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A MICROWAVE TECHNIQUE FOR DETECTING AND LOCATING CONCEALED WEAPONS

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16. Abstract The subject of this report is the evaluation of a microwave technique for detecting and locating weapons concealed under clothing. The principal features of this technique are: (1) Persons subjected to search are not exposed to "objectional" microwave radiation; (2) A simple threshold detector can be used as the decision element obviating complex signal processing; (3) System operation does not require extensive operator training; (4) The resolution of the system (2 inches x 2 inches) permits location of a suspected weapon. This latter feature eliminates the need for a complete search of a passenger. Results of a loboratory measurement program are presented in support of the technique. An engineering analysis of the system implementation identifies an optimum operating frequency and an estimate of system cost is presented. Finally, several areas requiring additional experimental evaluation preceeding a system implementation are identified.

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PREFACE

The work described in this report was initiated by the Office of the Director of Technology and conducted in the Measurements & Instrumentation Division for the Office of the Secretary of Transportation. The principal objective was to establish the feasibility of using a microwave technique for detecting and locating concealed metallic weapons.

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INTRODUCTION

In recent years commercial airline hijackings have become recognized as a serious threat to public safety. This problem has generated a requirement to screen boarding passengers for the detection of concealed weapons. The possibility of detecting concealed weapons using a scanning microwave radiometer has been investigated. The radiometric technique investigated detects concealed weapons as regions of high microwave reflectivity against a background of human body tissues with lower microwave reflectivity.

REVIEW OF CURRENT TECHNOLOGY IN METAL DETECTORS

Common commercially available weapon detectors operate by detecting perturbations in a magnetic field produced by the introduction of a metallic object. Such instruments are unable to accurately locate or discriminate among metal objects carried by passengers. Consequently, false alarms are often produced by such innocuous items as metal shoe arches. In order to reduce an unacceptably high false alarm rate, the detection threshold is raised to a level at which small weapons or weapons concealed at unusual orientations may go undetected. If an alarm is sounded, a complete search of the passenger is required since location information is crude if it exists at all.

Far infrared imaging systems have been proposed for weapon detection. A basic limitation of all such systems is that clothing is nearly opaque at these frequencies. Furthermore, the detector technology is presently only in the research stage.

Microwave detection systems have a considerable advantage over far infrared systems since even heavy clothing is nearly transparent. However, the spatial resolution of a microwave system is limited by the longer wavelengths at microwave frequencies coupled with limitations on antenna aperture size. Presently, microwave imaging systems are being developed which use point source coherent radiation to illuminate a subject[1]. Such systems depend on specular returns from a weapon. The weapon orientation relative to the illuminator and receiver greatly affects detection possibilities. Such a system will require extensive operator training in order that weapons be detected at the same range as the human body which has a reflectivity of 0.5 to 0.3.

Two suggested microwave techniques which are less affected by weapon orientation are described below. A resonant scattering technique detects objects with specific geometries, such as the L shape of a gun[2]. The principle employed by this technique is to illuminate the object with a broadband RF pulse which induces modes on the surface of the object that are characteristic of the object's shape. The frequency structure of the scattered field is determined by these modes. In the receiver, the scattered return undergoes a Fourier transform to the frequency domain. The spectrum is sampled at various frequencies and correlated with typical spectra of "gun-shaped" objects. Consequently, a return does not simply indicate the presence of a metal object but more specifically indicates the presence of one or more predetermined shapes of interest. Such a detector required no trained operator, since the alarm decision is inherent to the detection system.

Another approach employs a form of microwave holography[3]. Only phase information in the receiving plane is used to reconstruct the image. The dependence of phase return on orientation is small, thus providing immunity from orientation effects.

SYSTEM CONCEPT

OBJECTIVE

The objective of this study was to assess the potential of developing a concealed weapon detector at microwave frequencies under the following constraints:

1. The passenger may not be illuminated by coherent microwave radiation. If there is to be any illumination, it must be of a type which, by its nature, is completely acceptable and requires no health or safety certification.

2. The system must not require extensively trained operators. The decision as to whether a weapon is present must be made without the influence of human judgment. This reduces operating costs and the effects of operator fatigue.

3. The system must not depend on any new component development because of the inherent cost and performance uncertainties.

4. System cost should be kept low.

5. False alarms must be acceptably low. False alarms are always a source of embarrassment for both airlines and passengers.

OPERATIONAL PRINCIPLES

A candidate system has been formulated which has the potential of meeting all objectives. The physical parameter of contrasting microwave reflectivity is the key principle of the microwave technique exploited for the detection and location of metal objects on passengers. In the microwave region considered (10 to 100 GHz), the human body tissues may be treated as lossy dielectrics with a microwave reflectivity of 0.5 to 0.3. In this same region the reflectivity of metals is almost perfect, assuring that nearly all the incident power is reflected. A system that can map reflectivity over the surface of a passenger will be useful in locating weapons as regions of high reflectivity.

To implement detection the passenger is illuminated by a spatially distributed source of amplitude-modulated microwave noise. The illumination is reflected by the body of the passenger and by concealed metallic weapons in accordance with their reflectivity. A receiver scans the passenger, and, if a metallic object fills a particular resolution cell of the scan, the reflected illumination will exceed that from surrounding cells. The cell is identified as containing a "suspicious" object. The noise source illumination is spatially distributed and has a broad radiation pattern so that specular reflection occurs for a large range of weapon shapes and orientations.

The microwave illumination noise used is at an extremely low power level. It is white noise uniformly distributed over the receiver bandwidth. When receiving noise-like signals of wide bandwidth, it is common to specify system parameters and power levels in terms of blackbody radiation temperature[4].

At microwave frequencies the brightness, I, of blackbody radiation is given by the Rayleigh-Jeans law

$$I = \frac{2kT}{\lambda^2}$$

where

I = Brightness, Joules/M^2
k = Boltzmann's Constant (1.38×10^{-23} joules/^{o}k)
T = absolute temperature, ^{o}k
λ = wavelength, m

The power received by an antenna when observing a region of uniform brightness is

$$P = 1/2\ IB \iint_{4\pi} A_e d\Omega$$

where

P = received power, watts
B = receiver bandwidth, Hz
A_e = effective antenna aperture, m^2
Ω = antenna beam solid angle, $(\text{radians})^2$

