between the transmitter and receiver. Unless multiple transmit/receiver pairs are used, the system could easily be by-passed just as with optical beam break devices. Using multiple transmit/receive pairs may become cost ineffective due to the number of elements required, installation labor involved, and recalibration if the facility is altered. The amount of correlating information is also limited (i.e. no range, size, or velocity data).

3.4.11.2.3 Multi-Element Reflection Techniques (CW) - The principle advantage to multi-element reflection techniques lies in the ability to separate the transmitting and receiving elements, thus permitting CW to be used rather than pulsed waves only.

A simple CW acoustic system consists of a transmitting element, a receiving element, and a mixer amplifier circuit. The transmitter sends out a continuous single frequency carrier, which in the presence of a moving target, will be reflected at a slightly different frequency (Doppler shift). The mixer detects the difference frequency only, thus providing the moving target indication. The advantages of such a system are its simplicity and its immunity to stationary clutter interference. The biggest drawbacks, however, are its susceptibility to false alarm and lack of range information. Since the receiver is on continuously, any source of ultrasonic energy which creates a beat frequency within the Doppler pass-band is a potential nuisance. Even the slight motion associated with the expansion and contraction of a facility's walls or air turbulence can falsely trigger the simple CW motion detector.

One possibility for decreasing the nuisance susceptibility of simple CW motion detectors is to analyze the spectrum of Doppler frequencies returned for patterns indicative of human motion. Human motion consists of a complex set of velocities due to limb motion. Therefore, if the pattern(s) can be uniquely characterized through pattern recognition techniques, then there exists the potential for developing a discriminant function based upon the spectral content of the return. The utter simplicity of CW motion detectors makes the technique attractive even if pattern recognition must be used. The outstanding question is whether or not pattern recognition would be selective enough to discriminate the wide variation in potential intrusion modes from the variety of potential nuisances. This subject was discussed in Section 3.4.10.1.

The nuisance susceptibility of CW devices can also be reduced by providing a range measurement capability. CW ranging can theoretically be accomplished by one of several methods including frequency modulation, multifrequency carrier transmission, or interferometry.

In order to extract range information from a CW return, the signal must be coded in some way to provide reference marks. A frequency modulated carrier can provide the necessary reference. As an example, suppose the carrier is frequency modulated in a triangular pattern, symetric about some center frequency. Figure 3-19a shows this triangular modulation function. A target reflecting the carrier will be detected at time $t = \frac{2R}{c}$ (R = target range, C = acoustic velocity) and the reflection will appear as the dotted line in Figure 3-19b. Mixing the transmitted and received signals will produce a beat frequency directly proportional to the range. It can be shown that this beat frequency (or range frequency) $f_b = \frac{4RF_m\Delta f}{c}$ where R = target range, Δf = range of frequency modulation, and f_m = rate of frequency modulation over Δf. For linear modulation functions as depicted in Figure 3-19a, the beat frequency corresponding to a given range will be constant except near the transition points in the waveform as shown in Figure 3-19b. It is not essential to use a linear modulation frequency. It can be shown that the average beat frequency measured over a modulation cycle will give the correct range when used in the relationship $f_b = \frac{4RF_m\Delta f}{c}$. Therefore, a sinusoidally varying modulation function can be used if this presents less of a design problem.

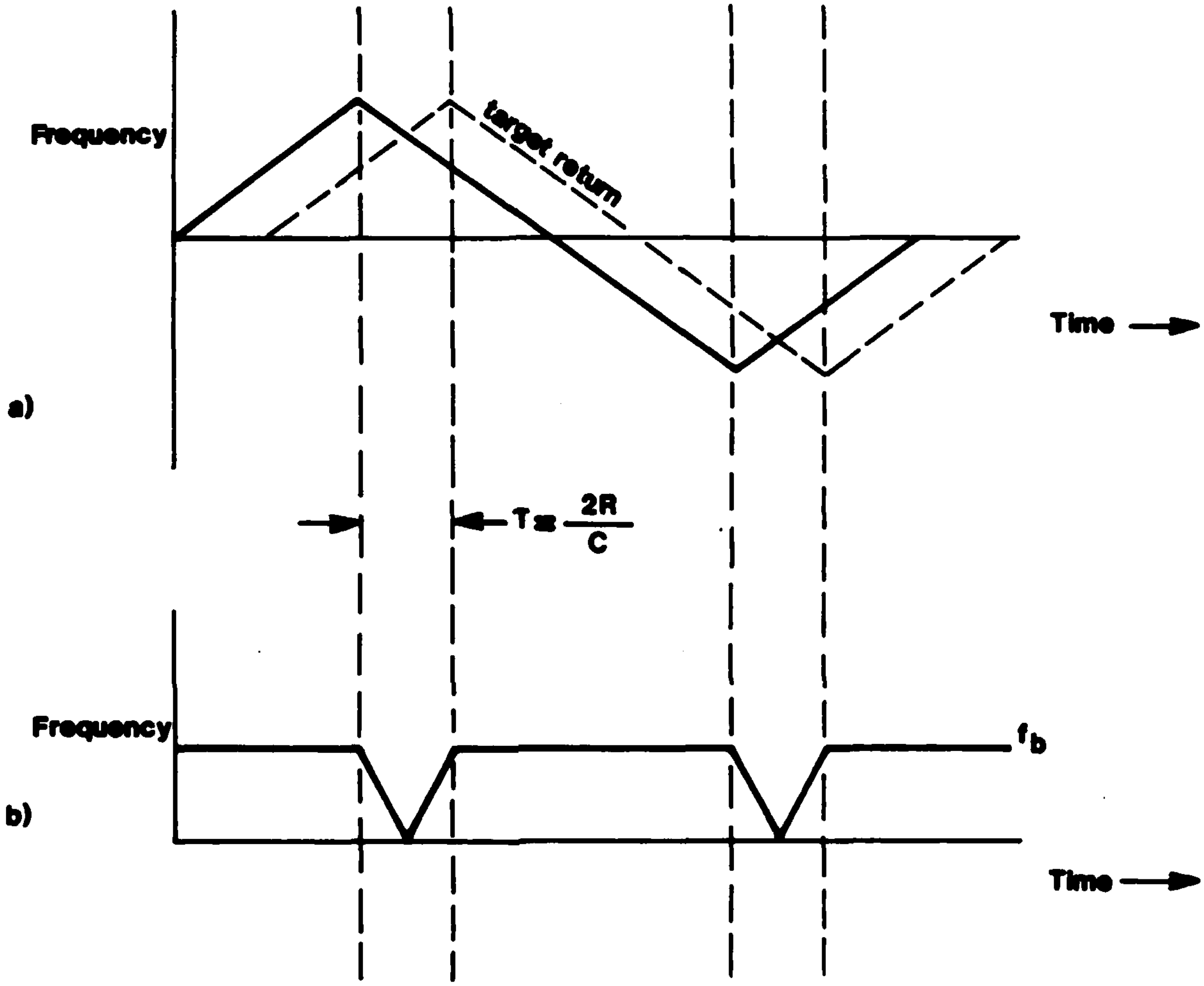


Figure 3-19. Frequency Modulated CW Ranging Technique (From Reference 7)

As described above, the frequency modulated CW technique provides only range information. If used in a highly cluttered environment such as that encountered in an interior facility, the device would be hopelessly inundated by a vast assortment of returns. Therefore, the frequency modulated CW technique offers no compelling advantage over a pulsed ranging system. An alternative CW technique which might provide both range and motion detection is accomplished by transmitting two different carrier frequencies simultaneously. In principle, the motion of a target will set up a different Doppler frequency for each of the two carrier frequencies. Because the Doppler frequencies are different, their relative phase is continually changing in proportion to the distance propagated. By measuring the phase difference between the two Doppler components, $\Delta\phi$, the range can be determined by the following relationship:

$$R = \frac{C\Delta\phi}{4\pi\Delta f}$$

where R = range
C = velocity of sound
ϕ = phase difference between the two Doppler components
f = frequency difference between the two carriers

In order for the range measurement to be unambiguous, the carrier frequencies (and the expected range of Doppler frequencies) must be chosen such that $\Delta\phi$ will not exceed 2π over the range of interest. If $\Delta\phi$ is set to 2π in the above equation, then one can see that the maximum unambiguous range will be:

$$R_{unamb} = \frac{C}{2\Delta f} \cdot$$

A necessary condition for the use of a two-frequency ultrasonic CW technique is that the bandpass of expected Doppler frequencies about each carrier must be separate and distinct. If not, the Doppler shift from one carrier might fall into the other "channel", and therefore no phase comparison could be made. Figure 3-20 graphically depicts this condition. Mathematically, the intersection of the two Doppler passbands may be represented as follows:

$$f_1 + f_{d_1} \leq f_2 - f_{d_2}$$

$$\text{or } f_1 + \left(\frac{2V_r\ f_1}{c}\right) \leq f_2 - \left(\frac{2V_r f_2}{c}\right)$$

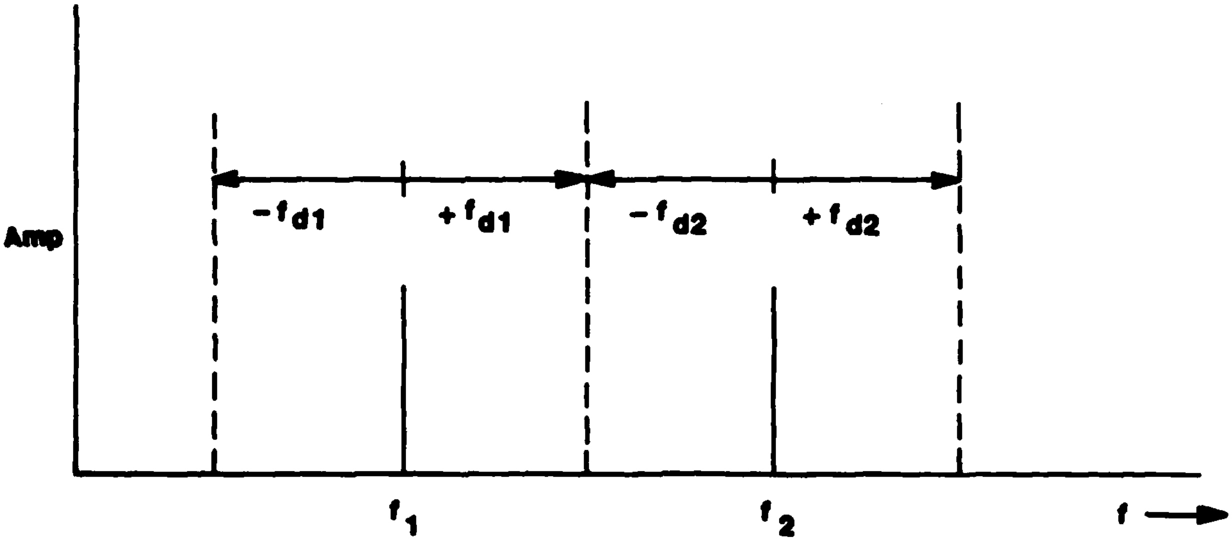
$$\text{or } f_1\ (C + 2V_r) \leq f_2\ (C - 2V_r)$$

If one assumes that a human intruder will have a maximum velocity (V_r) of about 20'/sec and that the velocity of sound (C) is 1130'/sec, then the relationship is further defined as follows:

$$1170\ f_1 \leq 1090\ f_2$$

$$\text{or } f_1 \leq 0.9316\ f_2$$

At a carrier frequency $f_2 = 25{,}000$ Hz, f_1 must be 23,290 Hz. The unambiguous range is 0.3306 feet. This is not adequate for an intrusion detection sensor. If one chooses $f_2 = 100{,}000$ Hz, then f_1 must be 93,162 Hz for the condition to hold. The unambiguous range in this case becomes 0.0826 feet. This too is not adequate for the intended application. It is therefore reasonable to conclude that an ultrasonic two-frequency CW ranging device is not appropriate for intrusion detection, and will not be considered further.



f_1 = lower carrier frequency

f_2 = upper carrier frequency

f_{d1} = maximum doppler shift associated with f_1

f_{d2} = maximum doppler shift associated with f_2

Figure 3-20. Necessary Condition for Dual Frequency Ranging Using Ultrasonic CW

Interferometric techniques can be used to extract target bearing from a CW carrier. This is accomplished by (indirectly) measuring the angle of incidence of the echo using two spatially separated receivers. The angle is determined by measuring the phase difference of the echo between the two receivers. Figure 3-21 depicts the target/receiver relation for a CW interferometer. As shown in Figure 3-21, the interferometer can measure the angle (phase difference) unambiguously over a +/- 90° sector if the two receivers are separated by one half wavelength at the carrier frequency. This corresponds to equivalent phase shifts of less than +/- 180° for any target. The wavelength of a 20 kHz carrier in air is about 0.68 inches; at 50 kHz the wavelength is about 0.27 inches. Therefore, from the standpoint of angular resolution and error, the simple ultrasonic interferometer is not a practical method for bearing determination (i.e., the receivers ideally must be considered as points. This is a bad assumption when their diameters in actuality are on the order of, or larger than their $\frac{\lambda}{2}$ separation).

An interferometric technique is plausible if the ultrasonic carrier is amplitude modulated at some lower frequency. In this case the phase shift at the modulation frequency would be measured rather than at the carrier. For instance, if the carrier was amplitude modulated at 1 kHz, the modulation wavelength would be about one foot, and therefore the receiver spacing could be about six inches. The dimensions are more reasonable, but still, only target bearing will be provided.

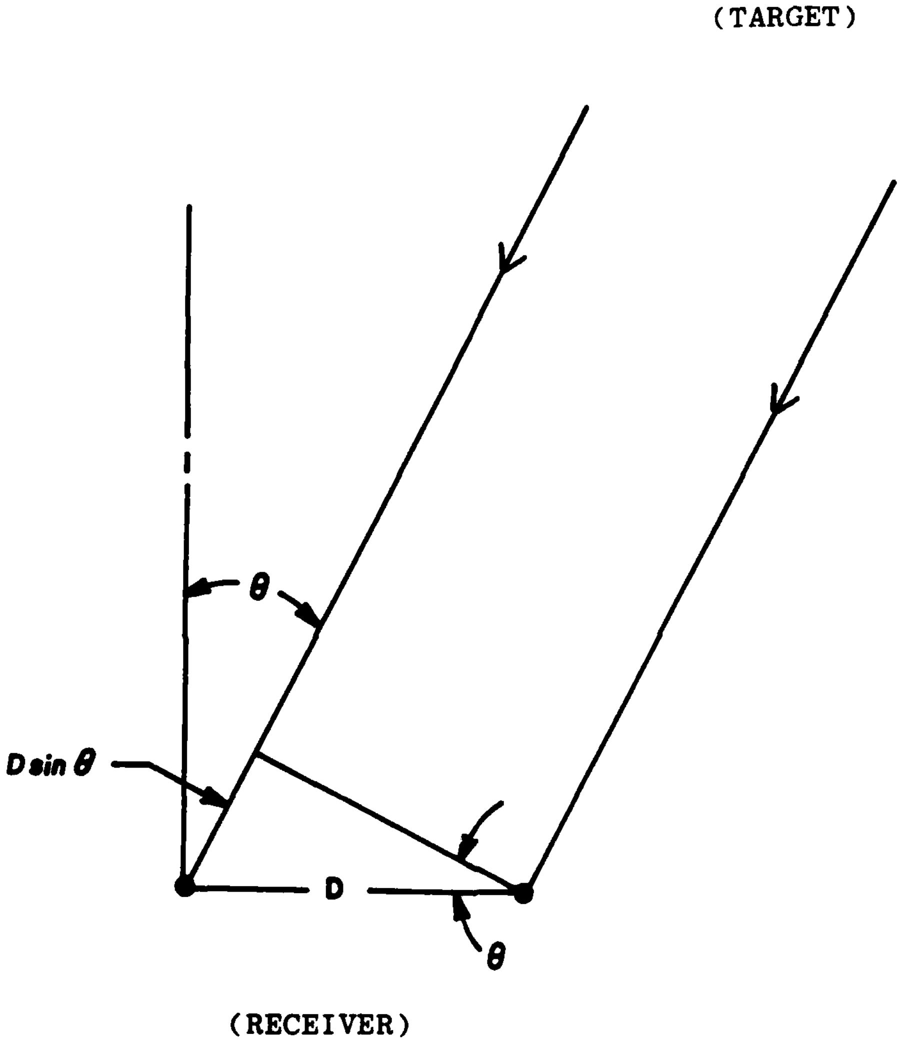


Figure 3-21. Principle for Bearing Determination Using CW Interferometer

Though not a ranging technique, an interesting CW method for target presence detection is provided by standing wave pattern analysis. The method operates under the following principle. If a single frequency CW source is enclosed in a room, the acoustic waves will fill the enclosure, thereby setting up an interference pattern. The precise pattern will depend upon the room geometry, the frequency and orientation of the source, and the contents of the room. A receiving element positioned at some arbitrary point in the room will detect a signal whose phase relative to the transmitter has been altered by the sum of all path contributions between the transmitter and receiver. Whatever the resultant phase happens to be (relative to the transmitter), it will remain constant so long as the frequency does not change and none of the multipaths between the transmitter and receiver are changed. When an intruder enters the room, his body introduces new paths and obstructs old ones. The net result is a change in the interference pattern that is summed at the receiver, causing a shift in the relative phase between the transmitted and received signals. A circuit that monitors the phase and provides an output when it changes will provide an indication of intruder presence. If the intruder is moving, the phase change becomes dynamic, and therefore the interference signal is both phase and amplitude modulated.

This technique was investigated and reported by the National Bureau of Standards (Ref. 8). Their work concluded that a frequency range of 1.0 kHz to 3.4 kHz is optimum. Below 1.0 kHz, consistent response cannot be obtained due to ambient acoustic noise and the target's variable scattering cross section at those corresponding wavelengths. At carrier frequencies above 3.4 kHz, the sound pressure field becomes unstable due to environmental factors.

Environmental factors included the expansion and contraction of the facility due to temperature variations. Because the device must operate in the audio range, its applicability for FIDS is limited by the annoyance it would present to persons in the area. Also, the long term stability and nuisance susceptibility of the technique have not been considered in depth.

3.4.12 Chemical Detection Techniques

Chemical detection techniques rely upon the detection and characterization of effluents from humans while discriminating against the environment by either composition or quantity of given compounds. Bodily processes produce a number of sources of effluents including feces, urine, skin particles, sweat, sebum, gases, and breath. The constituent compounds and their quantities vary considerably from person to person according to health, race, sex, physical activity, environment (temperature, humidity), and diet. Human effluents are estimated to contain between 500 to 1000 different compounds, based upon indications from two-stage gas chromatographic resolution.[9] Processing of chemical detector data must then analyze the various compounds sampled within an environment, and sort those associated with humans from those related to the environment only.

Chemical detection techniques share the need to concentrate airborne effluents for qualitative and quantitative analysis. Any given air sample from a room containing humans will contain only a small fraction of effluents actually due to their presence. The specific quantity present depends primarily on the length of time the person(s) is present, the particular compound, and the variables previously mentioned. For example, carbon dioxide exhaled in breath is one of the major components, and is emitted at approximately 40 gm/hr. by a man at rest. Acetaldehyde is emitted at about a rate of 4.15 μg/hr. Many others are emitted in quantities that are described only as "low"[10]. In order to achieve adequate sensitivity within existing detector resolution, large volumes of air must be sampled to concentrate the compounds. The concentration is achieved by circulating the air through gas chromatographic absorption columns. The columns continuously absorb the small quantities of effluents (particulates, gases), until saturation or equilibrium is achieved. Various materials are used to absorb different classes of compounds. After collection in the columns, the particles are eluted from the absorber (usually by isothermal application of heat) and subsequently detected and identified.

Detection and identification is provided by flame ionization, electron capture, thermal conductivity, and/or mass spectrometry. Each type of detector is best suited for certain classes of compounds, therefore several may be needed to separate a wide spectrum of compounds such as those contained in human effluents. Mass spectrometry is the most precise overall technique for detection and identification.

A novel detection technique was introduced by General Electric which they called the Condensation Nuclei Counter. "The Condensation Nuclei Counter (CNC) is capable of detecting and measuring submicroscopic liquid and solid particles as small as 0.001 microns in radius and of detecting mass concentrations of 1 part in 10^{14}. These particles serve as the nuclei for the condensation of water vapor and are called condensation nuclei. This condensation, which occurs in a few milliseconds, causes the nuclei to grow into larger particles, which will scatter light in a dark-field optical system. The microscopic water droplets formed are related to the original number of particles and can be measured by the intensity of light scattered onto a photomultiplier tube in the detecting circuit."[11]

Without delving further into the actual principles of operation of each device, it is pertinent at this point to discuss the practical limitations of chemical detection devices for the FIDS application. The foremost problem is the vast variability in the compounds present and their concentrations as a function of health, race, sex, physical activity, environment, and diet. Reference 12 concludes that statistical pattern analysis requires between 2 to 15 features within a gas chromatographic signature "to reach meaningful classification of the signatures by their sources." The above study, however, did not consider in depth the influence of environmental factors which might interfere with the signature classification, i.e. all measurements were taken under extremely controlled conditions. Subjects were sealed in a glass enclosure, most were bare to the waist, and purified air was pumped into the enclosure for ventilation. The conclusion therefore, is not entirely valid for a FIDS application where such environmental control does not exist.

Even if a perfect predictive function could be derived based upon a chromatographic signature, the response (processing) time required for chemical detection is a major limitation. The processing time involved using conventional techniques is on the order of minutes to hours. Even fluidized bed gas columns, which are noted for their speed in equilibrating, require 20-30 minutes[13]. In this time frame, an intrusion event could be completed well before the first alarm indication. It was stated in Reference 14 "...there is no fundamental difficulty in development of processes that can characterize chemical signatures of humans within a few seconds to a degree sufficient for classification by sources. The actual choice of processing steps requires however, a massive experimental and theoretical effort." Massive experimental and theoretical development is beyond the scope of this contract.

Other negative aspects of chemical detection techniques include residual effects associated with authorized personnel's effluents during both working and non-working hours. Both the facility and the device would require purging before the device is armed to prevent alarm from residual effluents. If a common ventilation system is used in the facility, precautions must be taken to ensure that air is not drawn in from inhabited areas during the "on" period. For example, a common ventilation system could carry effluents from a guard station to the monitored area, thus setting off the alarm.

Chemical detection techniques are inherently non-ranging, and correlation would be difficult given the problems already mentioned. Installation and maintenance of a chemical detection system are hampered by the possibility of contaminating the device. If improperly handled, the system could give a continuous alarm due to contaminants <u>in</u> or <u>on</u> the device.

3.4.13 Change in Mass Distribution

Newton's law of gravitation states; Every particle of matter in the universe attracts every other particle with a force which is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between them. Thus,

$$F_g = \frac{Gmm'}{r^2}$$

where F_g = gravitational force between the particles
G = gravitational constant
$= 6.67 \times 10^{-11}\ Nm^2/K_g{}^2$
m, m' = masses of the particles
r = distance between the particles

This formula (law) indicates that the mass presented by an intruder's body offers a potential "cause" to "effect" a change in a local gravitational force distribution. In one case, the Earth's mass can be selected as the reference mass m'. The relatively large mass of the Earth produces a quite measurable interaction with a human's mass, better known as a person's weight. This type of measurement is discussed under Section 3.4.14, Pressure Sensing Techniques.

By not considering mass measurement using Earth as the reference mass, another reference must be provided. One possible reference is a large mass suspended by a long, fine fiber within the facility. In theory, an intruder approaching the suspended mass will disturb the local gravitational field, causing the mass to move. Small deflections can be "amplified" by reflecting a light beam off a mirror on the fiber. Over a long path, the arc created by a very small deflection can be more easily measured. These are the principles employed in the Cavendish Balance.

To provide an example of the F_g magnitude for realizable conditions, choose the following values for substitution into Newton's equation.

m = average mass of intruder
= 82Kg ($\cong$180 lbs)
m' = one foot diameter lead sphere
= 160 Kg
G = 6.67×10^{-11} Nm^2/Kg^2
r = 9.14 meter ($\cong$30')

For these conditions, the gravitational force is about 10^{-8} N. Under the best of conditions it may be possible to measure this small force.

Let us assume that such a device has been constructed and can measure 10^{-8} N. Remember that this is the force due to a 180 lb. man standing about 30 feet away. Now suppose a small automobile pulls up outside the facility. Its weight is 3000 lbs. or equivalently its mass is 1368 Kg. If the automobile is closer than 38 meters or 125 feet, its gravitational attraction will exceed that of the intruder. The "gravitometer" in other words, in order to be sensitive enough to detect human intruders, will be more sensitive to nonrelevant nuisances. Solar and lunar cycles will probably present more of a nuisance than any man-made factors. For example, the force presented by the sun (to the lead sphere) is on the order of 1N, eight orders of magnitude difference.

3.4.14 Pressure Sensing Techniques

Pressure sensing techniques respond to the weight presented by an intruder's body to detect his presence. Weight can be detected by pressure activated switches, load cells, and/or strain gauges. Another potential pressure sensing technique exists in monitoring the air pressure wave which propagates ahead of an intruder as he moves. Experiments performed at SCOPE with a pressure transducer, however, did not demonstrate evidence of a measurable effect. The transducer utilized (National Semiconductor LX0503A) was not sensitive enough to detect an entry into a small room. Swatting the air immediately ahead of the transducer with a hand did not produce a measurable response either. Optimization in the selection of the transducer may have produced a more sensitive device, but it was evident that the effect would be very small. It was therefore concluded that air pressure wave sensing was not a highly ranked candidate for FIDS.

Pressure activated switches present a positive indication of an intruder, if he has activated the switch by virtue of his mode of entry or his position in a facility. Switches can be placed on doors and windows to detect intruder entry. These techniques fall under perimeter control methods and therefore will not be discussed as interior sensors. Switch mats however can be placed at one or more locations in a facility. The weight of the intruder's body activates the switch when he stands or walks across the mat. Switch mats can be designed such that they require some minimum force to open or close the contacts. In this respect, they can be very immune to false alarm from small animals and insects. Their biggest drawback, however, is the need to locate them precisely in the path the intruder will take. This is not an easy task since the intrusion path is usually an unknown. In addition, without covering a major portion of the floor area and without careful concealment, these devices are easily bypassed.

Load cells can be used to provide an analog voltage output that is proportional to the weight of the intruder. Load cells are generally constructed using piezoresistive elements; a change in pressure on the element alters its characteristic resistance. Load cells would be utilized in much the same manner as switch mats. The only advantage they offer is a continuously variable output voltage in contrast to the switch mat's binary on/off states. The variable output enables more flexibility in applying the devices since an adjustable threshold can be used. For instance, suppose load cells were integrated into the floor of a facility. If a piece of furniture or equipment was moved onto an area over a cell, the threshold could be adjusted or biased for the new arrangement. An intruder's weight would add to the existing bias, and thus the cell might still be operable, given adequate sensitivity and dynamic range. A switch mat in contrast might be rendered useless because it would constantly be in the open or closed state under these conditions. To prevent false alarm, the mat would have to be moved or disabled from the system.

Strain gauges are an alternative pressure sensing technique which may be used in place of switch mats or load cells. Strain Gauges produce an output proportional to the amount of strain induced in the structural members to which they are attached. Strain is induced in the floor structure due to the load presented by an intruder's weight. Motion detection can be provided by monitoring sudden stress changes with time. If the floor is a relatively contiguous structure such that loads are distributed over a broad area, range/location information can be obtained by analyzing the stress/strain distribution within an array of strain gauges. This would not be as straightforward a technique as with acoustic or radar ranging techniques. Analytical solutions would be limited to very simple structures and possibly not at all applicable to a real FIDS environment. Since each environment will be different, an empirical "calibration" is probably more appropriate.

Gauges would be mounted at strategic locations, nulled, and then their outputs would be observed and characterized for a variety of intrusion modes. The "calibration" process would be analogous to the pattern classifier training described in Section 3.4.10, Passive Acoustic. Because of similar difficulties in training an intruder classifier, range/location determination using strain gauges presents a formidable task and is not justified in view of other candidate techniques which provide this information directly.

