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CONCEPTUAL DESIGN OF A MULTIFUNCTION INFRARED RADAR FOR THE TAC--ETC(U)
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CONCEPTUAL DESIGN OF A MULTIFUNCTION INFRARED RADAR FOR THE TACTICAL AIRCRAFT GROUND ATTACK SCENARIO

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ABSTRACT

In this report we examine the feasibility of a multifunction infrared radar for use in a close air support ground attack scenario. First, the characteristics of infrared radars are compared with those of FLIRs and conventional radars. From this comparison it was determined that there was no a priori reason why a single system could not perform a variety of functions. Among these are terrain avoidance imaging, MTI target acquisition, target identification (active and passive imaging), target designation, and fire control. Based on this reasoning a systems concept was developed and a baseline system was designed. Novel features of this baseline system include a dual array of heterodyne and direct detectors, the use of specially-shaped laser pulses for time-shared range and Doppler analysis, and a quasi-three-dimensional display obtained by coding the range information into a color scale. The signal-to-noise and signal-to-clutter ratios of the baseline system were calculated and performance was found to be appropriate for the defined mission.

CONTENTS

1. INTRODUCTION

Recently, significant progress has been made in the design [1], [2] and technological development [3], [4] of an infrared airborne radar (IRAR) system. The IRAR system is intended for use as a bad-weather, day/night target acquisition and identification system on tactical aircraft involved in the close air support mission (see Fig. 1). A schematic of the IRAR system is presented in Fig. 2. In the target acquisition mode a cw beam from the transmitter CO_2 laser is shaped into a fan beam and projected by a telescope onto the ground in front of the aircraft. A combination of the aircraft's forward motion and a horizontal rocking motion of the pointer-scanner mirror provides a line scan search of the area in front of the aircraft. The back-reflected radiation is collected by the telescope, combined with the beam from a local oscillator laser, and imaged onto a one-dimensional array of HgCdTe heterodyne detectors. The outputs from the heterodyne detectors are then Doppler analyzed to provide moving target indication (MTI). When a moving target is detected, the pointer mirror is pointed in the direction of the target, the transmitter laser is switched to a repetitively-pulsed mode, and the image plane scanner is activated. This mode of operation provides a high resolution, point-by-point raster-scanned CRT image of the target for identification purposes. Range information from the pulse delays can then be used in conjunction with the azimuth-elevation information from the image and information from the aircraft's inertial platform to provide closed-loop fire control.

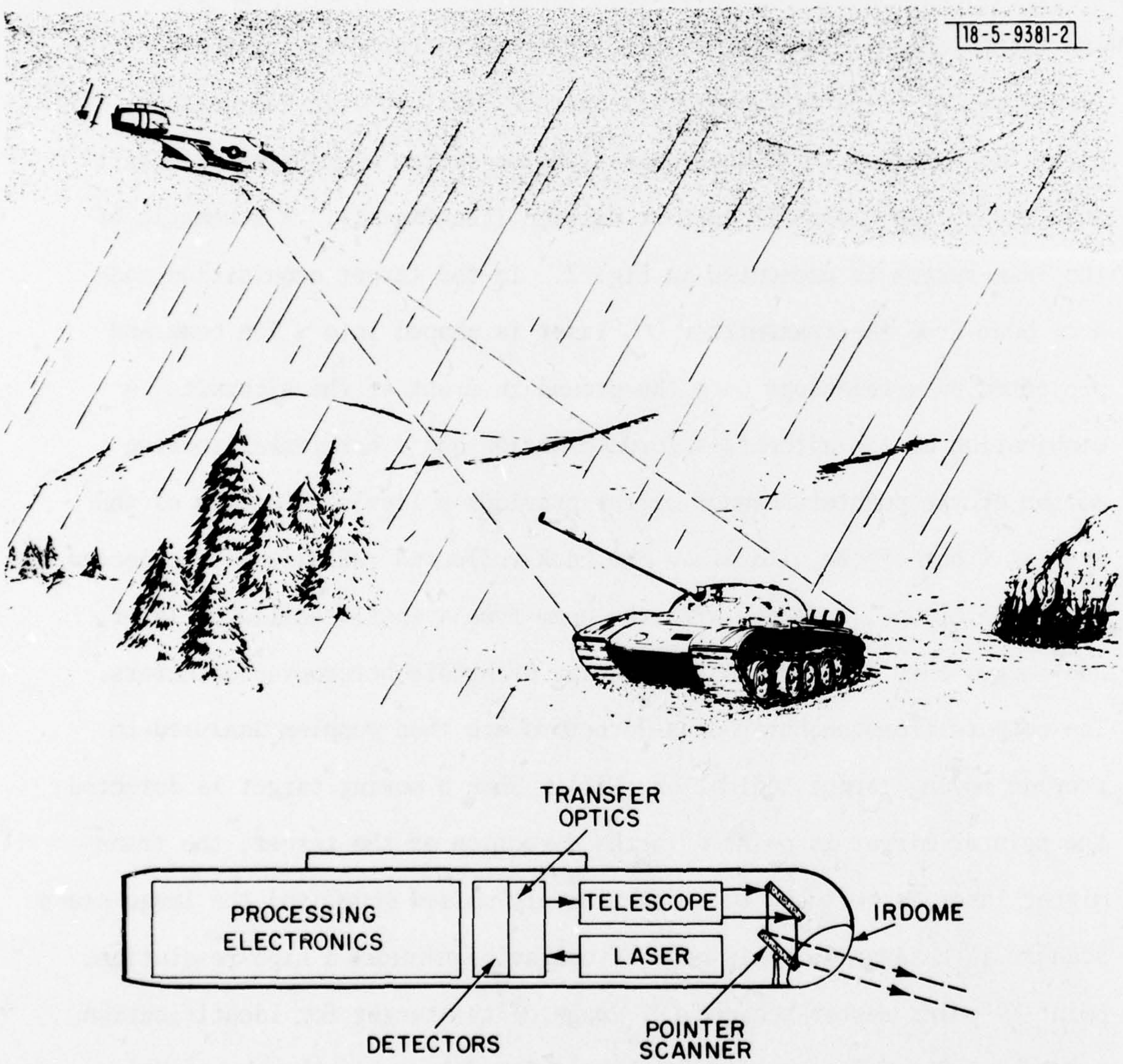

Fig. 1. IRAR-equipped A-10 flying a close air support mission against an armored fighting vehicle. The inset shows a schematic representation of an IRAR pod.

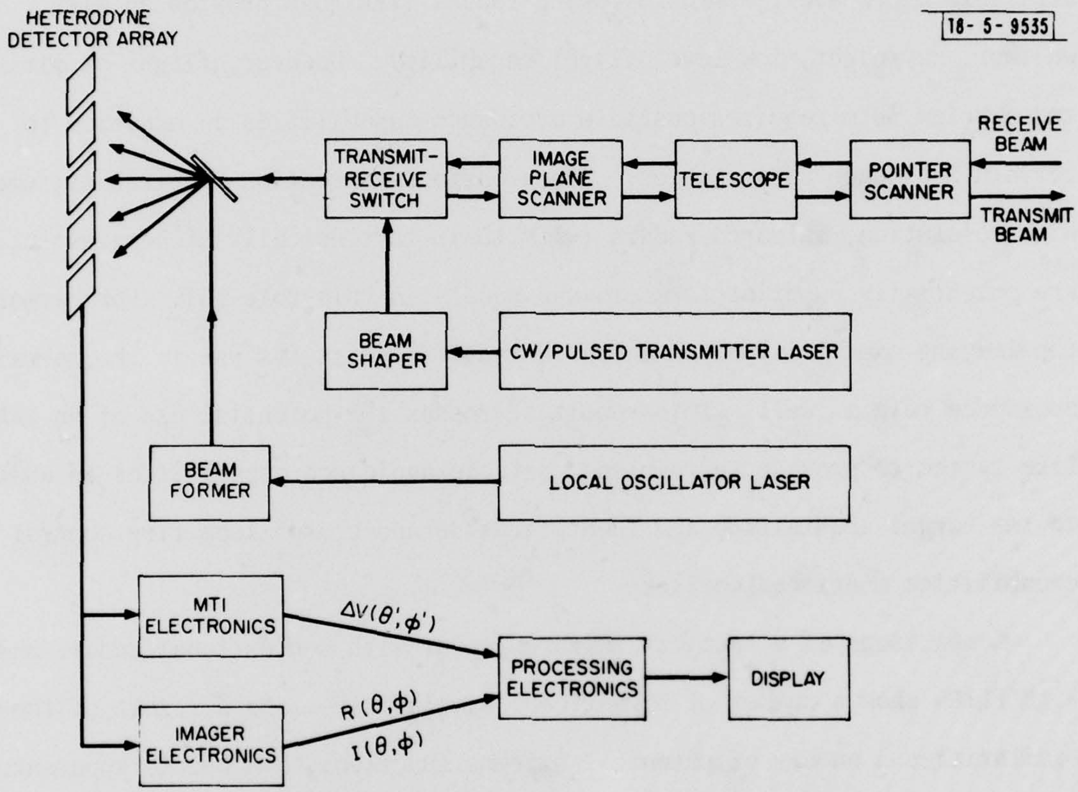

Fig. 2. Schematic diagram of the IRAR system.