and $\iint_{4\pi} A_e d\Omega = \lambda^2$

Combining the above expressions, the total power received is given by

$$P = kTB$$

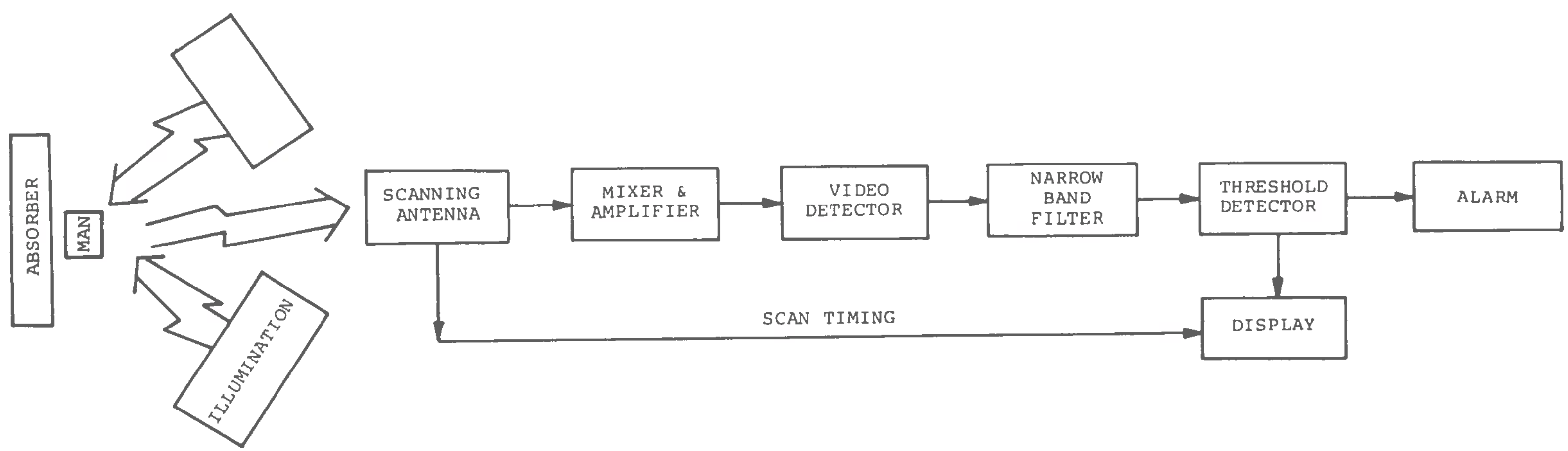


Figure 2. Simplified Block Diagram of Weapon Detector

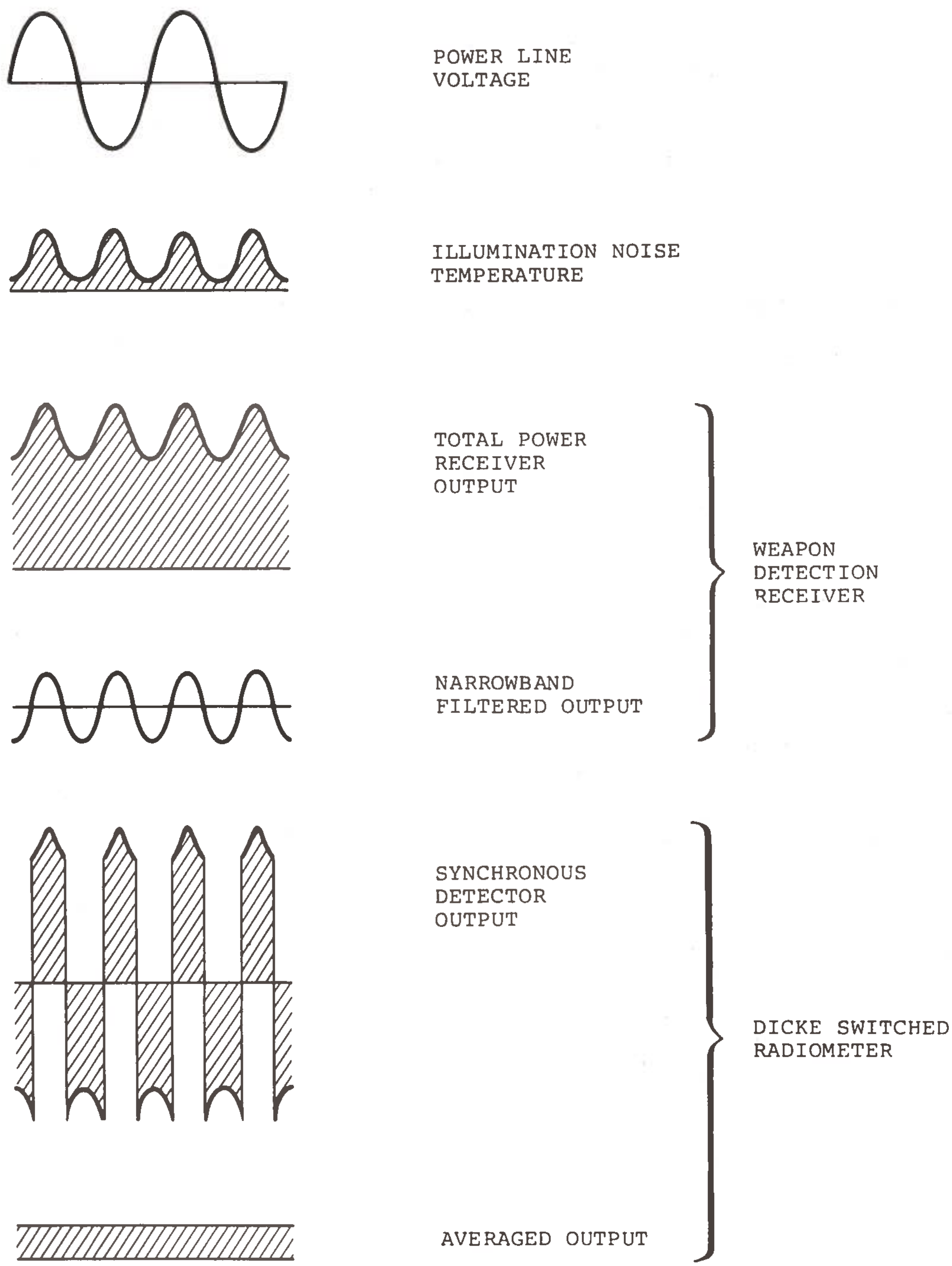


Figure 3. System Waveforms

seconds of a frame. In the next 1/120 of a second the scan drops verically by one resolution cell and another horizontal line is scanned in the period 9/120 to 18/120 seconds into the frame. This process continues until all 30 lines are scanned. The resultant 270 resolution cells are scanned in 270/120 seconds.

Figure 4 depicts a noise-free return from a line sweep containing nine resolution cells. The simulated materials scanned include absorber, human tissue and metal.

The signal processing consists of a detector set to trigger when the instantaneous ac amplitude from the receiver exceeds a preset threshold. The threshold should be set sufficiently high so that a return from human tissue with superimposed receiver noise does not exceed it frequently yielding an unacceptably high false alarm rate. In addition, the threshold must be below the level of the return from a weapon with superimposed receiver noise to permit detection. The possibility of having a satisfactory threshold as described above depends on the contrast between returns from human tissue and from a metallic object and on illumination signal to receiver noise ratio.

The output display is a bank of indicator lamps arranged to correspond to each of the resolution cells. If during a frame, one or more cells yield a return above threshold, the corresponding lamp or lamps are activated and remain in that state. An alarm is also activated to alert a guard who determines the nature of the object. The guard is directed to the location of the object by observing which lamps are activated. After such an incident, the guard initiates a reset and the system continues to screen passengers.

Figure 1 illustrates a simple screening procedure. A passenger enters from one side and stands in a referenced area. An automatic optical detector determines that the subject is in position and initiates the scan. Upon completion of a scan in which there are no returns above threshold, the subject reverses position. His back is scanned in identical fashion. If again there are no returns above threshold, the passenger leaves, and the next passenger enters to be scanned in the same manner.

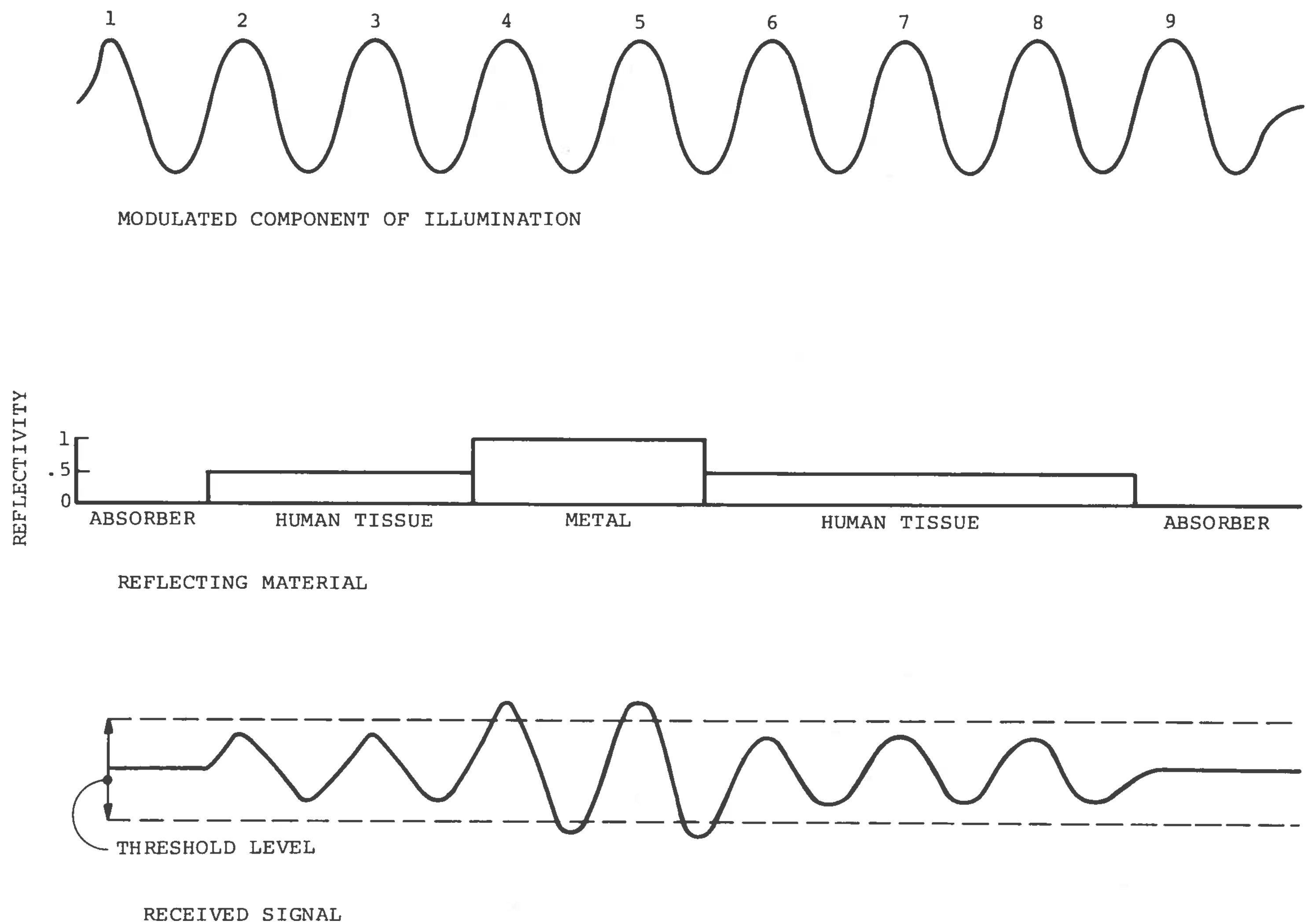


Figure 4. Simulated Noise-Free Signal From a Single Line Sweep

KEY ELEMENTS AND APPROACH

The ability of the system to operate as described in the previous section is dependent on several elements. Serious deficiencies in any one of these elements would preclude system implementation. This section identifies the key elements and outlines the approach to obtaining the required data.

HUMAN TISSUE REFLECTIVITY

The system operates by detecting weapons as regions of high reflectivity against human tissues of lower reflectivity: It is necessary that human tissue reflectivity be sufficiently different from the almost complete reflectivity of metals to permit adequate contrast for reliable detection. This evaluation requires values of human tissue reflectivity over the microwave region 10 to 100 GHz.

A literature search has uncovered measurements of the dielectric constants of human tissues in the 10 to 24 GHz region which agree with values calculated using Debye's equations[5]. At the higher frequencies, the literature search uncovered only calculated dielectric constants of human tissues. Dielectric data readily permit modeling of the human body as a planar structure. The approach was to use the available dielectric data to calculate a planar human reflectivity rather than to attempt measurements which would take into account actual human contours. Such measurements would be the logical subject of a continuing program if the candidate system shows promise.

RADIATIVE TRANSFER

Regardless of how large the initial contrast is between weapons and human tissues, the intervening clothing has the effect of reducing the contrast. This problem lends itself to an analytical approach using the well-established equations of radiative transfer[6].

All materials both absorb and emit radiation in accordance with their dielectric properties. The incident radiation brightness, I, is altered both by absorption and emission according to the requirements of conservation of energy. The change in brightness, dI, of radiation passing through a lossy dielectric is given by:

$$dI = -\alpha I ds + \eta ds$$

where

dI = change in brightness through a differential path length;
I = incident brightness;
α = absorption coefficeint per unit length;
η = volume emissivity;
ds = differential path length through the dielectric.

For materials in thermodynamic equilibrium, α and η are related by Kirchoff's Law, and the brightness, I, is identified with temperature through the Rayleigh-Jeans Law. Solution of the differential equation as applied to a homogeneous lossy dielectric at a uniform temperature, as illustrated in Figure 5, leads to the following result.

$$T_R = T_B \exp\left(-\int_0^S \alpha ds\right) + T_C \left[1 - \exp\left(-\int_0^S \alpha ds\right)\right]$$

where

T_R = received temperature, ^{o}k;
T_B = illumination temperature, ^{o}k;
T_C = absorber temperature, ^{o}k;
S = absorber thickness;
α = absorption coefficient per unit length.