In addition to the problems mentioned, the above devices will require, to some degree, modification to existing facilities. In the case of switch mats, modifications would be required for concealment of the mats and for the laying of cables back to a common interfacing device. Load cells and strain gauges need to be attached directly to the floor covering or structural members. Outfitting these devices in current facilities may then involve re-installing sections of floor supported entirely by load cells or gaining access to subflooring structure for strain gauge mounting. Again, provisions must be made for cable runs so that the devices are not easily tampered with, detected, or inadvertently disabled.

3.5 EVALUATION CRITERIA

Given the large number of identified detection and processing techniques, evaluation criteria are needed to identify those sensors that are viable candidates for further consideration in the breadboard or brassboard phase. From the purchase description, three criteria are clear. The sensor must be immanently capable of determining range and must be based upon standard hardware and standard technology. Our investigations into published reports of previous and also current work in intrusion detection (e.g. Carnahan Conferences, MERADCOM Reports, commercial literature) and our own work in the laboratory form a fourth criterion of existing data/prior knowledge.

Nearly any scheme can be made ranging if enough detectors and enough processing are used. Non-obvious ranging techniques certainly merit some thought, however it is not the purpose of this contract to invent novel or elaborate ranging schemes. Rather the purpose is to detect an intruder, using ranging. The requirement that ranging be immanent is justified by an inherent argument against a complicated system if a comparable simple system is available. Further, the time required by any system to make a range determination diminishes the time available to apply nuisance alarm reduction processing. Schemes then which require a large tasking effort to determine a range parameter become unattractive. In the course of the investigation, sensors have been identified that do not range but can locate a human with regard to angular position. In that these sensors provide the capability to localize an intruder and to track the motion of an intruder they have been considered to merit further attention. Other non-ranging sensors are dismissed.

The criteria of standard hardware and standard technology have some degrees of overlap, yet a functional distinction can be made. Hardware is generally considered the physical equipment of the sensor, separate and apart from the theory or operating design of the device. Hardware shall be considered standard if it is available from a manufacturer as a regular item. While any instrument has some degree of custom design, the transducers and other equipment of the sensor should be available for purchase in a routine manner, as opposed to availability only through special manufacturing arrangements.

Technology, construed as theory or operating design of the device, is considered standard if it is existent in present commercial or military applications, not necessarily intruder related. Novel applications of well known technologies are considered standard.

For many potential sensing schemes, previous work in intrusion detection and in other fields has created a large body of data on their feasibility and performance. Many potential sensors that meet the criteria of ranging, standard hardware, and standard technology can be judged inadequate based on these studies and on our own investigations. Evidence regarding viability and conformance to any criteria must be judged not merely with respect to detection of a human but also with regard to operation within a FIDS context.

For purposes of organizing and evaluating the various detection and processing methods which have been described above, a basic three step evaluation process has been carried out. The first step directed attention to the available signal environments. The second step was a technique evaluation aimed at the principal candidates selected from the environment evaluation. Finally, breadboard experiments were conducted to provide supporting data for the selected techniques. The first two steps have required establishment of criteria for evaluating environments and techniques.

3.5.1 Environments

The first level evaluation of potential system candidates has been carried out by considering all of the possible signal environments in which intrusion signals can be found. As is evident in the detailed discussion on each environment presented earlier in the report, basic conclusions regarding their viability can be made without pursuing the signal processing techniques which may be available for use on those signals. Hence, the suitability of each particular signal environment has afforded a first cut at finding candidate systems and eliminating others from further consideration. Criteria which will be considered are the potential for acquiring spatially dependent data, that is range or bearing information, from the signal source. The factors of standard hardware and standard technology along with availability of existing data will round up the first level evaluation criteria.

3.5.2 Techniques

Given that several signal environments offer the potential to be viable choices to operate an intrusion detection system, then it is necessary to break down the signal environments according to the possible ways in which the intruder signals can be processed to achieve various detection goals. Each of these will then be rated according to several criteria. Once again the good of obtaining spatially dependent data such as range or bearing is a primary evaluation criterion. Added to this are the ability to sense intruder motion, the relative immunity of the process to nuisance signals, the ease of testing by remote stimulus and ultimate hardware simplicity. The previously described processing and detection techniques will be listed and rated according to these criteria.

3.6 CANDIDATE SELECTION

The important process of selecting the candidate intrusion detection systems for further development has required a careful sifting of all of the information regarding signal environments and target detection techniques within the process described in Section 3.5.

Table III lists all of the environments considered for intrusion signal sources and provides a summary comparison of these environments for application to the FIDS requirement. although detailed discussions of these data have been presented, a brief summary of facts and conclusions relating to each environment will be given here.

3.6.1 Environments

Passive Magnetic Field

Passive magnetic field sensors have been devised to detect vehicle motion or armed personnel movement in exterior settings. The required hardware is readily available and the technology is well known. Sensing requires an intruder to pass by the sensor carrying a metallic object with magnetic properties, precluding any further consideration of this scheme.

	Range or Bearing Data	Standard Hardware	Standard Technology	Existing Data	Prime Candidates
Passive Magnetic Field		X	X		
Active Magnetic Field		X	X		
Gravitational			X		
Chemical					
Breakwire		X			
Pressure		X	X		
Thermal		X			
Passive Electric Field		X	X		
Active Electric Field		X	X		
Active Electromagnetic	X	X	X	X	Active Electromagnetic
Passive Infrared	X	X	X	X	Passive Infrared
Active Acoustic	X	X	X	X	Active Acoustic
Passive Acoustic		X		X	

TABLE III. COMPARISON OF POTENTIAL SIGNAL ENVIRONMENTS FOR INTRUSION DETECTION

NOTE: "X" DENOTES CRITERION SATISFIED

Active Magnetic Field

The principle of operation of this type of sensor, detecting a change in inductance, is well known. The scheme requires large sensing coils, possibly involving custom manufacturing. The sensor is non-ranging and the ability to restrict a detection to events interior to the protected area is doubtful.

Gravitational

A detection scheme based on universal gravitation ($F\alpha\frac{M_rM_2}{R^2}$) is non-ranging. A detector would be similar in form to a Cavendish or torsion balance. The magnitude of the force produced by a mass at a distance is so miniscule as to make the time to detection impractical.

Chemical

Chemical detection is non-ranging, allowing for dispersion of effluents through a gaseous medium yields a time to detect no faster than minutes. The existence of standard hardware, appropriate to a FIDS context is extremely doubtful at best. While the technology and techniques of chemistry are certainly well-known, a specific procedure of chemistry for detection of a human is unknown. Research on development methods for detecting and measuring volatile human affluents done at Edgewood Arsenal and other locations has been discontinued.

Breakwire

Several varieties of standard hardware are available for breakwire schemes. Breakwire methods are used for perimeter and penetration protection, they have no particular capacity for volumetric protection of an interior area. Ranging can only be effected to the degree that if a detection occurs, the intruder is somewhere along the length of the sensor.

Pressure

Pressure detection of a human intruder involves relatively simple technology and hardware is readily available. Ranging is possible only by extensive emplacement of sensors. Emplacement to provide total volumetric coverage would be to such degree as to require some interior remodeling. Nuisance signals from vibration are presumably extreme.

Thermal

Thermal detection is non-ranging for any practical application. Several varieties of temperature sensitive devices are available, satisfying the standard hardware criterion. The standard technology criterion is not satisfied as no practical volumetric technique based on thermal exchange is known. Time to detection with thermal techniques is long and there is no particular capability to distinguish human from non-human heat sources.

Passive Electric Field

The most significant electrical event in the body is cardiac depolarization and repolarization. The only other significant signal source is cortical neuronal activity. These events have a magnitude of microvolts to millivolts, detectable via skin electrodes. Detection can occur only if the intruder is in contact with the sensor, precluding volumetric coverage. No hardware or technique suitable to a FIDS context is available.

Active Electric Field

Ranging is not possible (immanently) with sensors of this type. Leaky cables, capacitive, and proximity sensors are all designed to provide perimeter or point protection and not volumetric coverage.

Active IR/Visible/High Energy

In the upper part of the electromagnetic spectrum two general techniques are used, beam breaking and imaging. The viability of these techniques is discussed more in-depth in an earlier section. From a prima facie standpoint it is sufficient to note that many hardware sources exist, some ranging techniques can be identified, and that at least some detection techniques involve relatively simple technology. There are human exposure considerations for any active electromagnetic technique, particularly those in the high energy part of the spectrum.

Passive Infrared

Single element passive IR detectors are not true range or bearing detectors. There are, however, a variety of relatively simple ways to determine range or bearing of a moving intruder using PIR elements.

Single element passive infrared sensors are standard hardware items of low cost. Passive infrared detection schemes are not particularly suited to processing to determine whether a signal appears to be characteristic of a human or not, however passive infrared systems have a relatively small nuisance alarm set.

Active Acoustic

Active acoustic devices can potentially detect an intruder by such techniques as radar, signal absorption, interferometry, or analysis of standing wave patterns. Hardware is readily available and the acoustic technology of these techniques is well-known. A detailed discussion of the ranging techniques was given earlier. At sonic frequencies, human annoyance is a consideration.

Active RF

In the active RF environment an intruder can potentially be detected using radar, interferometry, or change in signal equilibrium techniques. These techniques each utilize well known technology and hardware is readily available. The ranging techniques were discussed in detail earlier.

Passive Acoustic

Many varieties of hardware exist for passive acoustic signal pick-up, however ranging can be accomplished only by triangulation or other involved means. Pattern recognition processing can be developed to identify signals within a specific environment. However, a processing technique that can identify a human within any interior environment is unknown. Passive acoustic methods are used in intruder detection not as motion sensors but as detectors of characteristic frequencies such as that of shattering glass or wood, or as detectors of assault on installed barriers with devices such as saws or drills.

3.6.1 Summary

The three environments which satisfy all conditions for selected criteria are the Active Acoustic, Active Electromagnetic, and Passive Infrared.

These three environments will be examined to discover the most promising detection techniques among the diverse methods investigated.

3.6.2 Techniques

In order to refresh the readers mind of the general techniques, their capabilities and limitations, a brief discussion of pertinent techniques will be given here as an introduction to the evaluation of techniques. This will be followed by a presentation of the tables of candidates systems along with a brief discussion of each general area.

3.6.2.1 General Discussion

In the Environments Section, several schemes with the potential for ranging are noted. In this section, the techniques of beam-breaking, imaging, and radar are assessed in review to serve as a basis for further candidate system evaluation with a particular emphasis on the ability to acquire range data.

Beam-Breaking

Beam-break schemes have as their greatest advantage, and also their greatest disadvantage, their relative simplicity. With a modulated transmitter and a receiver protected from saturation by ambient radiation, beam-break schemes are susceptible to few nuisance signals. The system will respond only when a physical object is present between the receiver and transmitter. Small mammals and large birds are nuisance sources and potentially quite troubling given the simplistic nature of beam-break detection. The simpleness of the detection becomes a drawback when deployment and environment are considered, with many of the same problems as a breakwire system. To determine range or location requires a large number of receivers placed throughout the volume and characterization by size, essential to discriminate mammalian and avian signals, requires an even greater number of receivers in more dense arrays. Deployment then becomes a problem as a great number of receivers and perhaps many transmitters must be emplaced with precise angular orientation required for each. In environments with irregular features some sophistication will be required to achieve an effective deployment. Any environment with movable fixtures, furniture, etc. will require redeployment of the receivers/transmitters for any significant change in interior environment. There are some (many?) interiors where dense deployment of sensors along multiple surface areas is logistically unacceptable due to the presence of maps, charts, furniture, hardware, etc. As argued in the previous sections, a high component count alone argues against a system and in this case the large number of receivers will require a significant amount of front-end processing. Increasingly dense receiver arrays will begin to resemble imaging motion detectors. Any advanced processing scheme will require a knowledge of the transmitter-receiver configuration within a room making each and every sensor application dependent. The effectiveness of the beam-break's simple detect-no detect response is seriously compromised in any interior environment where casual rearrangement of fixtures, furniture, etc. during the access mode can occur, with the possibility of placing an object directly in a beam. Elaborate processing can perhaps provide for long-term, stationary beam-breaks but the attractive features of the system, simpleness and positiveness, are then destroyed. The system is also opened to defeat by knowledgeable intruders. Beam-break schemes are generally used to protect access routes or narrow corridors. There is some limited use of beam-break schemes for volume protection but in the FIDS context, where ranging is required and characterization of a disturbance as a human is at least highly desireable, beam-breaking is too crude for effective use.

Imaging

Imaging can be accomplished in several signal environments and can be considered in ranging and in non-ranging applications. Ranging is conventionally done with two separated units, each containing its own optics and detector. The separation distance between the units must be known and the range is computed by comparing the position on each detector of the target. With one detector ranging can be done more novelly by determining the focusing distance of an image or by using laser striping techniques. The more traditional use of imaging in intrusion detection is that of a single detector used in a non-ranging role. The degree of resolution and the amount of processing employed determine the capabilities of any particular device.

Low resolution detectors are used to detect motion, triggering on general changes in gray level or changes in contrast within the scene. Historically the problems associated with various realizations of these systems have been enormous. Vidicon cameras are plagued with image burn-in after looking at the same scene over a long period of time, which reduces the cameras sensitivity to motion. Image blooming occurs around any bright object when a silicon vidicon is used. Extraneous light sources contribute heavily to nuisance alarms, including such sources as flashlights of security personnel, vehicle headlights, and bright sunlight. Related to this is personnel in adjoining areas performing seemingly innocuous tasks, as opening doors or turning on fans and causing sudden changes in light level or motion within the area of coverage. Vibration pickup from the camera mounting has contributed heavily to nuisance alarms. Cameras have shown high vulnerability to temperature extremes, particularly on the upside.

Rats and birds have caused problems for video motion detection systems as have spiders, by crawling across or building webs over the lens. Correct lighting is of paramount importance in the overall performance of a video system. Careful attention must be given to all illumination needs to provide optimum video capabilities. Depth of field, field-of-view, image size, and camera iris, must be considered to determine illumination requirements.

High resolution detectors, those that can identify scene-to-scene differences as human or not-human, are the subject of a great deal of current research and development. So much so in fact that current state-of-the-art capabilities can only be obtained from technical reports and conference proceedings. The major emphasis of this work is on military and automated factory applications with different goals and different working constraints than with intrusion detection applications. The rate of progress in intrusion detection is very rapid yet several problem areas remain.

The basic cost of vision technology is extremely high. The design and development costs are comparable to those of other systems (radars, etc) but hardware costs can be expected to range from a minimum of approximately $2000 to more than $30,000 for more complex systems while special applications using state-of-the-art in real-time hardware could exceed $100,000. Software costs are indeterminate and depend upon the existing collection of software tools and the experience level of the personnel. System cost at this time is moving downward and the expectation is for further downward movement.

The most severe problem at this time for imaging applications is the lack of system flexibility. While the performance of any intrusion detection system is dependent on the environment, the very ability to identify a human is absolutely specific to each site. Every application would require special attention and perhaps system modifications at a level not considered possible for inexperienced, unskilled personnel. Off-the-shelf vision systems are becoming a reality for automated factory applications where the visual environment is known and the system is trained by presenting standard reference targets. These systems are presently in the $35,000 to $70,000 price range.

Rapid technological progress has made the lack of real time hardware a smaller barrier than before. The state-of-the-art in computer technology can effectively address the processing requirements for a computerized vision, image understanding system with real-time capability. The large memory requirement and the very high throughput requirement still dictate CPU power comparable to that of a large minicomputer. The continuing successful development of chip level image analysis algorithm modules will further lower the hardware barrier.

Another barrier that is still significant yet being lowered with time, is the lack of widespread knowledge about how to best apply computer vision within the constraints of the state-of-the-art. For the imaging intrusion detection system to be successful there must be continued improvemet in image engineering techniques, such as determination of optimal lighting characteristics for an area, methods of contrast improvement, and recognition algorithms for partially eclipsed objects whose shape is not fixed.

Radar

Radar techniques can be evaluated independently of the carrier nature, EM or ultrasonic. Bound up with radar techniques are the signal processing techniques to be used before or in conjunction with the alarm decision routine. Digital signal processing techniques (transform processing, etc.) are applicable to the nuisance rejection problem and radar techniques can be compared with each other independently of this.

Radar technique begins with a simple continuous wave system. In the absence of timing marks, this system can only determine Doppler frequency shifts and thus functions only as a velocity detector. The system cannot determine range or bearing.

The simplest radar technique that can be used to determine range is a frequency modulated CW system. These systems are suited best to applications where there is a single, stationary target. Determination of range is complicated when a Doppler frequency shift is present and there can be confusions of range and Doppler velocity when fast, nearby targets are present. When multiple targets are present the problems of resolving targets and measuring the range of each becomes so complicated as to eliminate practical solution. A double-modulated FM radar can eliminate the fixed error of a single-modulated system, however it is more complicated and more limited in range. This system and others which find range from Doppler signal amlitude have a tremendous problem with regard to a human target. Amplitude changes due to actual changes in range with movement are masked by the complex nature of human movement, e.g. cyclic patterns of arm and leg swing and velocity variations between arms, torso, and legs.

Multiple frequency CW radar can determine range without reliance on Doppler amplitude by use of a phase-difference measurement. The unambiguous range is determined by the difference in the transmitted frequencies. Multiple frequency CW radars are single-target devices. The echo signal becomes complicated and the meaning of the phase measurement is in doubt if more than one target is present. Range can be determined only if one return is dominant above all others.

Amplitude modulation of a CW radar yields the most straightforward ranging technique. A simple pulse radar measures time-of-return with an unambiguous range determined by the pulse repetition frequency. More complex radars use the Doppler shift in frequency caused by a moving target to distinguish fixed from moving targets. Pulse radars using Doppler can discern moving targets in the presence of fixed targets even when the echo signal from fixed targets is orders of magnitude greater.

Coherent MTI (moving-target-indication) radars and pulse Doppler radars both use pulses to measure range and Doppler to measure or detect motion. The distinction is that pulse Doppler radars use high enough pulse repetition frequencies so that Doppler frequencies may be measured unambiguously. (Pulsing produces a sampled version of the Doppler waveform and must at a rate at least twice the maximum Doppler frequency to avoid ambiguity.) The high PRF may produce range ambiguities from multile-time-around echos. In coherent MTI radars the PRF is low enough to provide range unambiguously. Doppler frequency may be ambiguous, but it is not used to measure velocity, merely to indicate motion. MTI may be coherent (phase fluctuations are measured) or noncoherent (amplitude fluctuations are measured) with noncoherent MTI being less complex. Noncoherent MTI requires large clutter signals to be present to effect moving target detection. In the absence of clutter, detection can take place if more than one moving target is present with the lowest Doppler frequency acting as the reference signal.

In the FIDS context then, CW and FM CW are inappropriate given the range indeterminancies and the lack of detection in the presence of multiple targets. In an office or storeroom environment, multiple stationary returns can certainly be expected, arguing for MTI or pulse Doppler techniques. The relative effectiveness of simple pulse radars, range gating, delay line cancelers, etc. requires experimental assessment. Multiple frequency CW will be viable only if torso return dominates all other signal returns.

3.6.2.2 Techniques Evaluation

From the assessment of signal environments, active electromagnetic (both RF and IR/visible/High energy), passive infrared, and active acoustic have been selected as the most promising milieu for a FIDS intruder detector. Contrasting these with the evaluations of techniques yields the candidate sensors of interest. Tables IV, V, and VI list the processing techniques available for the respective environments of Active Acoustic, Active Electromagnetic and Passive Infrared systems. As in Table III above, the X denotes suitability of the technique for satisfying the criterion specified in the column. A few of the key points raised in earlier discussions will be presented here for purposes of review.

Active Acoustic

From the techniques section, an MTI or pulse Doppler radar is the best theoretical sensor for FIDS applications. A simple pulse radar system will determine range with less hardware complexity. The system performance versus system complexity can be effectively assessed in the laboratory. In the infrasonic domain, insufficient target return is present for these techniques to be viable. Sonic frequencies, as noted before, are feasible technologically, however human annoyance is a consideration. Ultrasonic transmitters and receivers are readily available.

Active Electromagnetic

Given EM wave velocity and FCC bandwidth restrictions the practical implementations of RF radar are more limited. Pulse systems are incompatible with these considerations,

	Spatial Data			Relative	Ease of	
	Ranging	Bearing	Motion	Nuisance Imunity	Remote Stimulus	Hardware Simplicity
Pulsed						
Simple Pulsed	X			Poor	X	X
Pulsed Doppler	X		X	Good		
Pulsed w/Digital Range Gate	X		X	Good	X	X
Absorption (Beam-Break)				Good	X	X
CW						
Simple CW Doppler			X	Poor	X	X
Frequency Modulated CW	X			Poor		
Dual Frequency CW		(Insufficient Range at Ultrasonic Frequencies)				
Interferometer		(Not Feasible at Ultrasonic Frequencies)				
Interferometer w/Modulated Carrier		X		Poor		X
Standing Wave Pattern Analyzer			X	Poor	X	
Absorption (Beam-Break)				Good	X	X
Ganged Simple Devices						
Simple Pulsed/Simple Pulsed	X	X	X	Poor		
Simple Plsed/CW Doppler	X		X	Poor		
CW Doppler/CW Doppler			X	Fair		

TABLE IV. COMPARISON OF REPRESENTATIVE TECHNIQUES WITHIN ACTIVE ACOUSTIC ENVIRONMENT

	Frequency Band				Spatial Data						
	RF	IR	VIS	HE	Range	Bearing	Motion	Relative Nuisance Immunity	Ease of Remote Stimulus	Hardware Simplicity	Tolerant Radiation (Per BRH, FCC Regs.)
Beam Break											
Single Element		X	X	X				Good	X	X	X (Ex. HE)
Multiple Element		X	X	X		X		Good	X	X	X (Ex. HE)
CW											
Simple Doppler	X						X	Poor	X	X	X
Quadrature	X						X	Fair		X	X
Multi-frequency	X				X			Poor			X
Interferometer	X					X		Poor		X	X
Change in Equilibrium	X	X	X					Poor	X	X	X
Frequency Modulated	X				X			Poor			X
Pulsed											
Simple Pulsed	X	X	X		X			Poor	X		X (Ex. RF)
Pulsed Doppler	X				X		X	Good			X (Ex. RF)
Imaging											
Linear Array		X	X			X	X	Good			X
Two Dimensional Array		X	X			X	X	Good			X
Paired Arrays		X	X		X	X	X	Good			X

TABLE V. COMPARISON OF REPRESENTATIVE TECHNIQUES WITHIN THE ACTIVE ELECTROMAGNETIC ENVIRONMENT

	Spatial Data		Motion	Relative Nuisance Immunity	Ease of Remote Stimulus	Hardware Simplicity
	Ranging	Bearing				
Single Element Detector				Poor	X	X
Linear Array		X	X	Fair	X	X
Two-Dimensional Array		X	X	Fair	X	
Paired Arrays	X		X	Good	X	

TABLE VI. COMPARISON OF REPRESENTATIVE TECHNIQUES WITHIN THE PASSIVE INFRARED ENVIRONMENT leaving multiple frequency CW radar as the best candidate for ranging purposes in this domain. As noted in the techniques section, multiple target returns (possibly from a single target) can cause a lack of detection with this method, rendering it inferior to pulse ranging systems.

Beam breaking and imaging are less promising ranging techniques vis-a-vis radar for FIDS applications, as discussed previously. Further, there is the capability to implement these techniques in the passive infrared domain, eliminating the need for active illuminants. Given this, there is no reason to consider techniques in this signal domain as prime sensor candidates.

Passive Infrared

The single-element PIR cannot determine range or bearing even with a faceted mirror for multi-beam coverage. A rotating mirror combined with a single-element detector or a motor-mounted single-element detector with enough processing and hardware coordination could determine bearing, however this is done much more easily with a multi-element sensor. Bearing can be determined almost arbitrarily well with an appropriate combination of mirror facets and detecting elements. Both range and bearing can be determined with two multi-element sensors. The location of a moving intruder can be determined to within a particular cell, determined by the overlap of the coverage beams from the two units. The more coverage beams, the more precise the locating. The sensors must be installed at a fixed separation distance and with precise angular orientation for this processing to be effective.

A sensor that uses a two-dimensional, multi-element detector can determine bearing and two sensors can determine range and bearing, as with the simpler one-dimensional, multi-element detectors. A two-dimensional array can be used to do passive image formation. The considerations for passive IR imaging are exactly the same as for the active case with the exception that active illumination is not required.

As noted in the infrared section, single-element PIR sensors are standard hardware items of low cost. Multi-element, one-dimensional arrays are still standard hardware yet exhibit a large price increase, becoming moderatly to very expensive. Two dimensional arrays are just beginning to enter the market and at enormous costs.

The tables show a number of viable candidates satisfying many or all of the chosen criteria. There is little doubt that quite a few of the systems could be pursued through development to a working system. In order to further reduce the list of candidate systems, the breadboard testing has attempted to preview the complexity and performance to be realized for a number of the listed systems.

3.6.3 Breadboard Investigations

The purpose of the breadboard investigations was to gain first hand experience with the systems identified as highly ranked candidates, thus providing a more solid foundation for comparing their applicability to FIDS. Table VII lists the systems actually evaluated by breadboard experiments and the potential information to be gained from each. Although it has been stated that the principle requirement for the candidate sensor(s) is ranging capability, non-ranging candidates were also considered for breadboard evaluation because of their utility as correlating channels for false alarm reduction.

TABLE VII. BREADBOARD EVALUATIONS

SYSTEMS EXAMINED	POTENTIAL TARGET INFORMATION AVAILABLE
Active Electromagnetic - RF	
● CW Doppler	Motion Detection
● Dual Frequency CW	Motion Detection; Range
Passive Infrared	
● Single Element	Motion Detection
● Dual Element Differential	Motion Detection with back ground cancellation; Direction sense of target motion.
● "Linear Array" using two Dual Element Detectors	Motion Detection with background cancellation; Bearing; Increased coverage.
● Two Dimensional Array	Imagery; Motion detection; Bearing; Large volume coverage
Active Acoustic	
● Simple Pulsed with MTI Processing (25 KHz, 40 KHz)	Motion Detection; Range
● Coherent Pulsed Doppler with MTI Processing (25 KHz).	Motion Detection; Range; Increased sensitivity

3.6.3.1 Active Electromagnetic - Simple RF CW Doppler

Evaluation of the CW Doppler microwave system was not a major hardware task due to the judicious selection of commercially available RF modules. Two varieties of modules were obtained from Microwave Associates. One was a K-band Doppler Transceiver (MA 86859), consisting of a Gunn diode oscillator and a Schottky barrier mixer diode packaged in a single unit. The device need only be supplied with +5 VDC to the Gunn oscillator, and the mixer output (Doppler) is tapped directly off of the module. The only external circuitry needed is an audio amplifier to boost the mixer output to a convenient level. Motion detection at ranges in excess of 40 feet was demonstrated with this arrangement.

The second Microwave Associates module was an X-band Varactor Tuned Transceiver (MA 87105), featuring an electrically tunable carrier frequency, ferrite circulator, and a Schottky barrier mixer diode in a single package. By fixing the tuning voltage at one value, this module operated identically to the K-band module by providing the Doppler frequency (motion indicator) at the mixer output pin. Again, the only external hardware needed was an audio amplifier.

Figure 3-22 shows the two modules and two X-band waveguides. The MA 87105 module is on the left and the MA 86859 is shown on the righthand side of the photo.

