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NEAR-FIELD MILLIMETER-WAVE IMAGING FOR WEAPON DETECTION

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ABSTRACT

Various millimeter-wave imaging systems capable of imaging through clothing for the detection of contraband metal, plastic, or ceramic weapons, have been developed at PNL. Two dimensional scanned holographic systems, developed at 35, 90, and 350 GHz, are used to obtain high resolution images of metal and plastic targets concealed by clothing. Coherent single-frequency amplitude and phase data, which is gathered over a two-dimensional scanned aperture, is reconstructed to the target plane using a holographic wavefront reconstruction technique. Practical weapon detection systems require high-speed scanning. To achieve this goal, a 35 GHz linear sequentially switched array has been built and integrated into a high speed linear scanner. This system poses special challenges on calibration / signal processing of the holographic system. Further, significant improvements in speed are required to achieve real time operation. Toward this goal, a wideband scanned system which allows for a two-dimensional image formation from a one-dimensional scanned (or array) system has been developed. Signal / image processing techniques developed and implemented for this technique are a variation on conventional synthetic aperture radar (SAR) techniques which eliminate far-field and narrow bandwidth requirements. Performance of this technique is demonstrated with imaging results obtained from a K_a-band system.

1. INTRODUCTION

Millimeter wave imaging is currently of interest for the detection and identification of concealed contraband, such as firearms and explosives. Millimeter wave imaging methods are useful for this application due to the ability of millimeter waves to penetrate common clothing materials and to detect non-metallic or dielectric objects.

Existing personnel inspection systems typically rely on metal detectors to detect weapons and explosive devices. Millimeter wave imaging systems are potentially superior to metal detectors because of their ability to provide a lifelike image of the person and any concealed contraband. Providing this additional information would prevent insignificant items such as eyeglasses, belt buckles, shoes, etc. from triggering manual searches or repetitive passes through a metal detector.

X-ray systems for the detection/imaging of metal or non-metallic contraband might be used, but are most likely unacceptable due to the known harmful effects of x-rays. Low power millimeter wave illumination is not known to cause health problems in humans.

Microwave and millimeter wave holography was proposed some time ago for weapon detection and other applications [1,2]. However, improved scanning, digital reconstruction, and display techniques have improved the image quality markedly since that time. Millimeter wave focal plane array imaging systems, using both passive and active illumination, have also been proposed for weapon detection [3].

In this paper, two coherent millimeter wave imaging methods are demonstrated for potential use in personnel inspection devices. The first is a continuous wave (single frequency) holographic imaging technique, which uses measured amplitude and phase of the scattered wave over a two dimensional aperture and a computer reconstruction algorithm to form a focused image of the target object or person. The second is a wideband coherent swept frequency imaging technique, which records the amplitude and phase of the scattered wave over a linear aperture and wide frequency range. This data is then reconstructed using a computer reconstruction algorithm.

2. HOLOGRAPHIC IMAGING TECHNIQUE

At millimeter wave frequencies, both the amplitude and phase of scattered wavefronts can be measured directly. Knowledge of both magnitude and phase allows wavefront reconstruction, or holographic, techniques to be applied. In essence, holographic processing mathematically back propagates the wavefront from the measurement plane to the target plane to form the reconstructed image[4]. The hologram is typically obtained using an antenna scanned over a two dimensional aperture. The measured magnitude and phase are stored and then processed digitally using a computer reconstruction algorithm. Optical holograms are typically recorded on film and then later reconstructed optically. Historically, long wavelength (acoustic and microwave) holography has often made use of similar optical reconstruction processes. Presently, computer reconstruction techniques are much more convenient to apply for millimeter wave holographic image reconstruction.

The millimeter wave holographic imaging systems demonstrated in this paper consist of a continuous wave transceiver that is mechanically scanned over a two dimensional aperture. The magnitude and phase of the scattered wavefront are sampled across this two dimensional aperture. This configuration is referred to as simultaneous source-receiver scanning and it effectively doubles the phase shift that would be observed in the stationary source case (which is the case for optical systems). This doubling of the phase shift effectively doubles the resolution of the system. Expected resolution of this system is,

$$\delta = \frac{r}{L}\left(\frac{\lambda}{2}\right) \tag{1}$$

where r is the distance to the target, and L is the width of the aperture, and λ is the wavelength.