The basic problem of how a pilot flies his aircraft at extremely low altitudes and high speeds at night or in bad weather to reach the target area and then finds and attacks targets is very difficult. Currently available microwave terrain following radars (TFR) can provide an all-weather, day/night, low-level flight capability. However, flight at altitudes below 50 m requires obstacle avoidance capabilities in addition to terrain avoidance capabilities. Since obstacle detection requires extremely high resolution, infrared radars (with their intrinsically higher resolution) are potentially superior to microwave radars in this role [5]. Furthermore, the imaging capability of an infrared radar suggests its use in the terrain avoidance role as well. This report addresses the potential use of an IRAR-like system to provide terrain and obstacle avoidance capabilities in addition to the target acquisition and identification and closed-loop fire control capabilities mentioned earlier.

Comparisons of a tactical infrared radar with conventional radars and with FLIRs show a number of significant similarities. As a result of these similarities a number of potential systems functions have become apparent. In an attempt to exploit fully these potential functions, a conceptual design is presented of a multifunction infrared airborne radar for use as an integrated avionics system (terrain avoidance, target acquisition and identification, and fire control) on close air support aircraft. The modes of operation of this multifunction system are discussed, numerical estimates of its performance are made, and systems problems unique to a multifunction system are analyzed in some detail.

2. CONVENTIONAL RADARS, FLIRS, AND INFRARED RADARS

In attempting to understand the full potential of any system it is usually instructive to compare it with existing systems to determine what similarities and differences exist. Therefore, as a first step in understanding tactical infrared radars, they have been compared with conventional radars. Schematic representations of a conventional radar [6] and an infrared radar are presented in Figs. 3a and 3b. In a conventional radar, electromagnetic radiation from a power oscillator is directed by a transmit-receive switch out through an antenna onto a target. The radiation reflected by the target is then collected by the antenna and directed through the transmit-receive switch onto a mixer where it is heterodyned with radiation from a local oscillator. The heterodyne signal is then electronically processed and suitably displayed. In an infrared radar electromagnetic radiation from a transmitter laser is directed by a transmit-receive switch out through a telescope onto a target. The radiation reflected by the target is then collected by the telescope and directed through the transmit-receive switch onto a detector where it is heterodyned with radiation from a local oscillator laser. The heterodyne signal is then electronically processed and suitably displayed. From Fig. 3 and from the descriptions of their operation, it is obvious that there is no fundamental difference between an infrared radar and a conventional radar. The only real differences are in the wavelength of the electromagnetic radiation which

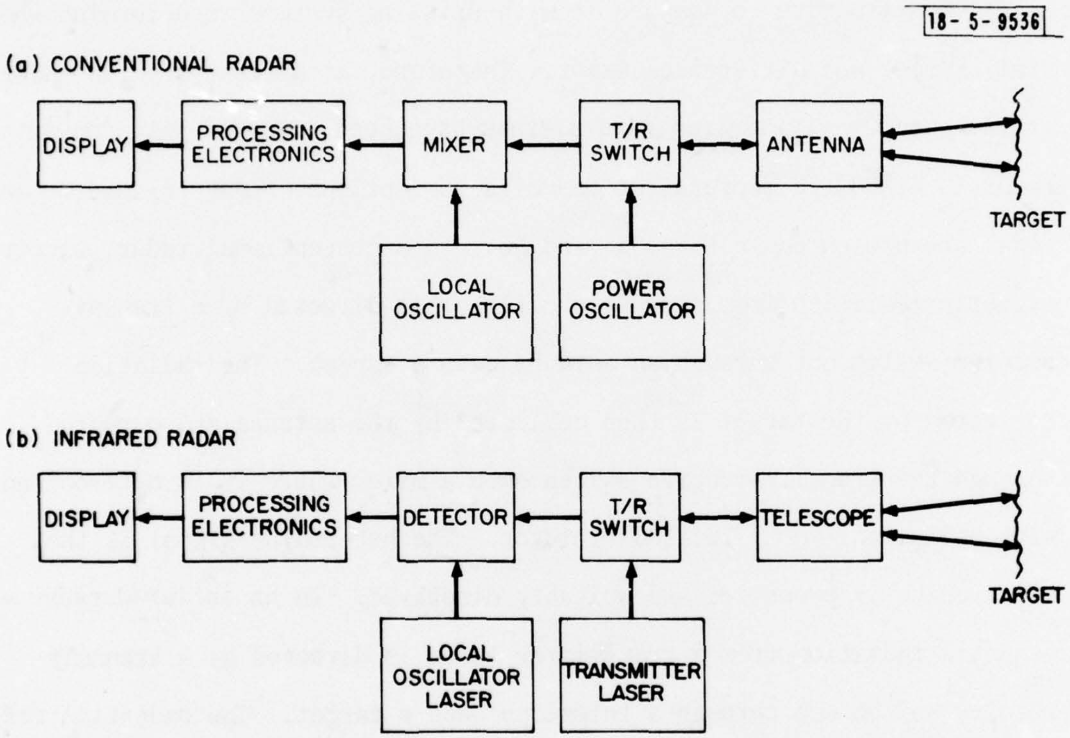

Fig. 3. Comparison of conventional and infrared radars. Schematic representations of (a) a conventional radar and (b) an infrared radar.

is employed (infrared vs. microwave) and the specific devices with which the necessary radar functions are performed (lasers vs. magnetrons, telescopes vs. antennas, etc.). As a result of this high degree of similarity, we would expect an infrared radar to be capable of performing any of the functions of which a conventional radar is capable, although key differences in performance are anticipated in the areas of resolution (infrared better) and weather penetration (microwave better).

Forward-looking infrared (FLIR) imaging systems [7] are finding increased usage on tactical aircraft. Consequently, it will also prove interesting to compare a FLIR with an infrared radar. The essential elements of a FLIR are shown schematically in Fig. 4a. Infrared (thermal) radiation from the scene is imaged by a lens (or telescope) onto an array of infrared detectors. A pointer-scanner mirror repetitively scans the image of the desired scene across the detector array. The time-dependent outputs from the detectors in the array are then electronically processed to produce a television display of the scene.

In some FLIR systems a laser has been added to provide one or more additional functions. In one type of laser-aided FLIR a separate laser and detector system (not necessarily operating at the same wavelength as the FLIR) is bore-sighted with the optical system of the FLIR. On command the laser is pulsed to determine the range to any designated point in the scene being observed by the FLIR. Another type of laser-aided FLIR is depicted in Fig. 4b. In this system a cw (or possibly repetitively-pulsed) laser illuminates the scene through the FLIR optics. The back-reflected radiation is imaged onto the detector array through a narrowband