3.6.3.2 Active Electromagnetic - Dual Frequency RF CW Doppler

Since the Microwave Associates X-band module contained varactor tuning, an alternating dual frequency carrier could be

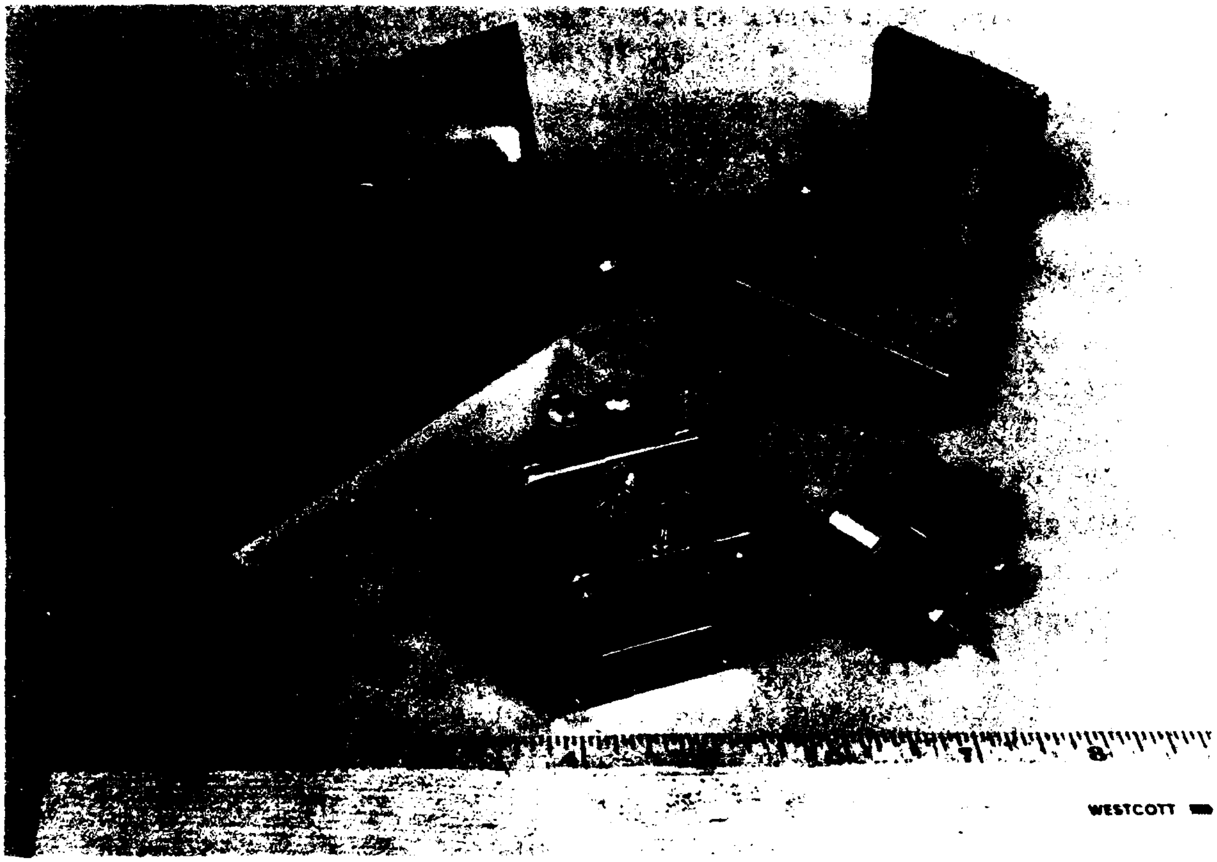


Figure 3-22. Microwave Associates Radar Modules

generated by applying a square wave to the varactor input. As discussed in Section 3.4.5.7, the dual frequency configuration permits moving target range determination by measuring the phase difference between the two resulting Doppler frequencies.

The experimental circuit is shown in Figure 3-23 and its corresponding functional block diagram is shown in Figure 3-24. The square wave applied to the varactor input is simultaneously applied to the address line (output select) of the analog switch/multiplexer. Toggling of the address line switches the mixer output between the two analog switch outputs. Therefore, the switch acts as a demultiplexer, providing two discrete channels of Doppler output, with each channel uniquely providing the Doppler output from one of the two carrier frequencies.

The duty cycle of the information on each channel (analog switch outputs) is 50%, therefore low-pass filtering is used to smooth the discontinuous output into continuous sinusoids. Figure 3-25 shows the two channels of switched output prior to any filtering. If the switching frequency (square wave) is set too low, the filtered output retains a choppy appearance. Figure 3-26 depicts the filtered output using a switching frequency of about 50 Hz. At 50 Hz, the filter is not effective at smoothing the waveforms. By increasing the switching frequency, the filter's smoothing action becomes more efficient. Figure 3-27 depicts the filtered outputs using a switching frequency of about 5 KHz. As evidenced by the photograph, the chopped appearance has disappeared.

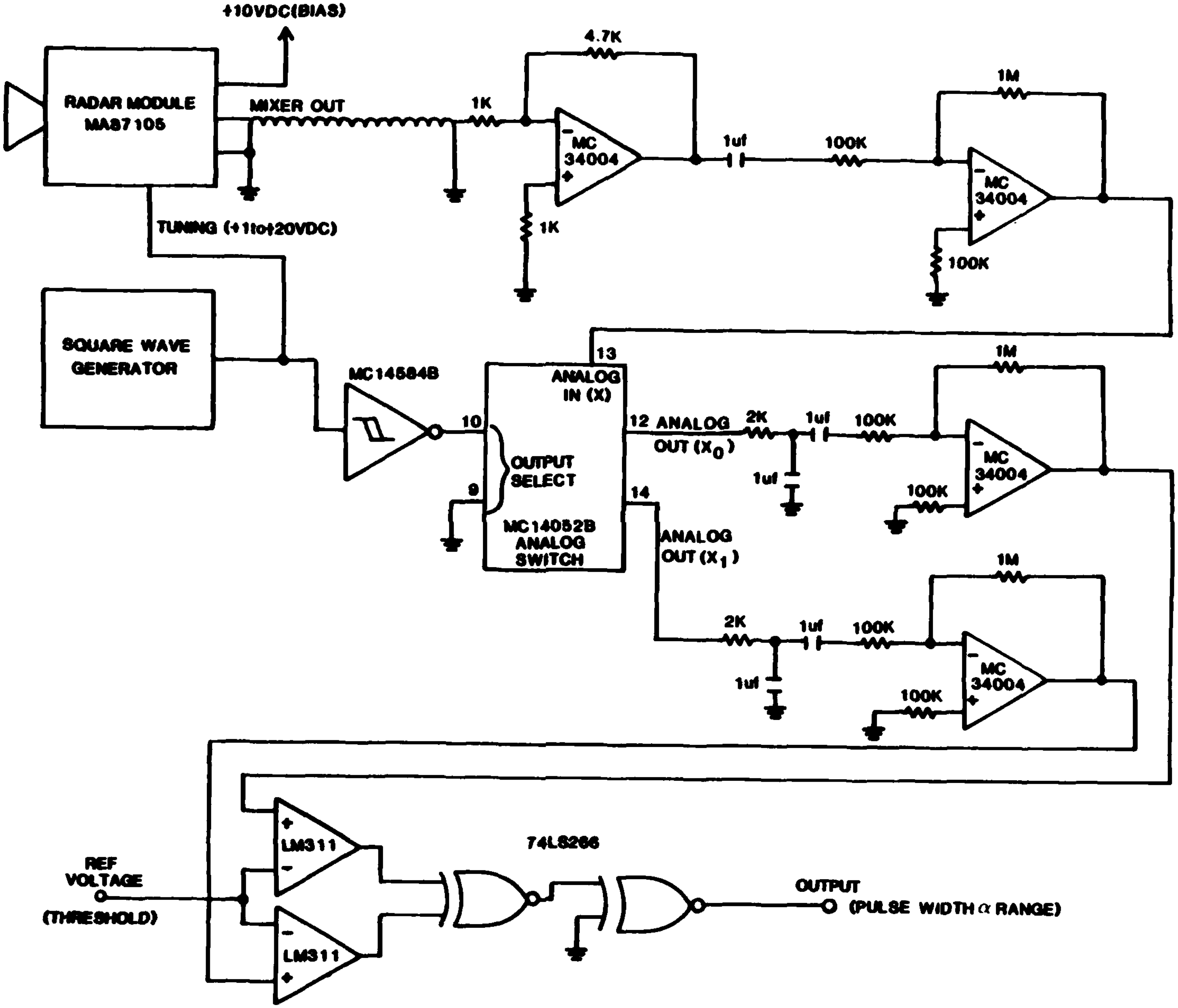


Figure 3-23. Schematic Diagram of Dual Frequency Microwave Radar Breadboard

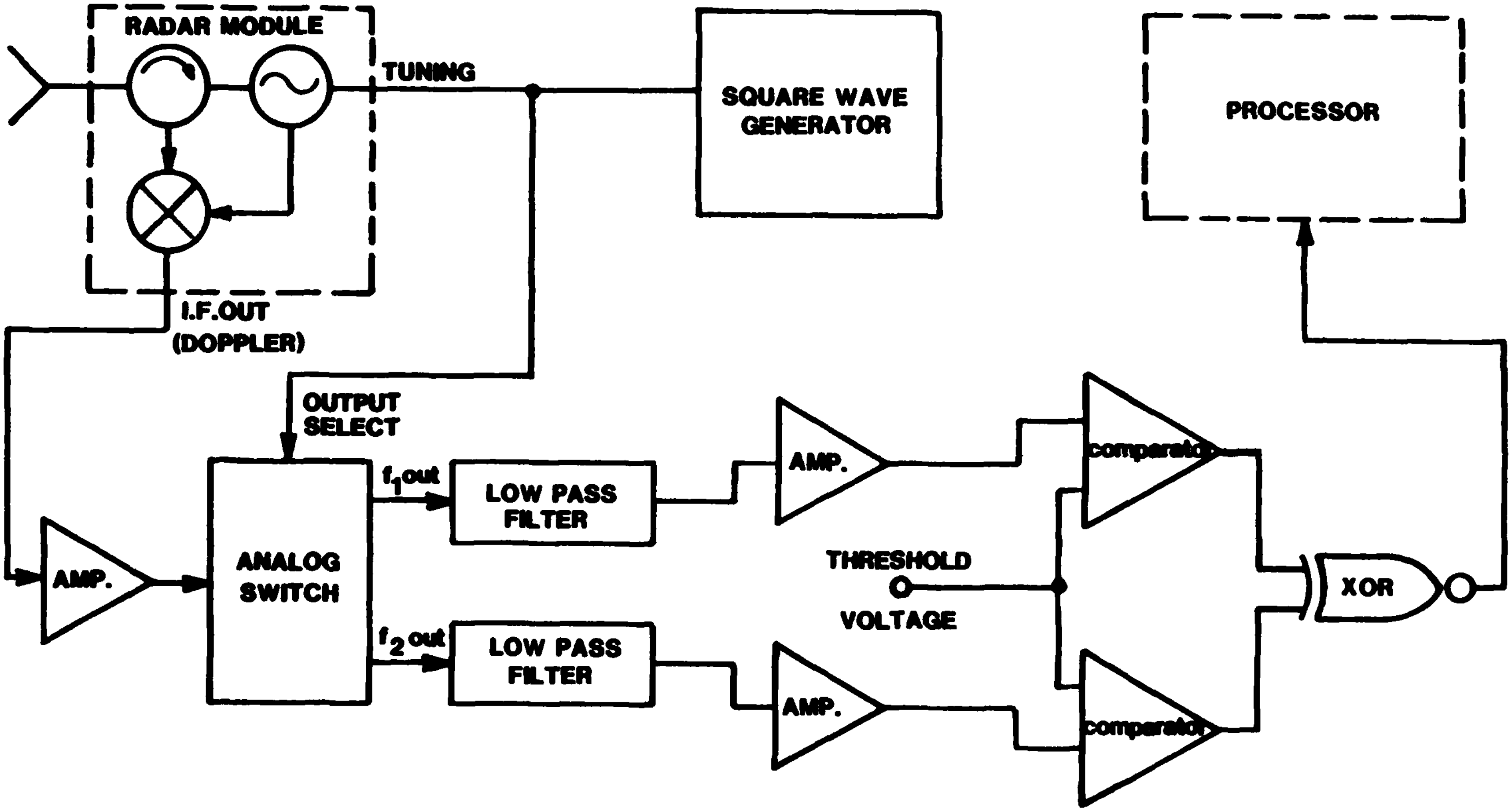


Figure 3-21. Functional Block Diagram of Dual Frequency Microwave Radar Breadboard

Figure 3-25. Dual Frequency Microwave Radar; Unfiltered Analog Switch Outputs, Switching Frequency 50 Hz.

Figure 3-26. Dual Frequency Microwave Radar; Filtered Analog Switch Outputs, Switching Frequency 50 Hz.

Amplifiers are used after the low-pass filters to boost the signals to convenient levels for threshold detection. The remainder of the circuit functions as a phase difference detector. As discussed earlier, the range of a moving target may be determined by the phase separation between Doppler returns generated at two different carrier frequencies. The dual comparator and XNOR combination produces output pulses whose widths are proportional to the target range. Figure 3-28 depicts the idealized sinusoidal waveforms from each channel as they are input to the comparators. As each waveform crosses the voltage threshold, the respective comparator output goes high. Any delay between the two channel's threshold crossings (due to phase lag) will also occur in the comparator outputs. Figure 3-29 depicts the typical outputs of the two comparators for a moving target. The slight time delay between the logic level transitions on each of the two channels is proportional to the phase difference between the original sinusoids. Application of the comparator outputs to the serial XNOR logic (to yield XOR) produces a logic high when one or the other input is high, but not both. Figure 3-30 shows the XOR output obtained by moving the transceiver towards a wall at three feet. The final output then is a sequence of pulses occuring at twice the Doppler frequency and whose widths represent the time delay (Δt) between the two channels. Knowing the Doppler frequency permits conversion of the Δt values into phase differences, from which range can be computed directly.

Several problems were noted during the evaluation of the technique. The first problem was the device's ability to "see" through walls and thin partitions. Physical barriers (non-metallic) are invisible to microwaves, therefore the

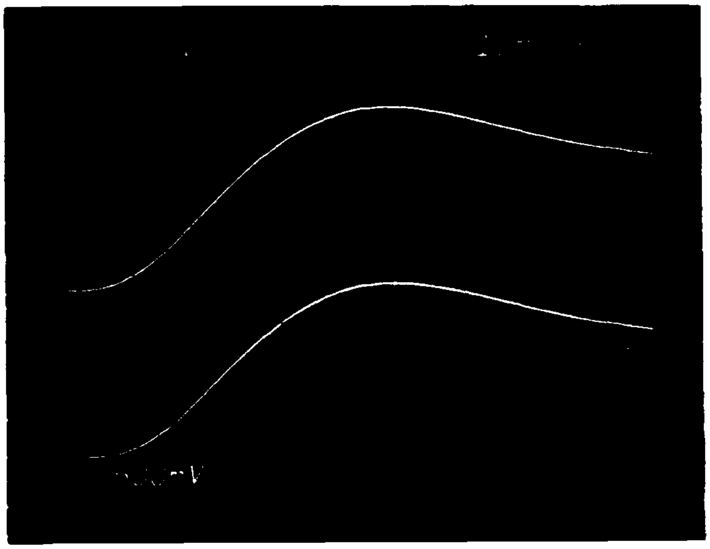
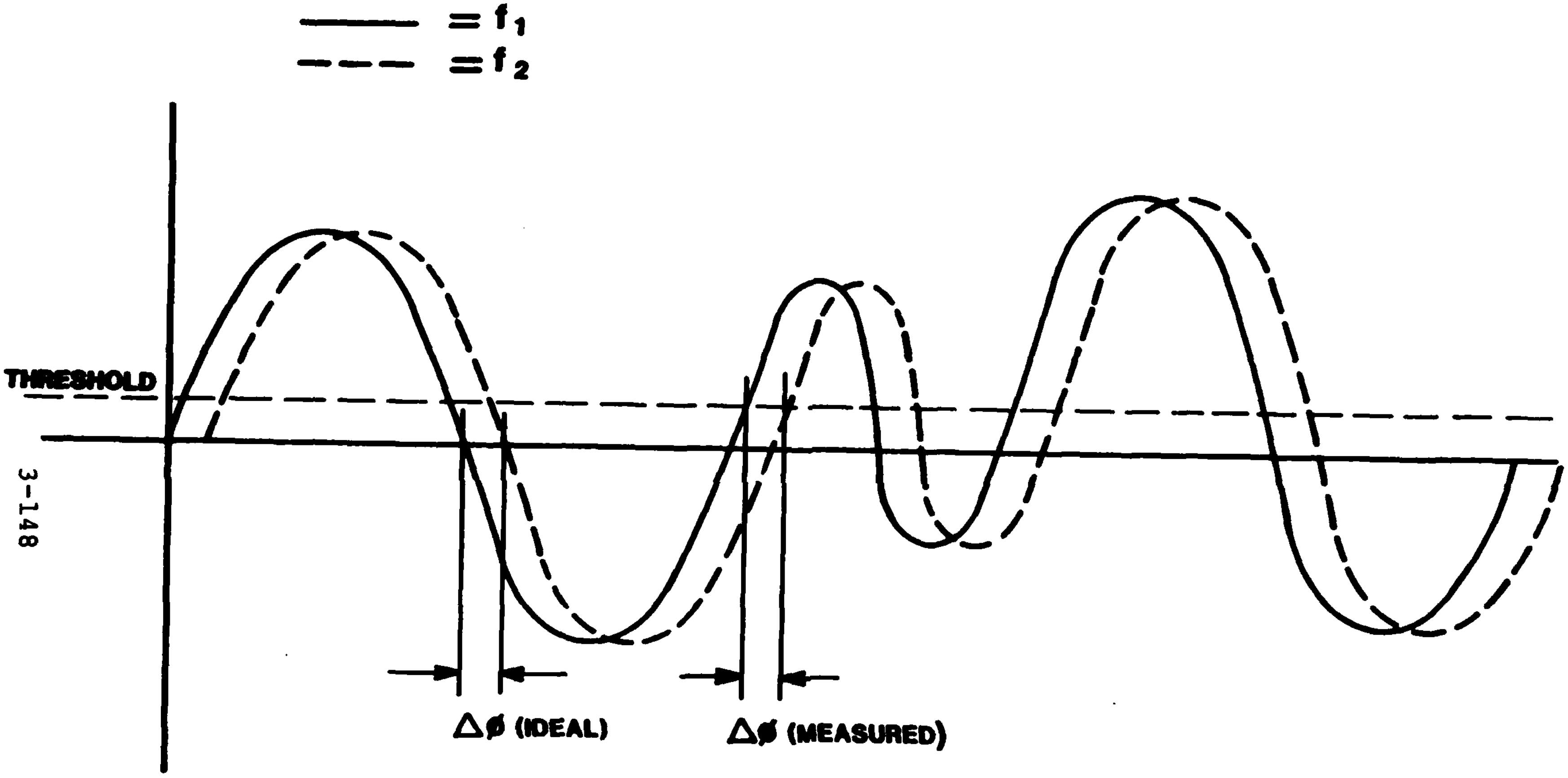


Figure 3-27. Dual Frequency Microwave Radar; Filtered Analog Switch Outputs, Switching Frequency 5 kHz.



$$R = \frac{(C)\ (\Delta\phi)}{(4\pi)\ (\Delta f)}$$

Figure 3-28. Idealized Dual Frequency Radar Doppler Waveforms. Phase Separation is Proportional to Moving Target Range

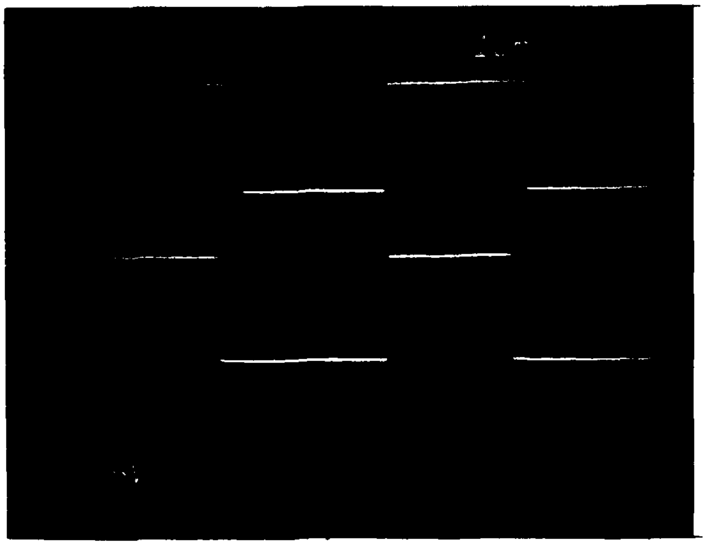


Figure 3-29. Dual Frequency Microwave Radar; Outputs From Comparators While Moving Target is Present

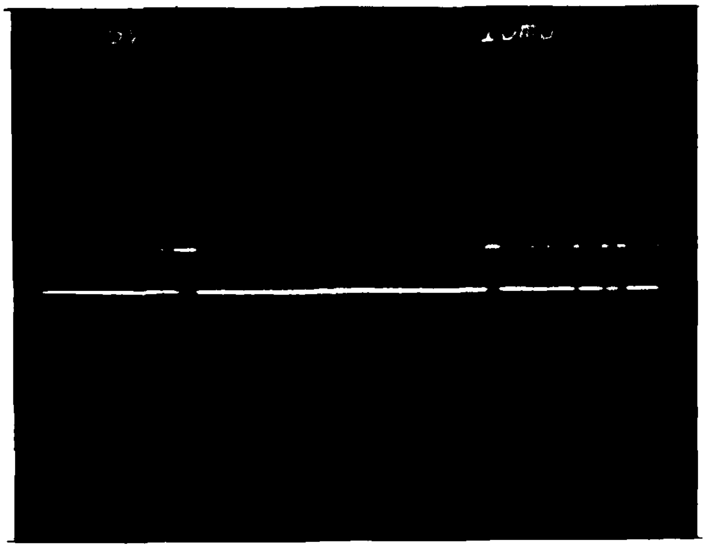


Figure 3-30. Dual Frequency Microwave Radar; Final Output From XOR Operation. (Transceiver Motioned Towards Wall at 3 Feet)

energy from the transceiver was not contained within the room. To prevent interference from outside the room, the sensitivity of the receive amplifiers had to be reduced or the threshold voltage on the comparators had to be increased. Both of these actions however create marginal detection ability at the maximum range inside the room.

The problem discussed above could be dealt with if reliable range data was provided. For instance, the sensitivity could be set high enough to provide good detectability within the protected interior. If targets outside the room could be seen at that sensitivity level, the range information could be used to ignore them. Unfortunately, consistent range output was not provided by the circuit described.

Another problem noted during the radar evaluation was an acute sensitivity to 120 Hz noise pick-up from fluorescent lights. Figure 3-31a shows the 120 Hz noise superimposed on the Doppler frequency. Fluorescent lights emit broadband interference at microwave frequencies. The 120 Hz component appears at the mixer output because the current in the tube's plasma is modulated at 120 Hz. The noise level from fluorescent lights directly in the radar beam is sufficient to mask an intruder at a range of 10 to 20 feet. Exercising caution in the placement of the transceiver and in the selection of waveguide horns helped to alleviate most of the interference. Notch filtering at 120 Hz was examined but had limited usefulness since this frequency is contained within the passband of anticipated intrusion signatures.

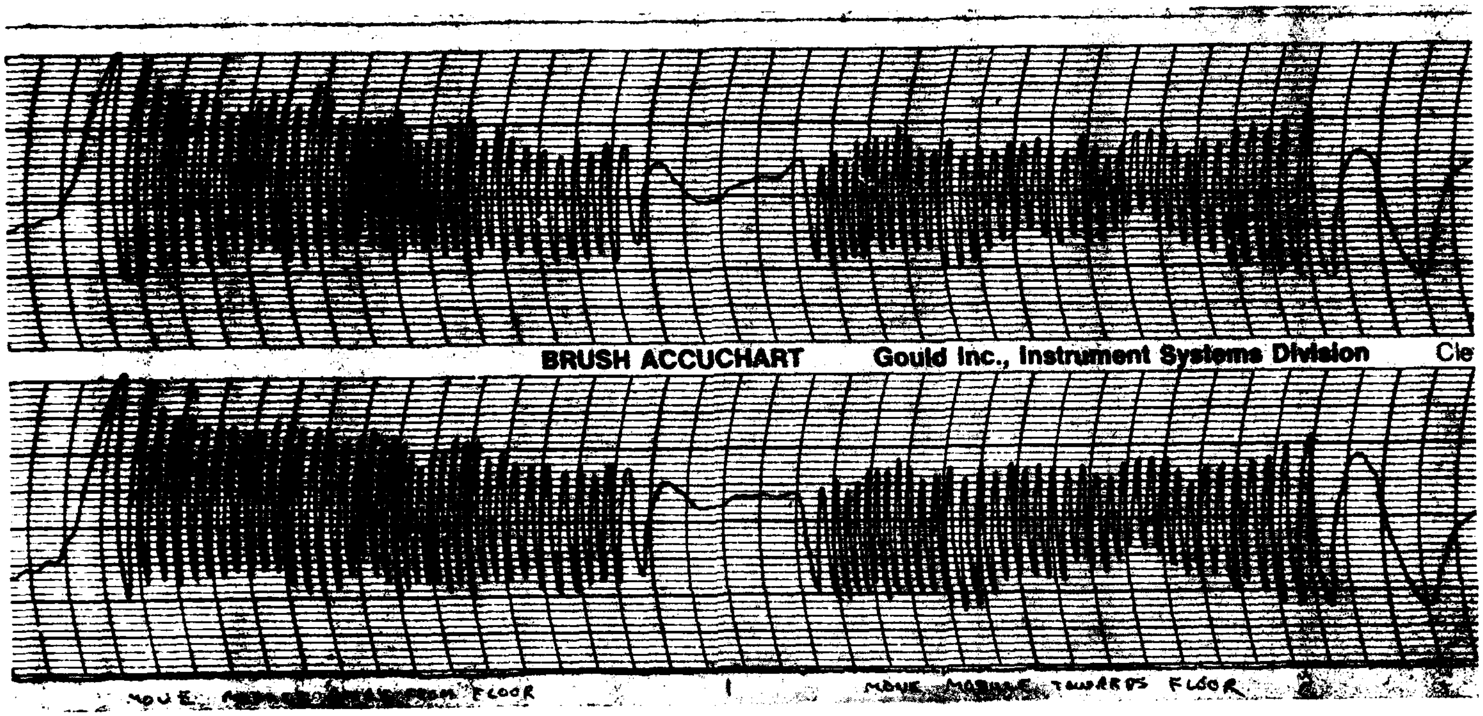
Initially, the transceiver was positioned in a hallway to monitor the signals obtained from normal traffic. When a person walked towards the transceiver, the XOR output consisted of pulses with largely random frequency and width. To

Figure 3-31a. Dual Frequency Microwave Radar; 120 Hz Noise From Fluorescent Lights Superimposed on Doppler Signals

ensure that the circuit was functioning properly, the transceiver itself was motioned towards the floor and ceiling. In these instances, uniform outputs were achieved. Suspecting multipaths in the hallway to be a source of confusion, the system was moved into a 17' x 40' room containing few obstructions. While there was a noticeable improvement in the output, conflicting range indications were still obtained from single walking targets. Observing the signals appearing at the comparator inputs revealed complex Doppler waveforms created by human motion; not the idealized sine waves shown in Figure 3-28.

Figures 3-31b and c show strip chart recordings of the outputs of the two channels of the receiver under various conditions. In Figure 3-31b, the target motion is approximately uniform. This condition was produced by manually moving the sensor head toward a fixed target. Although some amplitude modulation of the return is present, there is only one Doppler frequency present and the zero crossing technique for phase measurement could be employed.

Figure 3-31c shows the output produced by a walking human target. Note that the waveform is considerably more complex. Multiple frequencies are present. The zero crossing technique (infinite clipping of the waveforms followed by an exclusive-or comparison of the outputs) will obviously not produce a series of uniform width pulses as in the single frequency case. It is valid at this point to ask whether the zero crossing technique will produce a waveform of consistent duty cycle proportional to range as in the single frequency case even though the pulse series is not uniform.



(Chart Speed 125 mm/sec)

Figure 3-31b. Dual Channel CW Radar Response Generated by Uniform Target Motion (Simulated by Moving Transceiver Head Towards and Away From Floor at Univorm Velocity).