Once the physical properties and thickness of the absorbing material are specified, the term multiplying T_C in the above equation is identified simply as the single path loss, L.

$$L = 1 - \exp\left(-\int_0^S \alpha ds\right)$$

Therefore,

$$T_R = T_B (1 - L) + T_C L$$

The effect of clothing in reducing contrast will be evaluated by applying the form of the last equation to multiple transmissions through clothing.

ILLUMINATION SOURCE

The candidate system places the following requirements on the illuminating noise source:

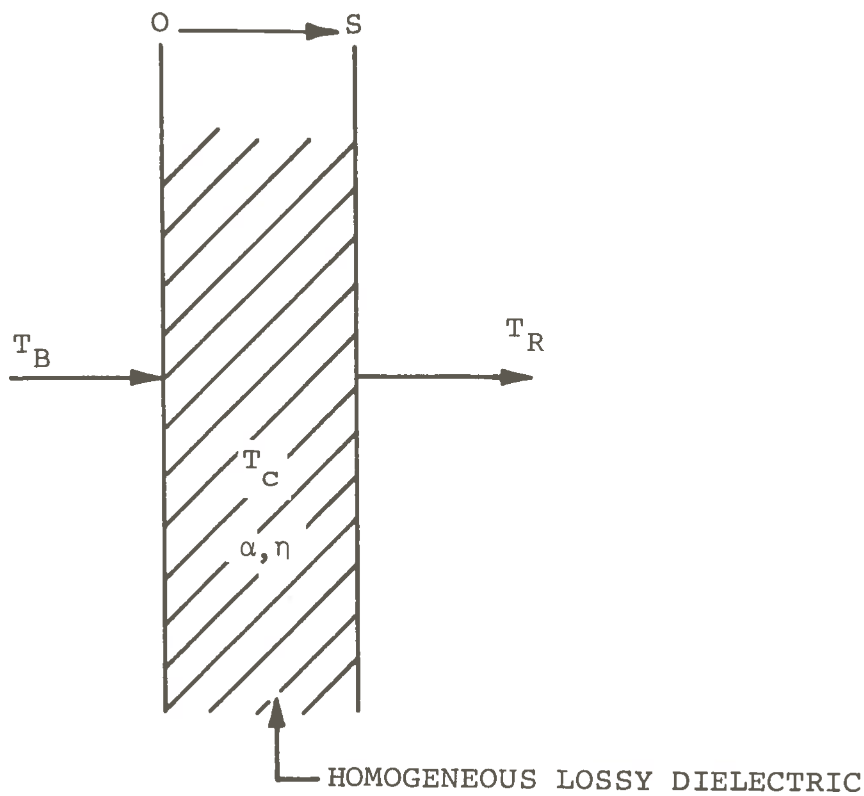


Figure 5. Radiative Transfer Through Homogeneous Material

1. The illumination must be intensity modulated at 120 Hz.

2. Since the system depends on specular reflection by a target, the illumination should be almost continuously distributed over the region in front of the passenger.

3. To permit reflections from a wide angular orientation of weapons, the illumination should have a broad radiation pattern.

4. The illumination intensity must be great enough to override receiver noise.

5. The illumination must be acceptable to the general public and clearly not considered as a health or safety hazard.

A gas discharge source such as the type used in fluorescent lamps or neon signs may meet all the requirements. There is a lack of engineering data concerning the use of gas discharges to generate microwave noise illumination in free space. Gas discharges are widely used to generate microwave noise in waveguide where dimensional and coupling problems have been solved[7,8]. In waveguide design, the discharge diameter is small compared to wavelength, and the discharge is introduced into the waveguide at a very shallow angle. It is possible to have a small discharge diameter in waveguide, because the length of the arc is short and it is well supported at its intersections with the waveguide walls. In order to obtain an extended free space source several feet long, it is necessary to have a discharge with a diameter of 1/4 to 3/4 inch for mechanical strength. The radiation is also required to be most intense normal to the lamp axis.

Due to the lack of available engineering data, the approach taken was to undertake laboratory measurements to determine significant characteristics of the microwave noise generated by gas discharges. In the course of the measurements six potential illumination sources were investigated at three frequencies in the 10 to 100 GHz region. The particular frequencies were determined by availability of receivers and other components.

RECEIVER

The proposed system requires a receiver which produces a voltage proportional to the illumination scattered back from human tissue or a metal weapon. It is necessary that the receiver noise level be low relative to the received backscattered illumination. Only with an adequate illumination to receiver noise ratio can the system function with a low false alarm rate.

An experimental approach was undertaken which permitted actual monitoring of receiver output with typical illumination levels. Three broadband microwave receivers were fabricated with center frequencies of 10, 35 and 94 GHz. The receivers including their microwave and IF sections are shown in Figure 6. The specifications of each are given in Table 1. All three receivers employ superheterodyne detection techniques.

The advantages of operating at 35 GHz became clear early in the experimental program. Consequently, most of the laboratory measurements were carried out at that frequency. A simplified block diagram of the 35 GHz receiver is shown in Figure 7. A klystron local oscillator at 35 GHz drives a balanced mixer which converts the double sideband RF (100 to 150 MHz either side of the carrier) to the intermediate frequency, IF, which is located at 100 to 150 MHz. Video detection after IF amplification provides a signal that is proportional to received noise temperature. A narrowband video filter centered at 120 Hz with an empirically chosen 54 Hz half power bandwidth is used to suppress noise outside the information band. The expected peak-to-peak amplitude for white noise filtered as described above is[4]

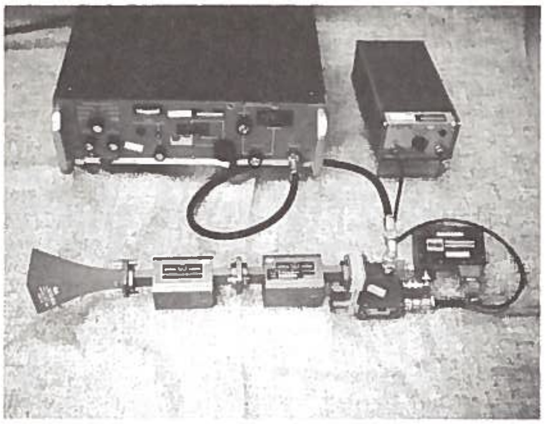
$$T_{pp} = \frac{6(T_R+T_A)}{\sqrt{B_{rf}/2B_V}} = 18.3^{o}k$$

where

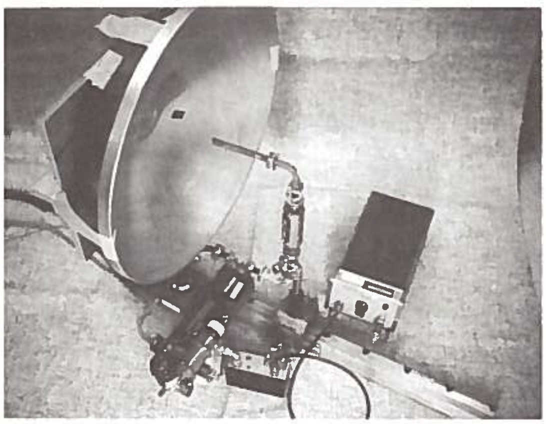
T_{pp} = peak-to-peak receiver noise temperature (^{o}k);
T_R = receiver temperature ($2{,}640^{o}k$)
T_A = antenna temperature ($\approx 290^{o}k$);
B_{rf} = double sideband bandwidth (100 MHz);
B_V = video bandwidth (54 Hz).

In the proposed system the filter output is monitored by a threshold detector. For the laboratory program the detected output was observed with an oscilloscope, as shown in Figure 8, in order to visually observe signal and noise amplitudes. Figure 9 represents the filtered output with peak-to-peak illumination of $0^{o}k$, $35^{o}k$ and $70^{o}k$. Random receiver noise is present in these outputs.

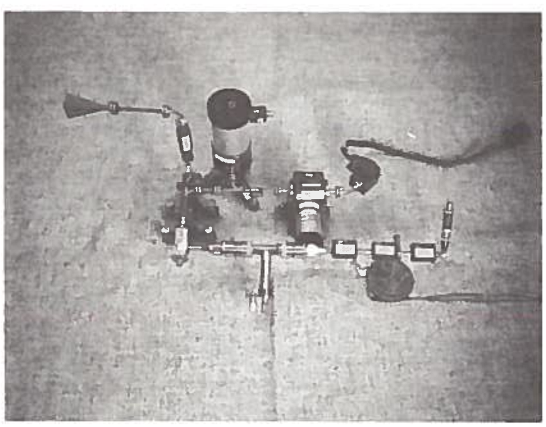
In the laboratory program the receivers are also used for calibrating and adjusting the illumination sources. This is



10GHz



35GHz



94GHz

Figure 6. Receivers: Microwave and IF Sections

TABLE 1. RECEIVER SPECIFICATIONS

RECEIVER FREQUENCY	RECEIVER BANDWIDTH DSB	RECEIVER TEMPERATURE ^{o}k	PEAK TO PEAK NOISE (ΔT_{pp})		MIN. SOURCE TEMP. FOR S/N=4
			DICKE RADIOMETER 1 SECOND INTEGRATION	SYSTEM RECEIVER POST DETECTION BW OF 54 HZ	
10 GHZ	44 MHz	1,270^{o}k	3.1^{o}k	14.6^{o}k	58^{o}k
35 GHz	100 MHz	2,640^{o}k	3.9^{o}k	18.3^{o}k	73^{o}k
94 GHz	1,800 MHz	25,400^{o}k	8.0^{o}k	32.8^{o}k	131^{o}k