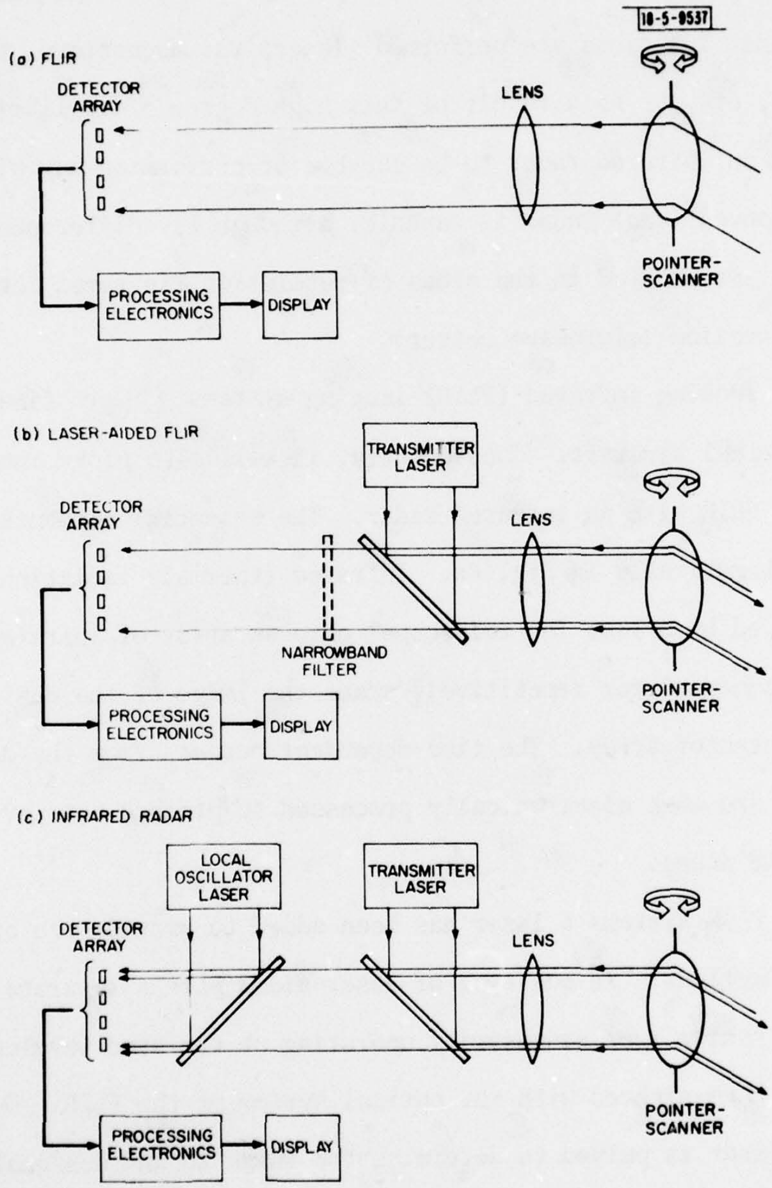

Fig. 4. Comparison of electrooptical avionics systems. Schematic representations of (a) a FLIR, (b) a laser-aided FLIR, and (c) an infrared radar.

filter (which essentially eliminates the thermal radiation from the scene). The detector signals are processed to yield a television display exactly as in a FLIR. The difference between this form of laser-aided FLIR and a conventional FLIR is that the image is constructed from reflected laser radiation rather than from emitted thermal radiation. If the laser radiation is repetitively-pulsed, the range to each point in the scene can be obtained. Such a pulsed laser-aided FLIR would be more accurately called a noncoherent infrared radar.

If a second cw laser is used to illuminate the detector array directly and the resulting heterodyne signals from the detectors are processed, the laser-aided FLIR of Fig. 4b becomes a coherent infrared radar (shown schematically in Fig. 4c). As in the preceding system, the signals from the detectors can be processed to give a television image of the scene in reflected radiation. If the transmitter laser is operated cw, the fact that heterodyne detection is employed means that Doppler information can be extracted for each point in the image. If the transmitter laser is repetitively-pulsed, range information can be obtained for each point. Since any infrared detector capable of heterodyne detection is also capable of direct (noncoherent) detection, if the two lasers are turned off, the infrared radar will function exactly like a FLIR. Thus, in principle, it is possible to obtain images in either thermally-emitted or reflected radiation from a single system.

Before proceeding to summarize the potential functions of an infrared radar there is one more system which should be mentioned. Many advanced weapons systems rely on laser designators to identify targets and provide a strong signal for missile homing purposes. Since an infrared radar contains a laser, which in the target imaging mode must be capable of being pointed at the target, it is clear that an infrared radar can also serve as a laser designator (if the seeker detectors are changed to be sensitive to the proper laser wavelength).

Because an infrared radar is basically identical to a conventional radar and contains all of the essential elements of a FLIR and a target designator, an infrared radar is in principle capable of performing all of the functions of these three systems. Thus we may immediately write down the following list of potential infrared radar functions:

1) Wide-angle search (i.e., wide field-of-view, low-resolution imaging) in either an active (reflected radiation) or passive (thermal radiation) mode.

2) Target ranging.

3) Doppler resolution of target velocities (allowing moving target indication to be performed).

4) Target identification (using narrow field-of-view, high-resolution imaging) in either the active or passive mode.

5) Target designation.

It is suggested that a single system capable of performing all of these functions would be most useful. For example, the wide-angle search mode coupled with ranging to each point in the scene could in principle give the pilot all the information he requires for terrain avoidance in low-level flight. If MTI could be performed simultaneously, the pilot would have an automatic target acquisition capability which would not distract him from flying his aircraft. A high resolution imaging capability would allow rapid identification of suspected targets. Here both passive and active modes would be desirable as some targets have better passive signatures than active signatures and vice versa. Coupled with a ranging capability the high resolution imager would provide all of the information necessary for closed-loop fire control. Finally, the inherent target designation capability would prove beneficial for use with many potential airborne weapons systems. As a consequence of the high desirability of such a multifunction system we have arrived at a conceptual design which is presented in the next section.

Clearly, the operational utility of any optical avionics system will be limited by bad weather. However, the limitations are usually much less severe in the infrared than in the visible, and since weather is a statistical phenomenon, infrared avionics systems may still find great practical utility in the close air support role [1]. The statistical effects of weather on the performance of the multifunction infrared radar are analyzed in Section 4 of this report.

3. A MULTIFUNCTION INFRARED AIRBORNE RADAR SYSTEM

An infrared radar capable of performing all of the functions outlined in the preceding section is shown schematically in Fig. 5. The beam from a transmitter CO_2 laser (which may be operated either cw or pulsed) is shaped (to provide optimum illumination of the scene [2]), directed by a transmit-

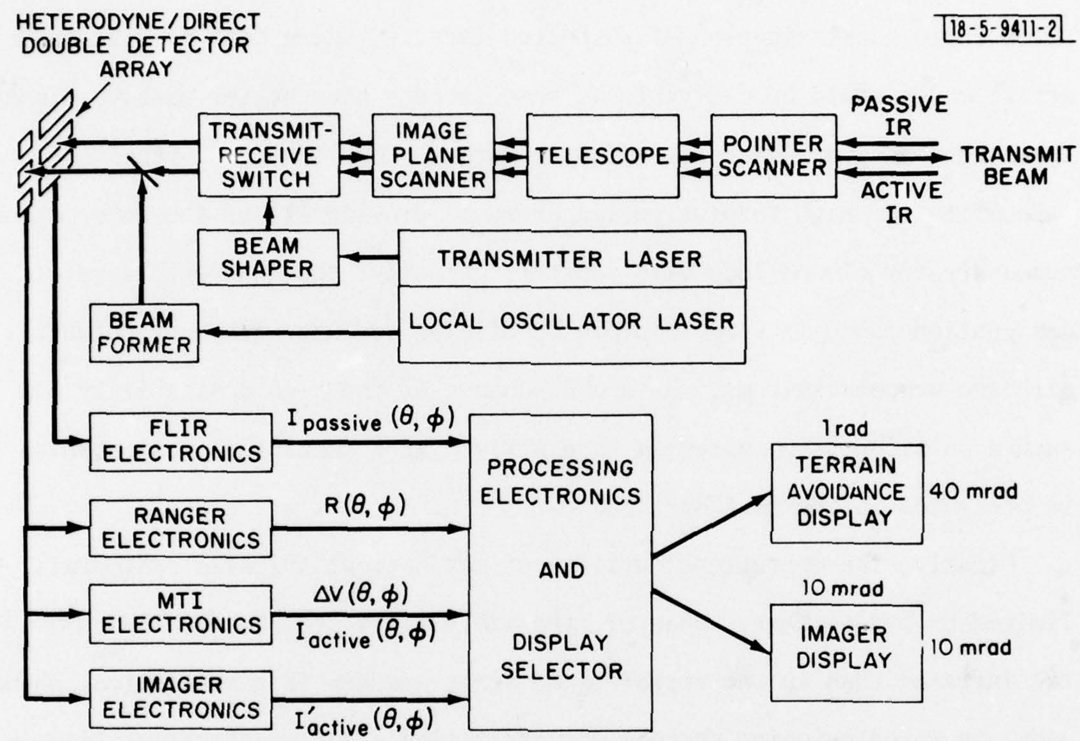

Fig. 5. Schematic diagram of a multifunction infrared airborne radar system. The quantities θ and ϕ are the angular coordinates of pixels in the scene.

receive switch [3] through an image plane scanner and telescope, and deflected off a pointer-scanner mirror onto the target plane. 10.6μm laser radiation reflected from objects in the scene is collected by the optical system and directed by the transmit-receive switch onto an array of heterodyne detectors (photovoltaic HgCdTe). The output of the local oscillator laser is formed into a suitable wavefront (perhaps by a holographic technique [1]) and used to illuminate the heterodyne detector array. Passive infrared radiation (8-14μm) from the scene is also collected by the optical system and imaged onto a direct detector array (photoconductive HgCdTe) located immediately adjacent (on the same semiconductor chip, if possible) to the heterodyne detector array. The signals from the direct detector array are processed by conventional FLIR electronics to provide passive image information, while the signals from the heterodyne detector array are processed by various electronics packages (depending on the mode of operation) to yield range, Doppler (moving target indication) and/or active image information. This information is then further processed to provide a variety of displays to the pilot.