To answer this question consider the simplest case where two frequencies w_1 and w_2 are present with amplitudes a_1 and a_2. The waveforms are

$$a_1 \cos w_1 t + a_2 \cos w_2 t$$

and

$$a_1 \cos (w_1 t + \theta) + a_2 \cos (w_2 t + \theta)$$

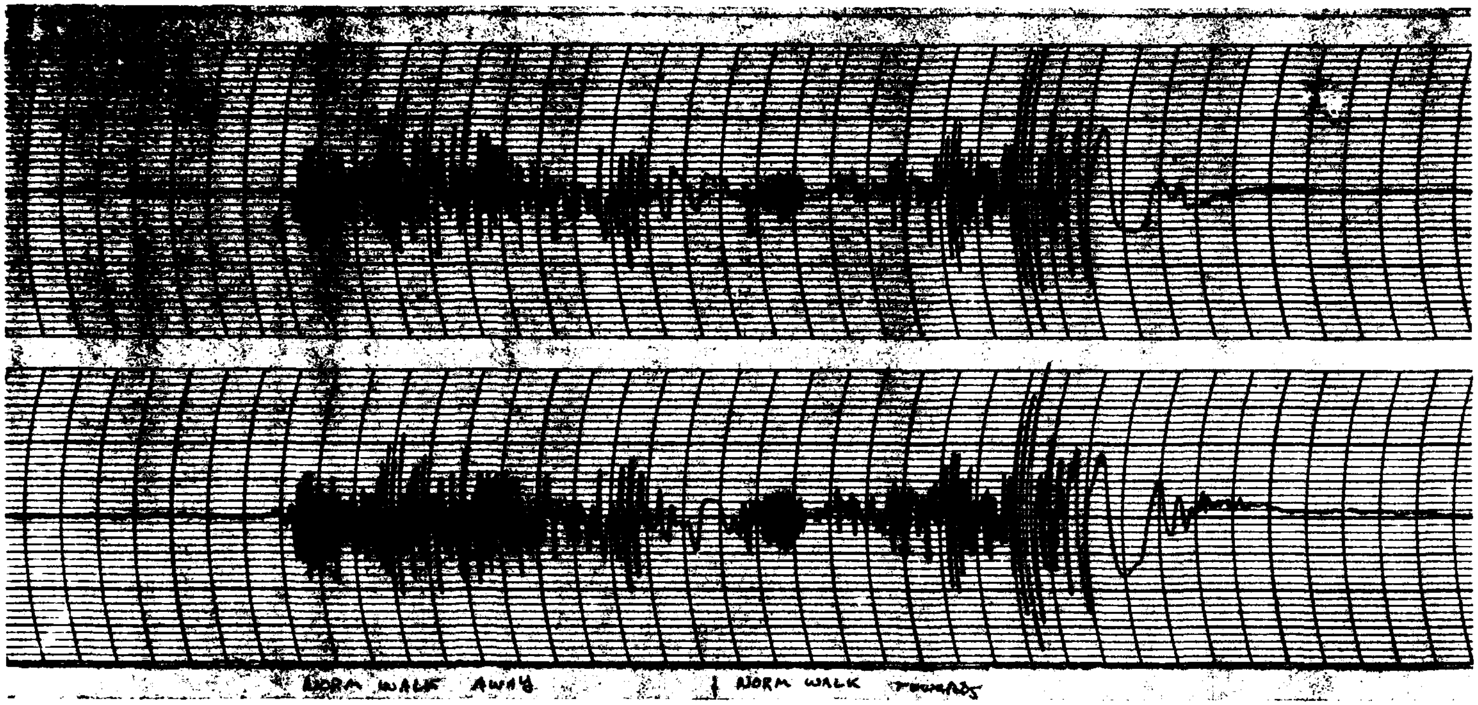
Each of these has zero average value and hence, when infinitely clipped, will produce a bi-level waveform of 50% duty cycle. If the second waveform were of the form

$$a_1 \cos (w_1 (t+t_0) + a_2 \cos (w_2 (t+t_0))$$

then it would be simply a time-shifted version of the first. The exclusive-or process would produce a waveform with duty cycle proportional to the time-shift. This is not the case with the constant phase-shift-with-frequency waveform actually obtained. The infinitely-clipped versions of the first and second waveforms have different patterns and hence do not produce a consistent duty cycle proportional to phase shift.

More sophisticated processing would be necessary to extract the range information.

One approach would be to use phase-locked loops to extract single-frequency components from the waveforms. The zero crossing phase detector process could then be applied to the output. Another approach would be to normalize the powers in



(Chart Speed 125 mm/sec)

Figure 3-31c. Dual Channel CW Radar Response Generated by Reflection From Walking Human Target. Note Presence of Complex Frequency Components.

the two waveforms by automatic gain control and then take their linear product. If the waveforms are represented by

$$f_1(t) = \sum_n A_n \cos w_n t$$

and

$$f_2(t) = \sum_n A_n \cos (w_n t + \theta)$$

then the average value of the product is

$$\overline{f_1(t) \cdot f_2(t)} = \cos \theta \, \Sigma \, A_n^2$$

The AGC process keeps A_n^2 constant. Hence the output is proportional to $\cos\theta$ as desired.

Neither of these more elaborate phase detection techniques were attempted because they were considered beyond the scope of the breadboard investigations. We believe that neither would work very well because of the complex nature of the waveforms obtained with a real target. It would be difficult to find time constants for either that would cover the range of frequencies involved. The complexity of the processing involved as well as the vulnerability to interference from fluorescent lights and the transparency of walls to the microwave signals make the dual frequency technique a poor choice in comparison with other ranging sensors.

During the course of the investigation data were furnished by MERADCOM describing a microwave sensor developed by Stewart et als at Queen's University, Belfast, Northern Ireland. Part of this data was UK Patent Application GB 2056213A which describes a dual frequency ranging sensor essentially equivalent to the device described above. The circuit diagram included in the patent application as well as the device described in an operators manual for the device (also supplied as part of the data) do not operate in this way but are motion detectors only.

3.6.3.3 Passive Infrared - Single Element and Dual Element Differential Pyroelectric Detectors

Two low cost pyroelectric detectors were used to evaluate intrusion signals in the passive infrared environment. The first type was an Amperex RPY96, single element detector using lead lanthanum zirconium titanate (PLZT) as the pyroelectric material. The detector is housed in a TO-5 case with an integral FET for impedance conversion. The RPY96 has an optically coated silicon "daylight filter" built into the housing which transmits only wavelengths from 6.5 μm to >14 μm. The filter thus prevents sensitivity to short wavelength infrared that may be present in sunlight and other general illuminants.

Hardware circuitry to produce the intrusion signal required only the addition of amplifiers and a bandpass filter to the pyroelectric detector. Figure 3-32 shows the hardware schematic and Figure 3-33 shows the corresponding block diagram of the IR amplifier/filter. Reflecting optics consisting of a 50 mm diameter, 40 mm focal length spherical mirror was used to image the intrusion scene on the detector. The optics provided sufficient concentration of the IR energy to detect a man moving in the field of view at greater than 100 feet.

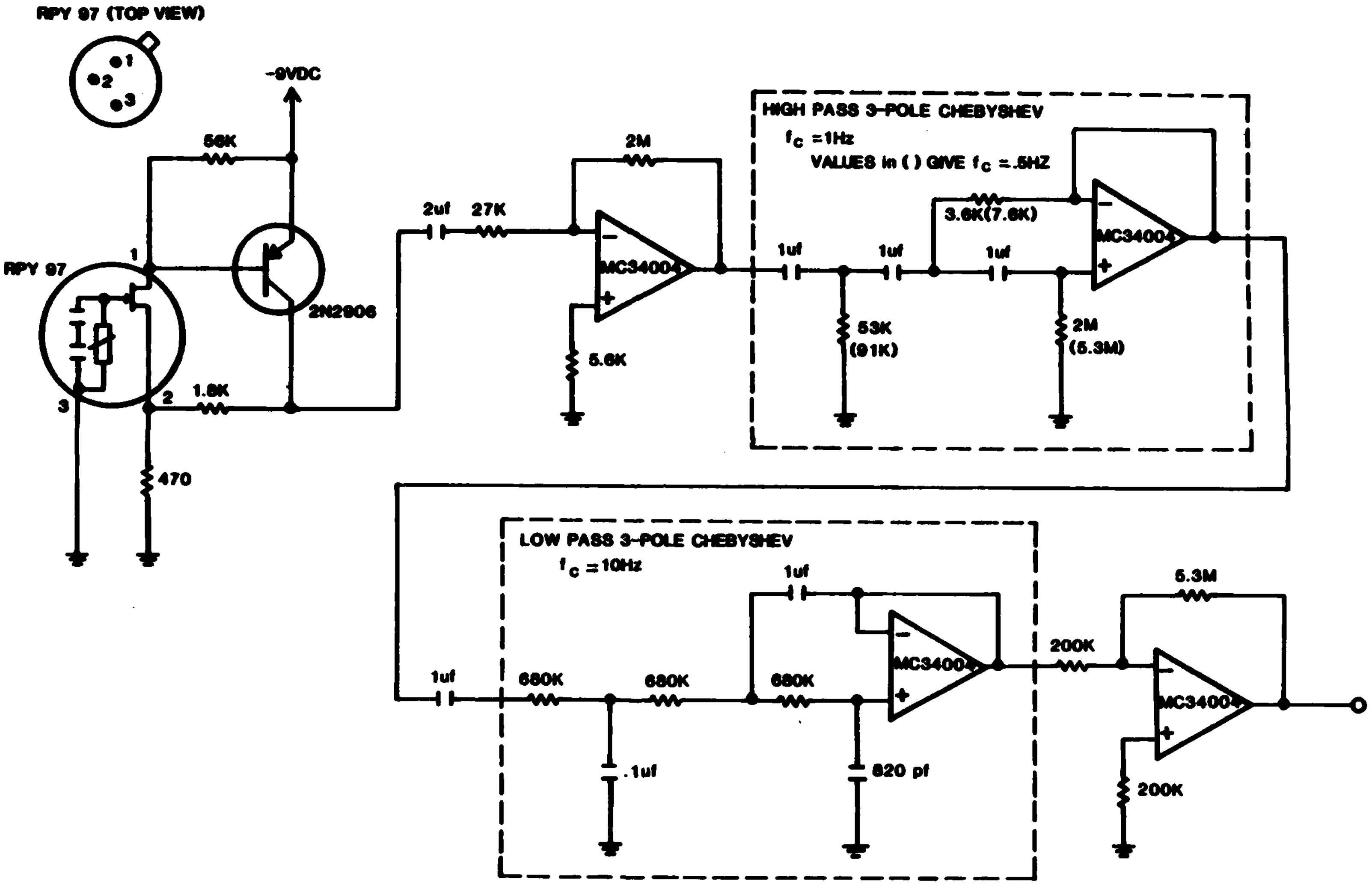


Figure 3-32. Schematic Diagram of the Passive Infrared Amplifier/Filter Breadboard

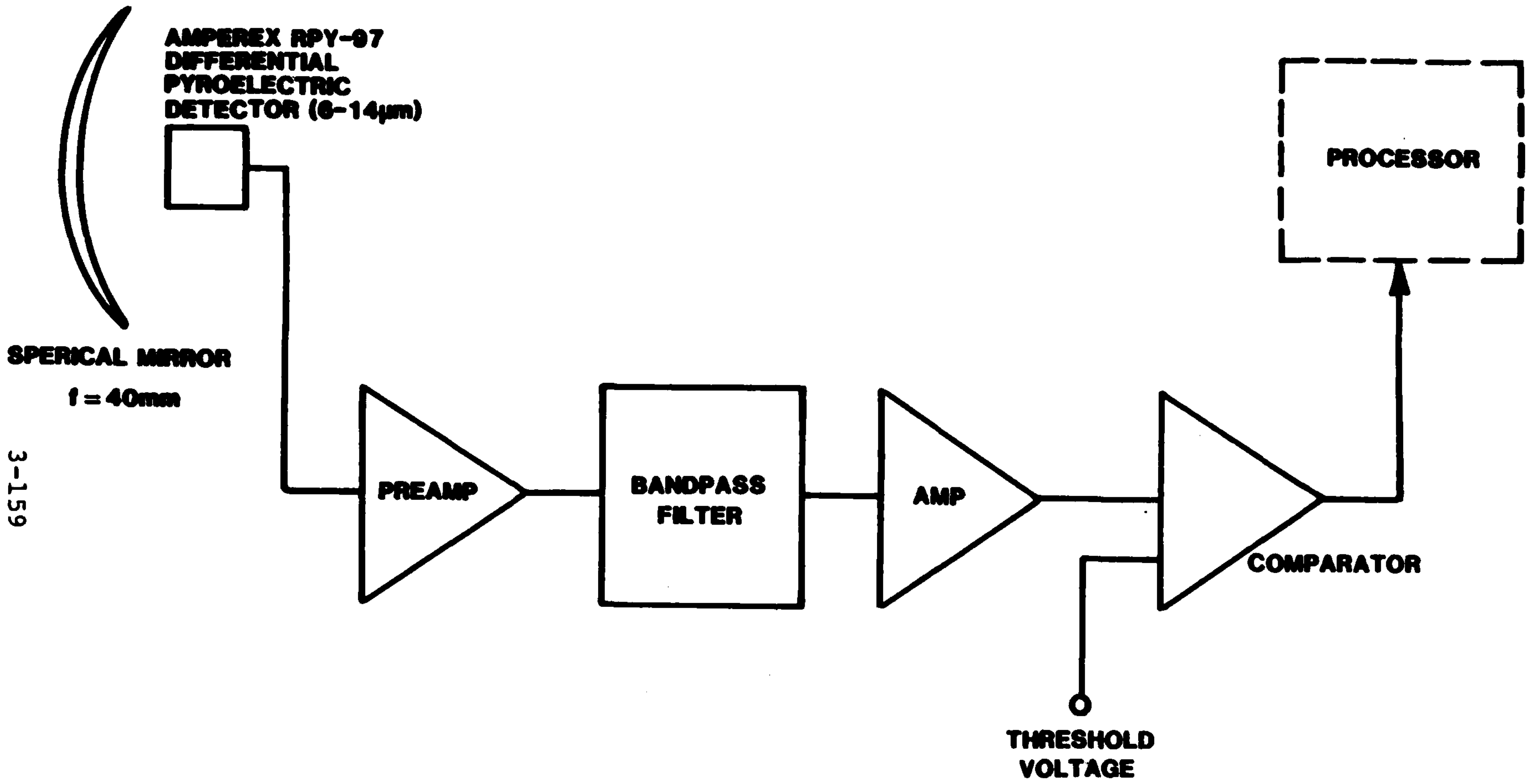


Figure 3-33. Block Diagram of Passive Infrared Amplifier/Filter Breadboard

At this point it is worth noting that the pyroelectric detector inherently produces an output only when the element temperature is actually changing. Therefore a man must illuminate the active element with varying intensity levels to produce an indication. This criteria is most conveniently met by positioning the detector's field of view such that a man must pass through it. A man stationary in the field of view will not produce an indication. Unfortunately the single element detector will produce an output for any infrared (6.5 μm - 14 μm) intensity change "seen" in its field of view. Therefore a draft of cooler or warmer air (or any cycling thermal source) in the field of view can produce an output and becomes a potential false alarm source. The bandpass filter incorporated in the circuit of Figure 3-32 tends to alleviate some of the susceptibility to thermal transients, especially the high pass section. The rationale behind the filtering is that airborne thermal transients will be diffused across the detector's field of view, and therefore the net change in infrared flux seen by the detector will be of low frequency and intensity. This is in direct contrast to a man who at one instant is outside the field of view and then steps into the field of view. Stepping into (or out of) the field of view produces a higher frequency flux change (depending on intruder velocity) that is separable from background transients through filtering.

Further immunity to ambient temperature variations can be gained by utilizing a dual element differential pyroelectric sensor. This was the second type (Amperex RPY97) of pyroelectric examined during the breadboard studies. Figure 3-34 shows both detectors. The RPY96 is on the left and the RPY97 is on the right. The RPY97 has nearly identical construction

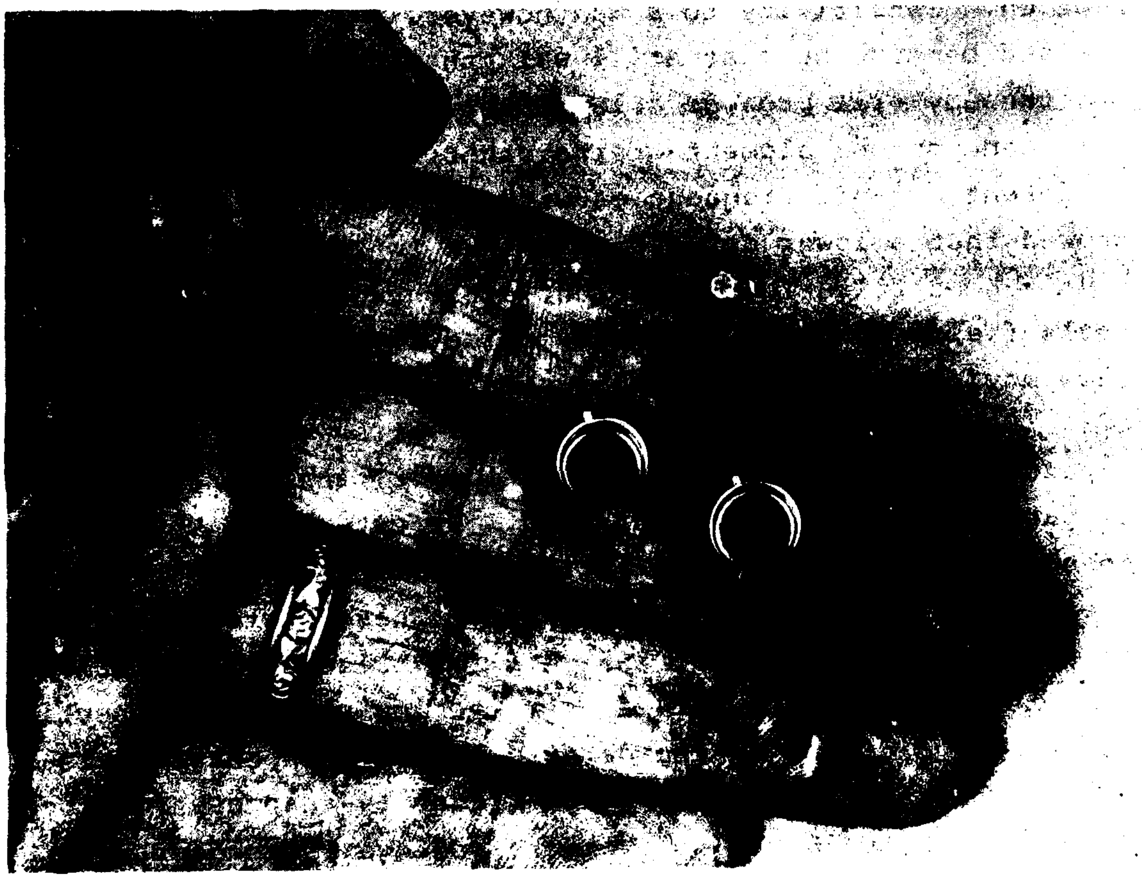


Figure 3-34. RPY96 (Left) and RPY97 (Right) Amperex Pyroelectric Detectors

and operational characteristics as the RPY96, with the exception that it contains two elements configured in a differential mode. In the differential mode, an output is produced only when the two elements "see" differing levels of changing IR intensity. In the example of the air draft, as long as both elements see the same IR intensity, no indication will be produced, thereby providing ambient thermal noise discrimination. Sensitivity to a man however, is essentially unchanged because he must still walk through the field of view and thereby will produce a large relative intensity change in the scene on one element or the other. Experimentation with different cut-off frequencies with the high pass filter showed that a lower cut-off of 0.5 Hz to 1 Hz provided relatively good filtering of ambient air currents in the detector's fields of view. Both the noise level and signal from a slow moving target are reduced about 50% using the 1 Hz cut-off. For a fast moving target (i.e., brisk walk or run as opposed to crawling or creeping) however, the signal level is comparable using either 1 Hz or 0.5 Hz cut-offs. The S/N then becomes a function of anticipated target velocities, and the particular optics system in use. These factors should be considered in a trade-off analysis for brassboard and ADM development. The upper cut-off for the low pass filter section is largely dictated by the detector's response characteristics. The manufacturer's quoted frequency response for the RPY97 is 0.1 to 20 Hz, however the voltage responses at 10 Hz and 20 Hz are -25 dB and -31 dB relative to 0.1 Hz. The corner frequency of the low pass filter was designed for 10 Hz, which permits some contribution up to 20 Hz through roll-off characteristics. Increasing the corner frequency to 20 Hz did not significantly increase the detector output but did, however allow sufficient 60 Hz line noise into the circuit to degrade its performance.

Figure 3-35 shows the signal obtained at the output of the RPY97 using the manufacturer's recommended preamp. The signal was produced by a man walking slowly across the field of view (using reflective optics) at ten feet. The noise evidenced by the wide trace is 60 Hz. The double peak nature of the output is characteristic of the differential element configuration. A temperature increase on one element produces a positive-going output while a temperature increase on the other element produces a negative-going signal. (The voltage swing reverses during a temperature decrease.) If desired, the direction which a man traverses the field of view may be determined by observing whether the output swings positive first or negative first. Figure 3-36 shows the output obtained from a man walking slowly across the differential detector's field of view at 100 feet. The signal was recorded after bandpass filtering between 1.0 to 20 Hz., and an additional stage of amplification. It is apparent from the photograph that sufficient signal-to-noise ratio exists at 100 feet to permit threshold detection of the indication. If the bandpass filter had been increased to 0.5 Hz to 20 Hz, the amplitude of the signal in Figure 3-36 would have been increased but the noise level would have exhibited a similar increase. There would not have been any real increase in signal-to-noise ratio for slow moving targets.

3.6.3.4 Passive Infrared - "Linear Array" Using Two Dual Element Detectors

Two RPY97 differential detectors were positioned in the focal plane of the spherical mirror to qualitatively simulate a small linear array. Figure 3-37 depicts the background noise level simultaneously seen by the two detectors in this con-

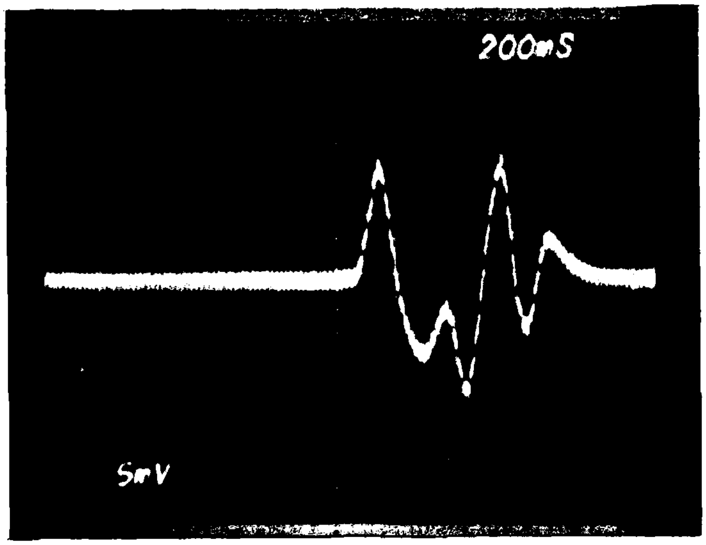


Figure 3-35. Infrared Detector Preamp Output (Unfiltered); Response Obtained From Man Walking Slowly at 10 Feet

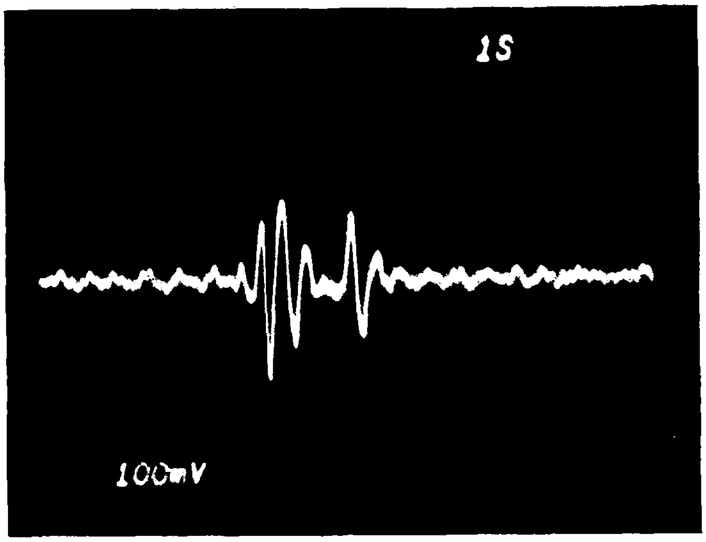


Figure 3-36. Infrared Detector Bandpass Filter Output (1.0 - 20 Hz Bandpass); Response Obtained From Man Walking Slowly at 100 Feet

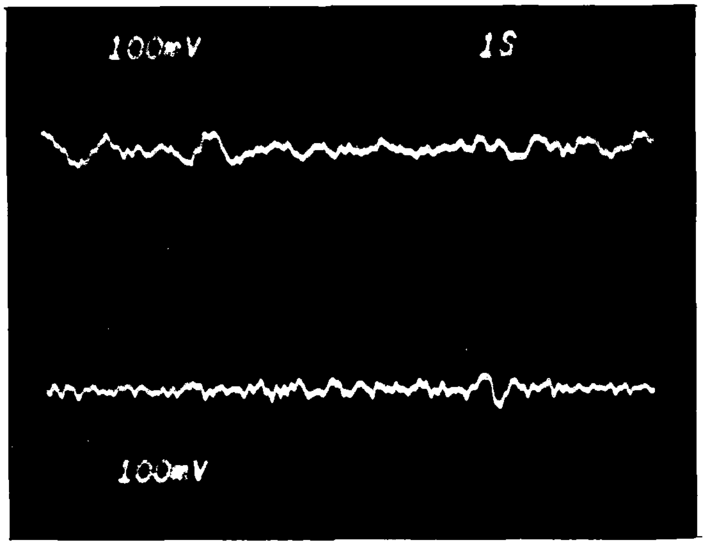


Figure 3-37. Infrared Detector Bandpass Filter Outputs; Dual Detector Configuration.
Upper Trace, Noise Level for 0.5 - 20 Hz Bandpass
Lower Trace, Noise Level for 1.0 - 20 Hz Bandpass

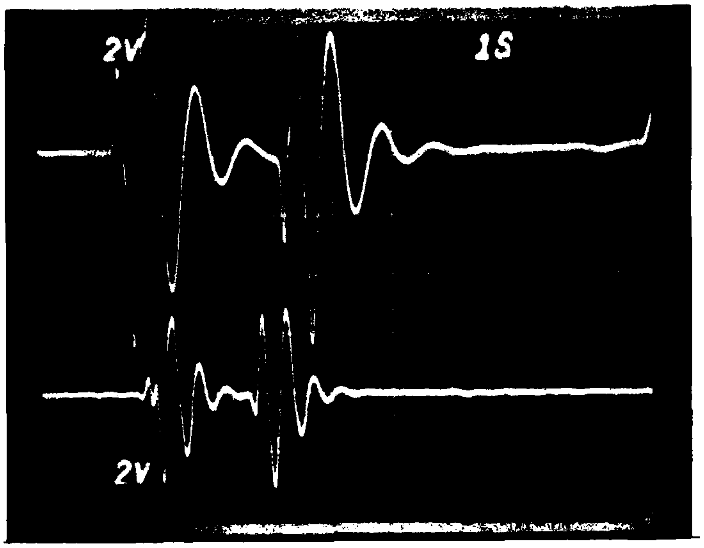


Figure 3-38. Infrared Detector Bandpass Filter Outputs, Dual Detector Configuration; Response Obtained From
Man Walking Slowly at 10 Feet
Upper Trace, 0.5 - 20 Hz Bandpass
Lower Trace, 1.0 - 20 Hz Bandpass

figuration. Note that the top trace (right detector) was amplified and bandpass filtered in the 0.5 - 20 Hz band. The lower trace (left detector) was bandpass filtered in the 1.0 - 20 Hz band to contrast the output from the two filter settings simultaneously. As stated previously, the noise level for the 1.0 - 20 Hz bandpass is roughly half that of the 0.5 - 20 Hz bandpass. Figure 3-38 shows the filtered output as a man walked slowly across the fields of view (and back again) at 10 feet. Again, the different filter bandpasses were used to contrast the output levels from the same target. In this instance, the output from the 0.5 - 20 Hz channel (top trace) is more than double the amplitude of the other channel. The signal-to-noise ratio at a target range of less than 30 feet is sufficient to permit effective use of either filter. Note that the direction of target movement may be obtained by observing the polarity swings on an individual channel and by observing the sequence of detection between channels.