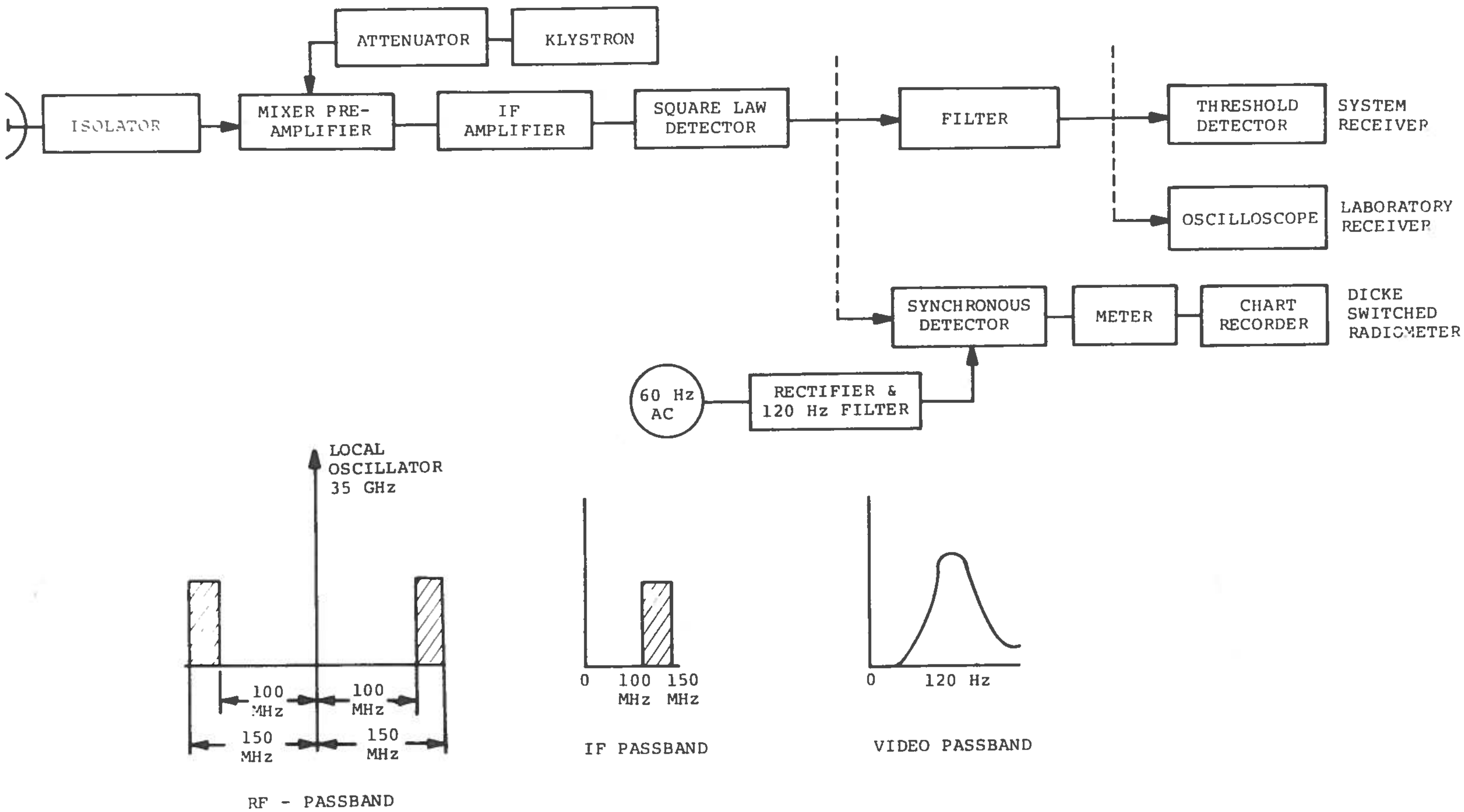
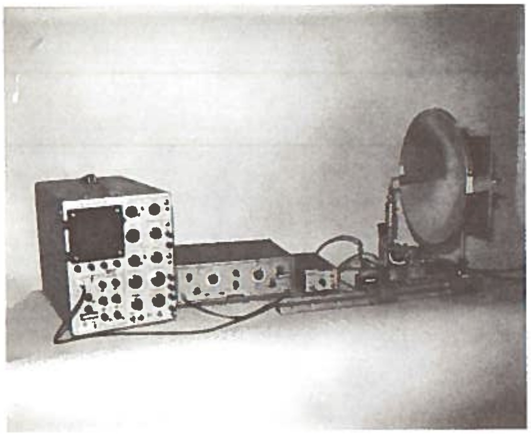
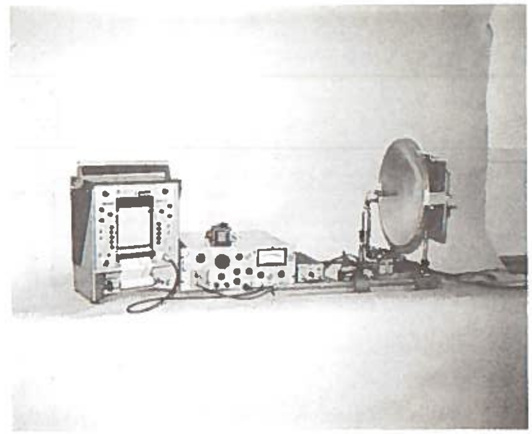


Figure 7. Block Diagram and Passbands of 35 GHz Receiver



8a Laboratory Receiver



8b Dicke Switched Radiometer

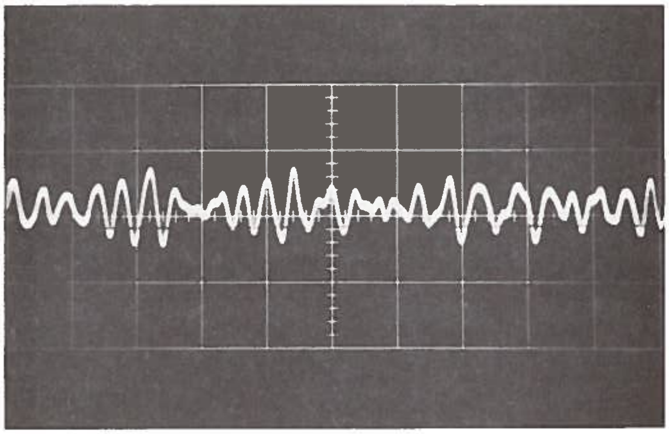
Figure 8. System Evaluation Setups at 35 GHz

accomplished by configuring the signal processing to conform to a Dicke switched radiometer[4]. In this case a synchronous detector and strip chart recorder replace the video filter and oscilloscope as shown in Figures 7 and 8. A synchronous detector subtracts signal amplitudes at half cycle intervals of the 120 Hz component and averages the resultant signal with a one-second time constant, as depicted in Figure 3. The averaged output is proportional to the 120 Hz component of the lamp noise. Calibration is accomplished by comparing the average signal with the peak-to-peak fluctuations of the output noise. The amplitude of the noise fluctuations for a Dicke switched radiometer receiving white noise is[4]

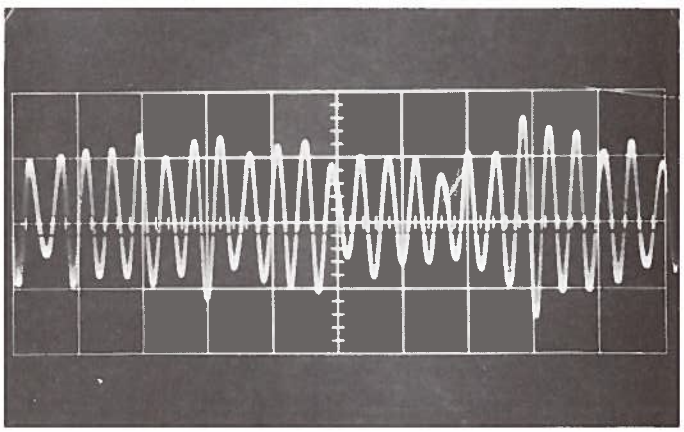
$$T_p = \frac{6\pi(T_R+T_A)}{\sqrt{2\tau\, B_{rf}}} = 3.9^{\circ}k$$

where

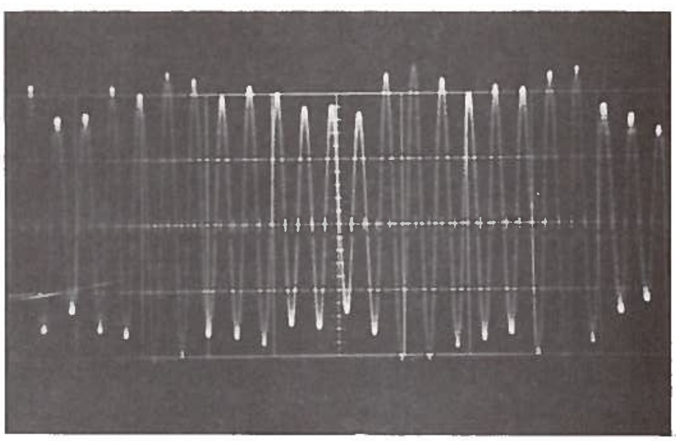
T_p = peak-to-peak radiometer noise temp (°k);
T_R = receiver temperature (2,640°k);
T_A = ambient temperature (290°k);
B_{rf} = double sideband bandwidth (100 MHz);
τ = integration time constant (1 second).



NO ILLUMINATION
(PURE RECEIVER NOISE)



35°K, 120 Hz
Illumination
and Receiver
Noise



70°K, 120 Hz
Illumination
and Receiver
Noise

Figure 9. Filtered Output With Receiver Noise and Modulated Illuminating Signal

ANTENNA

The receiver in both the proposed system and the experimental program requires a focused aperture antenna providing 2-inch half power beamwidth at the focal plane 80 inches from the antenna. If a sector of an ellipsoid is used as a reflector, the feed is placed at one focus and the image plane is located at the other focus. In these experiments, at 35 GHz an ellipsoidal reflector was unavailable. An 18-inch parabola with a focal length of 4.5 inches was substituted. Over its small area the 18-inch parabola was calculated to be dimensionally within a few hundredths of an inch of an ellipsoid, with a 90-inch major axis and a 41-inch minor axis. The parabolic reflector is fed from the focal distance of the ellipse to obtain focused operation in the Fresnel region. The feed is open-ended waveguide WR-28, resulting in an 8.5 dB edge taper[9]. With this edge taper it is possible to calculate the beam pattern in the focal plane at 80 inches[10]. The calculated full width to half power points is 2 inches.

In the laboratory a slit aperture was scanned over a distributed noise source and viewed by the 35 GHz receiver and antenna. Both the E-and H-plane patterns were mapped yielding a 2-inch resolution in agreement with the calculations.

RESULTS

This section presents the results of the literature search, calculations and laboratory measurements. In a final experiment the illumination sources and receivers were used at 35 GHz to simulate system performance from planar reflecting materials.