It should be noted that a dual detector array of this type is not unique. For example, a well-conceived optical system could transmit visible or 3-5μm radiations as well as 8-14μm radiation. Using an appropriate triple (or possibly quadruple) array a visible image or two-color passive infrared image information could be obtained. This latter information could be useful in target cuing by thermal signature analysis. However, for purposes of simplicity we will restrict the discussion to a simple dual array for the remainder of the paper.

To be able to fly an aircraft at low altitude under combat conditions, it is desirable that the pilot should be able to see at least $\pm 30°$ from the direction of the aircraft's motion. This would give him a view of any terrain features into which he might be forced to turn during sudden evasive maneuvers. Thus, the horizontal field-of-view (ϕ_x) of the wide-angle imaging system should be of the order of 1 radian (Fig. 6a). Effective target search imposes a similar requirement. The vertical field-of-view (ϕ_y) is determined by the facts that in level flight it is highly desirable to allow the pilot 1) to see the ground at some minimum distance, R_{min}, in front of the aircraft, and 2) to see well above the horizon plane (Fig. 6b). For an aircraft flying at (low) altitude h, the angular separation between R_{min} and the horizon is given by

$$\tan \phi_1 \approx \phi_1 \approx h/R_{min} \qquad (1)$$

The field-of-view which can be covered by raster scanning an array of N detectors of angular resolution α through n lines is

$$\phi_y = nN\alpha \qquad (2)$$

Consequently, we must have $\phi_y > \phi_1$.

The necessity of making accurate identifications of suspected targets places stringent requirements on the angular resolution of the optical system. Computer simulations [8] have shown that recognition of tactical targets (e.g., discerning tanks from trucks) requires roughly 8 resolution elements (or pixels) across the minimum dimension of the target, while target identification (e.g., discerning T62 tanks from M60 tanks) requires at

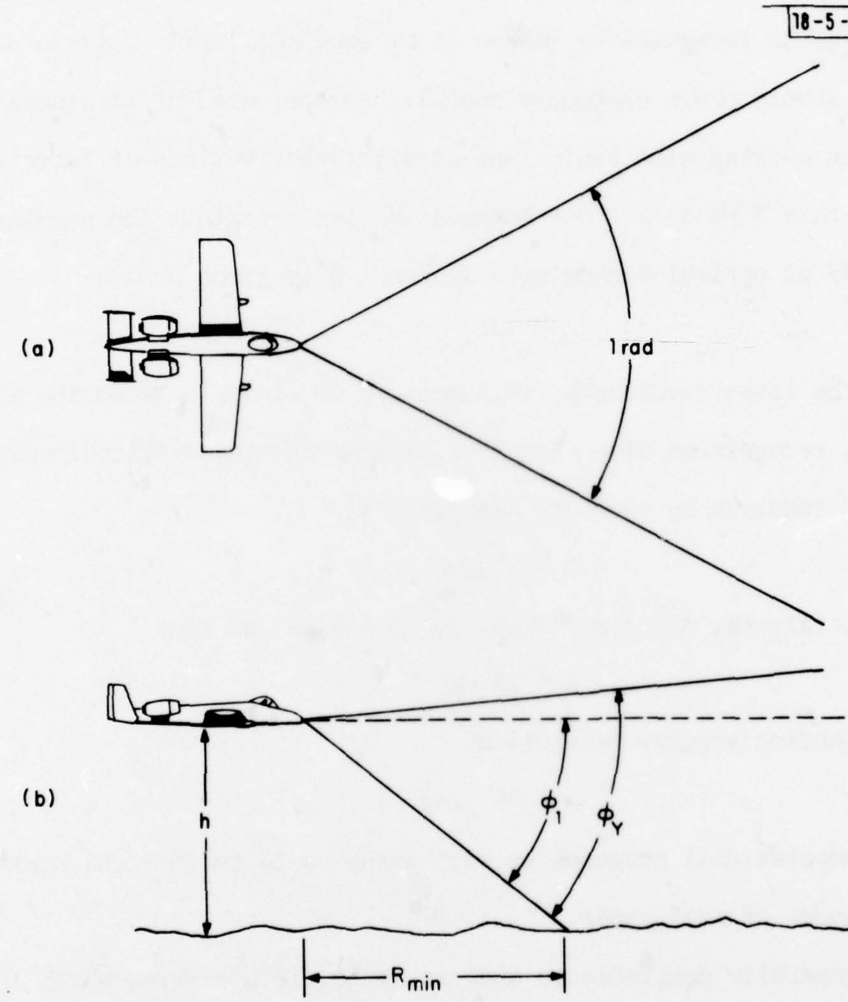

Fig. 6(a-b). Field-of-view considerations in the terrain avoidance imaging mode.

least 13 pixels across the minimum dimension. With the unaided eye, one is hard-pressed to recognize a tank-sized target at 2 km in good weather. As a result, if the infrared radar (operating in the high resolution imaging mode) can produce recognizable images of targets at 3 km at night or in bad weather, it should prove extremely useful. Furthermore, at altitudes below 100 m terrain masking will limit line-of-sight observations of targets to ranges less than 3 km in all but the most benign terrain. The angular resolution of an optical system with aperture D is given by

$$\alpha \approx \lambda/D \tag{3}$$

where λ is the laser wavelength (10.6μm for a CO_2 laser). From the statements above, recognition of a target of minimum characteristic dimension d at a range R requires an aperture diameter [1]

$$D \approx 8\lambda R/d \tag{4}$$

For tactical targets, $d \approx 2$ m. Thus, for R = 3 km, we find

$$D \approx 13 \text{ cm}$$

with corresponding angular resolution

$$\alpha \approx 80 \ \mu\text{rad}$$

Thus, for computational purposes we will assume a 13 cm (5 inch) aperture in the remainder of this paper.

It is generally desirable to have an image field-of-view which is at least three times the angular size of the target. This enhances the probability of identification by using the contrast of the background and provides an allowance for image tracking errors. A tactical target of 6 m characteristic maximum dimension will have a linear size of 22 pixels at 3 km range. At closer ranges it will be larger. Thus, the high-resolution imaging system should have a field-of-view of at least 70 x 70 pixels. Since digital image processing systems prefer to have all quantities in powers of two, we will specify the high-resolution imager field-of-view at 128 ($\approx 2^7$) x 128 pixels or 10 mrad x 10 mrad. In view of the size of the system we have just proposed, it is noteworthy that a system of comparable size, namely the IRAR testbed radar (10 cm aperture, 128 x 128 pixel field-of-view)[3], has recently experimentally demonstrated that recognizable images of tactical targets can be obtained at 2.7 km range (see Fig. 7).

Because the same detector array is to be used for both the wide-angle search (terrain avoidance) and high-resolution imaging modes, we will assume that there are 128 heterodyne and 128 direct detectors in the array. This eliminates the need for raster scanning in the high-resolution imaging mode; a simple line scan by the image plane scanner will cover 128 x 128 pixels. However, 128 detectors are not sufficient to cover the required vertical field-of-view in the search mode. From Eq. (1), assuming h = 30 m (at higher altitudes the aircraft is vulnerable to enemy radar - directed weapons systems) and R_{min} = 1 km, we find

$$\phi_1 \approx 30 \text{ mrad}$$

For N = 128 and α = 80 μrad, Eq. (2) yields

$$\phi_y \approx 10 \, n \text{ mrad}$$

Consequently, a raster scan of at least 4 lines is required to satisfy the condition $\phi_y > \phi_1$.