2.1 Holographic Imaging System

A block diagram of the experimental holographic imaging system is shown in Figure 1. An x-y scanner with a maximum aperture of 5 feet is computer controlled to scan the aperture and gather the holographic data. The transceiver uses a Gunn oscillator for the source. A waveguide horn is used for the antenna with a circulator used to separate the returned signal from the transmitted signal. The magnitude and phase of the scattered field are obtained by mixing the returned signal with in-phase and quadrature (90°) reference signals to obtain the I and Q values, where the I and Q signals represent the real and imaginary components of the scattered wavefront, respectively. These signals are digitized with the A/D converter and stored in the computer.

After the data has been collected, the image is reconstructed and displayed on the computer. Computer reconstruction is very efficient due to the use of the backward wave reconstruction algorithm, which makes use of the two dimensional Fast Fourier Transform (FFT). Thus, reconstruction may be accomplished at high speed using modern array processors.

A sequentially switched linear array of antennas can be used to obtain the holographic data at high-speed by electronically sequencing the antennas along one dimension and performing a mechanical scan along the other dimension. A one-dimensional scan can be performed quickly (on the order of one second). A full-size (0.75 m by 2.0 m) prototype of this type of system has been constructed and is undergoing final testing at this time.

Figure 1. Holographic imaging system block diagram.

2.2 Holographic Imaging Results

The holographic imaging system is demonstrated using 35 GHz. Systems have also been developed that operate at 90 and 350 GHz. The 350 GHz system has extremely high resolution of less than 1 mm. Practical millimeter wave weapon detection systems are, however, expected to operate in the 30-100 GHz range.

A metal pellet gun and a plastic handled Glock 17 have been imaged to demonstrate the performance of the technique. A 35 GHz reconstructed image of the metal pellet gun is shown in Figure 2. In this image, the scanned aperture is 0.35 m by 0.35 m and the range to the target is 0.255 m.

The 350 GHz system has been used to demonstrate the level of resolution that is ultimately achievable with millimeter wave holography. A reconstructed 350 GHz image of a Glock 17 is shown in Figure 3. In this image the aperture is 0.25 m by 0.25 m and the range to the target is 0.074 m. This image indicates resolution of less than 1 mm.

The weapon detection and clothing penetration capabilities of the 35 GHz system are demonstrated in Figure 4, in which a clothed mannequin has been imaged. In this image, the scanned aperture is 0.9 m by 0.9 m, and the distance to the target plane is 0.38 m. A concealed weapon (a metal pellet gun) placed in the inside jacket pocket is clearly revealed in the image. Facial and body features of the mannequin are also evident in the image. An optical image of the mannequin is also shown in the figure for reference. The mannequin's facial and body features are at reduced intensity relative to the gun due to the very high radar cross-section of the gun's flat surfaces.

Figure 2. Reconstructed 35 GHz holographic image of metal pellet gun.

Figure 3. Reconstructed 350 GHz holographic image of Glock 17.

Figure 4. (a) Optical image of the mannequin. (b) Reconstructed 35 GHz holographic image of clothed mannequin carrying a concealed metal gun.

3. WIDEBAND IMAGING TECHNIQUE

A distinct disadvantage to the holographic technique presented in Section 2 is that a two dimensional aperture must be scanned to record the holographic data. Two dimensional holographic imaging requires a two-dimensional array to be practical for a real-time personnel surveillance system.

Synthetic aperture radar (SAR) systems are commonly used to form high resolution two dimensional images of terrain. In these systems, the bandwidth of the system is used to obtain range resolution while a large synthetic aperture is used to obtain cross-range resolution. Typical SAR systems and processing algorithms that are used in far-field terrain mapping applications often have far-field and narrow beamwidth assumptions, which limit their applicability for near-field high resolution imaging applications.

In this paper, a novel high resolution wideband imaging system is described. Recent reconstruction algorithm developments allow for efficient reconstruction of near-field, wideband data[5]. This system allows high resolution two dimensional images to be formed from data gathered using a one-dimensional mechanical scan, which could potentially be accomplished at high speed.

