CENTRAL INTELLIGENCE AGENCY
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Mr. George R. Berdes, Consultant
Subcommittee on International Security
and Scientific Affairs
House Committee on International Relations
Washington, D.C. 20515

Dear Mr. Berdes:

Per your request, enclosed is background information on multi-spectral scanning. Information concerning the status of research and development of this system will follow separately.

Sincerely,

SIGNED

George L. Cary
Legislative Counsel

Enclosure:
"The Military Application of Remote
Sensing by Infrared, p. 104 g
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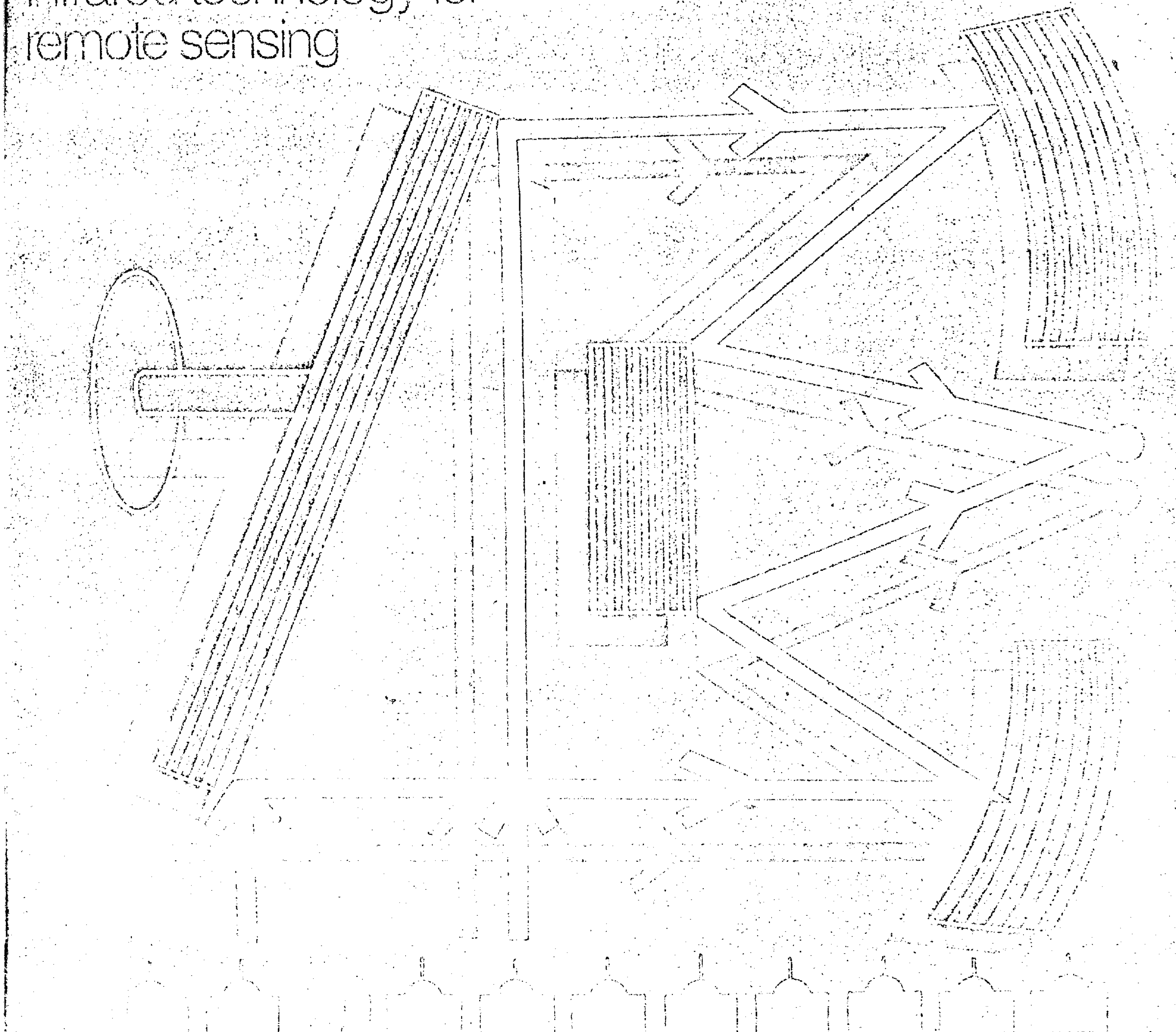
SPECIAL ISSUE ON infrared technology for remote sensing