The time required to scan one complete frame of the scene is given by

$$t_F = n\phi_x / \dot{\phi}\beta$$

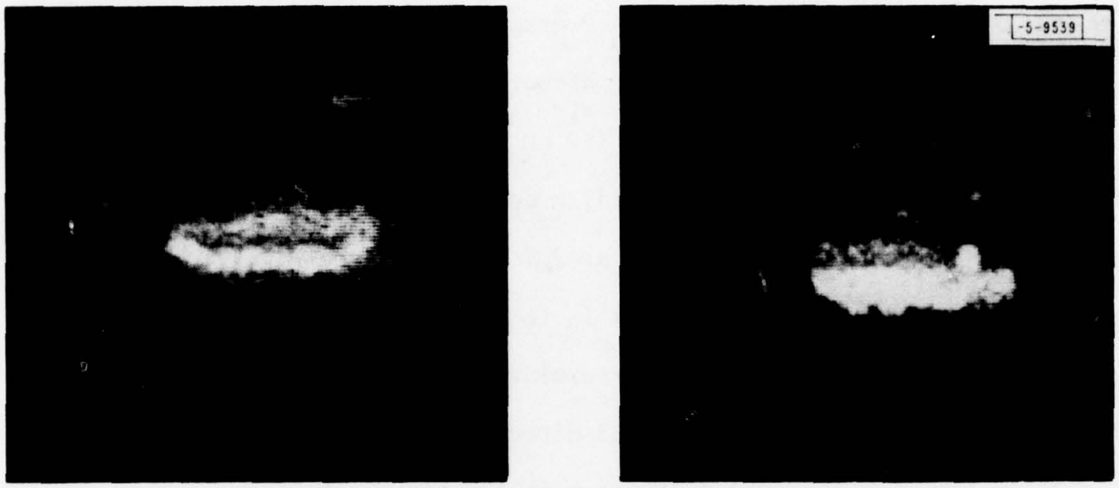

Fig. 7. Images of tactical targets at 2.7 km taken with the IRAR testbed laser radar. Left — M60 tank. Right — 2 1/2 ton military truck.

where $\dot{\phi}$ is the angular scan rate of the pointer-scanner (the image plane scanner cannot be used because it can cover at most $\phi_2 \approx \pi/m$, where $m \approx 10 - 20$ is the magnification of the telescope) and β is the scanner retrace efficiency. Clearly we wish to make n as small as possible, so n = 4 is the optimum choice. The Doppler resolution achievable from a scanning system is proportional to the single pixel dwell time,

$$t_D = \alpha/\dot{\phi} \qquad (6)$$

Since the frame rate $(1/t_F)$ and the dwell bandwidth $(1/t_D)$ are both linear functions of the scan rate, increasing $\dot{\phi}$ increases the frame rate but decreases the Doppler resolution. At 10.6 μm a velocity of 1 kmph corresponds to a 53 kHz Doppler shift. The theoretical minimum resolvable Doppler velocity, V_D (in kmph), is given by

$$V_D = (\dot{\phi}/\alpha) / 53 \text{ kHz} \qquad (7)$$

$$\approx \dot{\phi} / 4.3$$

A system capable of 8 kmph resolution would be of value in the close air support scenario. Using this value we obtain

$$\dot{\phi} = 34 \text{ radians / sec}$$

which for ϕ_x = 1 radian and n = 4 gives a frame rate

$$F = 8.5\,\beta \text{ frames/sec}$$

Retrace efficiences of large scanners are typically of the order of 0.5 or less. Therefore, we can expect a maximum frame rate of the order of 4 frames/sec. However, since a Mach 0.5 aircraft can move only 40 meters in 0.25 sec, this frame rate is high enough to allow a pilot to safely fly the aircraft.

For n = 4, the terrain avoidance mode field-of-view is roughly 12,000 horizontal x 500 vertical pixels. Since the best available television displays are limited to roughly 1000 pixels in any direction, the horizontal information must be compressed 12-fold. In the passive mode, this compression could be achieved by simply averaging every 12 pixels. In the active mode, the need for a 12-fold compression will allow us to time-share the range and Doppler functions. Ranging requires transmission of a short, high-intensity laser pulse and measuring the time delay to reception of the strongest return. Doppler measurement on the other hand requires the transmission of a long quasi-cw pulse with stable frequency and measuring the difference between the transmitted and received frequencies. If only a single pulse can be sent to a single pixel, the two functions are mutually exclusive. However, the 12-fold data compression means that data from 12 pixels are available to depict as one point on the display. By using specially shaped laser pulses (Fig. 8) both range and Doppler information can be obtained. The high intensity spike is used to obtain range information while the long, quasi-cw, low intensity tail provides the stable frequency for Doppler analysis. The time between adjacent pulses is 12 times the single pixel dwell time. For the values used in the preceding

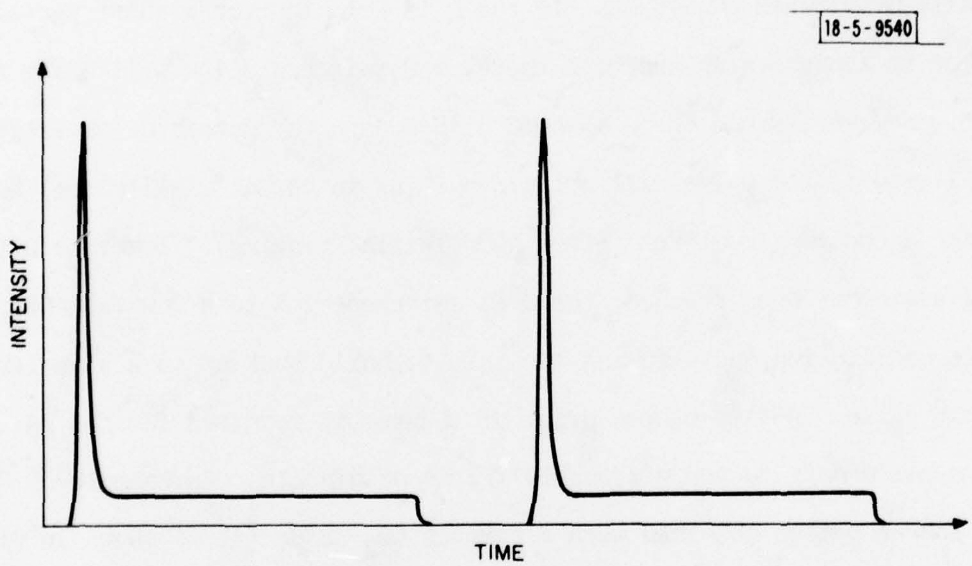

Fig. 8. Laser pulse shape required for doing time-shared range and Doppler determinations.

analyses 12 pixels corresponds to 28 μsec. This is sufficient to allow unambiguous ranging out to 4 km. The corresponding laser pulse repetition frequency (PRF) is 36 kHz, well within achievable limits [4].

Pulses with the desired shape can be readily produced from an electro-optically Q-switched CO_2 laser. If the Q is held low for a short period, then switched to a high value and held there, a Q-switched spike will quite normally result. However, since the Q is held high enough to sustain cw oscillation, the tail end of the pulse will not die out (as in normal Q-switching) but will approach a constant cw level (after some initial ringing). Sometime after the steady state has been reached, the Q is switched back to a low value extinguishing the oscillation and allowing the gain to build back up to a high level for the next pulse. A time of the order of 10 μsec is required for the gain build-up so a pulse duty factor of roughly 2/3 is obtainable. An example of one of these shaped pulses obtained with a compact CO_2 laser [4] is shown in Fig. 9.

One scheme for utilizing these shaped pulses for time-shared range-Doppler measurements is shown in Fig. 10. The output of each heterodyne detector is amplified and divided into two channels. One channel basically looks at only the high intensity spike. The signal in this channel is passed through a filter matched to the frequency content of the spike and an envelope detector. The signal is then analyzed by a digital peak detector which determines the time after receipt of a start pulse (generated by the Q-switch driver) at which the maximum signal occurs and the magnitude of that signal. This time is directly related to the range. The second channel, which basically looks at the tail of the pulse, is further divided into m channels. In each channel there is a filter (matched to the dwell bandwidth), an envelope detector, and a digitizer.

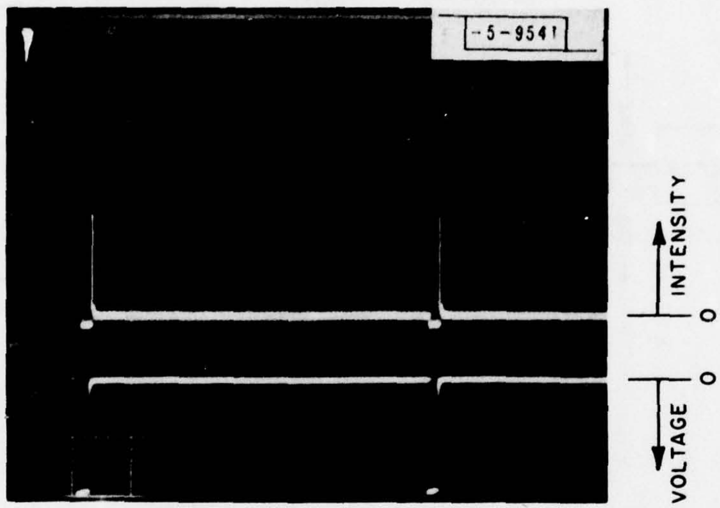

Fig. 9. Oscilloscope photograph of time-shared range-Doppler laser pulses. Upper trace - laser intensity. Lower trace - Q-switch voltage. Time scale is 100 μsec/div. Cavity Q is highest for zero voltage.