In the wideband system, a transceiver is scanned along a linear aperture. At each point along the aperture, the frequency is swept over a wide range, with the magnitude and phase of the scattered wave recorded at a number of discrete frequency points. Lateral resolution is provided by the synthetic aperture. Vertical resolution is obtained from range resolution, which is obtained from the Inverse Fourier Transform of the frequency domain data. The transceiver is typically inclined to the target plane. Too high an inclination would result in inadequate illumination of the target, whereas too low an inclination degrades resolution in the vertical direction. Reconstruction of the data is accomplished using the algorithm described in Reference 5. This reconstruction algorithm is very efficient since it also makes use of one and two dimensional Fast Fourier Transforms (FFT). Therefore, real-time computer reconstructions should be possible using modern array processors.

Expected resolution for this system is

$$\delta_x = \frac{r}{L}\left(\frac{\lambda_c}{2}\right) \qquad (2)$$

in the lateral direction, and

$$\delta_y = \frac{c}{2B}\frac{1}{\sin\theta} \qquad (3)$$

in the vertical direction, where r is the distance to the target, L is the width of the aperture, λ_c is the wavelength at the center frequency, B is the bandwidth, c is the speed of light, and θ is the angle of inclination to the target.

3.1 Wideband Imaging System

The hardware block diagram for the wideband system is shown in Figure 5. An HP8510C vector network analyzer is used to record the magnitude and phase of the scattered wave over the wide frequency range. A waveguide horn antenna is connected through a phase stable coaxial cable to the 8510C using a coaxial to waveguide adapter. The antenna is scanned using a high resolution mechanical scanner with a maximum aperture of 5 ft. The scanner is stepped to each position under computer control and the data is downloaded to a Sun computer over the IEEE-488 (GPIB) bus.

Reconstruction of the data is accomplished using the algorithm described in Reference 5. Correction for the slant range distortion is applied using a simple interpolation scheme. Thus, the resulting image is in true vertical and horizontal coordinates, with little or no apparent distortion.

Since many targets will have widely varying scattering characteristics in this configuration, a high dynamic imaging system is required, and careful attention must be paid to sidelobe levels. A Kaiser window is used on the frequency axis to reduce range sidelobes to an acceptable level. Images are typically displayed using a dB scale, i.e. the image magnitude is converted to dB prior to display. This allows a wide dynamic range to be displayed, without extremely bright points dominating the image.

The frequency range used is from 22.0 GHz to 47.5 GHz. The waveguide horn antenna used is a K_a band horn. The nominal operational bandwidth of K_a band (WR-28) waveguide equipment is from 26.5 GHz to 40.0 GHz. The dominant mode cutoff, however, is 21.1 GHz. The first higher order modes occur at 42.1 GHz. Thus, the high end of our frequency range allows for the possibility of multiple waveguide modes. Experimental verification has demonstrated that the increased bandwidth (and therefore resolution) improved the image quality. Therefore, overmoding the waveguide adapter/horn does not appear to be a severe problem in this case. Expected resolution for this configuration is 6.8 mm in the vertical direction and 8.6 mm in the horizontal direction, for a 22.0 to 47.5 GHz frequency band, aperture of 0.5 m, range of 1 m, and angle of inclination equal to 60°.

Figure 5. Wideband imaging system block diagram.

3.2 Wideband Imaging Results

A wideband data set recorded over the 25.0 to 40.0 GHz range from a 3.25 inch diameter sphere placed at a range of 1 m has been reconstructed and the image is shown in Figure 6 . In this image, the scanned aperture is 0.75 m and the distance to the target plane is 0.6 m. Due to the illumination of the target from only one side, the image is largely that of the specular point on the sphere. A dynamic range of 30 dB is used to display the image.

Another test target was fabricated to further demonstrate the performance of the system. A block capital letter 'F' was constructed using two rows of 0.75 inch diameter metallized spheres. Spheres were used in the fabrication of the test target because of their omnidirectional scattering characteristics. A reconstructed image of the 'F' test target is shown in Figure 7, with a dynamic range of 30 dB displayed. The aperture scanned is 0.75 m and the frequency range is 22.0 to 47.5 GHz. This distance to the target plane is 0.33 m. This represents an angle of inclination to the target of 60°. Notice that the resolution is significantly better than 0.75 inch, as each sphere is clearly resolved. Also, notice that there is no significant distortion of the test target as would occur with other reconstruction algorithms.