3.6.3.5 Passive Infared - Two Dimensional Imaging Array

A pyroelectric two-dimensional imaging array was briefly examined for its potential in intrusion detection. To date, the array is under classified development for Night Vision Laboratories and therefore is not commercially available as yet. SCOPE was given the opportunity to witness several demonstrations of the device which is itself in a hardened breadboard state of development. SCOPE was also granted an opportunity to experiment with the device under the manufacturer's direct supervision.

The device is analogous to a solid state television monitor, operating in the infrared portion of the electromagnetic spectrum. The elements of the array are described by the manufacturer as ferroelectric, producing an output only when the elements are heating or cooling. While the material used is properly called a ferroelectric, it is used in its paraelectric state since the array is heated to above its Curie point. Electronically, the ferroelectric elements behave as temperature sensitive capacitors. In order to image a nonmoving scene, it is therefore necessary to chop the image on the detector at a regular interval. Chopping is achieved by opening and closing a shutter mechanism in front of the detector. When the shutter is open, the array heats up in proportion to the infrared energy imaged upon it. When the shutter closes, the array cools in opposite proportion. If the shutter is held open, the device operates in a staring mode. In the staring mode an image is produced only when an infrared source moves across the field of view. The resulting motion of the image across the array provides the necessary intensity modulation to cause an output from the ferroelectric elements. The output obtained in this manner defines the edges of a moving object (where intensity contrast is greatest) but no details about the rest of the object.

During the experiments with the device at SCOPE, both the chopped and staring modes were examined. The device was first operated in the staring mode because the motion sensitive aspect is most applicable to intrusion detection. While edge detection was provided for a very fast moving target (man sprinting), images were not obtained for a person walking at normal to brisk speeds. At the slower target velocities not enough difference occurs in the field of view from frame to frame to produce a significant output. This is a direct consequence of the sample rate used internal to the device, which results in an effective frame rate of about 30 Hz. It was concluded that an effective frame rate of less than 10 Hz will be needed to utilize the staring mode for this application. The effectiveness of the staring mode was further inhibited by the fact that the video output from alternate frames is inverted. This procedure is used to permit video output during the shutter closed period in the chopped mode. While the inverting process enhances the chopped display it has the effect of canceling any output in the staring mode. The manufacturer's representatives had not considered this fact at the time the equipment was evaluated at SCOPE.

Because neither the frame rate nor the video inverting schemes were field alterable, the remainder of the experiments utilized the equipment in the chopped mode. The ultrasonic processing algorithm (to be discussed in Section 3.6.3.8) was modified slightly to provide frame to frame differencing of the infrared sensor's video output. The greatest sensitivity to target motion was obtained by rotating the device 90°. An audible alarm was produced from the detection of a moving target. Using an optical system with an approximate 90° field of view, an alarm was easily generated at a target range of 15 to 25 feet, with the target walking at normal speeds.

An analog tape recording was made of the video output while the device was operated in the chopped mode. Target signals were provided by a man walking back and forth across a hallway while simultaneously increasing his range from several feet to about 80 feet. Subsequent examination of these tapes displayed a minimum S/N of 3 to 1 for any given pixel, corresponding to the maximum range. S/N ratios better than 10 to 1 were observed at closer ranges. The actual S/N figures are probably better than these, as some fidelity is always lost through record/reproduce operations. The observed S/N however, was sufficient for this application.

3.6.3.6 Ultrasonic Simple Pulse Ranging System With MTI Processing

3.6.3.6.1 Hardware - A pulsed ultrasonic system was breadboarded that permits time-of-flight measurement to determine target range. The hardware circuit and its functional block diagram are shown in Figures 3-39 and 3-40 respectively. Separate transmitter and receiver elements are used for two reasons. Principally, piezoelectric transducers can be manufactured such that they are most sensitive as either transmitters or receivers at a given frequency. While a single element can function as both, the electromechanical conversion efficiency of the device is compromised. Signal-to-noise ratio and sensitivity are therefore improved if the transmitting and receiving elements are distinct. Secondly, separate transmit and receive elements simplify the detector circuitry since no provision is needed to prevent the high voltage transmit pulse from penetrating the receive amplifiers.

In the experiments using the simple pulse ranging breadboard, the transmit pulses were provided by gated tone bursts from a Wavetek signal generator. Pulse width and pulse repetition interval were determined by a sync signal from the processor. In the receiver circuitry shown in Figure 3-39, a variable gain amplifier (MC1590) is utilized to correct the amplitude of the pulse returns with distance. Gain correction is required to compensate for signal attenuation and beam divergence with increasing range. Gain is continuously variable over a 60 dB interval by providing 0 to 12 V on pin 2. (0 V corresponds to maximum gain, 12 V corresponds to minimum gain.) The voltage on pin 2 is provided by an off-set and level set circuit whose input gain curve is provided by the

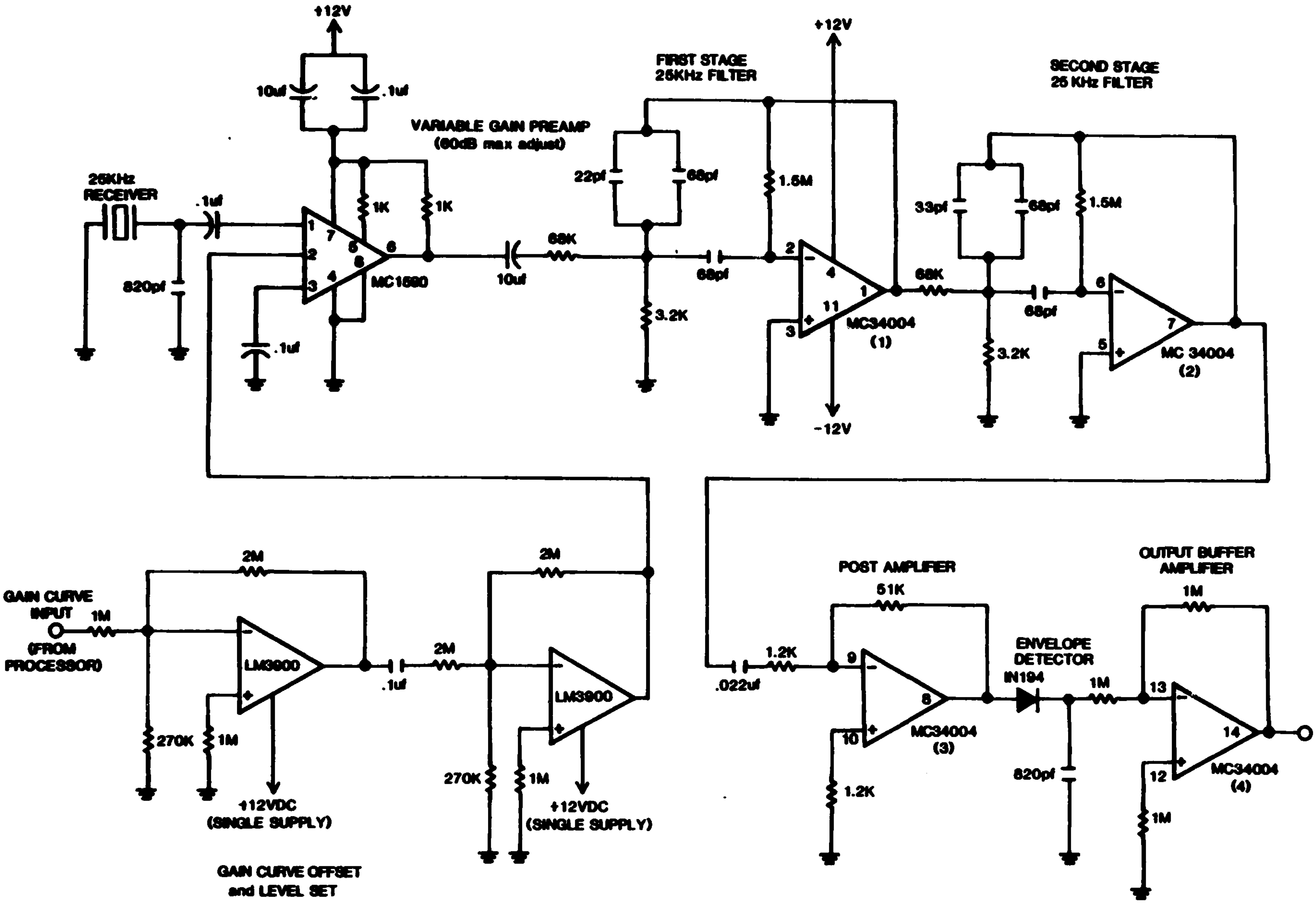


Figure 3-39. Schematic Diagram of Ultrasonic Simple Pulse Receiver Breadboard

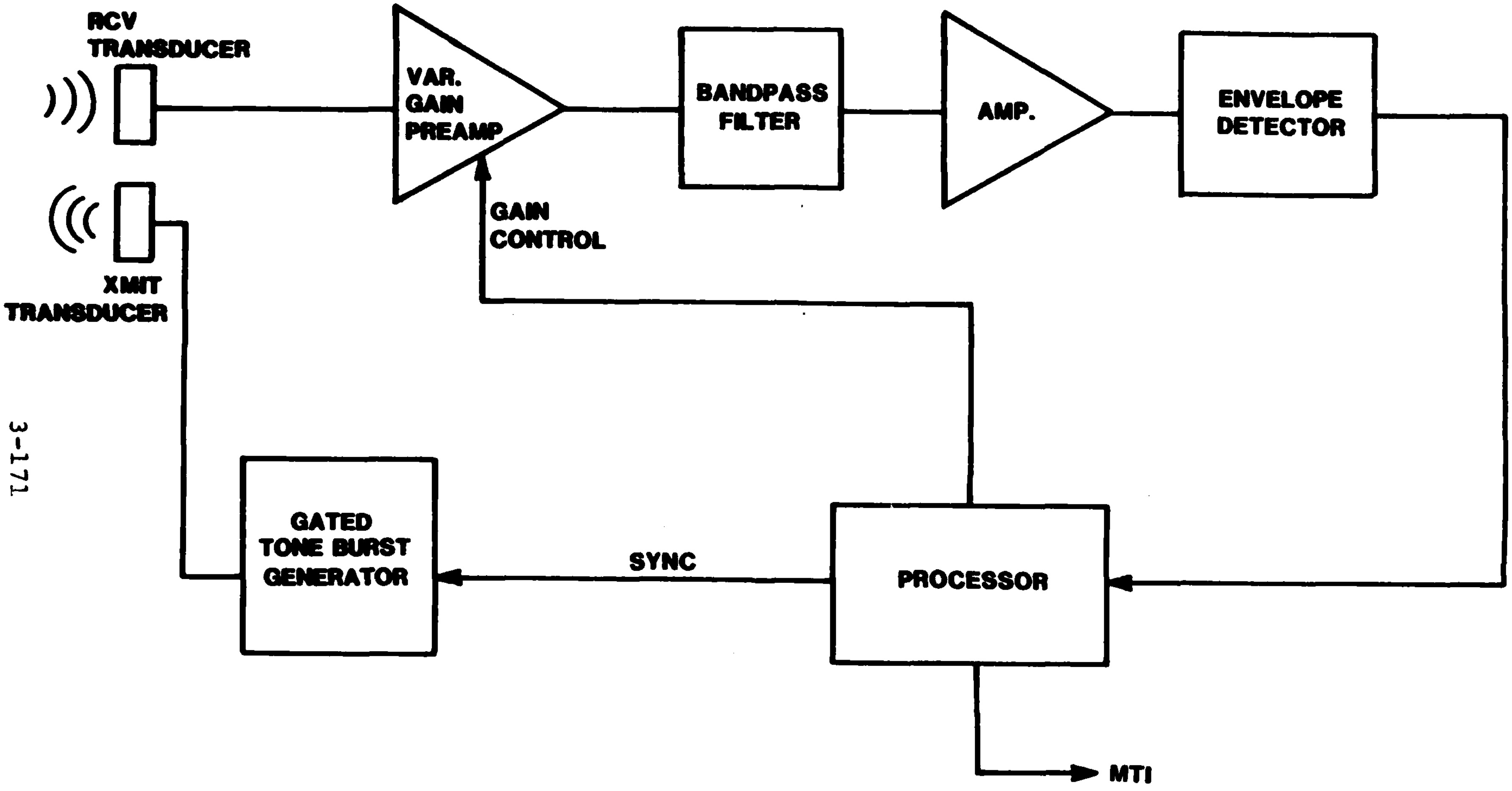


Figure 3-40. Functional Block Diagram of Ultrasonic Simple Pulse Receiver Breadboard

processor. Figure 3-41 depicts the gain curve typically used in the experiments, as it appears on pin 2. The gain correction curve stored in the processor memory was determined empirically by observing the signal loss from a human target at various ranges.

The output of the variable gain preamp undergoes two stages of active bandpass filtering. The 3 dB cut-off points of each filter are set at +/-2 kHz from the carrier frequency. A post amplifier is then used to increase the signal level after filtering. An envelope detector and output buffer is used to transform the high frequency pulse returns to a lower frequency better suited for digitization.

For these tests, MTI processing required digitizing and storing the returns from each pulse interval. Analog-to-digital conversion of the returns at the carrier frequency requires a sampling rate at twice (or more) the carrier frequency to adequately represent the waveform and to prevent aliasing. In a range of 30 feet, over 2,650 samples per pulse period would be required at a carrier frequency of 25 kHz. These large quantities of data would rapidly consume processor memory and time, especially if subtraction and other arithmetic operations are performed sample-to-sample between consecutive pulse returns. In contrast, the envelope representation rarely contains frequency components exceeding several hundred cycles per second. As will be shown in the following photographs, the envelope presentation contains the information necessary for target detection.

Figure 3-42 shows the output typically obtained by positioning the sensor in a hallway. The lower trace is the pulse return interval at a 25 kHz carrier frequency. The upper

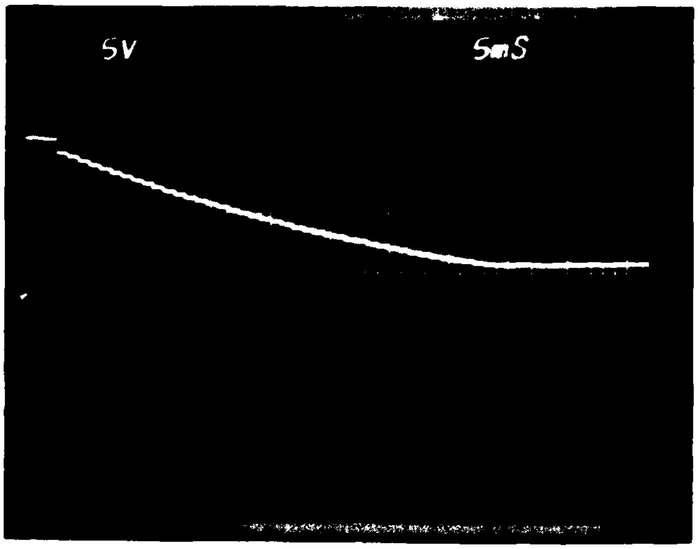


Figure 3-41. Ultrasonic Gain Correction Curve
(0V = Max. Gain, 12 V = Min. Gain)

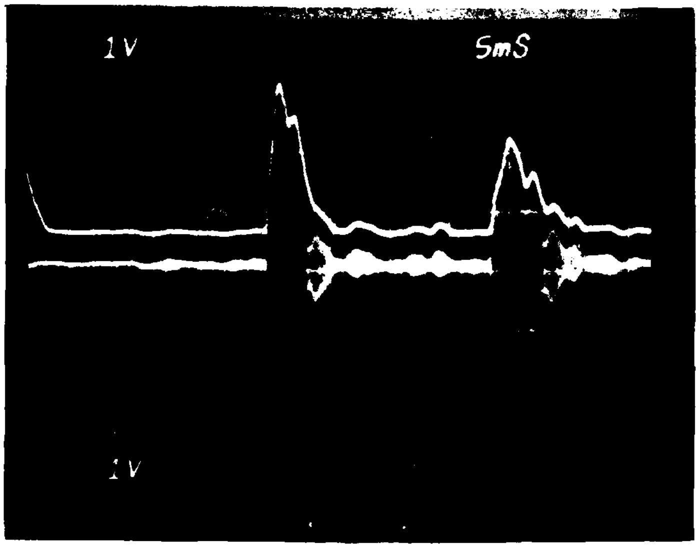


Figure 3-42. Ultrasonic Simple Pulse Return From
Hallway Scene. Upper Trace is the Envelope Representation.
Lower Trace is the Return at the Carrier Frequency (25 kHz).

trace is the envelope detector output for the same return. Each pulse within the wave train is the result of objects in the sound field reflecting energy back to the receiver. In the hallway, the large reflections were obtained from door jambs and doorways.

Figure 3-43 depicts the same outputs when a man is standing in the hallway at a range of about five feet from the sensor. His reflection appears to the left of the largest return shown in the photograph. Figure 3-44 demonstrates the effect of gain correction. In this figure, the man is still standing at about five feet, however the gain of the preamplifier was fixed at its maximum for the entire pulse interval. The reflection from the man has a much higher amplitude in this instance because he is relativly close to the sensor. If he were to increase his distance from the sensor, his return would rapidly approach the amplitude seen in Figure 3-43, however it would occur later in the pulse period. Note that the amplitude of the other reflectors shown in Figures 3-43 and 3-44 did not change significantly by removing the gain correction. This effect occurs because the corrected gain is already approaching its maximum at these ranges. (Refer to Figure 3-41, which shows the gain correction curve in an equivalent time scale).

Various combinations of transducer pairs were examined to determine the optimum set to use for the evaluations. Table VIII lists all the ultrasonic transducers purchased, their manufacturers, model numbers, and operating frequencies. Figure 3-45 is a photograph showing a sample of the various transducer configurations. Although precise calibration and

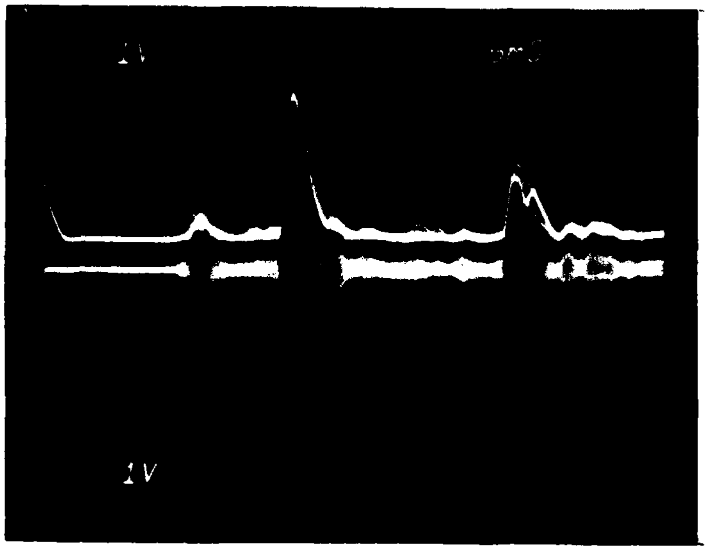


Figure 3-43. Ultrasonic Simple Pulse Carrier and Envelope; Man Standing at Approximately 5 Feet in Hallway

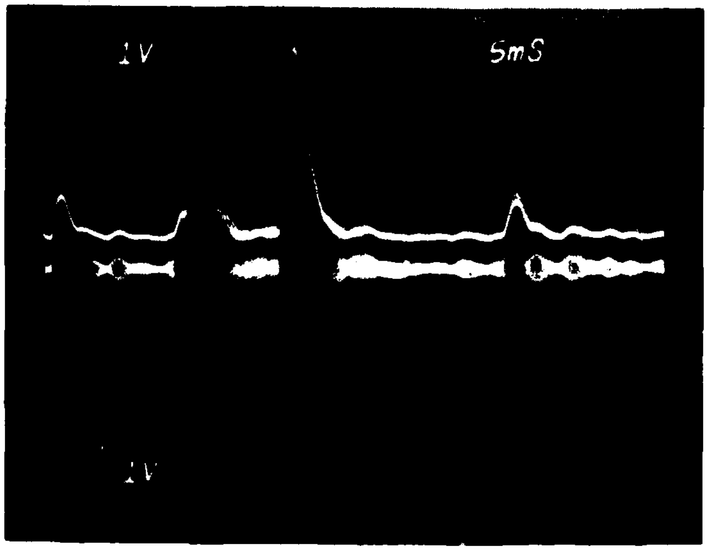


Figure 3-44. Ultrasonic Simple Pulse Carrier and Envelope; Man Standing at Approximately 5 Feet in Hallway No Gain Correction

TABLE VIII. LIST OF ULTRASONIC TRANSDUCERS EVALUATED

TRANSDUCER NUMBER	MANUFACTURER	TRANSDUCER DESCRIPTION
1	Massa Prod. Corp.	Security Transducer, MS-4, Receiver, 19.5 kHz.
2	Massa Prod. Corp.	Security Transducer, MS-3, Transmitter, 19.5 kHz.
3	Massa Prod. Corp.	TR89B, Type 31, 31 kHz.
4	Massa Prod. Corp.	TR89B, Type 23, 23 kHz.
5	Massa Prod. Corp.	TR89B, Type 40, 40 kHz.
6	MuRata Erie	Ceramic Microphone, MA4064, 30-50 kHz.
7	MuRata Erie	Ceramic Microphone, MA40L1R, 40 kHz Receiver
8	MuRata Erie	Ceramic Microphone, MA40L1S, 40 kHz Transmitter
9	Blatek Industries Inc	8020-25, Low-Med. Power, 26 kHz.
10	Blatek Industries Inc	8020-40, Low-Med. Power, 39 kHz.
11	Blatek Industries Inc	8010-25, Low Power, 25.6 kHz
12	Blatek Industries Inc	8010-40, Low Power, 39.6 kHz
13	Shigato Far East Ltd	SCM-405A, Receiver, 40 kHz
14	Shigato Far East Ltd	SCS-405, Transmitter, 40 kHz
15	TDK Corp of America	SE04B25R, Receiver, 25 kHz
16	TDK Corp of America	SE04B25T, Transmitter, 25 kHz
17	TDK Corp of America	SE08F40R, Receiver, 40 kHz
18	TDK Corp of America	SE08F40T, Transmitter, 40 kHz
19	NTK Tech. Ceramics	EDS A328, Transmitter, 32.8 kHz
20	NTK Tech. Ceramics	EDS B328, Receiver, 32.8 kHz
21	NTK Tech. Ceramics	EDS C328, Transmitter and Receiver, 32.8 kHz
22	NTK Tech. Ceramics	USP-A400T, Transmitter, 40 kHz
23	NTK Tech. Ceramics	USP-A400R, Receiver, 40 kHz
24	NTK Tech. Ceramics	USP-B400T, Transmitter, 40 kHz
25	NTK Tech. Ceramics	USP-B400R, Receiver, 40 kHz

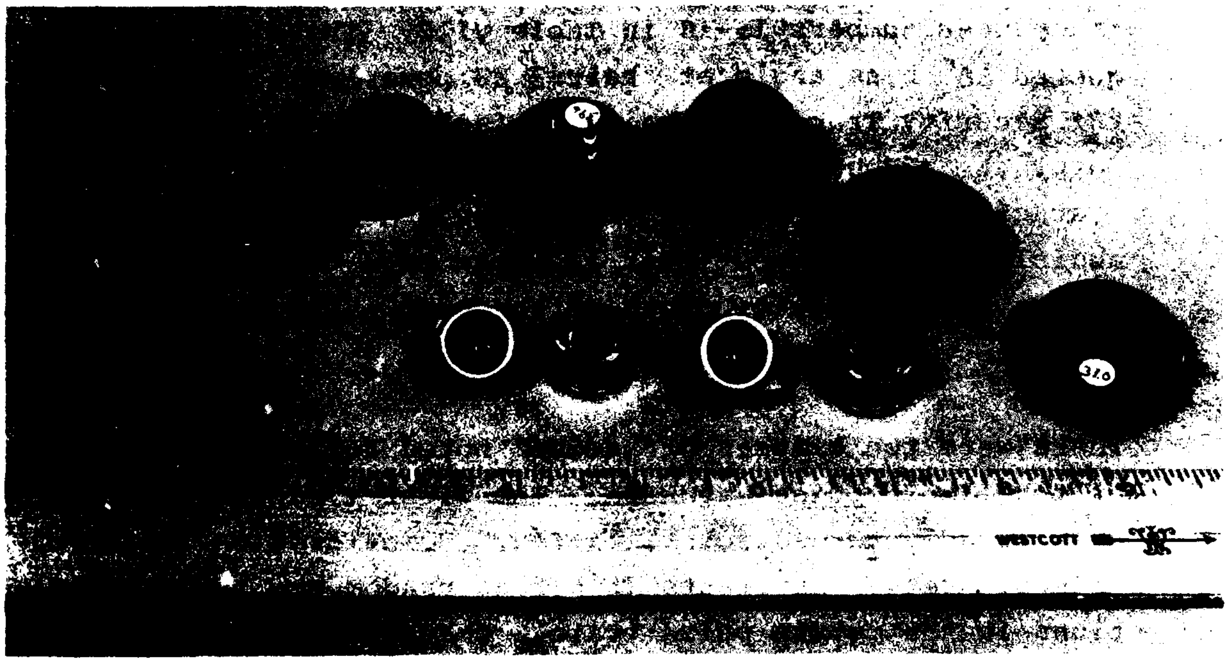


Figure 3-45. Representative Sample of Various Ultrasonic Transducers Obtained

characterization of each set's sound field and responsivity was not performed, each set was qualitatively evaluated on the basis of returned signal amplitude and pulse shape. Each transmitter was pulsed at its resonant frequency for a one millisecond duration, and the output of the corresponding receiver was observed on an oscilloscope. The reference reflector in these tests was a partition wall at ten feet. It was found that the best overall sensitivity and S/N was provided by the TDK transducer pairs, operating at resonant frequencies of 25 kHz and 40 kHz. These devices correspond to transducer numbers 15-18 in Table VIII. These pairs have a quoted 50° beam angle at their 3 dB power points. The 19.5 kHz Security Transducer pair manufactured by Massa Products Corp. (transducer numbers 1 and 2) also provided good signal characteristics, but they were large and bulky, produced an audible tone, and cost over 12 times more than the TDK transducers. The majority of the breadboard experiments therefore used the TDK pairs.

There were two classes of "noise" noted during the evaluation of the simple pulse hardware. The first type of noise has been broadly termed scintillation. Scintillation in the ultrasonic return manifests itself as random amplitude variations in the return pulse train. These variations do not occur uniformly over the entire return interval, nor do they have any distinct period of oscillation. Experimental observation of the effect under differing environmental conditions demonstrated that the major causes are air turbulence and temperature gradients within the sound field. When the transmitter/receiver pair is pointed in the direction of an air conditioning duct, amplitude variations up to 100% are typical. By contrast, the signal in still air does not change perceptively.

Pointing the sound field directly at an air conditioning duct represents a worst case situation because both turbulence and temperature gradients occur simultaneously. Turbulence or temperature variations by themselves produce less severe scintillation, but still significant. Figure 3-46 shows the return pulse interval for the hallway scene again, however a fan had been placed behind the sensor such that it induced turbulence in the sound field. The shutter on the camera was held open for two seconds so that multiple pulse intervals would be recorded on the same photograph. The smeared appearance of the large reflections in Figure 3-46 is the result of the amplitude variations occuring from pulse-to-pulse (trace-to-trace) in the two second interval.