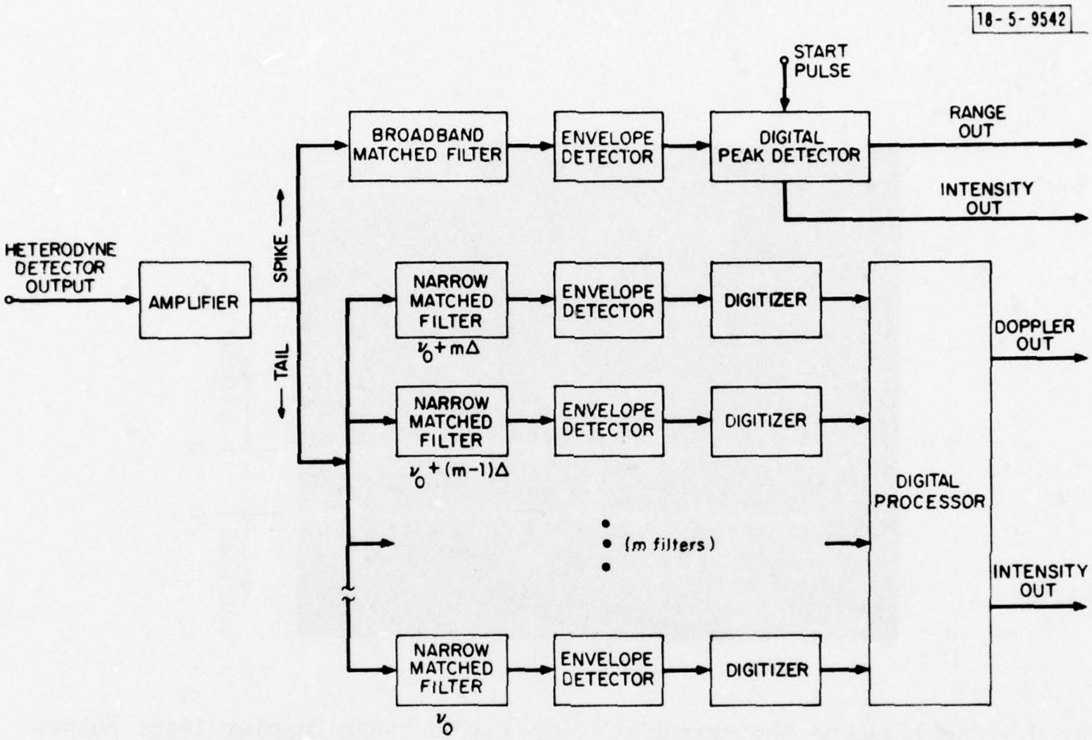

Fig. 10. Schematic representation of a time-shared range-Doppler processor using a filter bank.

The m channels cover the range of expected Doppler-shifted frequencies. The digital outputs (sampled once each dwell time) are analyzed to yield the Doppler shift and the intensity. The Doppler shift is determined by summing the temporal outputs in each channel over the interpulse time and determining which channel yields the largest value. The intensity can be determined by summing the outputs of all of the channels.

4. OPERATION AND PREDICTED PERFORMANCE

In this section one possible mode of operation of the multifunction infrared airborne radar is presented. Clearly, details of items such as displays and the mechanics of handover are meant to be illustrative only. The present discussion represents an initial conception of how such a multifunction system might be employed. For low-level flight (ingress, egress, target search) the image plane scanner would be disabled, the laser would be operated in the shaped-pulse mode, and the pointer-scanner mirror would raster scan a large field-of-view (approx. 40 mrad by 1 rad) in front of the aircraft. The range information would be coupled with either the passive or active intensity data (depending on pilot preference) to provide a wide field-of-view display (Display I in Fig. 11a) to the pilot. A quasi-three-dimensional display could be obtained by coding the range information into a color scale (e.g., blue = distant, red = near, various shades of purple = ranges in between). A cross hairs could be superimposed on this display to indicate the direction of flight of the aircraft (i.e., an artificial horizon). Such a display would allow the pilot to fly at night or in bad weather.

The Doppler information would be continually analyzed to look for moving targets. If a moving target (or targets) is detected, an overlay (in the

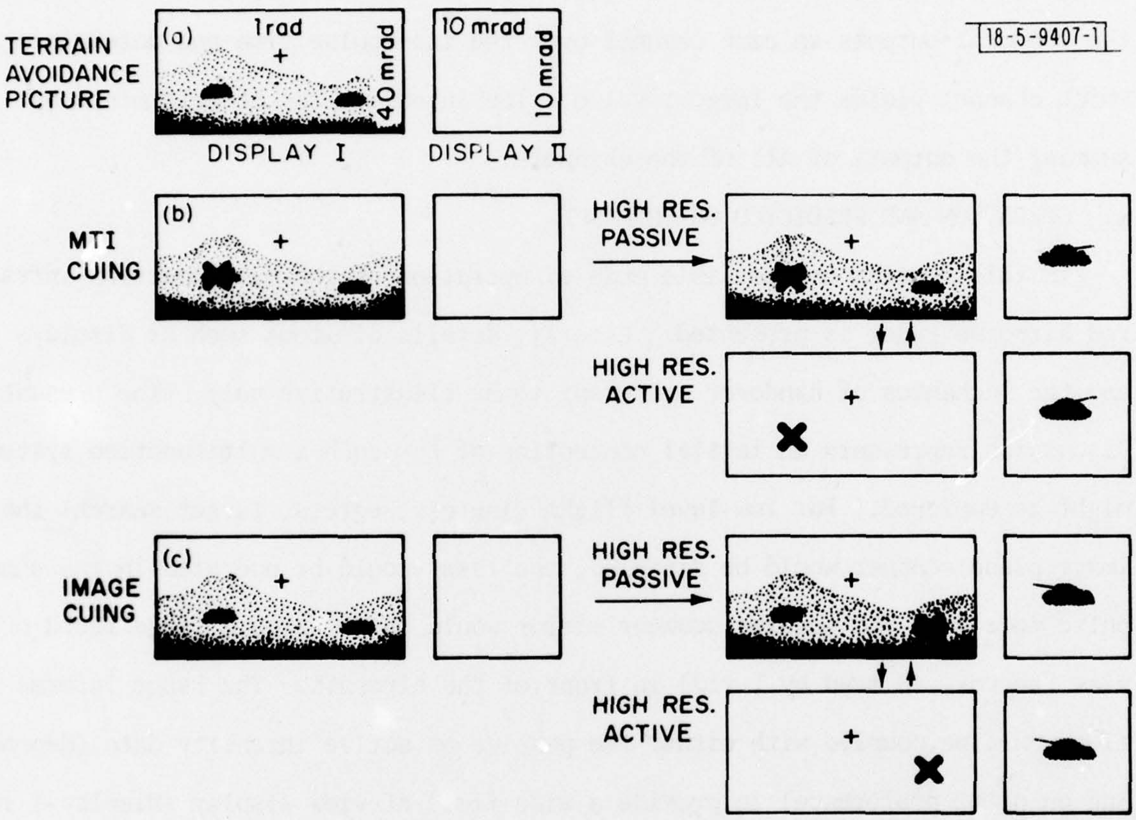

Fig. 11. Characteristic displays of the conceptual multifunction infrared airborne radar in various modes of operation. (a) Terrain avoidance (note cross hairs giving artificial horizon), (b) MTI cuing with subsequent change to the high resolution imager modes, (c) Image cuing with subsequent change to the high resolution imager modes.

third color) will be superimposed on the terrain avoidance image indicating the areas of motion (see Fig. 11b). At the pilot's discretion he could designate one of these moving targets (e.g., with a light pen) and display a high resolution passive image of the object on Display II. This can be done without interfering with the terrain avoidance image, because in the passive mode all 12,000 by 500 pixels are available for use. By storing all of this information contained in one frame in a memory before the pixel averaging (data compression) essential for using Display I is performed, the appropriate 128 x 128 pixels surrounding the designated display point can be recalled from memory and displayed on Display II. The resulting high-resolution passive image would be automatically updated at the same rate as the terrain avoidance image.

If the passive image is not of sufficient quality for identification, the pilot could push a button and switch over to the high resolution active imaging mode. The pointer-scanner would cease raster scanning and begin to track the designated area. The image plane scanner would be activated and the laser would be operated in a conventional Q-switched mode to yield a 128 x 128 pixel active image of the target. A frame rate of at least 100 frames/sec could be achieved allowing a significant reduction in target speckle by multiframe averaging. This is roughly the mode of operation of the present IRAR infrared radar.

The terrain avoidance image cannot be obtained in the high-resolution active imaging mode because the pointer-scanner must track the target. However, the time required to stop the pointer-scanner, obtain a high resolution active image, and restart the pointer-scanner could be as short as 1 - 2 sec.

Furthermore, the tracking information can be used to display (on Display I) information on the relative position of the target with respect to the direction of the aircraft's motion. Thus, switching to the high-resolution active imaging mode should not necessarily impair the pilot's ability to fly the aircraft.