HUMAN TISSUE REFLECTIVITY

A stratified model for simulating the body's microwave reflection characteristics consists of a skin 2 to 4 millimeters thick over a fat layer 0 to several centimeters thick with underlying muscle of semi-infinite extent[11]. The skin and muscle, being tissues of high water content, have large dielectric constants in the 10 to 100 GHz microwave region. Fat tissue has a much lower dielectric constant and at the lowest frequencies considered can act as a transformer changing the coupling between skin and muscle tissue[11].

Table 2 lists dielectric constants of water, skin, fat, muscle and whole blood with reference to the source of data. References 12 and 13 are measured data while the high frequency data of References 11 and 14 are calculated using the Debye equations[5].

An expression for calculating normal incidence reflectivity from a semi-infinite dielectric is[15].

$$r = \left| \frac{1 - \sqrt{\varepsilon' + j\varepsilon''}}{1 + \sqrt{\varepsilon' + j\varepsilon''}} \right|^2$$

where

r = microwave power reflectivity;
ε' = real component of complex dielectric constant;
ε'' = imaginary component of complex dielectric constant.

Reflectivity has been calculated for several materials and frequencies and is listed in Table 2 following the dielectric constants. Over the 10 to 100 GHz frequency range skin reflectivity for normal incidence varies from 0.53 to 0.30. In particular the reflectivity at 35 GHz is 0.45. On the basis of the decreasing reflectivity of skin with increasing

TABLE 2. DIELECTRIC PROPERTIES

FREQUENCY GHz	9.4	23.6	35	60	100	
WATER 20°C	ε' 61.5 ε'' 31.4	ε' 30.8 ε'' 35.2 r=.59	ε' 24 ε'' 30 r=.56			Ref. 12
SKIN 37°C	ε' 35.5 ε'' 16. r=.53	ε' 23 ε'' 13 r=.47				Ref. 13
WHOLE BLOOD	ε' 45 ε'' 23	ε' 32 ε'' 20				Ref. 13
FAT	ε' 4.5 ε'' 0.95	ε' 3.4 ε'' 1.1				Ref. 13
SKIN	ε' 36 ε'' 16	ε' 23 ε'' 20	ε' 14 ε'' 16 r=.45	ε' 9 ε'' 13 r=.41		Ref. 14
MUSCLE	ε' 42 ε'' 22	ε' 20 ε'' 24	ε' 15 ε'' 20 r=.48	ε' 9 ε'' 15	r=.30	Ref. 14; Ref. 11 (100 GHz)

frequency, it is desirable to operate at as high a frequency as possible.

In the low frequency region, at 10 GHz, incident radiation decays to e^{-1} of its surface value at 1.3 mm[11] in skin tissue. Since human skin is 2 to 4 mm thick, a portion of the radiation reaches the fat layer where it propagates with little attenuation to the muscle tissue. Depending on the thickness of the fat layer, the reflections at the tissue interfaces add or cancel. The net result is a reflectivity at the air-skin interface dependent on body fat thickness. Assuming a skin thickness of 2 mm, the reflectivity can vary as much as ±5 percent at 10 GHz[11]. Extrapolating to 20 and 30 GHz, only ±1 percent and ±.05 percent variations, respectively, are possible. The 1 percent variation at 20 GHz is considered the largest acceptable variation in skin reflectivity. Therefore, 20 GHz is considered the lowest practical frequency of operation for the proposed system.

CONTRAST THROUGH CLOTHING

The expected value of contrast between human skin and a metal object concealed under clothing is calculated in this section. The equations of radiative transfer previously introduced are used for this calculation. Figure 10 is the model used in calculating the effect of attenuating clothing.

The incident illumination is defined as

$$T_B \quad (1)$$

After passing through the clothing the radiation incident on the reflector (man or weapon) is

$$T_B(1 - L) + T_C L \quad (2)$$

where

T_B = incident illumination temperature, °k;
T_C = temperature of lossy clothing, °k;
L = single pass loss through clothing.

After reflecting from the man or weapon the radiation incident on the clothing for a second time is

$$\{T_B(1 - L) + T_C L\} r + T_R(1 - r) \quad (3)$$

where

r = reflectivity of man or weapon;
T_R = temperature of the reflector.

Finally, the radiation emerging from the clothing toward the receiver is

$$\left[\left\{T_B(1-L) + T_C L\right\} r + T_R(1-r)\right](1-L) + T_C L \qquad (4)$$

When the reflector is human skin, reflectivity is redefined as $r = r_s$, which may vary between 0.3 and 0.5. The loss is small, $L^2 \ll 1$, permitting terms containing (L^2) to be dropped. Thus, the received radiation is

$$r_s\left\{T_B(1-2L) + T_C L\right\} + T_C L + (1-r_s)T_R(1-L)$$

for skin. If the reflector is a metallic object the reflection is complete, $r = 1$, and the received radiation is

$$T_B(1-2L) + 2T_C L$$

for metal.

In the system only the alternating component of the illu-

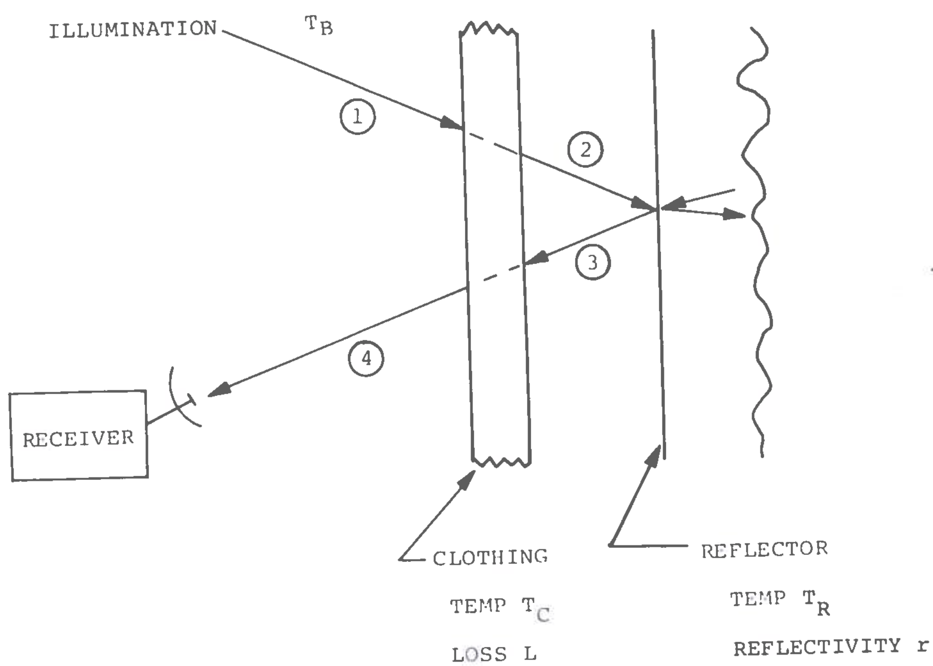


Figure 10. Transmission Through Clothing

mination, T_B, is used for detection. The alternating component varies in a sinusoidal manner, with a peak-to-peak amplitude of T_p. Therefore, the alternating component of the return has amplitude

$T_p(1-2L)$ for metal

and

$r_s T_p(1-2L)$ for skin

where

T_p = peak-to-peak amplitude of illumination, ^oK.

Thus, the anticipated contrast is

$$\Delta T_{120Hz} \Rightarrow (1-r_s)T_p(1-2L)$$

Normally, L is quite small and r_s is between 0.5 and 0.3, depending on frequency. For 35 GHz, a reasonable value of L is 0.05. Using an r_s of 0.45 the resultant contrast is

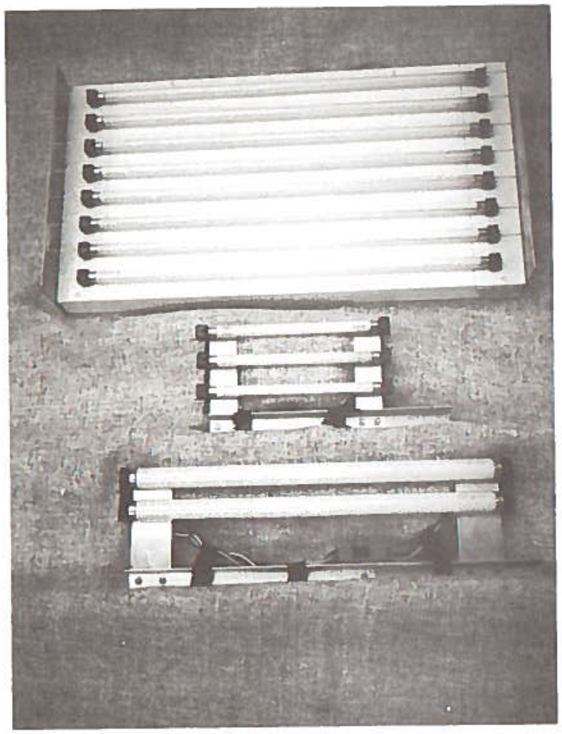
$$\Delta T_{120Hz} \Rightarrow 0.5\ T_p$$

ILLUMINATION

The six gas discharge illumination sources which were evaluated in the experimental program are shown in Figure 11. Three of the sources use common fluorescent lighting lamps in which a low pressure mercury discharge is the radiation source. Two of the sources are neon-filled grids such as are used in outdoor advertising. The last source is a high intensity laboratory neon arc. In the fluorescent lamp and neon grid sources, the spacing between tubes is a uniform 1.5 inches.