The Military Applications of Remote Sensing by Infrared

RICHARD D. HUDSON, JR., SENIOR MEMBER, IEEE, AND JACQUELINE W. HUDSON

Invited Paper

Abstract—Remote sensing is the process of acquiring information from the environment by the use of a sensor that is not in physical contact with the object under study. The military services are experienced practitioners of this old, but newly glamorous, art. Their accomplishments in the infrared, that region lying between visible light on the one hand and microwaves on the other, are both impressive and of increasing importance. Our purpose is to provide an overview of these accomplishments. We begin with a brief treatment of the characteristics and peculiarities of the infrared portion of the spectrum and of the sensors that operate there. Early military experience with remote sensing by infrared is described and an applications matrix is developed in order to provide a perspective from which the reader can view the full panorama of military applications. Specific applications are discussed. These include strategic systems for early warning of intercontinental ballistic missile launches, methods for the detection of atmospheric contaminants, such as poison gas, under field conditions, aids for the precision delivery of weaponry (including passive, active, and laser designator guidance techniques), and sensor systems for reconnaissance and surveillance. Wherever possible, details of sensor performance are given.

I. INTRODUCTION

MAN HAS BEEN a remote-sensing creature since his very beginnings. The ability of his eyes, ears, and nose to sense conditions in his surrounding environment often meant the difference between life and death. Remote sensing is simply the process of acquiring information from the environment by the use of a sensor that is not in physical contact with the object or phenomenon under study. When viewed in this context, it is evident that remote sensing is neither a new nor a particularly innovative discipline. It has, however, taken on an increasing importance because of the need for the collection of information on a scale hitherto unattempted and the emergence of many newly engineered sensors that are, for the first time, capable of unattended, long term, reliable operation.

The military services have, of course, always had a strong interest in remote sensing. What did the enemy do yesterday? What is he doing today? What will he do tomorrow? These are questions of absorbing importance and the answers are needed day or night, rain or shine, win or lose. Remote sensing can be done with sensors operating virtually anywhere in the electromagnetic spectrum, as well as with such nonelectromagnetic types as acoustic and seismic. This paper will be limited to those applications in which the remote sensing is done in the infrared portion of the spectrum. The infrared spans nearly 11 octaves, extending from the visible at a wavelength of 0.75 μm to the microwave region at 1000 μm. Because of absorption by the earth's atmosphere, only a small portion of this range is usable for terrestrial applications.

DESIGNATION	ABBREVIATION	LIMITS, μm
NEAR INFRARED	NIR	0.75 TO 3
MIDDLE INFRARED	MIR	3 TO 6
FAR INFRARED	FIR	6 TO 15
EXTREME INFRARED	XIR	15 TO 1000

Fig. 1. Subdivisions of the infrared.

Solid bodies not at a temperature of absolute zero radiate energy and, for all practical temperatures, the bulk of the radiation lies in the infrared. For this reason it is often called the heat region of the spectrum. It is convenient to subdivide the infrared into the four parts shown in Fig. 1. These subdivisions are somewhat arbitrary but they are still useful because the first three include spectral intervals in which the earth's atmosphere is relatively transparent, the so-called *atmospheric windows*. It is these windows that will be utilized by any infrared sensor that must look through the earth's atmosphere. In the extreme infrared, which is nearly 6 octaves wide, the atmosphere is essentially opaque. This region is generally used only for laboratory applications where the instrument can be evacuated.

Since its discovery by Sir William Herschel in 1800, the infrared has held a strong fascination for potential [illegible]. Herschel, the discoverer of Uranus, is remembered as one of the finest observational astronomers of all time. He had been looking for a better way to protect his eyes when observing the sun and it was this search that led him to the discovery of what he termed the "invisible rays." For the next 1[illegible] years many workers followed Herschel's lead and made the basic discoveries that have evolved into modern infrared technology. Applications for infrared techniques began to appear shortly after the turn of this century. By the time of World War I, the military forces of the world were beginning to apply these infrared techniques to the solution of military problems. Before discussing these applications let us look in more detail at the characteristics and peculiarities of the infrared region and of the sensors that operate there.