To demonstrate the weapon detection / personnel surveillance capabilities of this technique, several images of the metal pellet gun were made. In Figure 8, the metal pellet gun has been imaged from below with the barrel pointing to the left. The aperture is 0.75 m, the frequency range is 22.0 - 47.5 GHz, the illumination angle is 60°, and the distance to the target plane is 0.33 m. In this image, most of the features of the gun are visible, however, part of the gun handle is essentially invisible in the image. This is due to the specular nature of the gun handle. It looks essentially like a flat plate with the illumination incident at 60°, and therefore little of the incident energy is reflected in the backscatter direction. In Figure 9, the same gun and configuration is used except that the barrel is pointed down. In this image, most of the features of the gun are visible, with the handle now clearly imaged. The reconstructed image of a clothed mannequin carrying a concealed metal gun is shown in Figure 10. Note that the shape of the gun is clearly imaged as are many of the facial and body features of the mannequin. An optical image of the mannequin is also shown in the figure. Some features of the mannequin are relatively invisible in the millimeter wave image. This does not represent a serious problem since these are smooth areas which are not expected to scatter back in the direction of the transceiver. The image of the mannequin can easily be obtained using video images to aid in placing the detected contraband on the person under surveillance.

Figure 6. Reconstructed wideband (25.0 - 40.0 GHz) image of a 3.25 inch sphere.

Figure 7. Reconstructed wideband (22.0 - 47.5 GHz) image of a letter 'F' composed of 0.75 inch metal spheres.

Figure 8. Reconstructed wideband (22.0 - 47.5 GHz) image of a metal pellet gun with the barrel pointed to the left.

Figure 9. Reconstructed wideband (22.0 - 47.5 GHz) image of a metal pellet gun with the barrel pointed down.

Figure 10. Reconstructed wideband (22.0 - 47.5 GHz) image of a clothed mannequin carrying a concealed metal gun.

4. CONCLUSIONS

Experimental near-field millimeter wave imaging systems have been demonstrated. Holographic techniques have been used to obtain extremely high quality images of contraband concealed by clothing. A wideband imaging method has been demonstrated that requires only a linear array or mechanical scan.

The holographic imaging system yields images of very high quality. This is due to the high resolution capability of a large aperture coherent millimeter wave system, and to the superior illumination provided by the simultaneous source-receiver scanning configuration. The principle drawback to the holographic system is the necessity of scanning a two dimensional aperture. This renders the scan times long and restricts its use to stationary targets in the laboratory. A sequentially switched linear array of transceiver antennas can be used to reduce the mechanical scan to a linear scan, which would reduce scan times to seconds. A two dimensional switched array would eliminate mechanical scanning and allow real time imaging. It is our goal to develop a viable two dimensional switched array in the future.

The wideband imaging system is very attractive for use in real-time imaging, since only a linear scan is needed to form a two dimensional image. Thus, a sequentially switched linear array could be used to form a real-time imaging system which would not require any mechanical scanning. Image quality of the wideband system is not as good as the holographic system. This is due primarily to the scattering characteristics of the target, rather than a fundamental deficiency of the imaging technique. The wideband system illuminates the target primarily from one direction, thus some points on the target do not generate a significant reflection in the backscatter direction. Nevertheless, high quality images have been demonstrated using this technique.

5. ACKNOWLEDGMENTS

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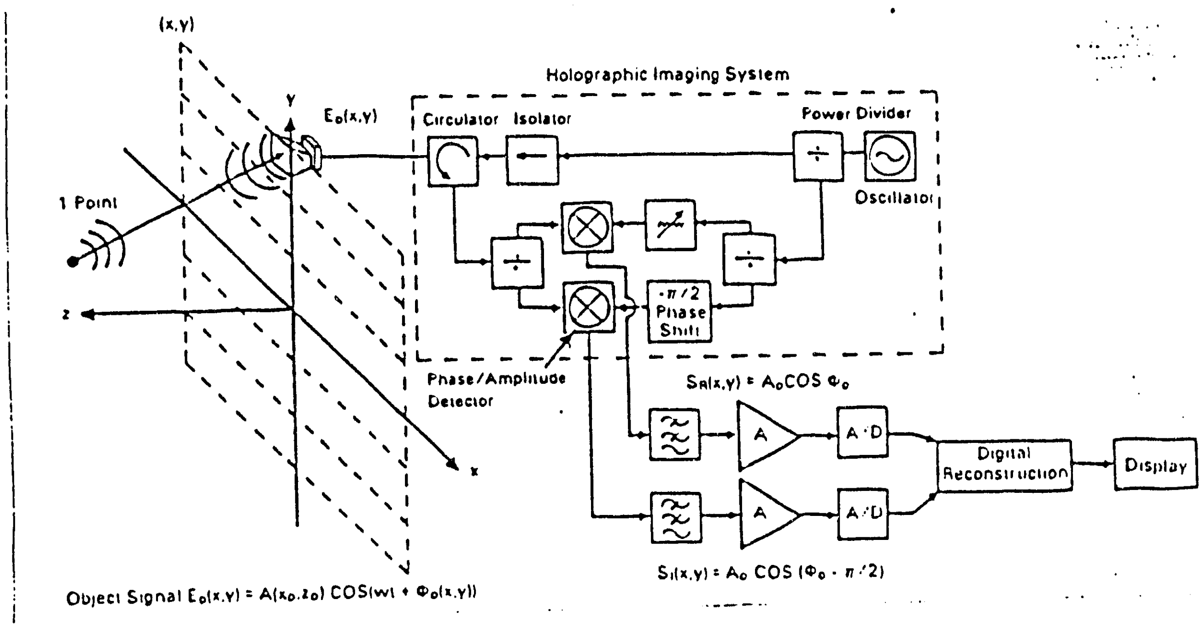