In the course of the experimental evaluation it was found that the noise from each of the sources is linearly polarized with the electric field, E, orthoginal to the lamp axis. The measured illumination intensity was found to be a function of the angle between the lamp axis and the receiver. In this measurement the receiver was moved in the plane containing the lamp axis. This will be referred to as the axial plane. In the axial plane the beam pattern depends on the shape of the reflector and on lamp type. Some examples of axial-plane patterns for different reflectors evaluated in conjunction with the 8-tube fluorescent lamp fixture are shown in Figure 12. The white painted reflector, on which the lamps are mounted in standard fixture construction, produces a peak intensity 25 degrees off normal. An aluminum plate pressed firmly against the lamp almost

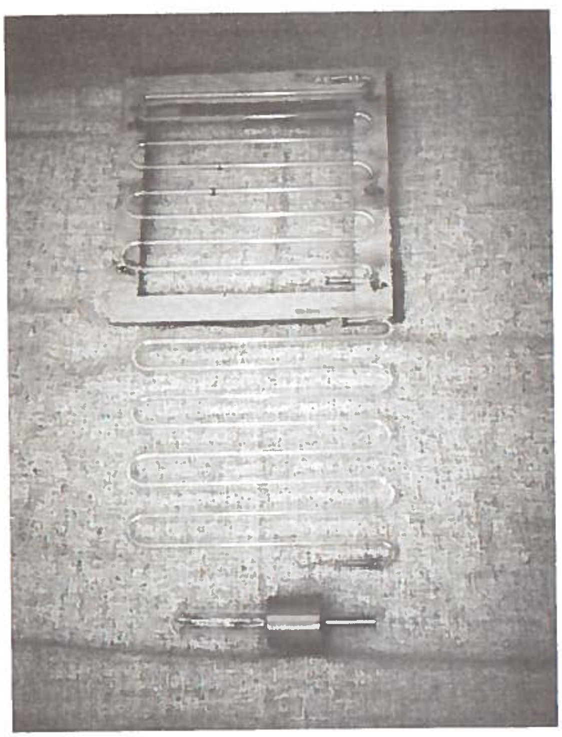
TUBE TYPE



FLUORESCENT
F 13 T 5

FLUORESCENT
F 6 T 5

FLUORESCENT
F 15 T 8



NEON
10 mm

NEON
13 mm

NEON ARC

Figure 11. Illumination Noise Sources

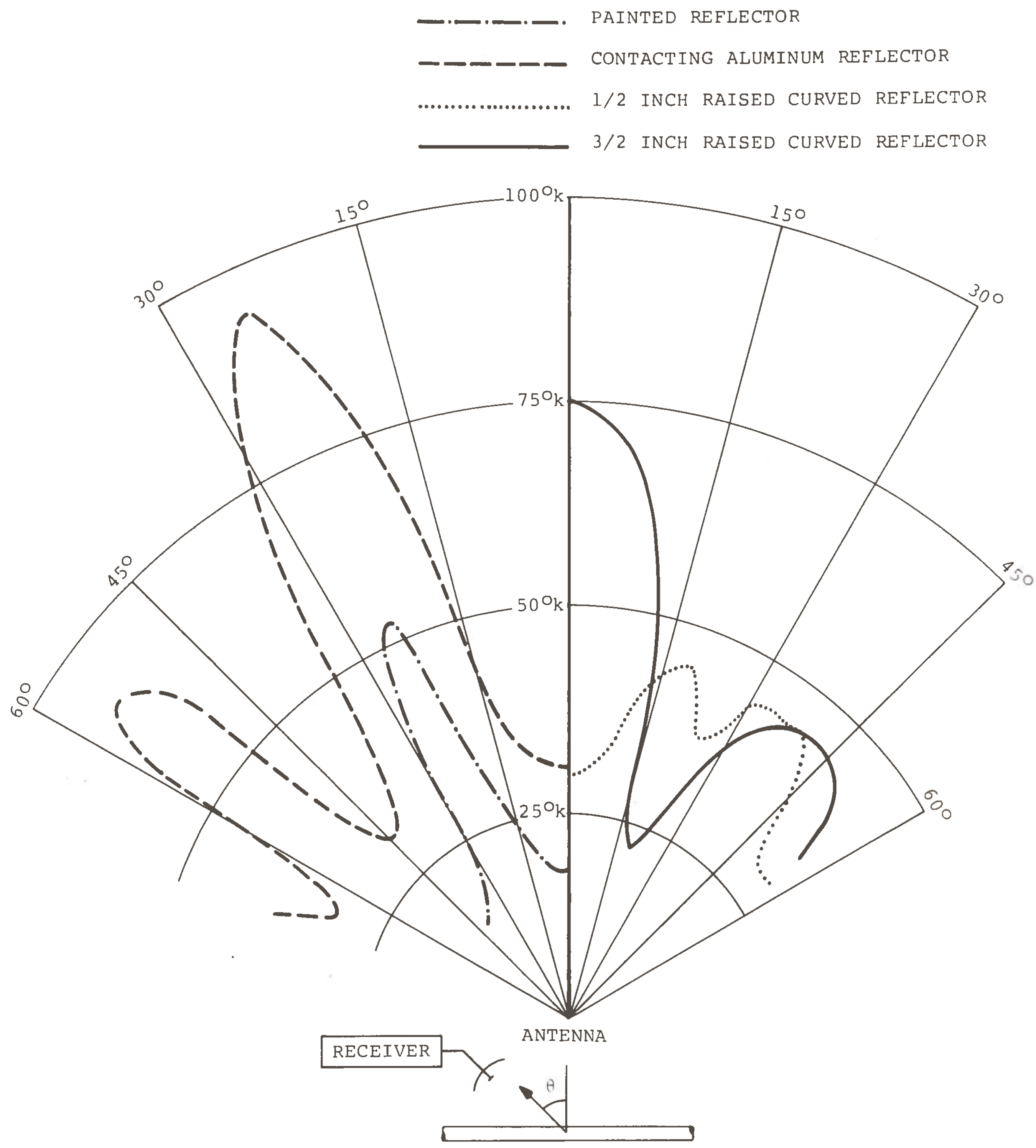


Figure 12. Axial-Plane Patterns for 13T5 Lamps

doubles the intensity while the beam structure remains similar. Another reflector was fabricated by running wires between adjacent lamps at a height of 0.5 inch above the lamp axis. Aluminum foil was run under the lamps and over the wires to result in a curved reflector. This resulted in a marked change in the axial pattern. The peaks became lower and closer to the normal direction. When the wires were spaced 1.5 inch above the lamp axis and a different curved reflector was fabricated with aluminum foil, the pattern changed again. The greatest intensity is normal to the lamps, and the axial pattern has a half power total beamwidth of 30 degrees. None of the axial patterns obtained are satisfactory. A half power beamwidth of 90 degrees is desired to permit a return from a wide angular orientation of weapons. Laboratory experimentation is required to determine if a suitable reflector can be developed to provide a broad beamwidth without a significant reduction in normal intensity.

Comparison of five of the sources at 35 GHz was accomplished in the laboratory using the previously described receiver, configured as a Dicke switched radiometer. For these measurements, each source in turn was positioned at the focal plane of the 18-inch focused aperture antenna.

Because of individual peculiarities of the lamps and time limitations, identical reflectors were not used for all the lamps measured. Details of the results are described below.

1. The 8-lamp fluorescent source used F13T5 tubes. The previously described curved reflector supported 1.5 inches above the lamp axis was employed in these measurements. The peak radiation of 73°k occurred normal to the lamp exis.

2. The 3-lamp fluorescent source used F6T5 tubes. A flat aluminum reflector was in close contact with the tubes. The peak radiation of 216°k occurred 20 degrees either side of the normal to the lamp axis.

3. The 2-lamp fluorescent source used F15T8 tubes. A flat aluminum reflector was in close contact with the tubes. The peak radiation of 45°k occurred 10 degrees either side of the normal to the lamp axis.

4. The neon grid was constructed of 10 millimeter diameter glass tubing. To prevent arcs from the high voltage power supply, a flat aluminum reflector was spaced 2 inches behind the lamp. The peak radiation of 17°k occurred normal to the lamp.

5. The neon arc source, an Osram lamp, produced peak radiation of 91°k normal to its axis without the use of a reflector.

A summary of the results is given in Table 3. The highest intensity measured was the 20 degrees off normal radiation of the three lamp fluorescent source using F6T5 lamps. This radiation lobe is very narrow. With a reflector designed to enhance normal radiation and to broaden the beam, this source would probably give performance comparable to the 8-lamp fluorescent source using F13T5 lamps. Both sources employ lamps of 5/8 inch diameter with comparable power densities. The 8-lamp fluorescent source with a curved reflector is considered as the best source among those evaluated.

Three of the sources were also measured at 10, 35 and 94GHz to determine frequency dependent characteristics. The receivers were configured as Dicke switched radiometers. For this evaluation, open-ended, single mode rectangular waveguides at each frequency were used as antennas. The 8-tube fluorescent lamp and neon grid were measured one foot in front of the open-ended waveguide. The high intensity neon discharge was measured at a 4-inch range. The results are shown in the last column of Table 3.

This latter measurement indicates that the power received decreases approximately as the inverse of the square of frequency. Thus, operating at a frequency $35/\sqrt{2}$, or 25GHz, the received power should be twice that measured at 35GHz.

TABLE 3. LABORATORY MEASUREMENTS OF MODULATED NOISE LAMP OUTPUT

LAMP TYPE	TEMPERATURE ^{o}K AT 35 GHz	AXIAL PLANE RECEIVER ORIENTATION	FREQUENCY GHz	TEMPERATURE ^{o}K 1 FOOT FROM OPEN WAVEGUIDE
F 13T5	73	NORMAL	10	495
			35	34
			94	5.4
F 6T5	216	20^{o} OFF NORMAL	-	
F 15T8	45	10^{o} OFF NORMAL	-	
NEON 10MM	17	NORMAL	10	205
			35	5.7
			94	-
NEON ARC	91	NORMAL	10	ERRATIC
			35	45
			94	9.6

On the basis of the illumination power received, it is most advantageous to operate at as low a microwave frequency as possible.

SIMULATED SYSTEM OPERATION AT 35GHZ

Of the illumination sources evaluated the most suitable for system operation at 35GHz is the eight-lamp fluorescent fixture employing the 1-1/2-inch high curved reflector. The peak-to-peak output of the illumination normal to the fixture is approximately 70°k. If this source is used for illuminating planar metal or human tissues, the received signals will be identical to the 70°k and 35°k illumination levels which are shown in Figure 9. In this case the illumination signal to receiver noise ratio is approximately 4. Receiver peak-to-peak noise was previously calculated as 18.3°k. By examining the traces in Figure 9, it is seen that the highest peaks with a 35°k received signal are comparable in amplitude to the lowest peaks for a 70°k received signal. This is an entirely expected result. The peak amplitude for skin reflections of 17.5°k plus in-phase peak noise amplitude of 9.1°k approximately equals the peak amplitude for reflection from metal of 35°k less the out-of-phase peak noise amplitude of 9.1°k.

$$17.5^{\circ}k + 9.1^{\circ}k \approx 35^{\circ}k - 9.1^{\circ}k$$

Thus, an illumination signal to receiver noise ratio of 4 is the minimum illumination, which under ideal operating conditions can yield error free operation. Under actual operating conditions a S/N of 4 should be expected to lead to occasional false alarms or misses. Obviously, an actual system will require a higher signal-to-noise ratio for satisfactory operation. An S/N of 10 appears desirable.