II. FUNDAMENTALS OF INFRARED TECHNOLOGY

The elements of an infrared remote sensing system are shown in Fig. 2. Such systems may be *passive*, in which case they sense the radiation emitted by a target, or *active*, in which case the target is illuminated and the system senses the radiation that is reflected by the target.[1] We can make a

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[1] We use the word target in the military sense as connoting an

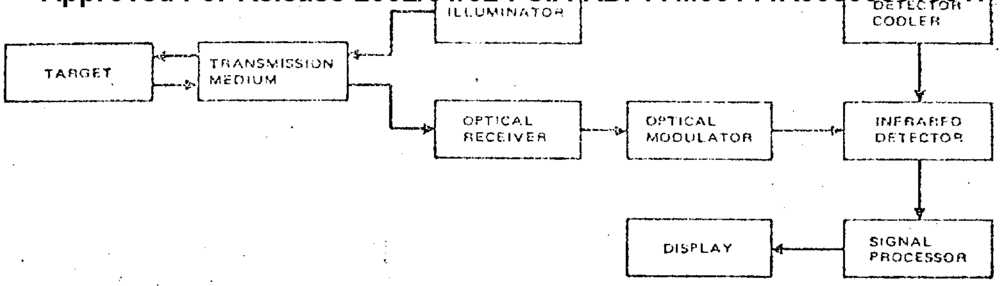

Fig. 2. The elements of an infrared remote sensing system.

further distinction between *active* systems in which the illuminator is an integral part of the sensor system and *semiactive* systems that use a naturally occurring illuminant. By this definition, photography with a flashbulb would be an example of an active system while daytime photography with the sun as an illuminant would be an example of a semiactive system.

With Fig. 2 as a guide, let us look more closely at the elements of the infrared remote sensing system [1].

A. Targets

With an active system, the reflectance characteristics of the target are important. Reflectance will vary with wavelength, viewing and illuminating angle, and surface conditions. With a passive system, the radiating characteristics of the target are important. The radiated energy will vary with the temperature of the target, its emissivity, and, to a lesser extent, with viewing angle (a hot spot may be shielded by target structure from some angles). Radiation can be grouped into two classes; *gaseous* radiation from hot gases and *thermal* radiation from heated solids. Most combustion processes produce water vapor and carbon dioxide both of which, when excited, radiate at characteristic wavelengths in the infrared. As a result, the exhaust gases of turbojet, turbofan, rocket, and internal combustion engines show intense radiation at 4.4 μm from carbon dioxide and in the 2.6- to 2.8-μm region from carbon dioxide and water vapor. The presence of this gaseous, or exhaust plume, radiation often makes it possible to detect a target from nearly any aspect angle rather than only those angles from which the hot metal of the exhaust structure is visible.

Planck's law describes the spectral distribution of the energy radiated by a *blackbody*. A blackbody is a theoretical concept, much as are the noiseless receiver and the frictionless plane, and it represents a perfect radiator. By Kirchhoff's law, good absorbers are good radiators. Thus an alternate definition is that a blackbody absorbs all of the radiation incident on it. The radiation from many solid bodies approximates quite closely to that from a blackbody at the same temperature. We can estimate the radiation from a solid by first calculating the radiation from a blackbody and then multiplying it by the emissivity of the solid. The emissivity of most electrical conductors lies in the range from 0.02 to 0.2 while that of insulators ranges from 0.8 to nearly unity.

Integrating Planck's law over all wavelengths gives the *Stefan–Boltzmann law*, an expression for the flux (or power) radiated into a hemisphere above a blackbody having an area of 1 cm^2.

$$M = \sigma T^4 = 5.67 \times 10^{-12} T^4 \tag{1}$$

where M is called the *radiant exitance* and is expressed in W/cm^2, σ is the Stefan–Boltzmann constant, and T is the temperature in kelvin. Thus the total (summed over all wavelengths) radiated flux varies as the fourth power of the absolute temperature. Differentiating Planck's law and solving for the maximum gives *Wien's displacement law*

$$\lambda_m T = 2898 \tag{2}$$

where λ_m is in micrometers and is the wavelength at which the maximum radiant exitance occurs.