Since all targets of interest in a battle scenario may not be moving, it is of interest to note that the light pen alone (without an MTI cue) could be used for cuing the high resolution imagers. That is, if an object in the terrain avoidance image appears suspicious (due to shape, intensity contrast, or temperature contrast) it could be designated with the light pen to call up the high resolution passive image from memory (Fig. 11c). As before, if the passive image is inadequate, the system could be switched over to the active imager mode with the push of a button.

The combination of accurate angular information (with respect to the aircraft's inertial platform) and range information, both of which are available in the high-resolution imaging mode, provides all the information that is theoretically needed by a fire control system. Therefore, after the pilot has identified a hostile target and aligned his aircraft with it (using the terrain avoidance image), he could switch back into the high-resolution active imaging mode for a gun run or missile launch. The latter might be directed by a fire control computer being fed the range and position information. In fact, transmitted imager laser pulses could in principle serve as a designator for an infrared-seeking missile. In the attack mode, the pilot may not need the terrain avoidance image as he is flying straight at the target, must have an unobscured line-of-sight, and still has the range information for the restricted field-of-view of the imager. Furthermore, the last available terrain avoidance image could be retained on Display I to indicate the nature of the terrain beyond the target.

It is of interest to estimate the signal-to-noise which might be achieved with this multifunction infrared airborne radar. The signal-to-noise ratio for the heterodyne detector array is given by [2]

$$SNR_h = \frac{P_T}{N\,h\nu B}\,\frac{A_R}{\pi R^2}\,\varepsilon\,\bar{\rho}\,\eta\,e^{-2KR} \tag{8}$$

where P_T is the transmitter laser power, N is the number of detectors in the array, $h\nu = 1.87 \times 10^{-20}$ J is the photon energy (at $\lambda = 10.6$ µm), B is the IF bandwidth, A_R is the receiver area, R is the slant range, ε is the round-trip optical efficiency of the system, $\bar{\rho}$ is the average reflectivity of the target, η is the quantum efficiency of the detectors, and e^{-2KR} is the atmospheric extinction.

The effective signal-to-noise ratio for the direct detector array is given by [1]

$$SNR_d = \left(\frac{\Delta P_R}{NEP}\right)^2 = \frac{(A_R\,\alpha^2\,\sqrt{\varepsilon}\;e^{-KR}/\pi)^2\,([\partial M/\partial T]\Delta T)^2}{A_D B/D^{*2}} \tag{9}$$

where ΔP_R is the difference in power received from a target and that received from the background (including emissivity effects) if the temperature difference between them is ΔT, NEP is the noise equivalent power of the detector, α is the angular resolution of a single detector, A_D is the area of a single detector, D* is the detector detectivity, and $\partial M/\partial T$ is the temperature derivative of the radiant exitance of the scene. All other symbols have the same meaning for both the heterodyne and direct detector cases.

The parameters of the multifunction infrared airborne radar are summarized in Table I. Some of the values in this table deserve special comment. First, Freiburg et al. [9] have shown that the average power from a repetitively passive Q-switched laser decreases for PRF values less than about 100 kHz, while Freed and Marcus [10] have shown that the pulse duration of such lasers increases with increasing PRF. Although electrooptically Q-switched lasers are expected to behave similarly, the results should be quantitatively quite different. Therefore, we have performed average power, peak power, and pulse duration measurements on a compact, electrooptically Q-switched CO_2 laser as a function of PRF. Using the results (which are summarized graphically in Fig. 12), we estimate that for 20 kHz PRF lasers, pulse durations of roughly 300 nsec are obtained with peak power enhancements $P_{peak}/P_{cw} \sim 85$ over the power which could be obtained by running the same laser in the cw mode. For the shaped pulses the tail behaves as a cw output, but because of the short off time (high duty cycle), a 36 kHz PRF causes the spike to behave more like a 100 kHz laser pulse would. For this value we estimate pulse durations of 350 nsec and $P_{peak}/P_{cw} \sim 20$. These results are reflected in the powers and bandwidths listed in the Table. Second, to illustrate the potential limitations imposed by bad weather, two values are listed for the atmospheric attenuation. 0 dB/km obviously relates to perfect weather (i.e., to the absence of all atmospheric effects). Modica and Kleiman [11] have performed a statistical

TABLE I

BASELINE MULTIFUNCTION INFRARED AIRBORNE RADAR PARAMETERS

Transmitter Power (Nominal 50 W cw output) - P_T		
Shaped Pulses ($\sim$ 36 kHz PRF)		1.0 kW spike 50 W tail
Q-switched Pulses ($\sim$ 20 kHz PRF)		4.3 kW
Bandwidth - B		
Doppler Analyzer		430 kHz
Range Analyzer		3.0 MHz
Imager		3.3 MHz
FLIR (Terrain Avoidance Mode)		430 kHz
FLIR (High Resolution Active Mode)		20 kHz
Number of Detectors - N		128
Quantum Efficiency - η		0.5
Average Reflectivity - $\overline{\rho}$		0.1
Transmitter/Receiver Area - A_R		133 cm^2
Atmospheric Attenuation	clear weather bad weather	0 dB/km 2 dB/km
Range - R		3 km
Optical Efficiency - ε		0.1
Angular Resolution - α		80 μrad
Detector Area - A_D		10^{-4} cm^2
Detectivity - D*		2×10^{11} cm $\sqrt{Hz}$/W
$\partial M/\partial T$ (at T = 300K in 8-14 μm band)		0.00026 / K

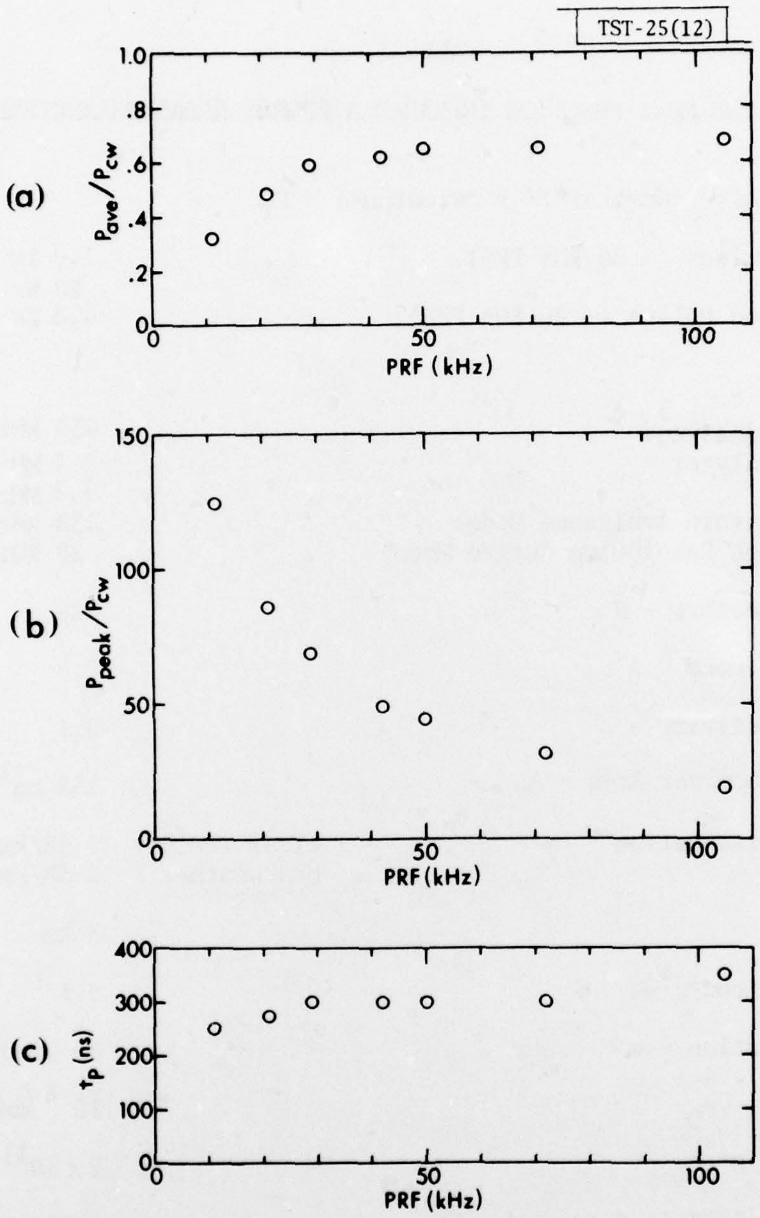

Fig. 12. PRF-dependent performance data for an electrooptically Q-switched cw discharge CO_2 laser. (a) Average output power (normalized to the cw power available from the same laser) versus PRF, (b) Peak output power (also normalized to the cw power) versus PRF, and (c) Pulse duration versus PRF.

analysis of weather effects on atmospheric transmission and determined that at $\lambda = 10.6$ μm an atmospheric attenuation of 2 dB/km or less occurs 70% of the time in summer and 60% in winter in Central Europe. Currently, an aircraft without avionics is non-operational at least 50% of the time (i.e., at night) neglecting weather effects. Clearly, a system not limited to daylight operation and with the ability to penetrate at least 2 dB/km atmospheric attenuation would find practical utility in a realistic combat scenario.