The other principle source of interference noted during these tests was due to noise sources that produced frequencies in the ultrasonic range. One concern was the effect of telephone ringing since the intended application is interior intrusion detection. Telephones do not, however interfere significantly when they are not directly in front of the sensor. Figure 3-47 shows the hallway scene with a ringing telephone positioned on the beam's axis at a range of five feet. Even under these conditions, the interference is not severe. Note that the interference becomes more apparent during the latter part of the pulse interval. This effect arises because the receiver gain is greater there than at the start of the interval. Likewise the signal-to-noise ratio is degraded towards the latter part of the pulse interval.

Another ultrasonic noise source evaluated in these tests was the jingling of keys. Figure 3-48 shows the interference produced when keys were jingled in a room adjacent to the

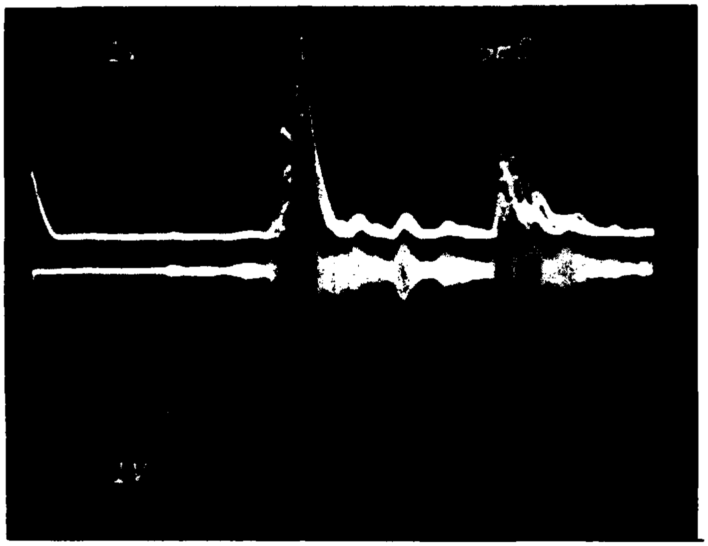


Figure 3-46. Ultrasonic Simple Pulse Carrier and Envelope; Fan Induced Scintillation in Hallway

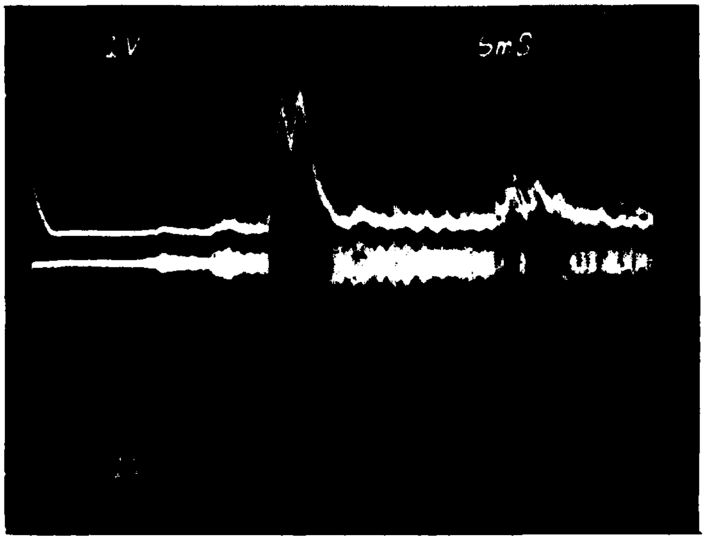


Figure 3-47. Ultrasonic Simple Pulse Carrier and Envelope; Telephone Ringing in Hallway at 5 Feet

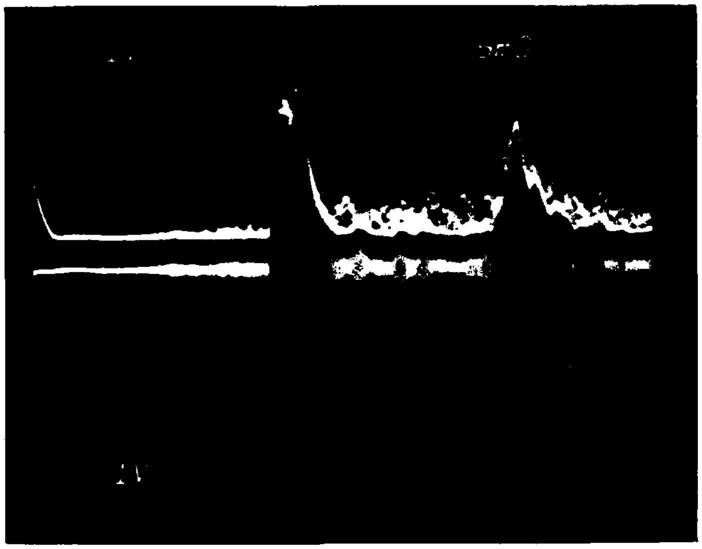


Figure 3-48. Ultrasonic Simple Pulse Carrier and Envelope; Response Obtained by Jingling Keys in Vicinity of Receiver

sensor. The carrier frequency is 25 kHz. Note that the noise amplitude is similar to that produced by a telephone directly in the beam. If the keys were jingled directly in the sound beam at a five feet range, the resultant interference would completely mask the signals of interest.

Operation at 40 kHz was examined to determine if the higher carrier frequency lies outside the spectra emitted by both telephones and keys jingling. There was however, no readily discernable improvement in the susceptibility to these ultrasonic noise sources at 40 kHz. In fact, scintillation was noticeably more prevalent, ard increased attenuation resulted in reduced signal strength when operating at 40 kHz. Because of these factors, remaining tests were conducted using the 25 kHz transducer set. Effects of these nuisance signals was subsequently reduced through an increase in the transmitted pulse power which permitted equivalent signal return at reduced receiver sensitivity.

3.6.3.7 Ultrasonic Coherent Pulse Doppler Ranging System With MTI Processing

3.6.3.7.1 Hardware - A coherent pulse Doppler system was breadboarded that inherently provides a moving target indication with ranging capabilities. The moving target indication is provided by measuring phase modulation induced by a target's motion. Since the system is pulsed, the modulation will occur only at a time corresponding to the round trip propagation delay between the transmit/receive pair and the moving target. By measuring the delay time the target's range is thus determined.

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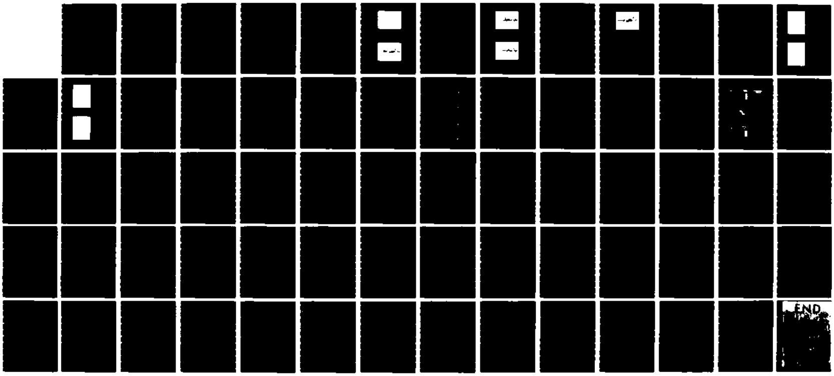

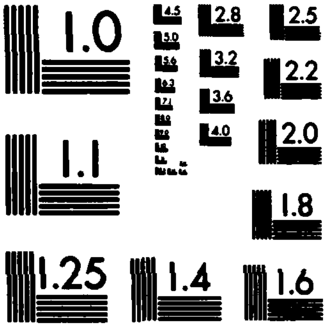

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Figure 3-49 is the schematic diagram of the coherent pulse Doppler detector. The receive amplifier is identical to that used in the simple pulse breadboard minus the envelope detector (see Figure 3-39), therefore it is not repeated in this drawing. The receive amplifier's output is applied at the point denoted as "RCV IN". An external CW sine wave oscillator operating at the carrier frequency (25 kHz) is applied at the point denoted as "CW IN". The CW oscillator is adjusted for a 2V peak-to-peak output.

Figure 3-50 depicts the functional block diagram for the entire system. In operation, the 25 kHz oscillator runs continuously. Pulses to the transmit transducer are generated by an analog switch that gates a portion of the CW on and off. The pulse width and repetition interval are determined by sync pulses from the processor. As in the simple pulse system, the gain of the receive amplifier is controlled by the processor through the variable gain preamp. The gain control provides distance/amplitude correction over the pulse repetition interval for a more uniform response. The return signal is bandpass filtered about the carrier frequency and amplified again. The multiplier performs the analog equivalent of the mathematical operation, (sin a) (sin b) = 1/2 [cos (a-b) - cos (a+b)], where sin a represents the return wavetrain and sin b represents the CW oscillator reference. The output of the multiplier then contains two terms; the differenced term and the summed term between the return and the reference. The multiplier output is low pass filtered to remove the summed term.

Analysis of the differenced term reveals that in the absence of a moving target, the "a" frequency and the "b" frequency are identical and will cancel. There remains however, a

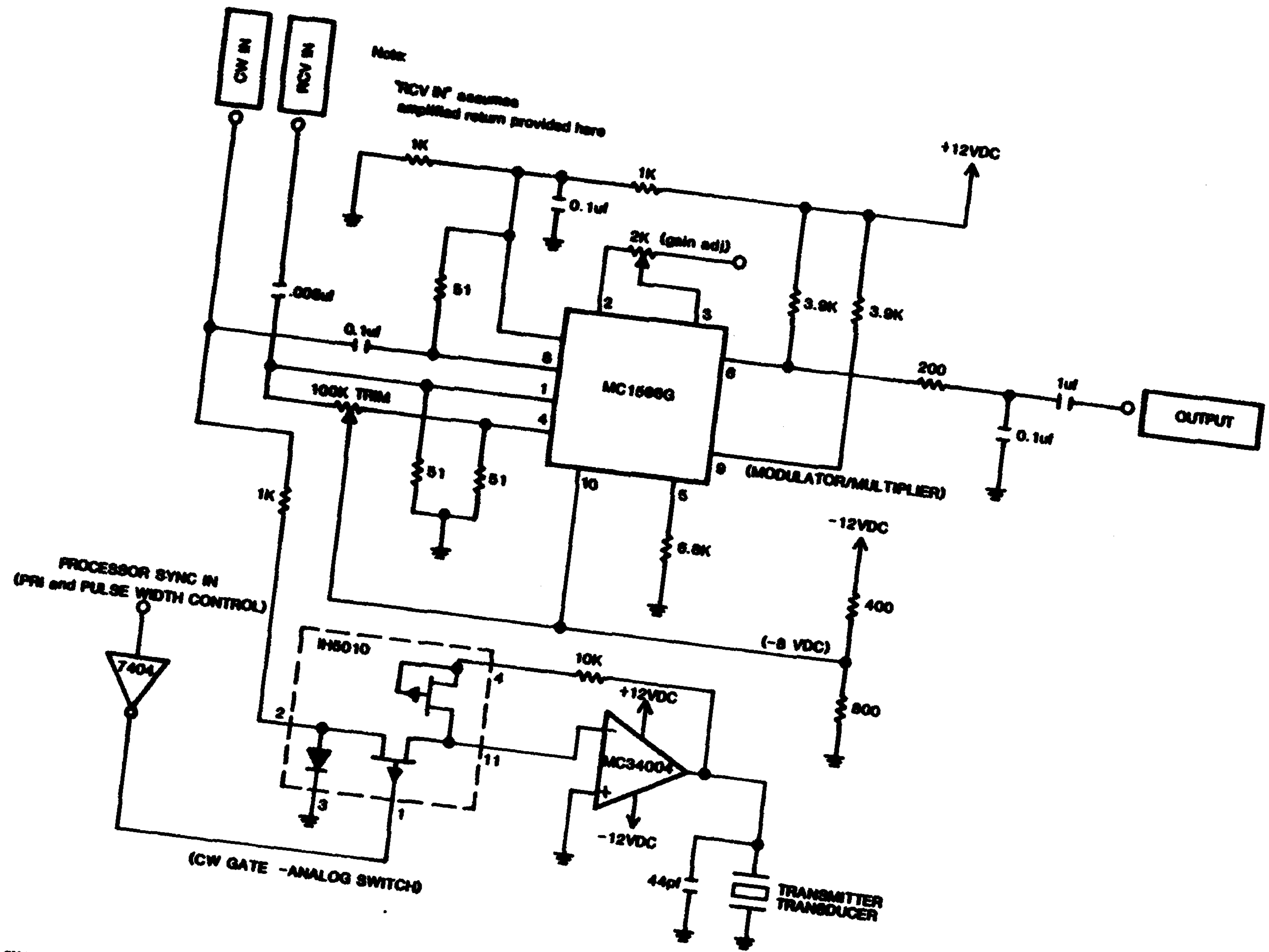

Figure 3-49. Schematic Diagram of Ultrasonic Coherent Pulse Doppler Breadboard

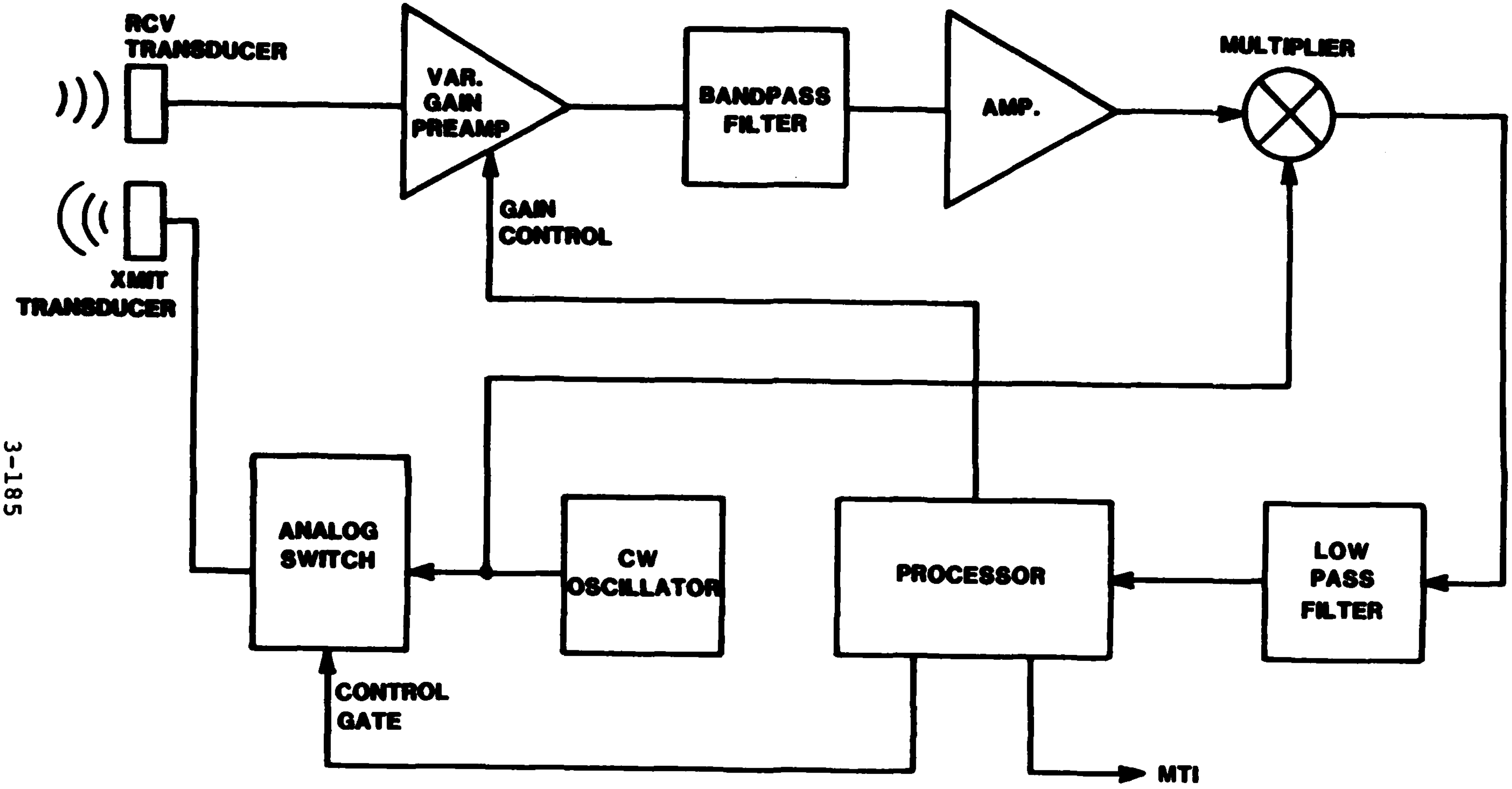

Figure 3-50. Functional Block Diagram of Coherent Pulse Doppler Breadboard

residual phase factor that is range dependent. Therefore, stationary target returns can produce non-zero outputs depending on their range. Their output however, remains constant from pulse-to-pulse since the relative phase difference between the reference signal (oscillator) and the returns is always constant. This is the coherent aspect of the system.

When a moving target returns energy, two effects take place. First, the range dependent phase term is no longer constant from pulse-to-pulse due to the target's change in range. This is the principle source of output modulation. Secondly, the target velocity imparts a Doppler shift so that frequencies "a" and "b" are no longer identical. They do not cancel in the cos(a-b) term and therefore will also contribute to the output modulation.

Figure 3-51 is the coherent return obtained for the same hallway scene previously depicted in Figures 3-42 and 3-43 for the simple pulse system. The pattern displayed in Figure 3-51 may be considered as a relative phase map of the stationary reflectors in the hallway. This map remains constant from one pulse to the next so long as the fixed targets do not move. Figure 3-52 shows the coherent return for a man rocking back and forth at a range of about five feet. In order to show the "butterfly" effect of the phase modulation, the shutter on the oscilloscope camera was held open for two seconds. The long exposure enabled the film to record multiple pulse intervals.

There are several features to note about the coherent return. The most important features are the increased sensitivities to both target detection and target motion sensing. The

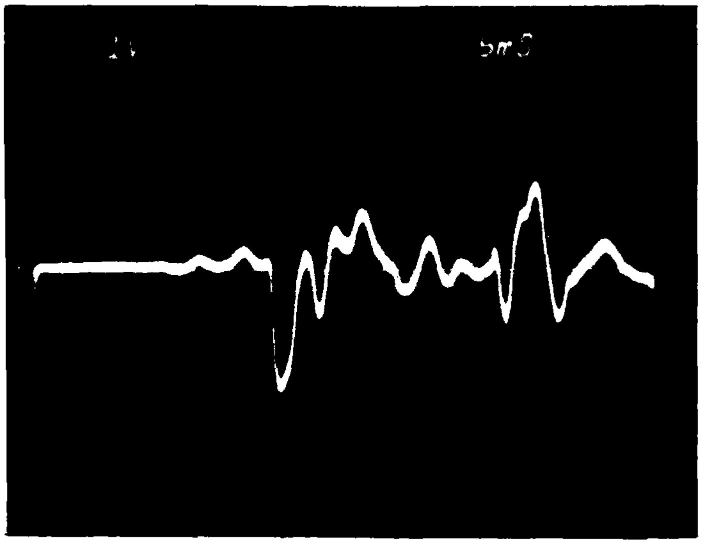

Figure 3-51. Ultrasonic Coherent Pulse Doppler Return From Hallway Scene

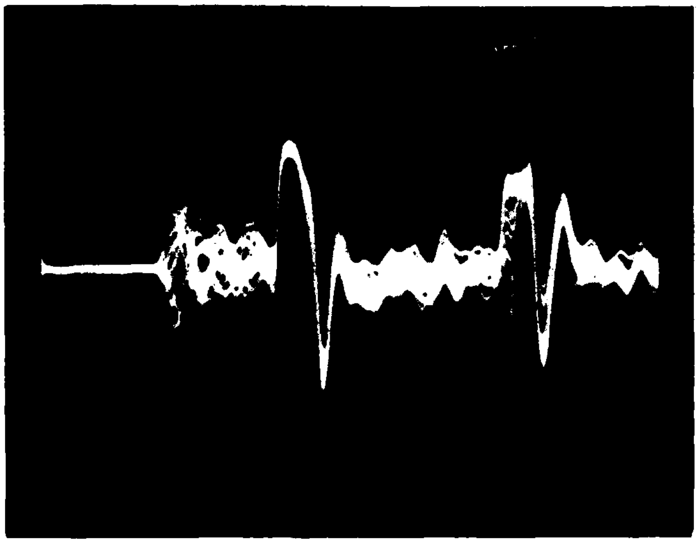

Figure 3-52. Ultrasonic Coherent Output; Man Rocking Back and Forth at Approximately 5 Feet

total signal change shown in Figure 3-52 is about five times the level shown in the corresponding simple pulse photo (Figure 3-43) under similar test conditions. Unlike the envelope detected output, the coherent output is bipolar, thus contributing to the increased sensitivity. A moving target will produce a full cycle polarity swing for a radial position change equivalent to one-half wavelength at the carrier frequency. At 25 kHz, this distance corresponds to a movement of about 0.27". Motion detection using the simple pulse system on the other hand can occur only during the target's transition from one range bin to the next. Typically, the digital range bins are set at equivalent one to two feet intervals in the processor.

Another point to note about the coherent return is the modulation that occurs following the target's true range at five feet. This modulation is the result of phase changes induced by the moving target's presence. That is, since the man is at a relatively close range to the sensor, his body blocks a portion of the sound field which otherwise could have illuminated the area behind him. The target's movement modulates the sound field behind him which modulates the observed output. The same effect occurs in the simple pulse return, however the increased sensitivity of the coherent detector accentuates it. Range accuracy in either case is unaffected since the multipath signals all occur later in time (behind) the target's main return.

The coherent system was subjected to similar nuisance conditions as the simple pulse detector. Figure 3-53 shows the effect of fan induced scintillation upon the coherent output. Like the simple pulse system, the amplitude variations are most evident at the points in the return corresponding to

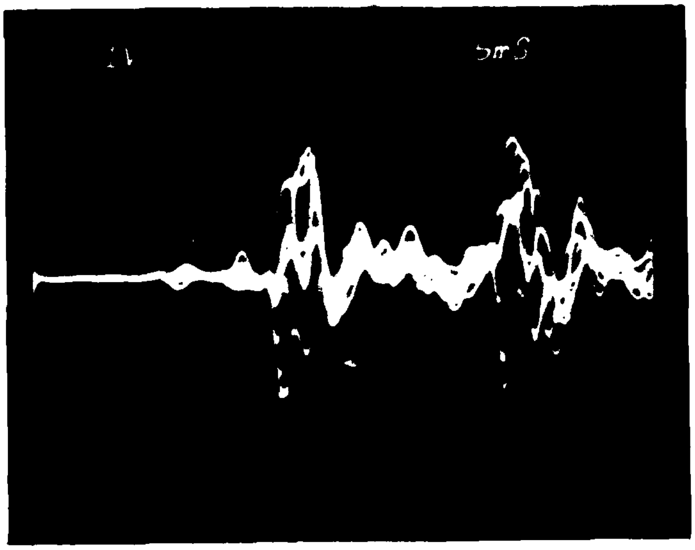

Figure 3-53. Ultrasonic Coherent Output; Fan Induced Scintillation in Hallway

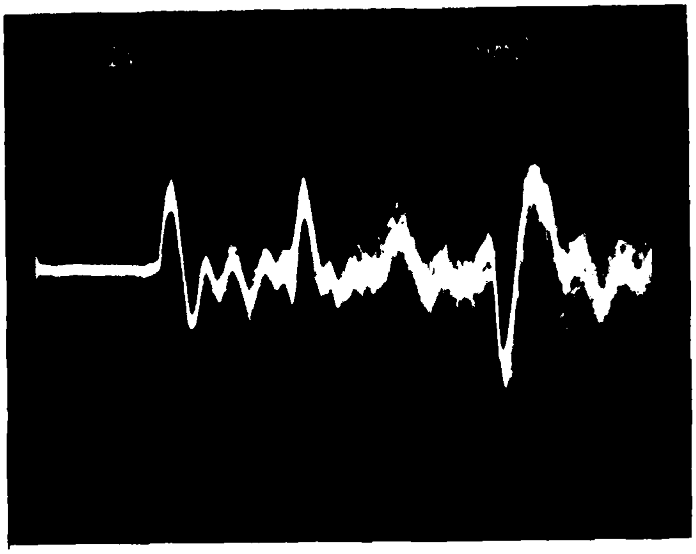

Figure 3-54. Ultrasonic Coherent Output; Telephone Ringing at 5 Feet in Hallway

large reflections from stationary targets. The total amplitude variation is worse for the coherent output, primarily due to the bipolar nature of the output. If the coherent response was limited to the upper half of the waveform (as the envelope representation is), then the responses would be comparable.

Figure 3-54 depicts the coherent detector response to the ringing telephone directly in the sound beam at five feet. The level of interference is equivalent to that of the simple pulse output. Again, if the phone is not directly in the sound beam or at a more distant range, the interference is negligible. (Consideration has been given to the suggestion that the telephone ring may have somewhat of a coherent nature with respect to the ultrasonic pulses. Additional thought along these lines however dismisses the idea, and evidence of this is contained in Figure 3-54. The signals displayed in Figure 3-54 were recorded during a single ring of the telephone, with the camera shutter open for two seconds. In the two second interval approximately 35 pulses were transmitted. If the telephone ring had constant phase (coherence) relative to these pulses, the interference would have been uniform from one pulse to the next. The random nature of the interference shown in Figure 3-54 suggests that this is not the case.) Figure 3-55 shows the coherent output responding to jingling keys in a room adjacent to the hallway. The keys produce major interference at ranges greater than about five feet (where gain begins to increase significantly). Although the absolute magnitude of the key interference is greater than the corresponding simple pulse output (Figure 3-48), the (target) signal-to-noise ratio remains better for the coherent return.

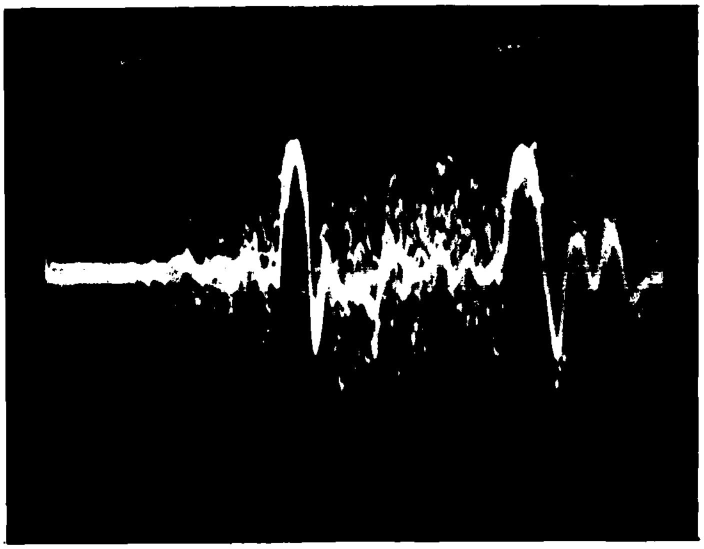

Figure 3-55. Ultrasonic Coherent Output; Response Obtained by Jingling Keys in Vicinity of Receiver

Further efforts to improve signal-to-noise ratio and reduce susceptibility to ultrasonic noise interference were devoted to increasing the intensity of the transmitted pulses. In the circuit shown in Figure 3-49, the transmit transducer is driven directly from an op-amp output. Using the +/-12 VDC supply, the maximum peak-to-peak voltage that can be applied directly is then 24 volts. The TDK 25 kHz transducer however, has a maximum input rating of 70 V peak-to-peak in pulsed operation. Therefore additional acoustic power can be obtained by driving the transducer with higher voltages. Audio transformers were used in a step-up configuration to produce voltage gain at the output. While gain was achieved in the unloaded state (transducer disconnected), the low impedance of the transmitter operating at resonance (~350Ω), loaded the secondary windings too much to produce significant step-up voltage. The output of the op-amp driver was then buffered through a power transistor to increase the current available in the primary of the transformer. Using this configuration, the transformer was able to drive the transducer with increased voltage. The pulses actually driving the transducer however, were severely distorted and therefore precluded the usefulness of the circuit. The output drive circuit must be the subject of a careful design effort if increased power is desired.