Equations (1) and (2) are convenient for rapidly calculating the wavelength at which the radiation from a solid body is a maximum and the effect of changes in temperature of the body. Many targets, such as personnel, trucks, ships, and terrestrial backgrounds have a temperature of about 300 K. From (2), the maximum of the radiation distribution occurs at 9.7 μm and, from (1), each unit area of surface radiates 0.046 W. The hot tailpipe of a turbojet has an effective temperature of about 900 K. The maximum of its radiation distribution occurs at 3.2 μm and each unit area radiates 3.7 W. To carry the calculations a step further, the sun radiates like a blackbody at a temperature of about 5900 K. The maximum of its radiation distribution occurs at 0.49 μm and each unit area radiates nearly 6900 W (although the sun is a mass of hot gas, rather than a solid body, the thermodynamic conditions are such that its radiation very nearly obeys Planck's law).

B. Transmission Medium

The earth's atmosphere is not a very favorable transmission medium for infrared radiation. Before the radiation from a target reaches an infrared sensor it will be selectively absorbed by atmospheric gases, scattered away from the line of sight by small particles suspended in the atmosphere and, at times, modulated by rapid variations in some atmospheric property (in much the same way as the light from stars appears to twinkle). Fig. 3 shows the spectral transmittance measured over a horizontal, sea level path 1828 m (6000 ft) long. The molecule responsible for each absorption band, water vapor, carbon dioxide, or ozone, is indicated in the upper part of the figure. The transmission curve can be characterized by several regions of high transmission, the aforementioned atmospheric windows, separated by intervening regions of high absorption. The subdivisions of the infrared, shown in Fig. 1, are also included. Note that each subdivision includes at least one atmospheric window. The transmission depends upon the amount of absorber along the path, the altitude of the path, the angle the path makes with the horizontal and the wavelength of observation. The calculation of the transmission over any arbitrary path is a difficult analytical problem but there are various tables and nomograms available from which reasonable engineering estimates can be made [1, pp. 142–159].

The theory of scattering shows that a particle is the most efficient scatterer when its radius is equal to the wavelength

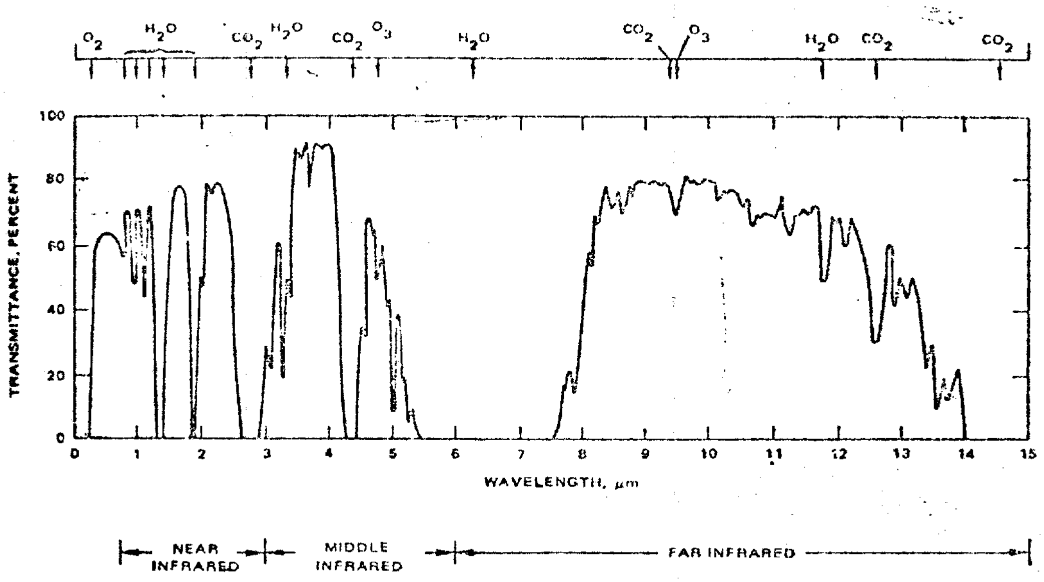

Fig. 3. Transmittance through the Earth's atmosphere (horizontal path at sea level, length 1828 m). (Adapted from Hudson [1] and Gebbie [2].)

of the radiation being scattered. Since most atmospheric scatterers (haze particles) have radii that are from 0.05 to 0.5 μm, the shorter wavelengths of the visible portion of the spectrum are scattered much more than are the longer wavelengths of the infrared. Unfortunately, the particles in fogs and clouds have radii ranging from about 2 to 20 μm so that they are very effective infrared scatterers. As a result, clouds and fogs are essentially opaque in the infrared with the consequence that infrared sensor systems working in the earth's atmosphere can never have a true all-weather capability.