To simulate system operation for planar reflectors, the 35GHz receiver, eight-lamp fluorescent illumination source and a rotating mechanical chopper were configured to provide alternating reflectivities of 1 and 0.25. Reflectivity of 1 is provided by the metal paddle of the chopper and reflectivity of 0.25 is provided by a lossy dielectric behind the paddle. The experimental configuration is shown in Figures 13 and 14. Figure 15 shows the output waveforms of the receiver for this simulation. The transitions are not sharp because the rotating paddle is partially present in the resolution cell during transitions from reflectivity of 1.0 to 0.25. Increasing video bandwidth did not sharpen the transitions. The effect of several layers of heavy wool clothing is not significant, as shown in Figure 15. From these results it again appears that a signal-to-noise ratio equal to 4 is the minimum illumination condition.

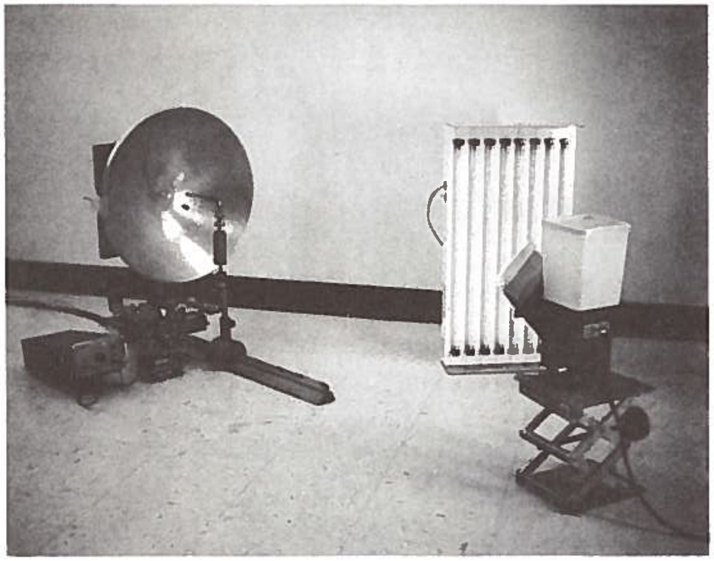


Figure 13. Configuration Used to Produce Alternating Reflectivities

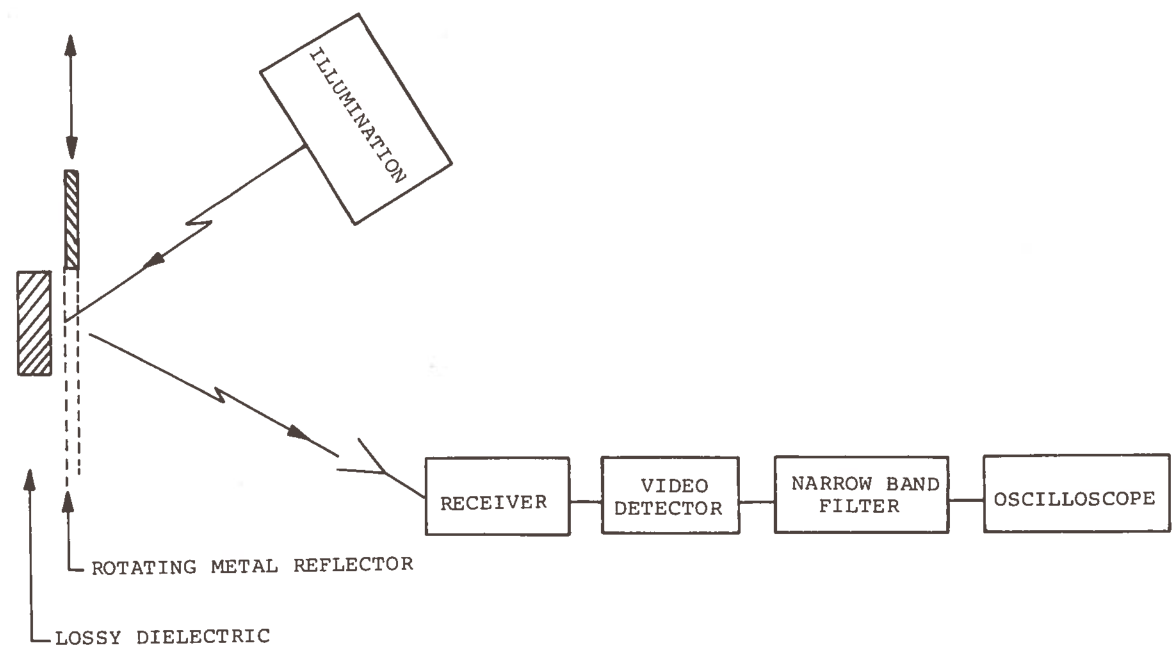
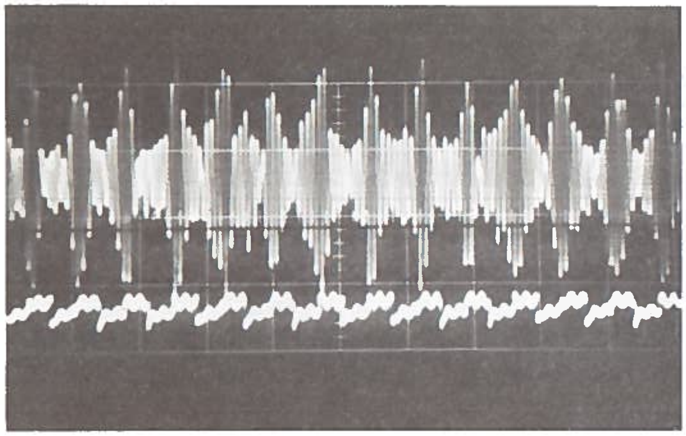
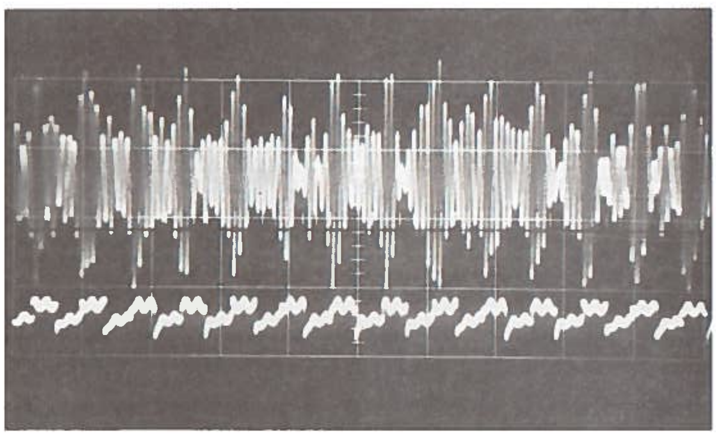


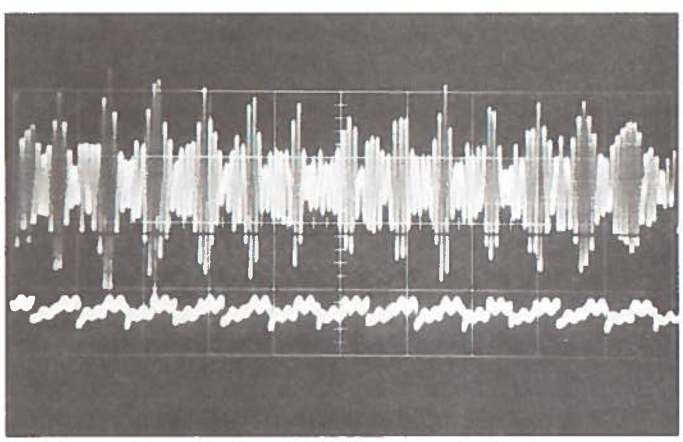
Figure 14. Block Diagram of System Simulation Setup



No Clothing



2 Layers Heavy
Wool Cloth



2 Layers Heavy
Wool Cloth and
2 Layers Foam
Backed Wool
Overcoat

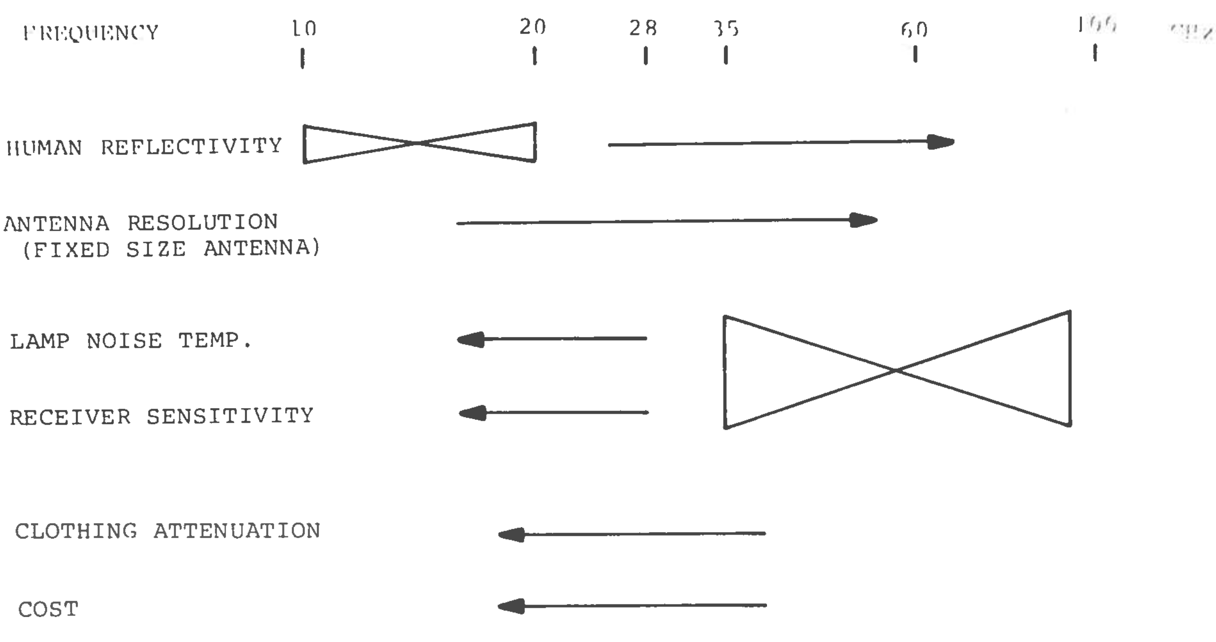
Figure 15. Alternating Reflectivities of 1.0 and 0.25 With Attenuating Clothing

CONCLUSION

The simulated system operation at 35GHz demonstrates the ability of the proposed system to discriminate between planar lossy dielectrics and metals. With further reflector design, fluorescent lamps show promise of being suitable sources of illumination, and receivers providing adequate system sensitivity below 35GHz are available.