3.6.3.8 Ultrasonic Software Development

3.6.3.8.1 Simple Pulse Radar - Simple pulse radar operation begins with the transmitter emitting a pulse-modulated sine wave. The distance of any target from the transmitter is determined by measuring the time interval between signal transmission and signal return. Preliminary testing of ultrasonic transducers was done at 19.5, 25, 40 and 56-60 kHz to determine optimum received signal levels. Human annoyance was significant at 19.5 kHz. 25 kHz provided the best received power levels.

Software processing of the simple pulse radar began by differencing returns from successive pulses. To do this, the return was sampled at fixed time intervals and stored digitally. Digital subtraction was performed on the two most recent returns and the result routed to an oscilloscope. Output pulse width, pulse repetition interval, and sampling intervals are all determined in software. The large noise signals seen in this difference are due to signal scintillation (Figure 3-56).

To obtain a smoother difference signal, several pulses were transmitted initially, the returns averaged to create a reference, and then the difference of each pulse from the reference was displayed. The noise level of this difference signal was still unacceptable. To eliminate the low-level noise, differences below a negative threshold were assigned a uniform negative value, differences above a positive threshold were assigned a uniform positive value, and all other differences were assigned a value of zero. The effects of scintillation were so great that the vast majority of differences exceeded the most liberal of practical thresholds. To further reduce the differences due to scintillation, multiple pulse returns were averaged for differencing from the reference. Prior to this differencing, both the reference and the averaged returns were converted via thresholds to 3-level signals. To improve the received signal characteristics, a gain control voltage on the receiver amplifier was modified

Figure 3-56. Upper Trace: Unprocessed Pulse Return
Lower Trace: Pulse-to-Pulse Difference
No Intruder

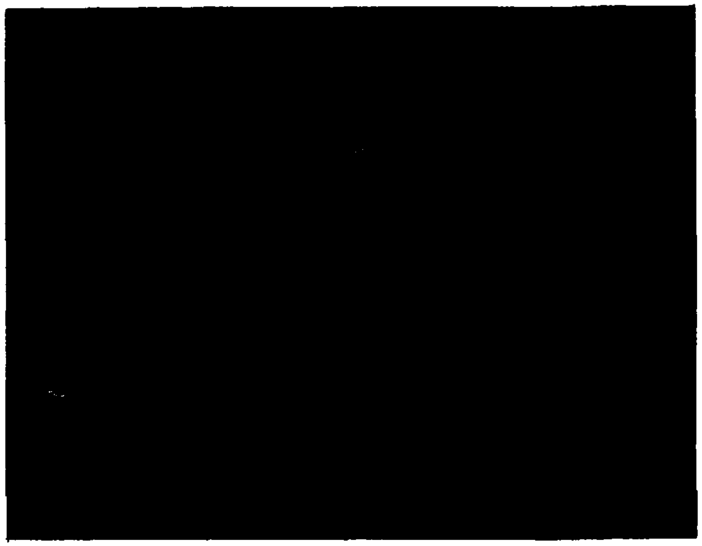

Figure 3-57. Upper Trace: Pulse-to-Pulse Difference
Lower Trace: Unprocessed Pulse Doppler Return
Intruder at 18 Feet

via software as time-since-transmit increased. With these modifications the difference signal was the most reliable produced. Stationary targets such as walls and doorways still produced difference signals indicative of motion. The return from any flat reflector (doorjambs, ceilings, walls, doors) was orders of magnitude greater than the return from a human, resulting in sporadic detection of human targets.

3.6.3.8.2 Coherent Pulse Doppler Processing - The pulse Doppler system specifically detects moving targets, as opposed to the simple pulse detection of all signal reflectors. Software processing of this signal also began by examining the difference of successive pulse returns. Scintillation noise is still present, however the signal-to-noise ratio is vastly improved (Figure 3-57). Averaging of several pulses before differencing was tried and then discarded in consideration of the AC nature of the pulse Doppler signal. This AC nature also produces an AC characteristic in the difference signal between two pulses. In consideration of this, after pulse-to-pulse differencing all differences are converted from absolute differences to magnitude differences. The differenced return from an intruder typically has one or more zero crossings, creating multiple peaks in the difference signal from a single target. Multi-path returns and air turbulence induced by a moving intruder created additional peaks in the differenced signal (Figure 3-58).

To smooth scintillation noise from the difference signal and to eliminate multiple peaks due to zero crossings each difference in the differenced signal was averaged with it's nearest neighbors. A threshold value equal to the average amplitude of this signal was subtracted from each averaged difference. A new, filtered signal was output, equal to the

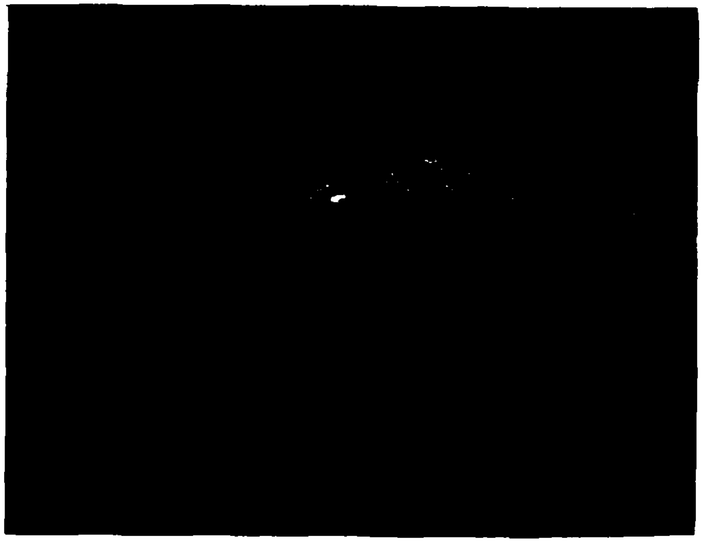

Figure 3-58. Pulse-to-Pulse Magnitude Difference
Intruder at 12 Feet

Figure 3-59. Upper Trace: Filtered Signal
Center Trace: Binary Display
Lower Trace: Target Tracker
Intruder at 10 Feet

thresholded, averaged difference if this thresholded, averaged difference is part of a group of at least n consecutive, non-zero, thresholded, averaged, differences. The filtered output is equal to zero otherwise. n is varied with pulse width and with the characteristics of the averaging function. Another new signal was output, a binary signal with a single pulse present for each group of non-zero outputs in the filtered signal. This binary signal is the beginning of an alarm decision routine to assess the absolute motion of targets. A binary target-tracking display is output with pulses present where time and space continuity are observed in the first binary signal (Figure 3-59).

To increase the effectiveness of thresholding, the greater of a constant minimum value or the average amplitude is subtracted when producing the filtered signal. An alarm indicator was installed with the alarm condition being movement on the target-tracking display greater than a fixed distance. Detection was satisfactory with walking, creeping, running, wall-hugging, or crawling intruders. Nuisance alarm rates were higher than desired when keys were shaken near the sensor. It is believed that further refinements in producing the filtered output will improve both detection capabilities and nuisance alarm rejection capabilities.

4. CONCLUSIONS AND RECOMMENDATIONS FOR BRASSBOARD EVALUATION

As was discussed in the sections pertaining to evaluation criteria and candidate selection, virtually any scheme envisioned for interior intrusion detection can be forced to be ranging if enough sensors are deployed and one is not concerned with installation, maintenance, or reliability constraints. Deployment, installation, maintenance, and reliability however, are significant factors that cannot be ignored. The problem addressed in this study has been the distillation of the many conceivable schemes into those few candidates that meet the requirements of being ranging and correlating, and which do so in the most direct manner with the fewest practical limitations.

The theme stated above was carried through the breadboard investigations and in the evaluation of their results. Of the eight systems examined, those in the active acoustic and passive infrared environments displayed the best overall performance. While the dual frequency RF radar in principle offers a ranging capability, its performance was impeded by the complex frequency components contained in human target returns. Since the problem relates to the inherent nature of the signals, the technique has fundamental limitations as well as the practical problems associated with penetrating radiation. Little improvement can be expected even with hardware and signal processing development. Alternative RF ranging techniques that offer fundamental improvements in the signal available for processing have other limitations such as bandwidth requirements that exceed FCC regulations. The active electromagnetic environment therefore, is not viewed as a primary candidate for interior intrusion detection.

SCOPE proposes the coherent pulse Doppler ultrasonic technique (with MTI processing) to be used as the principle ranging component of the sensor. The breadboard tests demonstrated its superiority in sensitivity for target range detection and motion indication over the simple pulse scheme. The principle sources of nuisance are ultrasonic noise interference and severe air turbulence. The susceptibility to noise interference can be improved by increasing the output power of the transmitting transducer. This will have the direct effect of increasing the signal-to-noise ratio. (In the breadboard experiments, the transmitter was only driven at approximately one-third of its maximum voltage rating.) Experiments performed after the writing of this report demonstrated that by driving the transmitter with 60 VPP pulses, a useable range of approximately 40 feet was achieved. Since ultrasonic transmitters' outputs are governed by safety regulations, consideration will be given to the actual acoustic power being generated and whether operation at these levels is in violation of the safety regulations.) The susceptibility to air turbulence has no direct solution other than addressing the positioning of the device within the interior volume to be protected. The magnitude of turbulence generated during tests of the ultrasonic systems was intentionally severe and most likely will not be encountered in actual service. The systems were normally operated in lab areas ventilated by conventional forced-air circulation. During normal operating conditions, the signal processing algorithm had no difficulty distinguishing scintillation from true intruder activities. Nevertheless, caution should be exercised in the mounting of the device such that it does not direct the ultrasonic field at heating or air conditioning ducts.

The correlating aspect of the sensor can be achieved through a number of options. Correlation can assume different meanings depending upon the context in which it is used. For this application, "correlating" will be defined by its intent; that is to reduce false alarms by establishing the relationship between events (intrusion) occuring in the environment and the signals detected through independent measurements. Since the ultrasonic detector is a pulsed system, independent measurements are obtained from one pulse to the next. Imposing the requirement of tracking a target through several range bins before alarming creates one form of correlation that can alleviate susceptibility to nuisance. Another type of correlation that can be used is to compare range data obtained from two distinct ultrasonic channels. Correlation here is obtained when the moving target range reported by each unit is identical (within predetermined error limits).

Target detection based upon two independent techniques represents a higher order of correlation. It is at this level that the passive infrared techniques will become useful. The infrared channel may be considered as the correlating factor for an ultrasonic target detection. In the simplest form, an alarm condition exists only when an ultrasonic channel detects (and tracks) an intruder <u>and</u> a single passive infrared channel provides a target indication during the same relative time period. In this form of correlation or coincidence detection, a target indication provided by one <u>or</u> the other channel will not be cause for alarm. Correlation at this level and higher is appealing for interior intrusion detection since the phenomenon responsible for nuisance alarms on one channel will not necessarily affect the other. The potential for false alarm therefore may be significantly reduced.

The passive infrared channel can be expanded to provide both range (spatial) and coincidence (temporal) correlation with the ultrasonic channel. This is accomplished by using a pair of passive infrared linear arrays or multiple single element detectors to simulate linear arrays. Positioning the arrays in the manner depicted in Figure 4-1 will create overlapping zones of coverage. Each zone represents the intersection of two elements' fields of view, with each field of view emanating from a different array. Since each zone created in this manner is unique, an intruder's position (by zone) can be unambiguously determined by measuring which pair of elements "sees" him. Resolution by zone is determined by the number of elements in the arrays. In this scenario, an alarm condition will be invoked only when the event (intrusion) occurs at the same time on both the ultrasonic and infrared channels, and the range provided by the ultrasonic measurement coincides with the zone determined by passive infrared.

In the correlation scheme just described, the passive infrared channel's zonal detection ability is two-dimensional, providing both target range and bearing simultaneously. The bearing information, however, is not used in the correlation process because a single ultrasonic channel determines range only. An even higher order of correlation can be implemented by using two spatially separated ultrasonic ranging channels. When positioned as shown in Figure 4-2, the ranges provided by the two ultrasonic channels will uniquely intersect at one point at all locations interior to the room for real targets. Now the ultrasonic channel can also provide moving target location in two dimensions, and therefore correlation with the infrared channel can be obtained in both the range and bearing parameters. By imposing added constraints such as target tracking and time coincidence between the independent channels, this scheme provides the highest level of nuisance rejection.

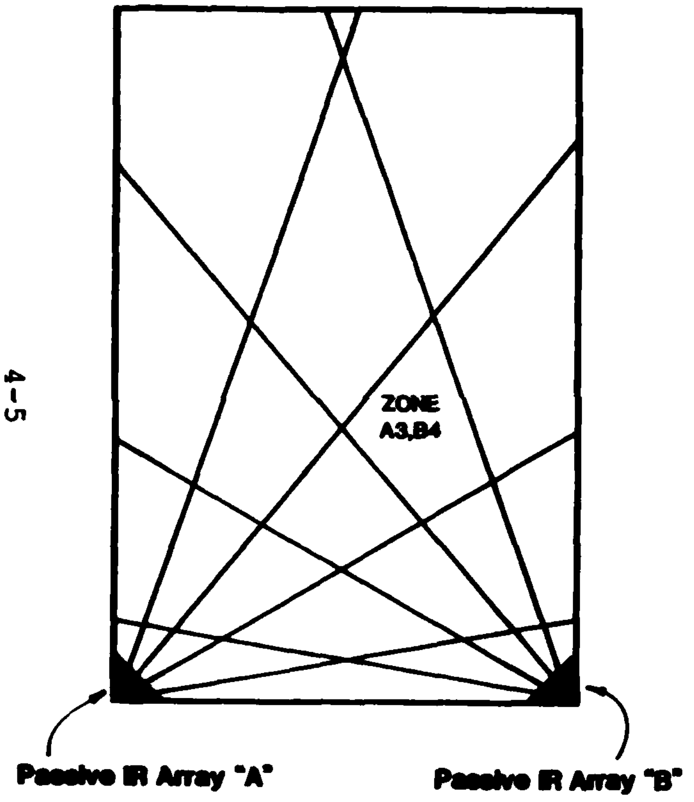

Figure 4-1. Target Position Determination
By Zonal Intersection of Passive
Infrared "Beams"

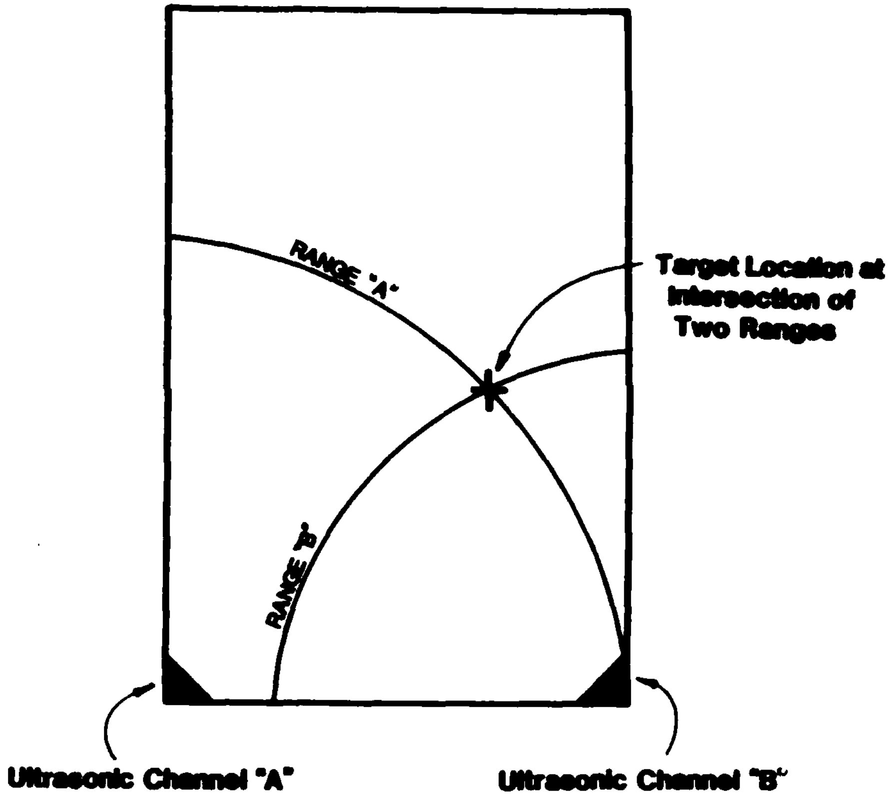

Figure 4-2. Target Position Determination
By Intersection of Ranges Measured
By Two Ultrasonic Modules

The brassboard phase will determine what level of correlation is required to provide the best trade-off between nuisance rejection and alarm sensitivity. This phase will require constructing the devices described and measuring their responses in a typical FIDS environment under various nuisance and intrusion conditions. By logging the data provided by each device simultaneously, the results can be analyzed in the various combinations to arrive at the optimum sensor configuration.

For the brassboard effort, SCOPE proposes to construct two ultrasonic coherent pulse Doppler modules, and to evaluate these in conjunction with two passive infrared modules. Since the passive infrared portion of the sensor is the least defined at this point, two avenues of investigation will be explored.

The first approach (and most cost-effective) is to configure the two passive infrared modules from the Amperex pyroelectric detectors. Each module will be constructed using five RPY-97 differential detectors such that five distinct "beams" of coverage will be produced as depicted in Figure 4-1. Optics will be selected such that the detectors will cover an approximate 90° field-of-view. Two such modules properly oriented will then permit zonal location of a human target by the intersections of the ten corresponding "beams". Since each detector channel will be independent, the use of single detectors can be examined by simply ignoring the others. A single detector using a multifaceted mirror can be simulated by "OR-ing" the outputs of several channels on one module.

The second approach involves using the Texas Instruments passive infrared cameras to examine additional detector configurations. By devising an appropriate interface device, the pixel data corresponding to one or more individual array elements can be extracted from the video output. In this manner, many array configurations can be simulated by selecting and processing only those pixels (elements) of interest, without generating new hardware each time. For example, a linear array may be simulated by sampling and processing a single line of the video output. Various linear array lengths and elemental spacings, as well as smaller two-dimensional arrays can be simulated by sampling only the desired portions of the video output. Different element sizes can be simulated by post detection integration of several adjacent elements' outputs.

It may also be possible to extract target range and bearing from a single two-dimensional array. Figure 4-3 graphically depicts the concept. An off-axis parabolic mirror section is used to image the protected area onto the two-dimensional array. The array is positioned on the true axis of the parabola with a slight skewness so that the focused energy will impinge on its surface more directly. According to the laws of reflection and refraction, an object at a large distance from the mirror will be imaged at a point further away than objects at closer distances. Therefore an intruder at position "A" in Figure 4-3 will be imaged at a different point on the array than if he was at point "B". A one-to-one map between target range and the elements of the array illuminated is therefore possible. Although not depicted in Figure 4-3, a lateral movement of a target in the field of view will translate into a lateral shift of the image point on the array. It is therefore possible to obtain both range and

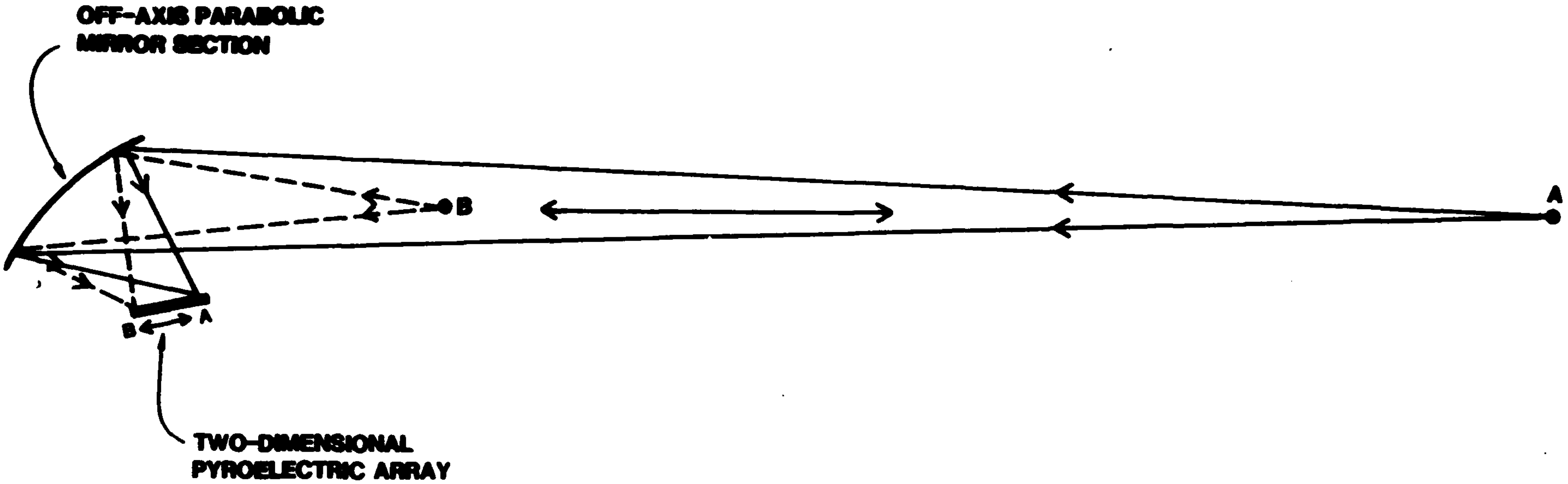

Figure 4-3. Conceptual Technique for Determining Target Range and Bearing Using Single Passive Infrared Two-Dimensional Array

bearing from a single array. The concept is untested at this time so it is uncertain what the sensitivity and resolution for range and bearing information will be. SCOPE proposes to examine the concept in more detail during the brassboard phase.

In summary, the brassboard effort will be used to construct two ultrasonic coherent pulse Doppler modules and two passive infrared modules based upon the Amperex pyroelectric detectors. A parallel effort will be to design and fabricate two interfaces to the Texas Instruments passive infrared cameras to permit evaluation of additional detector configurations.

Conceptually, the brassboard system will appear as depicted in Figure 4-4. The modules will interface to one or more 6809 microcomputers. The 6809's will control data collection and data processing from the sensor modules, and also communicate with a microcomputer development system. The microcomputer development system will be used to log data output from the sensor modules and to download the data collection and processing programs to the 6809's. The programs will set-up the brassboard system in a variety of optional configurations whose performance will be evaluated in real-time and through subsequent analysis of the logged data. The principle options to be evaluated using the system described are listed in Table IX. The evaluation of these options will determine the best system to pursue for Advanced Development Models.

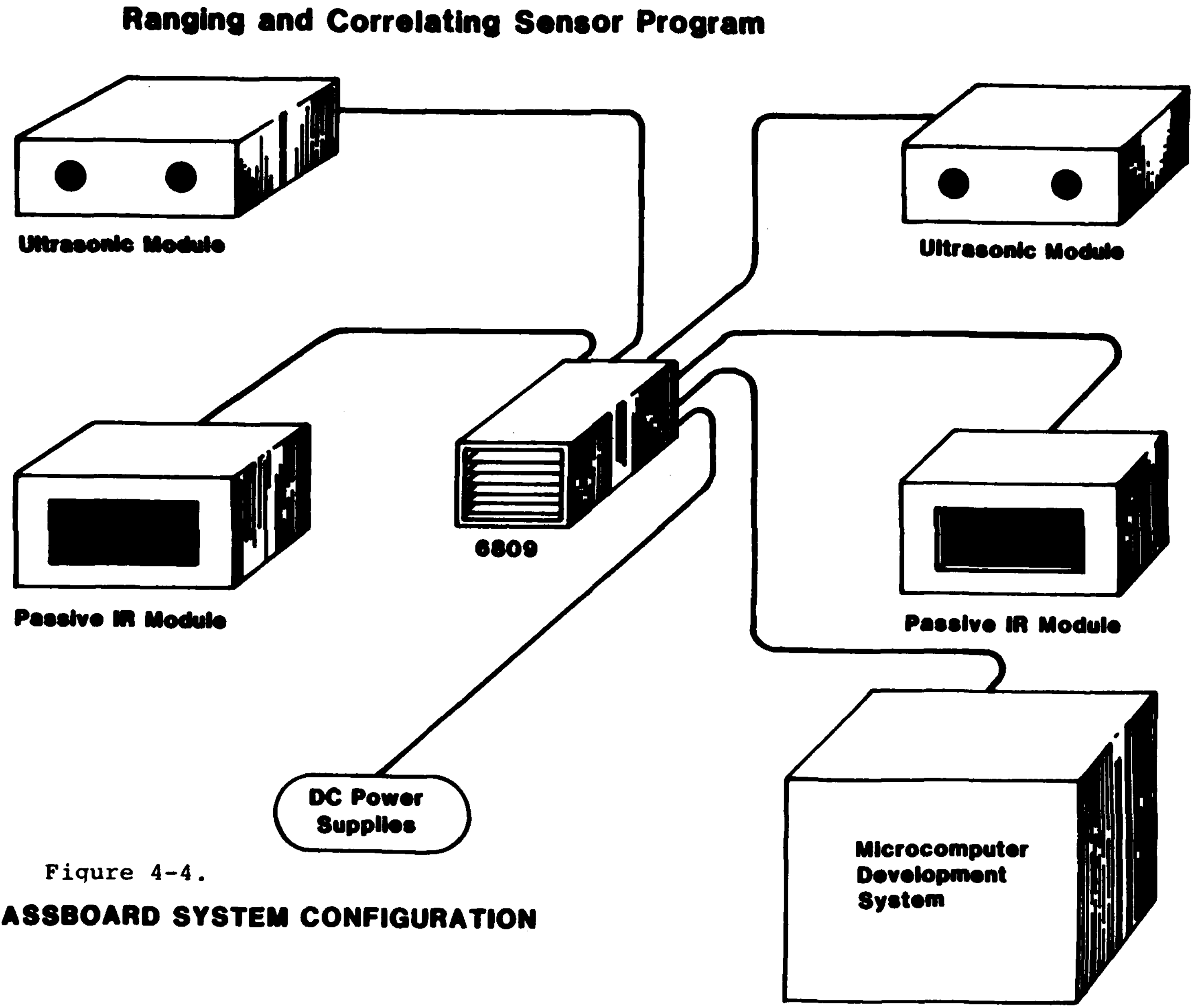

Figure 4-4.

BRASSBOARD SYSTEM CONFIGURATION

TABLE IX. SUMMARY OF PRINCIPLE OPTIONS AVAILABLE USING BRASSBOARD MODULES

1) SINGLE CHANNEL ULTRASONIC
   - RANGE AND TRACKING

2) TWO CHANNEL ULTRASONIC
   - TWO DIMENSIONAL LOCATION AND TRACKING

3) SINGLE CHANNEL ULTRASONIC + SINGLE CHANNEL IR
   - RANGE AND TRACKING + CORRELATION IN SECOND SIGNAL ENVIRONMENT

4) TWO CHANNEL ULTRASONIC + SINGLE CHANNEL IR
   - TWO DIMENSIONAL LOCATION AND TRACKING + CORRELATION IN SECOND SIGNAL ENVIRONMENT

5) TWO CHANNEL ULTRASONIC + TWO MULTI-DETECTOR IR CHANNELS
   - TWO DIMENSIONAL LOCATION AND TRACKING IN TWO DISTINCT SIGNAL ENVIRONMENTS

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APPENDIX A - SUMMARIES OF PERTINENT LITERATURE REVIEWED

THEORETICAL ANALYSIS OF INTRUSION ALARM USING TWO COMPLEMENTARY SENSORS

Term Kovattana

February 1973

Mathematical treatment of using two sensors in an AND combination. Results include:

- Sensor pairs should be chosen to have disjoint nuisance alarm sets.

- Nuisance alarm reduction depends as much or more on nuisance alarm rates of the individual sensors as it does on the effect resulting from their combination.

- Tables of nuisance alarm rates for various sensor pairs are given with microwave Doppler - passive IR, shadow detector-capacitance probe, ultrasonic Doppler-capacitance probe, ultrasonic Doppler-passive IR, RF field-capacitance probe, and RF field-passive IR combinations, among others, appearing as strong candidates.

This paper should be considered required reading for background purposes if a two sensor deployment is considered. Conclusions on sensor performance should be viewed with the caveat that this paper is 10 years old.