C. Illuminator

For semiactive systems, the most common illuminant is the sun. Occasionally, moonlight or night sky glow may be used. For active systems, typical illuminants include tungsten lamps, xenon lamps, and carbon arcs, all of which must be fitted with filters to suppress visible radiation, and various lasers that radiate in the infrared. It is interesting to note that the World War II development of ruggedized tungsten lamps for the illuminators in active infrared systems led to the sealed beam headlamp that is found on virtually all modern automobiles.

D. Optical Receiver

Most of the optical materials commonly used in the visible portion of the spectrum do not transmit in the infrared beyond a wavelength of a few micrometers. For this reason, nearly all early infrared sensor designs used reflective optics of the type commonly used for astronomical instrumentation. Strong military support following World War II led to the development of many new infrared-transmitting materials and effectively removed any restrictions on the use of refractive (lens type) optics. The optics in typical modern infrared sensors generally range in diameter from about 5 to 25 cm with some specialized systems running as large as 100 cm.

The smallest image that a set of optics can form of a point source is called the *blur circle*. The blur circle is caused by *aberrations* in [illegible] be minimized or eliminated by the optical designer (provided one is willing to pay the price). Diffraction is a consequence of the wave nature of electromagnetic radiation and it cannot be eliminated. The ability of an optical system to form two recognizable images of two closely spaced targets is characterized by its *angular resolution*. In the absence of aberrations (the *diffraction-limited* case) the diameter of the blur circle, and the minimum angular separation of two equal-intensity point targets that can just be resolved, varies directly with the wavelength and inversely with the diameter of the optics. Expressed another way, the ability to resolve objects with a small angular separation is directly proportional to the number of wavelengths in the receiving aperture. Here, then, is one of the fundamental advantages of infrared (or optical) equipment. Since the apertures of such equipment are thousands of times larger than the wavelength, the angular resolution capability is great. With radiation having a wavelength of 4 μm, for example, a lens with a diameter of 5 cm would have 12 [illegible] wavelengths across its diameter. To achieve the same angular resolution with a 10-cm (wavelength) radar would require an antenna with a diameter of 1.25 km. The importance of the number of wavelengths across the aperture is, of course, the compelling reason for the development of synthetic aperture techniques in radar and radio astronomy.

E. Optical Modulator

In tracking sensors the radiation from the target is coded, or modulated, with information concerning the direction to the target. This is accomplished with a small disk, often called a reticle, carrying a carefully contrived pattern of clear and opaque spaces. In addition, most reticles provide essential assistance in discriminating a target from its background, a process known as *space filtering*.

F. Infrared Detector

An infrared detector is a transducer that converts infrared radiation into some other observable form, such as an electrical current, a change in some physical property of a detector, or [illegible]sitive photographic film. There are two mutually exclusive classes of detectors. The