(x,y)
Holographic Imaging System
Y
$E_o(x,y)$
Circulator
Isolator
Power Divider
Oscillator
1 Point
z
x
-π/2 Phase Shift
Phase/Amplitude Detector
$S_R(x,y) = A_o COS\ \Phi_o$
A
A/D
Digital Reconstruction
Display
$S_I(x,y) = A_o\ COS\ (\Phi_o - \pi/2)$
Object Signal $E_o(x,y) = A(x_o,z_o)\ COS(wt + \Phi_o(x,y))$

Figure 1

Figure 2

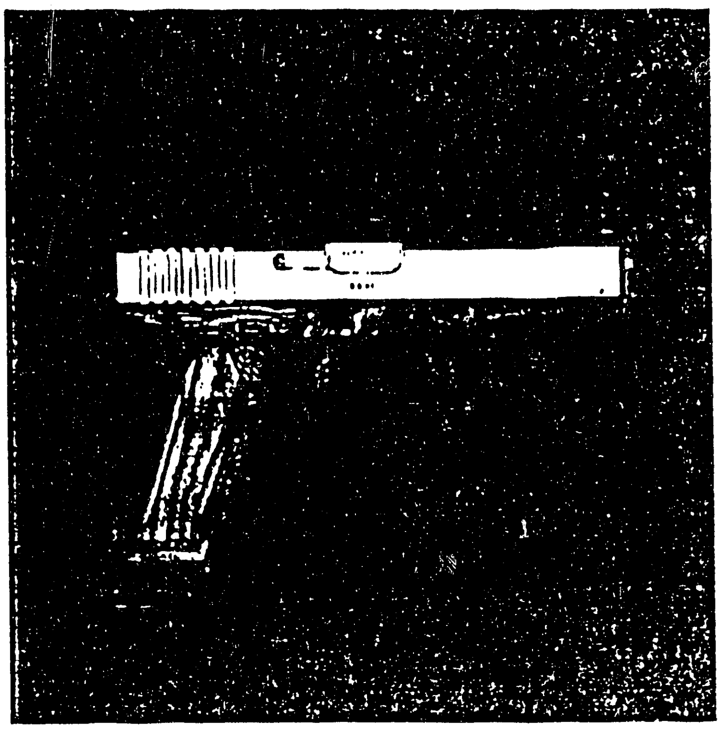

Figure 3

Figure 4(a)