Detection of Human Intruders by Low Frequency Sonic Interferometric Techniques

NBS
1974

An extensive report on detailed testing done in the frequency band .5-5 kHz. Noise was found to be from ambient acoustical sources and to arise from changes in the environment. Environmental noise was found to be the factor limiting detection at signal source levels of 54-66 dB. Environmental noise is greatest at low frequencies and decreases with increasing frequency. Intruders were detected consistently throughout four test volumes, independent of geometry. Additional test results are also presented. This work should be contrasted with the BDM and Sandia conclusions. This report establishes the capabilities of intruder detection at this part of the acoustic spectrum and must be considered when assessing sonic techniques.

REPORT ON SENSOR TECHNOLOGY FOR BATTLEFIELD AND PHYSICAL SECURITY APPLICATIONS

July 1977

MERADCOM

Use of the Pyroelectric Vidicon for installation security, Page 147.

IR thermal imager, detects motion. Application discussed is for perimeter security and surveillance. Field tests showed excellent results. No obvious ranging capabilities.

Piezoelectric and Pyroelectric Polymer Sensors, Page 204.

A discussion of the applications and potential applications of this polymer technology in sensing devices of various types. No direct information for our purposes.

Discussion of selected new sensor transducer technology, Page 213.

A preliminary report on new line sensors; strain, magnetic, and gamma radiation. Gamma ray beam-breaker looks promising though it is described for use as a perimeter sensor.

Selective Digital Filtering, Page 225.

Theoretical treatment of improvement in signal-to-noise characteristics of sensor analog signals.

Radar video processing with charge coupled devices, page 236.

A mathematical discussion of the use of CCDs in MTI and transform processing. Significant improvements in spectral analysis and radar video processing are possible with savings in A/D conversions, size, power, weight, and cost also possible. An important article in the consideration of MTI and transform processing.

Detection of mechanical waves generated by concealed persons, page 258.

A demonstration of the feasibility of presence sensing by low frequency mechanical waves with a low frequency geophone. The technique is not inherently ranging but is important for correlational consideration.

Comparison of available target classification techniques, page 297.

A very general discussion of target classification, applicable to the battlefield or to intruder detection.

Improved techniques for seismic and seismic-acoustic passive ranging from a single sensor, page 312.

By identifying and classifying attenuation in the frequency domain the range of a target can be determined. This approach seems primitive for our purposes yet can be considered for correlational purposes.

Passive infrared motion sensor, page 339.

Good, detailed discussion of specifications for one particular volume sensor. No peformance comments included.

Senior Test System for the FIDS, page 351.

A presentation of the overall FIDS. For matters of curiosity primarily.

Installation security radar employing microprogrammed signal processing and threat analysis, page 381.

A discussion of a specific radar under development. The paper is a bit too abstract for our purposes.

Personal attributes verification, page 414.

No relevance to our purpose.

AN/GSS-20, page 503.

Good in-depth discussion. System uses AND combination of microwave Doppler (915+/-13 MHz) and ultrasonic Doppler (23 kHz).

Practical testing and calibration of electrodynamic seismometers (Geophones), page 526.

Has application only to mechanical wave detection applications. See "Detection of Mechanical Waves Generated by Concealed Persons."

MICROPROCESSOR APPLICATIONS IN INTRUSION DETECTION SYSTEMS

James L. Shannon

From Carnahan Conference, 1977

The treatment of a microprocessor based signal classifier is primitive and the information presented is unsuitable for our purpose.

RADARS FOR INTRUSION DETECTION

Aaron A. Galvin, 1978

IR Radar - Very narrow, "pencil" beam which is easily circumvented if the beam location is known. Several units may be operated in close proximity without interference.

Microwave Radar - Mutual interference among units. Penetration through walls.

Ultrasonic Radar - Non-penetrating. Nuisance alarms due to vibrating walls or room objects, air motion, or ultrasonic noise can be reduced by rejecting double-sideband events and accepting single-sideband events.

Sonic Radar - Same features as ultrasonic, different techniques.

Proceedings 1978 Carnahan Conference on Crime Countermeasures

Electronic Antipilferage System, page 61

Retail store oriented system, shoplifting control.

Illumination Criteria in Imaging System Design for Security Applications, page 91

A general discussion of ilumination followed by specifics for exterior applications. Of interest if an imaging system is selected.

Improvement of CCTV Surveillance Through Selective Contrast Enhancement and Weighted Averaging Light Control, page 97

The techniques for contrast enhancement and weighted averaging are of interest for any processing scheme. The examples of hardware deployment could be of interest if an imaging system is selected.

Infrared Ilumination for Closed Circuit Television Systems, page 109

Three commercial IR illuminators are evaluated. IR imaging is primarily for covert purposes, and there is a minimum safe distance for human exposure to an IR illuminator.

1979 Carnahan Conference on Crime Countermeasures

Microwave Respiration Monitor, page 53.

Respiration monitoring could be useful as a correlation tool. This particular monitor has several drawbacks, including the fact that the area of illumination must be only the lower torso.

A Microcomputer-Based video Motion Detection System, page 127

A multi-camera, image subtraction system is detailed. The important results for our purposes are the alarm decision schemes and the deployment problems (including image burn-in, image blooming, extraneous light sources, vibration, and chordate and arthropodan activity). We should consider CCD's, photoconverters, photomultipliers, and IR illumination along with other devices as components in an imaging system. An imaging technique correlated with a ranging technique could be a powerful combination.

Reliability Demonstration of Imaging Surveillance Systems, page 173

Use of resolution charts and exponential accept/reject criteria are the only items of interest.

PROCEEDINGS, 1981, Carnahan Conference on Crime Countermeasures

Testing Intrusion Detection Devices for Probability of Detection, page 35

A statistical assessment of the difficulties in measuring sensor performance regarding Type I and Type II errors. A knowledge of these results will benefit anyone involved in the testing of sensors.

Cable Television Security Systems, page 117

A crude concept and outside the area of our application. Note the difference between a closed circuit television security system and a cable television security system.

Fiber Optics in Security Systems, page 121

A highly generalized description of applications. Of interest is the potential of fiber optic sensing of sound or temperature changes and fiber optic transmission of IR beams.

A Volumetric Terrain Following Sensor, page 125

A perimeter protection system operating at 915 MHz using multiple antennas. The concept as applied to an interior protection sensor seems to have only the operating frequency as a unique feature.

A Microprocessor-Based Burglar Alarm System for an Apartment Dwelling, page 129

A trip loop system, of no special interest for our application.

New 23 GHz Microwave Systems, page 159

Components are designed for microwave links, not for interior protection.

INTRUSION SIGNATURE DATA BASE: REQUIREMENTS ANALYSIS

THE BDM CORPORATION

September 1982

An excellent source with many reference tables including FCC regulations, nuisance alarm matrix, and sensor characteristics. The discussion of sensor characteristics here together with the technical details from the Ademco catalog and the Sandia handbook form a comprehensive base for a knowledge of conventional interior intruder technologies.

Much of the report is devoted to perimeter penetration activities, therefore a careful analysis is required to find the applicable information.

SIGNATURE DATA BASE REQUIREMENTS: PRELIMINARY ANALYSIS

The BDM Corporation

December 1981

A well detailed report devoted to four goals:

1) Describe security environments.
2) Identify detectable intruder activities.
3) Describe detectable intruder produced phenomena.
4) Identify detectable nuisance phenomena.

Among the results which are of interest to us are:

- Identification of threat categories:
  - Thieves, soft target
  - Thieves, hard target
  - Activists, cause
  - Activists, terrorists
  - Foreign nationals, agents
  - Foreign nationals, special operations units

- Detailing of interior intruder activities under the headings of:

  - Motion
  - Presense
  - Disturbance
  - Contraband

- Detailing of Nuisance alarm producing phenomena under the headings of:

  - Mechanical sources
  - E/M - Electrostatic sources

PROCEEDINGS, 1982 CARNAHAN CONFERENCE ON SECURITY TECHNOLOGY

Reducing Storage Requirements of Digitized Fingerprint Images, page 1.

Information compression theory can be useful in any form of imaging or scan-to-scan cancellation scheme. Distillation of general concepts from these specific fingerprint image techniques will be useful for the above schemes.

Security of the Smithkline corporation Building, page 15.

No technical discussion of any interior protection devices is given.

Remotely Monitored, Multichannel Magnetic and IR Intrusion Sensors, page 43

An OR sensor for personnel or vehicle movement in the field. The IR sensor uses a dual element pyroelectric lithium tantalate detector. A target must be detected by each element sequentially within a fixed timeframe of >60 ms and <2.4 seconds. The magnetic sensor operates by observing the change in a magnetic field vector produced by an approaching and passing magnetic target. Performance data are not given for either sensor. The technical discussions of the sensors are detailed and complete yet the important aspect of this paper is really that these sensors are designed to monitor military activity and may be entirely too crude for interior applications.

An Image Processing System for the Enhancement and De-Blurring of Photographs, page 67

A higher-level discussion of de-blurring. The specific information is not as useful as some of the other enhancement papers.

Near-Infrared Motion Detector, page 101

A simple yet conceptually pretty system. Unfortunately the only performance data given is change of effective distance with warm-up time. The addition of a reference voltage which varies with ambient environment is described. It is claimed that this eliminates the effects of environmental changes and yields a constant effective distance but no test results are given to support this. While there are obvious questions concerning the performance of this device, this short paper is worth reading for the concept alone.

Microprocessor Target Assessment for Microwave Intruder Alarms, page 105

A short paper with the most applicable results to date. Doppler returns of modulated and unmodulated radars were examined with results including the following: Due to the complex nature of human movement (arm and leg swing), results from artificial target experiments may be unduly promising. For unmodulated radars the frequency of Doppler returns is more consistent with velocity than return amplitude is with range. In fact, range determination based on Doppler amplitude proved unreliable. For diplex modulated radars, range determination by phase difference proved more accurate. Typical Doppler returns are shown for several experiments.

Application of a Ground Vibration Detector Security System, page 157

Though the article is directed primarily towards soil deployed sensors it highlights the difficulties of identifying a human via footfall phenomena. This article could be part of grounds to eliminate or de-emphasize detection of vibration from footsteps.

Measures of Effectiveness for Physical Security System Assessment, page 177

Description and discussion of a mathematical, probabilistic model to assess effectiveness of countermeasures to various intrusion scenarios. Of no direct utility to us.

A Subminiature Microwave Video Transmitter: Crime Countermeasures Applications, page 187

The discussion is primarily of the physical characteristics of the transmitter. Though the transmitter is presented for video applications, Doppler might well be another area of interest. This matchbox size transmitter greatly advances the state-of-the-art in size, power efficiency and frequency stability limitations. The transmitter is based upon GaAsFET technology and the developing company is located in Reston. This device is important in consideration of imaging schemes and in assessment of microwave-based sensors.

USE OF DIGITAL SIGNAL PROCESSING TO OPTIMIZE ON ALARM SYSTEM, J. W. Phillip

Discussion of a data base developed from tapes of attacks on arms rooms and from a variety of noise sources and simulations thereof.

INTRUSION DETECTION SYSTEMS HANDBOOK

Sandia National Laboratories

The Handbook is quintessentially a guide to purchasing an intrusion detection system, thus much information must be prised from it in an indirect fashion, as opposed to more straightforward techniques used with other technical literature. The point of view within the handbook is that intrusion detection system objectives should be defined in three primary areas; 1) probability of detection, 2) vulnerability to defeat, and 3) false alarm rate and causes of false alarm. The Handbook does not include discussions of all types of interior sensors and this is done by purpose. Three classes of sensors are discussed; motion, boundary penetration, and proximity. Four types of motion sensors are evaluated; ultrasonic, microwave, and audio Doppler, and passive IR. The only other evaluation included that possibly merits our attention is of vibration sensors. The enumeration of environmental considerations and known nuisance phenomena is the most comprehensive encountered to date, yet, as acknowledged in the Handbook, is far from exhaustive.

Remotely Monitored, Multichannel Magnetic and IR Intrusion Sensors

See abstract, page 43, Carnahan 1982 Conference. IR detector for exterior motion sensing. Dual element IR pyroelectric detector with very narrow beam widths. Block diagram of processing circuitry is given. Order in which each element picks up radiation determines which way target is moving.

"Security of the Smithkline Corporation Bldg," 1982, Carnahan

Cameras on the parking level utilize video motion detection after normal working hours to alert guards of activity.

"Multistatic Airborne Intruder Detection Radar," 1982, Carnahan Conference

Detects intruders carried by parachutes, hang gliders, and helicopters.

Radar unaffected by presence or absence of sun, clouds, and other thermal-optical energy sources which can mask operation of infra-red and optical sensing system.

Uses multistatic radar system. Single transmitter and remotely-located receivers which pick up the scattered radar signal.

Multistatic radar receiver can be kept on continuously because it does not have to be switched during the transmit pulse.

Disadvantages of bistatic system - more complex communication system. Receiver can be iluminated directly by the transmitted signal so more care must be taken in isolating receivers and transmitters.

System must - detect target, measure signal params, assess threat, track target, locate target, and discriminate against various targets.

Disadvantages of short pulse radar - required high power for transmit, require large bandwidth, not suitable for Doppler filtering.

Advantage of Pulse - no elaborate signal processing for detection and measure of target echo time.

Disadvantage of long pulse - the direct signal may overlap the return.

Disadvantage of CW - can't be used to detect range.

Ensco used CW signal composed of a small number of CW tones spread over a frequency band.

Has synthetic bandwidth comparable with short pulse radar. Has power requirements comparable with Doppler radar.

Has time ambiguities and coherence requirements.

<u>Near Infrared Motion Detector, Carnahan, 1982, Chung San Inst of S&T, Taiwan</u>

Active sensor. Uses LD271. GoAsIR diode at 950 nm. 20 ft. range for sensor.

Hot bodies (lighted cigarettes, matches, lamps) are sources of IR radiation.

IR beam is pulsed to increase S/N and increase pulse power.

Amplitude of detected return is processed. Rate of change of amplitude with respect to time is measured and is used to distinguish moving target from stationary target.

Microprocessor Target Assessment for Microwave Intruder Alarms, 1982, Carnahan

Discusses the processing of unmodulated and modulated CW returns with microcomputers.

Extracts range info from modulated CW operating in diplex mode.

The signal consists of 10.7 GHz with a frequency deviation ΔF of 8 MHz switched at a 10 kHz rate.

In most commercial units of CW radar, the Doppler return is processed to remove noise, to select frequency range corresponding to human motion, and to integrate signal energy. The work done here directly processes the Doppler return without any prior filtering or integration.

Advancements in Leaky Cable Technology for Intrusion Detection, 1982, Carnahan

Used for perimeter intrusion sensors.

Use leaky coaxial cable for transmitting radar signal and another leaky cable placed parallel to it to receive return from a target. Lines are buried in ground.

Basically it is a bistatic radar.

Can be pulsed or CW.

If pulsed, range is given by delay of echo from transmitted pulse. Range is that measured along cable.

Down looking to exclude false-alarms from distant hot sources.

Used sweep-to-sweep cancellation and computer processing of sweeps.

Testing Intrusion Detection Devices for Probability of Detection, 1981, Carnahan

Discusses perimeter intrusion alarm systems.

A mathematical analysis which uses probability theory to show that a particular performance specification as dictated by NRC leads to intolerably high rejection rates for sensors and excessive manhours required for testing and maintenance.

Fiber Optics in Security Systems, 1981, Carnahan

Optical fibers can be used to make sensors that are sensitive to

- Pressure or sound
- Magnetic field
- Temperature
- Light
- Motion

Optical fibers can be used in intrusion detection through fiber breakage.

Although fibers have been developed mainly for communication to be resistant to environment, they can also be developed to be highly sensitive to these changes.

U. S. Government is developing these sensors under the FOSS program, (Fiber Optic Sonar System) through NRL.

G. L. Mitchell, "Survey of Fiber Optics Magnetic and Acoustic Developments," 1980, Western Design Engineer Show and ASME Conference.

J. D. Montgomery and F. W. Dixon, "Fiber Optics for Sensor Applications," 1980, Western Design Engineering Show and ASME Conference.

An optical fiber can be used to detect any sound in a room.

<u>CCTV as a Viable Aid in Bank Hostage Situations, 1981, Carnahan</u>

Mentions use of a concealed TV camera that uses a narrow diameter fiber optic bundle (.5") to receive the image.

<u>Prospects for Computer Vision in Security Systems, Carnahan, 1980</u>

In the most sophisticated commercially available systems, a scene can be monitored automatically to detect motion changes and using other hardware, the moving objects can be tracked for recording.

Currently available systems only alarm on motion but have no ability to ignore harmless motions or to detect subtle changes.

Computer vision technology under development for 20 years. Started as pattern recognition.

Computer vision systems capabilities:

Detection - one model for comparison - yes/no output.

Identification - several models for comparison - outputs name.

Analysis system - supplies information about relationships, quantity, position, and contexts of objects.

Implementation problems:

High cost - Vidicon + memory =	$2,000	$6,000 for non-real time.
computer	$4,000	$100,000 for real-time.

Lack of System Flexibility - need new set patterns for different installations.

Real time hardware is not presently available.

Lack of knowledge as how to apply.

A microcomputer-based video motion detector system, 1979, Carnahan

Used in Oak Ridge Y-12 plant.

Motion detected by digitizing and comparing successive video frames and making an alarm decision based on degree of mismatch.

500 pixels per camera.

Alarm decision basis:

1. Percent change of video signal AMPL of a pixel.
2. Number of suspect pixels to distinguish motion.
3. Proximity of suspect pixels.

Thresholds based on:

1. Camera coverage.
2. Detected object size.
3. Undetected object size.
4. Noise of video signal vs temperature.
5. Reference frame refresh rate.

50 pixels per line by 100 lines per frame.

Two suspect pixels on a single frame cause alarm.

Problems:

1. Image retention on regular video camera reduces sensitivity.
2. Blooming on bright objects. Careful placement of camera so that no lights or bright reflections were in the field of view.
3. Extraneous light sources generated false alarms, such as through windows or doors.
4. Vibrations
5. Temperature extremes - require local cooling of each camera.
6. Insects crawling over lens caused false alarms.

Resource Protection by Segmented Leaky Coaxial Cables, 1979, Carnahan

Loop of leaky cable surrounds resource to be protected. One or more monopoles act as receiver elements inside circle. As intruder crosses cable he disturbs field producing change in signal level received.

Microwave Respiration Monitor, 1978, Carnahan

Used microwave unequal path Michelson interferometer to monitor respiration in human beings. Output of device varied in step with torso expansion and contraction that accompanies respiration.

D.O.E. Sponsored Evaluations of Interior Intrusion Detection Systems, 1978, Carnahan, Sandia Labs.

"Intrusion Detection Systems Handbook" provides guidance in selecting, procuring, installing, testing, and maintaining elements in an intrusion detection system.

Work in Sandia is funded by D.O.E., safeguards and security organization.

Paper discusses interior intrusion detection system only.

Use of all three types (penetration, motion, and proximity) detectors yields maximum protection and minimum false alarm rates.

Sensor performance characteristics:

1. Probability of detection - $\frac{\text{Detected attempts}}{\text{Total Attempts}}$

2. False alarm rate - rate of alarms not attributable to adversary or intruder activity.

3. Vulnerability to defeat - can be reduced by tamper alarms, anticapture circuitry, line supervision, and full end-to-end self test capability.

Probability of detection must (be qualified by) consider also the environment, method of installation and adjustments and assumed intruder behavior.

Above also applies for the other two performance characteristics.

Sandia doesn't assign numbers to the performance characteristics. Instead it identifies the sensors capabilities and limitations.

Examples:

Sandia determines detection pattern as function of intruder velocity.
Causes of false alarms.
Methods to render a sensor useless.

Sensor detection patterns are generated two ways:

1. With regard to the most sensitive modes of operation of the particular sensor technology.

2. With regard to general modes of operation of different types of sensors.

The human factor is removed as much as possible from the tests.

In testing motion sensors, the human target holds onto the end of a string which is pulled along at a constant velocity by machinery toward or away from a sensor mounted on a rotatable platform.

Intruder - A motor driven manequin, controlled by an HP9825 calculator/controller. Adequate as is for an ultrasonic sensor. Needs aluminum foil wrap for microwave. Needs bottle of hot water for IR.

Electronic Intruder Simulator - Speaker or antenna that returns a frequency of a controllable difference from the transmitted frequency to test Doppler sensors.

Above systems allow temperature testing without human intervention.

Sandia also measures transmitted and received power by placing a microphone or antenna/meter away from sensor and measuring the power as a function of azimuthal angle from the field of view centerline.

Sandia uses Anechoic chamber also to determine free-field (no-reflections) response of sensors.

Automatic Movement Detection Applies to a Television Surveillance System, 1969, Dept. of Supply, Australian Defense Scientific Service

Subtracts incoming picture from one stored previously in a storage tube. When motion occurs a non-zero difference voltage is detected.

False alarm rejection methods:

> First threshold detector is triggered from any different signal and coordinates of disturbance point are stored.
>
> The frame difference signal within this area is integrated and if it exceeds a threshold an alarm is generated.
>
> A second window can be set up to only look at a selected portion of the raster.

APPENDIX B - REPRESENTATIVE TRANSDUCERS FROM COMMERCIAL VENDORS

TRANSDUCERS

SPECTRAL REGION	TYPE	TRANSDUCER	MAN & MODEL	SPECIFICATIONS	PRICE
Visible to near IR	RCV	Pin Photodiode	Litronix BPX63	Response: 550-1050nm Freq range: dc to 500Mhz beam width: 120^{o} sensitivity: $70\frac{na}{lx}$	$ 2.15
		Photo-Transistor	Litronix BPX81-4	Response: 580-1000nm rise time: 5 us beam width: 38^{o} sensitivity: $\frac{1.2ma}{mw/cm^2}$	.80
		Photo-Voltaic Cell	Litronix TP61	Response: 550-1010nm sensitivity: $1\frac{ua}{lx}$ beam width: 120^{o}	18.75
		Photoconductive Cell	Clairex CL703L	Response peak: 735nm resistance: 2.7 K at 2FC beam width: not given rise time: 20ms at 2 FC	2.23
		Photomultiplier	Centronic Q4183R	Response: 180-820nm sensitivity: $95\frac{ua}{lm}$ beam width: not given rise time: 12 ns; gain: 10^{7}	585.00
		Photodiode Array, 1 dimension	EG&G RL256G	Array: 128x1 response: 400-1000nm; spacing: 1 Mil clock: 10 Mhz max	750.00

TRANSDUCERS

SPECTRAL REGION	TYPE	TRANSDUCER	MAN & MODEL	SPECIFICATIONS	PRICE
Visible to near IR	RCV	CCD, TV formatted	RCA SIP52501AD	Response: 500-1000nm sensitivity: 65 ma/w Hor, Res: 240 TVL/PH Vert, Res: 425 TVL/PH	$1295.00
		Camera Tube	RCA 4535/U	Response: 440-900nm sensitivity: 720 $\frac{na}{lm}/ft^2$ image diag: 16mm diam: 1"; length: 6.38"	320.00
		TV Camera	RCA TC 1501/8	Response: 400-800nm sensitivity: 6.13 lx dimensions: 8"x4"x2.6"	285.00
	XMT	Lamps, incandescent	G.E. 100A21	Power input: 100W Life: 750 hrs; Lumens: 1690 Dim: 5¼x 3 7/8 in.	0.93
		Lamp, fluorescent	G.E. F40/CW/RS/WM	Power input: 34W Life: 20000 hrs; Lumens: 2510; Length: 48 in.	2.45
Visible to near IR		Led,IR	RCA SG1010	Peak response: 940nm Peak current: 10a pulsed Peak flux out: 26mcv pulsed Rise time: 900ns	2.00

TRANSDUCERS

SPECTRAL REGION	TYPE	TRANSDUCER	MAN & MODEL	SPECIFICATIONS	PRICE
Visible to near IR	RCV	Laser, IR	RCA C30130	Peak response: 820nm max flux out: 15mcv max current: 400ma rise time 1ns	$ 375.00
Far IR	RCV	Pyroelectric Cell	Amperex RPY-97	Response: 6.5-14μ Dual Element; Beam width: 130°; Sensivitity: 750V/W N.E.P.: 1.5×10^{-10} $w\sqrt{Hz}$	15.00
		Thermistor	Omega 44004	Resistance: 2252 @$25^{\circ}C$ TC: $-100\ \Omega/^{\circ}C@25^{\circ}C$ Interchangeability: $\pm.2^{\circ}C$	13.00
		Thermocouple	Omega IRCO-001	Material: Iron-Constanton TC: $52\ \mu v\ /^{\circ}C@25^{\circ}C$ mv@$25^{\circ}C$: 1.277	3.00
		Pyroelectric cell Array, 1 dimension	Spiracon IR-64-42	Response: 2-25u; Sens., pulsed: $3\times10^{4}V/J$; Array: 64x1; NEJ: 3.3nj	9890.00
		Pyroelectric Camera tube	Amperex S58XQ	Response: 8-14 μ sensitivity: $5na/^{\circ}C$ resolution: 300TVL/PH responsivity: 32 $\frac{ua}{W/cm^2}$ life: 3000 hrs	2500.00

TRANSDUCERS

SPECTRAL REGION	TYPE	TRANSDUCER	MAN & MODEL	SPECIFICATIONS	PRICE
r-f	XMT/ RCV	Doppler Transceiver	Microwave Assoc. MA-86859-MO2	Freq: 24.125GHZ; Power out: 5 mw ; sensitivity: -95DBC; Dim: .89x.89x1.45 Operation: Doppler I&Q	$ 150.00
		Doppler Transceiver	Microwave Assoc. MA-87105	Freq: 10.525 GHZ; Power out: 10MW; sensitivity: -115DBC; dim: 1.63x2.1x2.0 Operation: Varacter tuned, diplex capability	370.00
		Horn Antenna	Microwave Assoc. MA-86554	Center freq: 10.525GHZ Beam width: 30° Gain: 12DB Dim: 2.9x2.7x1.6	25.00
		Horn Antenna	Microwave Assoc. MA-86552	Center freq: 24.125GHZ beam width: 30° gain: 17DB dim: 1.8x1.4x1.7	29.00
Ultrasonic	RCV/ XMT	Ceramic	Massa TR-89B	XMT Freq: 37-45KHz XMT Pwr: 27db vs 1μb at 1' RCV Freq: 35-45KHz RCV Sens: -48db vs 1v/μb Beam width: 30° Dia: 1" Thick: 15/32"	13.00
		Electrostatic	Polaroid 8665	XMT Freq: 48-70KHz RCV Freq; 40-65KHz DC Bias: 150V AC Drive: 150 Vpk DIA: 1.7" Thick: .328"	15.00

TRANSDUCERS

SPECTRAL REGION	TYPE	TRANSDUCER	MAN & MODEL	SPECIFICATIONS	PRICE
Sonic to Subsonic	RCV	Ceramic Microphone	Telex Com, Inc. LUM-2	Response: 200-5000KHZ Output: -72dB re 1v/μb Z = 10K	$ 35.06
		Condensor Microphone	Ercona DC-20	Response: 30-20000Hz, ±3db omni-directional Sens: -46db/Pa; Output: 5MV/Pa	240.00
		Electret Microphone	Audio-Technica AT803R	Response: 20-20000Hz, ±3DB omni-directional Sens: -45dbm (Odb=1mcv/Pa)	210.00
		Dynamic Microphone	Audio-Technica AT802	Response: 50-15000Hz, ±5DB omni-directional Sens: 56dbm(Odb=1mw/Pa)	140.00
		Carbon Microphone	Telex Com, Inc. LUM-1	Response: 200-4000Hz Output: -41db at 6VDC, 100 Ω Load RE IV/μb	33.16
	XMT	Ceramic Speaker	Motorola KSN1025A/1033A	Response: 2-40KHz, ±5db beam width: 90° 6"x4"x2" Max cont volts across speaker: 20VRMS	33.00
		Electrostatic Speaker	None found	None found	
		Dynamic Speaker	Quam 69A2Z10	Response: 70Hz-15KHz, ±5dB 6"x9" oval; 8-10 wil Max power in: 8W	9.30

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