Through the study of the individual aspects of the system, an optimum choice of operating frequency is possible. Figure 16 summarizes the aspects affecting frequency selection. The optimum frequency of operation lies between 20 and 35GHz. The various aspects are reviewed below.

The human reflectivity data indicate that system operation should be limited to frequencies above 20GHz. The ±1 percent variation of reflectivity at 20GHz due to the effects of fat layer thickness is considered the largest tolerable variation. Reflectivity monotonically decreases with frequency in the 10 to 100GHz region. The smaller the human reflectivity, the greater will be its contrast with metals. Therefore, it is desirable to



ARROWS INDICATE FREQUENCY PREFERENCE

Figure 16. Subsystem Frequency Preferences

operate at as high a frequency above 20GHz as possible.

In the laboratory evaluation an 18-inch diameter antenna was used to obtain the required 2-inch by 2-inch resolution. To maintain this resolution the diameter of the antenna must be scaled with wavelength. At 20GHz the antenna would need to be 75 percent larger in diameter. Such a size would greatly hinder scanning possibilities. On the basis of having a reasonable antenna size, high frequency operation is preferable.

Human reflectivity and antenna considerations both indicate preferred operation at the highest frequencies considered. It will be seen that the balance of the system aspects call for operation at the lowest frequencies.

Receivers are less sensitive at higher frequencies, primarily because of inefficiencies in the superheterodyne mixing processes. The last column of Table 1 lists the illumination source temperature that will provide the minimum illumination signal to receiver noise ratio of 4 for the three receivers configured in these experiments. Note that the 94GHz receiver requires the highest illumination temperature while the 10GHz receiver requires the lowest. The sensitivity of the 10GHz receiver could be further improved by using a slightly larger IF bandwidth. A two-fold increase in IF bandwidth will increase receiver sensitivity by $\sqrt{2}$.

The requirement for more intense illumination at higher frequencies conflicts with actual lamp performance. Measurements indicate that for the sources tested power detected by a receiver decreases as the inverse of the square of frequency. Since only the marginal illumination signal to receiver noise of 4 was achieved at 35GHz, it is obvious that operation must be at a frequency somewhat below this.

The improvement at slightly lower frequencies is dramatic. Using the eight-lamp fluorescent illumination source and a receiver of 100MHz IF bandwidth with a center frequency of 28GHz, a S/N of 10 is within reach. This is exactly the S/N level that an operating system should have for reliable operation.

As shown in Figure 15, the effect of clothing at 35GHz is small. However, attenuation increases linearly with frequency. Therefore, it is preferable to operate at the lower frequencies.

Finally, cost considerations make operation at the lower frequencies preferable. Receivers above 40GHz are not production items. The mixers and preamplifiers often require special development which can become prohibitively expensive. Below 40GHz receivers find many applications and are built on a semi-production basis.

Based on all aspects of the system, 28GHz is concluded to be the optimum operating frequency.

SYSTEM COST ESTIMATE

A cost breakdown for major components of the microwave concealed weapon detection system is presented in Table 4. The fluorescent lamps and their individual ballast transformers constitute a major expense. One hundred sixty of the 20-inch 13T5 lamps are required. Ballasts are available only for individual lamps so that 160 ballasts are also required. Considerable economy would be realized if longer fluorescent lamps were utilized for which multiple lamp ballasts are available. The noise source cost would be cut by more than 50 percent.

The primary expense for a vendor supplied focused aperture antenna is the initial design. Thus, while a first antenna costs $1000, additional units in lots of 10 would cost under $300 each.

Savings in large quantity purchases of the other electronic components will be far smaller since they already are standard components, while the cost of the scanning and structure are only rough estimates.

The estimated cost of components for each system in quantities over 10 is $5000. Assembly costs for a system manufacture are approximately three times the component costs. It should be possible to manufacture a complete system for $20,000 in production quantities once a prototype exists.

TABLE 4. SINGLE SYSTEM COMPONENT COST ESTIMATE

FLUORESCENT LAMPS (13T5)	320
BALLASTS	1,280
FIXTURE	500
ANTENNA	1,000
28 GHz RECEIVER	1,300
IF AMPLIFIER	400
SOLID STATE LOCAL OSCILLATOR	750
VIDEO DETECTOR & NARROWBAND VIDEO FILTER	150
THRESHOLD DETECTOR & DISPLAY	300
SCANNING	500
MICROWAVE ABSORBER	100
DC POWER SUPPLIES AC WIRING	200
STRUCTURE - WOODEN FRAME, CURTAINS, RUGS	600
TOTAL	7,400

UNRESOLVED ISSUES PRECEDING SYSTEM IMPLEMENTATION

Certain questions regarding system performance could not be considered in detail during the period of this program. The items requiring further work are spelled out in this section. In each case possible approaches to resolving the questions are presented.

SCANNING

The best scan pattern and the method of achieving the scan have not been considered in detail. The requirement is to scan an area of 18-inch width and 60-inch height. This is comparable to the trunk and legs of an average person. The resolution cells are to be 2 inches by 2 inches. If a rectalinear grid of resolution cells is desired, it can be accomplished with 30 horizontal lines of 9 resolution cells each. The total 270 cells are scanned in 270/120 seconds. Equally spaced parallel scan lines provide a uniform overlap between neighboring cells over the entire frame. This type of scan will be difficult to achieve. If antenna and feed are moved together, the horizontal line proceeds at a constant speed from cell 1 to 9. Between cell 9 and 10 the scan must reverse its horizontal direction and step down one line. To accomplish this reversal and step, accelerations at the edge of an 18-inch reflector are on the order of 5G. This is excessive and would require considerable motor control even with a low mass reflector.

Several alternative scanning techniques require evaluation. It may be possible to rotate the feed to get the horizontal lines. In this mode the beam deteriorates only slightly at the edge cells. The vertical scan is accomplished by moving the entire antenna in the vertical plane at a slow and uniform rate. The resultant sweep would have a sawtooth pattern giving non-uniform coverage in the horizontal plane.

A sinusoidal scan would be simplest to accomplish with the peak-to-peak amplitude corresponding to the width of the horizontal line. The frequency would be 6-2/3Hz resulting in small enough accelerations to cause no difficulties. This type of scan, however, results in non-uniform coverage in both horizontal and vertical planes.

A more desirable arrangement would be to keep antenna and feed fixed and accomplish the sweep with a moving reflector.

The several possibilities presented above have to be evaluated analytically. The most promising from a cost-effective standpoint has to be implemented in the laboratory preceding any attempt to implement the system.

ILLUMINATION BEAMWIDTH

To permit reflections from a wide angular orientation of weapons, it is necessary that the illumination sources radiate over a very broad angle. The laboratory experiments have shown that the axial plane patterns have directional characteristics which can be modified by choice of reflector. In the limited time for experimentation, the best pattern achieved with the 8-lamp fluorescent fixture had a half power total beamwidth of approximately 30 degrees at 35GHz. Additional reflector development should be undertaken with the objective of achieving a 90-degree beamwidth at 28GHz. This must be accomplished without any significant reduction in illumination intensity. When a satisfactory reflector design is achieved, fabrication techniques permitting mass production, such as aluminum extrusions, will have to be evaluated.

The fluorescent lamps used in the 8-tube source are relatively short and are powered by individual ballast transformers. These lamps and ballasts will constitute a major portion of system cost. From a cost-effective standpoint it is desirable to evaluate the use of other small diameter fluorescent lamps such as the "Slimline lamps." These lamps are over five feet long and are powered by multiple lamp ballasts. The cost savings would be substantial. A decision on the type of lamp to be used must be made before any large effort is made to optimize reflectors.

NON-PLANAR HUMAN REFLECTIVITY

The laboratory measurements have demonstrated the ability of the proposed system to discriminate between planar lossy dielectrics and metal. However, the proposed system will be required to locate metal objects of complex geometry and random orientation against the complex contours of the human body. Reflectivity of dielectrics of simple shape are the subject of comprehensive literature concerned with boundary value problems in electromagnetic theory[16].

In the present situation the contours are too complex to permit an analytical evaluation of system performance. An additional factor which confounds any attemped analytical evaluation is the non-uniformity of the illumination field. This is a result of the following:

1. An opening in the illumination field is provided for the antenna;

2. The illumination is discontinuous at the floor and ceiling;

3. Shadowing will occur between the legs and arms and the trunk of passengers.

An experimental approach is needed to resolve the question of system feasibility with confidence. The suggested approach is to make individual line scans across human subjects with and without concealed weapons. This will not require full implementation of the system. A horizontal line scan oscillating back and forth across the subject is required. The appropriate scan rate of one resolution cell in 1/120 second will have to be maintained. Furthermore, it may be possible to employ only one full row of the illumination source for these experiments.

The scan and illumination can be oriented manually to observe performance in detecting weapons over various areas of the human body. Therefore, it should be possible to simulate any arrangement of body contours and weapon orientations.

For meaningful performance of such single line scan experiments, a receiver at 28GHz is required to obtain an illumination signal-to-noise ratio of 10. Also, the reflectors for the illumination source must have been developed to the point at which broad radiation patterns are available for the simulation.

SUMMARY

In summary, while the basic concepts of the system appear reasonable there remain several crucial areas requiring laboratory evaluation. Technical failure or excessive costs in developing the scanning, illumination source or the inability of the system to detect weapon geometries against human contours will prohibit system implementation. The present estimated system cost of $20,000 is far in excess of conventional metal detectors and presents serious questions regarding the desirability of pursuing the proposed technique.

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