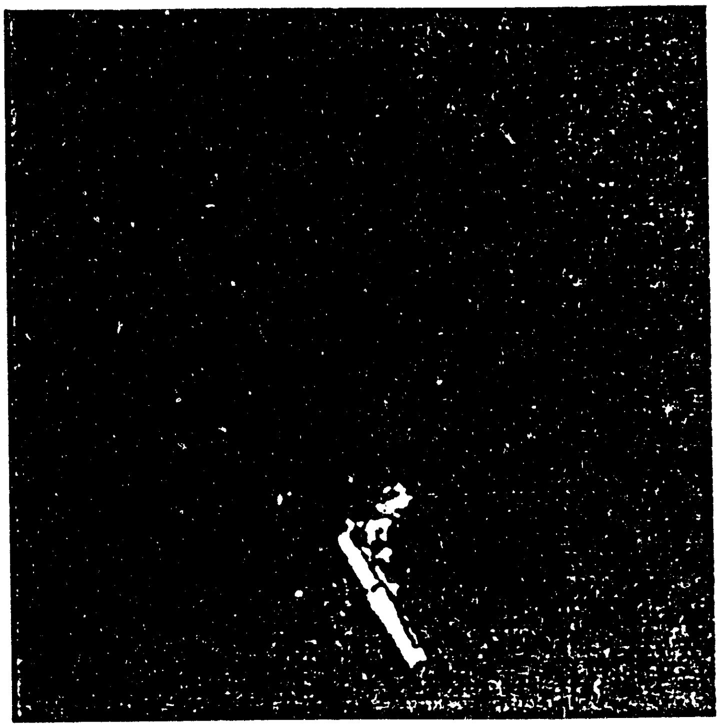

Figure 4(b)