Using the data in Table I and Eq. (8), we compute signal-to-noise ratios for the three heterodyne reception functions in clear and bad weather. The results are summarized in Table II. The phenomenon of speckle will degrade all of the heterodyne detection systems. However, the results in Table II (which are really carrier-to-noise ratios in electrical engineering parlance) are all well above unity, so that standard speckle reduction techniques [1, 2] should be readily applicable.

In discussing the passive imager performance it is convenient to determine the minimum detectable temperature difference (that difference in temperature between the target and the background that gives rise to a signal-to-noise ratio of unity). As in the heterodyne case we have computed minimum detectable temperature differences in clear and bad weather using Eq. (9) and the data in Table I and summarized the results in Table II. Three different computations were made as three types of passive image can be obtained. The first corresponds to the high resolution image stored in memory as the aircraft flies along in the terrain avoidance mode. The second corresponds to the passive terrain avoidance image which is obtained by averaging every 12 pixels

TABLE II

PREDICTED PERFORMANCE OF THE MULTIFUNCTION INFRARED AIRBORNE RADAR

Clear Weather (0 dB/km)	
Range Analyzer	SNR_h = 328
Doppler Analyzer	SNR_h = 114
Active Imager	SNR_h = 1280
Passive Imager	
High Resolution (Terrain Avoidance Mode)	ΔT_{min} = 1.6 K
Terrain Avoidance (12-pixel average)	ΔT_{min} = .46 K
High Resolution (High Res. Active Mode)	ΔT_{min} = .35 K
Bad Weather (2 dB/km)	
Range Analyzer	SNR_h = 21
Doppler Analyzer	SNR_h = 7
Active Imager	SNR_h = 81
Passive Imager	
High Resolution (Terrain Avoidance Mode)	ΔT_{min} = 6.1 K
Terrain Avoidance (12-pixel average)	ΔT_{min} = 1.8 K
High Resolution (High Res. Active Mode)	ΔT_{min} = 1.3 K

of raw data. The third calculation refers to the high resolution passive image which would be obtained when the system is operating in the high resolution active imaging mode.

The temperature differences induced by solar heating are generally of the order of a few degrees at most. Thus a system with $\Delta T_{min} \lesssim 1$ K would be suitable for imaging solar-heated objects. Consequently, except in the worst weather, the passive terrain avoidance picture should be usable. It will certainly be useful for cuing to engine exhausts, frictionally-heated parts, and fires (all of which have large temperature differences). If necessary, improvement in ΔT_{min} could be obtained by using a two-dimensional direct detector array and employing a time delay and integration technique for detectors along the scan direction. It will probably not be suitable for avoiding wires or telephone poles (fortunately, active 10.6 μm systems do an excellent job of finding wires and telephone poles). The high resolution (terrain avoidance mode) passive image will be marginally useful for imaging solar-heated objects but will clearly image hot objects. The high resolution (high res. active mode) passive image would be capable of imaging solar-heated objects as well as hot objects and should prove useful in target identification. The large ΔT_{min} values obtained at 2 dB/km in each case, however, tend to reinforce the conclusion of Ref. [1] that active imagers are potentially far superior to passive imagers in bad weather.

The optical system used in the multifunction infrared airborne radar is smaller than that envisioned for the IRAR system (13 cm as compared to 20 cm), while the laser and detector package are of roughly the same size. Although the processing and display electronics must necessarily be larger in the multi-function system, there appears no reason why the entire system could not be packaged in a standard pod (in much the same manner as indicated in the inset of Fig. 1 for the IRAR system). Such a pod-mounted system would be readily adaptable to any tactical airframe. Because of the wide variety of information available from such a system it might be better suited to twin-seat aircraft, although a single pilot would certainly find the system useful.

5. CONCLUSIONS

In this work we have analyzed the similarities between various types of avionics systems (FLIR's, microwave radars, and infrared radars). This analysis led us to believe that an infrared radar system could be built which could perform many of the functions of a FLIR and a conventional radar as well as its intrinsic imaging and ranging functions. Such a multifunction infrared airborne radar might well provide:

- Wide field-of-view terrain avoidance imaging for low-level flight
- MTI target acquisition
- Target identification by high-resolution active and/or passive imaging
- Target ranging
- Fire control
- Target designation

Basing a design on the experiences of the infrared airborne radar (IRAR) program, we have achieved a baseline design for such a system. Key features include a dual heterodyne/direct 128 element detector array, an optical aperture of 13 cm, a transmitter power of 50 W (nominal cw output), a novel technique of time-sharing range and Doppler analysis functions using shaped laser pulses, and a quasi-three-dimensional display using color scale coding of range information. The baseline system appears capable of providing:

- A 40 mrad vertical by 1 rad horizontal field-of-view terrain avoidance image at a 4 frames/sec refresh rate
- MTI cuing with 8 kmph resolution
- 80 μrad resolution active imaging at 100 - 200 frames/sec
- Ranging to within several hundred feet accuracy
- Passive imaging at 80 μrad resolution and either 4 frames/sec (terrain avoidance mode) or 100 - 200 frames/sec (active imager mode)

Clearly, however, more theoretical work and technology development is required before the feasibility of the multifunction infrared airborne radar concept can be firmly established, although, to date, no insoluble technical problems have been identified. Furthermore, it remains unclear as to whether attempting to perform all functions with a single infrared radar system is operationally the best solution to the multiple function problem.

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REFERENCES

1. R. J. Becherer, "System Design Study for Infrared Airborne Radar (IRAR)," Technical Note 1977-29, Lincoln Laboratory, M.I.T. (18 October 1977), DDC AD-A048979/9.

2. R. C. Harney, "Design Considerations for the Infrared Airborne Radar (IRAR) MTI Subsystem," Project Report TST-26, Lincoln Laboratory, M.I.T. (to be published).

3. R. J. Hull and S. Marcus, "A Tactical 10.6 μm Imaging Radar," Proc. 1978 National Aerospace and Electronics Conf. (IEEE, Dayton, Ohio, 16-18 May 1978), p. 662.

4. S. Marcus and J. W. Caunt, "A Compact CO_2 Laser for Infrared Heterodyne Radar," Rev. Sci. Instr. (to be published, Oct. 1978).

5. M. L. Skolnick, G. F. Gurski, A. A. Vuylsteke, and C. J. Buczek, "Laser Obstacle Terrain Avoidance Warning System," Technical Report ECOM-0145-1, United Aircraft Research Laboratories (February 1973).

6. M. I. Skolnik, Introduction to Radar Systems (McGraw-Hill, New York, 1962).

7. C. W. Ferguson and J. K. Taylor, "FLIR Systems Today" in Aerial Reconnaissance Systems, Proc. SPIE, Vol. 79, Reston, Virginia, (24-25 March 1976), p. 138.

8. R. A. Rosell and R. H. Wilson in Perception of Displayed Information, edited by L. M. Biberman (Plenum Press, New York, 1973).

9. R. J. Freiburg, C. J. Buczek, M. L. Skolnick, P. P. Chenausky, and A. R. Clobes, "High Power CO_2 Laser Devices," Technical Report ECOM-0124-F, United Aircraft Research Laboratories (November 1973).

10. Optics Research Report 1975-2, Lincoln Laboratory, M.I.T. (23 April 1976), p. 9, DDC AD-A025338/5.

11. A. P. Modica and H. Kleiman, "Statistics of Global IR Atmospheric Transmission," Project Report TT-7, Lincoln Laboratory, M.I.T. (8 March 1976), DDC AD-A024311/3.

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MTI target acquisition	baseline system	

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

In this report we examine the feasibility of a multifunction infrared radar for use in a close air support ground attack scenario. First, the characteristics of infrared radars are compared with those of FLIRs and conventional radars. From this comparison it was determined that there was no a priori reason why a single system could not perform a variety of functions. Among these are terrain avoidance imaging, MTI target acquisition, target identification (active and passive imaging), target designation, and fire control. Based on this reasoning a systems concept was developed and a baseline system was designed. Novel features of this baseline system include a dual array of heterodyne and direct detectors, the use of specially-shaped laser pulses for time-shared range and Doppler analysis, and a quasi-three-dimensional display obtained by coding the range information into a color scale. The signal-to-noise and signal-to-clutter ratios of the baseline system were calculated and performance was found to be appropriate for the defined mission.