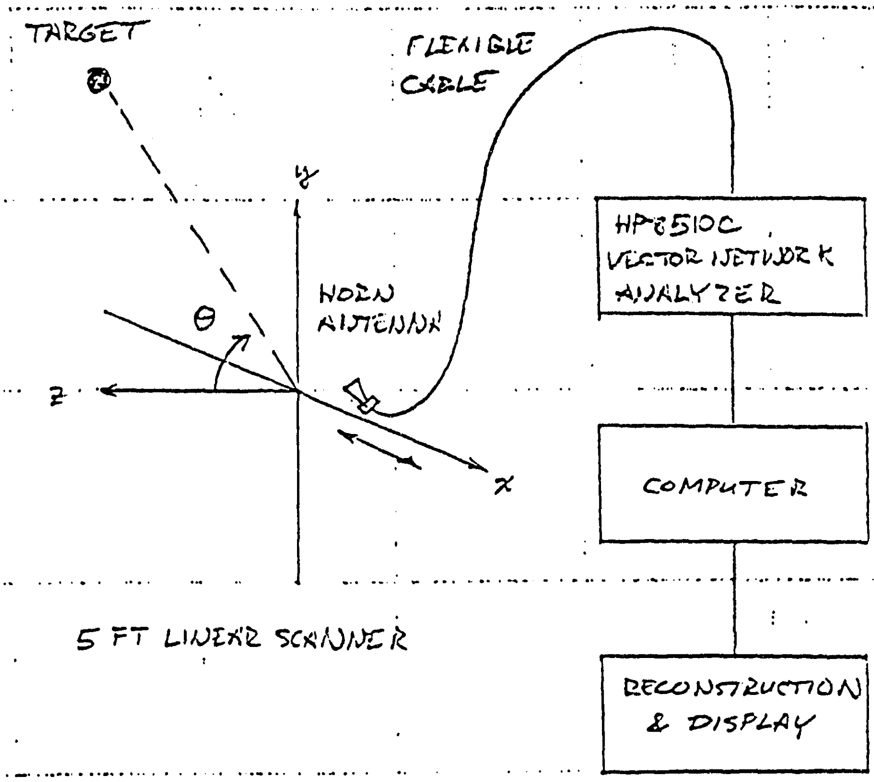

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Figure 5

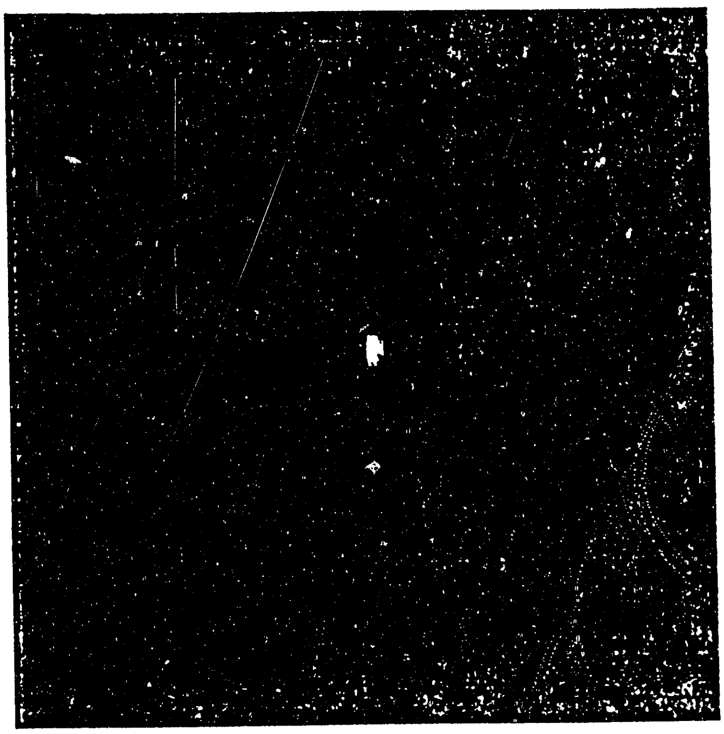

Figure 6

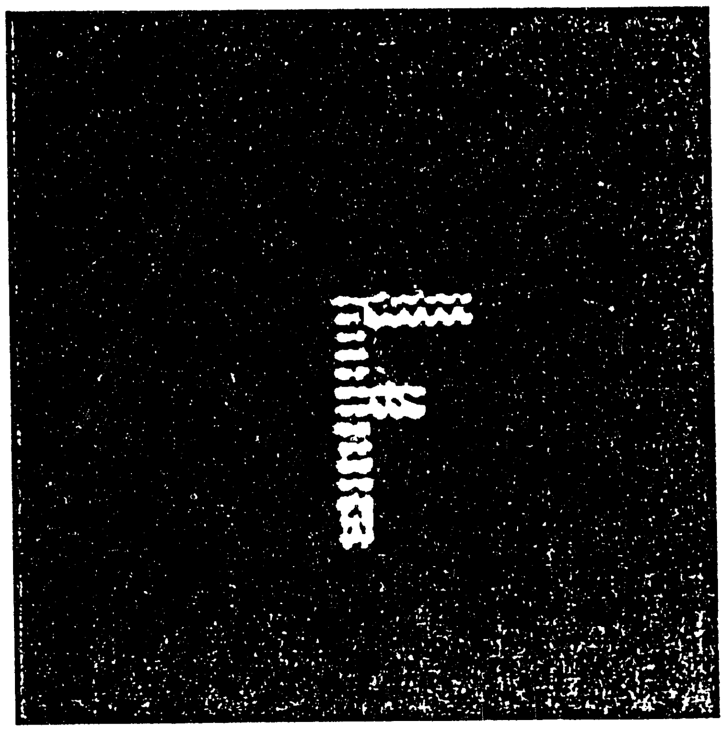

Figure 7

Figure 9

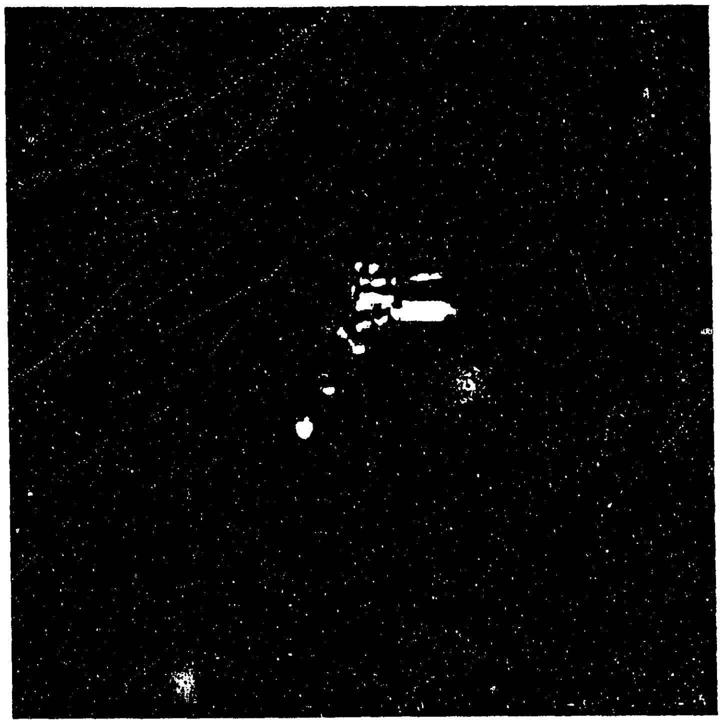

Figure 9

Figure 10 (a)

Figure ~~8~~ 10(b)

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