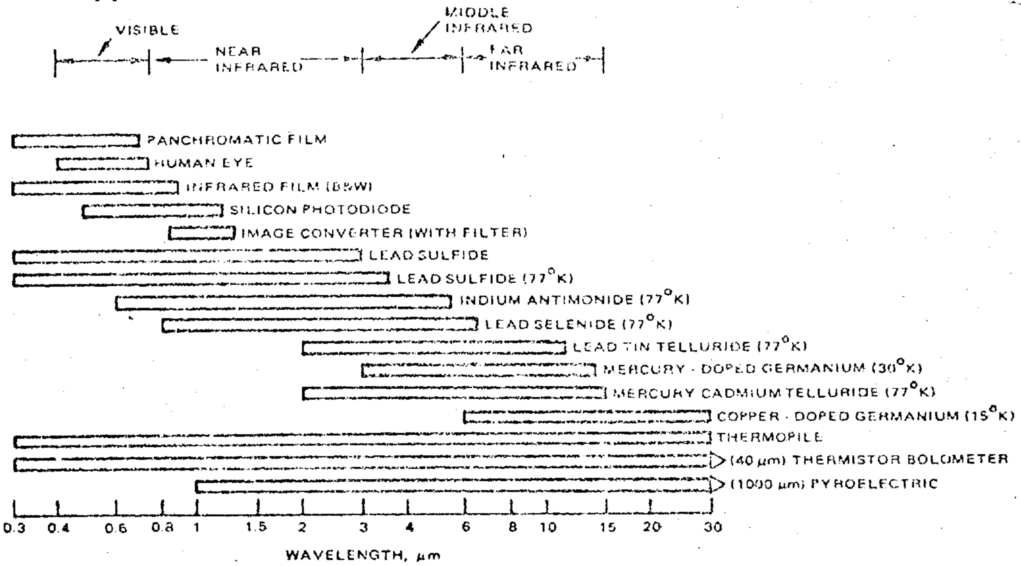

Fig. 4. Useful spectral ranges for infrared detectors (operating temperature of all detectors is 300 K unless noted) [3].

reason for the two classes stems from the modern concept that divides the solid into two thermodynamic systems, the lattice and the electronic. The way in which the incident radiation interacts with these systems results in two fundamentally different detection mechanisms, called the *thermal* and the *photon*. Radiation incident on a *thermal* detector is absorbed by a blackened coating which heats the lattice. This, in turn, affects the electronic system and results, for example, in a change of electrical resistance or the generation of a thermal EMF. When radiation is incident on a *photon* detector, the photons interact directly with the electronic system to produce, for example, a change in the conductivity of the detector. Many of the photon detectors in use today require cooling to cryogenic temperatures. Since the energy of a photon varies inversely with wavelength, there is a long-wavelength cutoff for each type of photon detector beyond which the energy of the photon is insufficient to cause a change in the electronic structure [3].

Fig. 4 shows the spectral interval over which typical infrared detectors are normally used. Notice that the response of infrared film extends only a short way into the near infrared. Infrared film is normally used to record the radiation (usually sunlight) that is reflected from objects rather than that which is emitted by them. There are a number of thermal imaging devices that work at longer wavelengths and some are even called cameras. These devices record objects by their own radiation and their imagery should not be confused with that produced by infrared film.

Numerous terms have been used to describe the performance of an infrared detector. *Sensitivity* springs naturally to mind but its use is not recommended because, all too often, sensitivity is used indiscriminantly to mean signal-to-noise ratio or simply signal. Instead it is customary to speak of the *detectivity* of a detector which is now expressed quantitatively by a parameter called D^* (pronounced Dee star). When two detectors are compared, the one that can detect the smallest amount of radiation is the one having the higher value of D^*. Note that Fig. 4 does not imply anything about detectivity.

It is not possible to offer a simple guide that will lead one to the optimum choice of detector. In general, thermal detectors can be operated without cooling, respond over large portions of the spectrum, have lower values of D^* than photon detectors, and exhibit relatively long response times so that they are not well suited for high-information-rate systems. Photon detectors, by comparison, generally require cooling for operation beyond 3 μm, respond over relatively narrow portions of the spectrum, have values of D^* that are 1 or 2 orders of magnitude higher than those of thermal detectors, and exhibit very short response times so that they are well suited for use in high-information-rate systems.

G. *Detector Cooler*

The requirement for cooling photon detectors has brought with it a requirement for convenient cooling devices featuring extreme miniaturization, minimum power consumption, simple maintenance, and high reliability. Such devices are a commercial reality and the cooling requirement need not deter any system designer from adopting a cooled detector for his sensor design [3].

H. *Signal Processor*

The signal processing techniques employed are, for the most part, quite similar to those used with radar, sonar, and television. Frequencies involved are usually in the audio region but with some systems they may go as high as a few megahertz. Signal levels out of detectors may be as low as a few microvolts so it is essential that good low-noise high-gain circuitry techniques be used. Preamplifiers have been designed for use at very low temperatures so that they can be packaged directly with cooled detectors. Integrated circuitry has been widely adopted and an increasing number of infrared sensors now use digital, rather than analog, signal processing.

I. *Display*

The final output of the sensor system must go either to a display for human or automatic interpretation or to some sort of control circuitry for guidance or tracking purposes. Most currently available display techniques, such as cathode-ray tubes, liquid crystals, and photographic film, are readily usable with infrared sensor systems.

III. Early Military Experience with Remote Sensing by Infrared

It is not difficult to understand the appeal that infrared techniques have for the military system designer. Since infrared radiation cannot be detected by the human eye, it offers the opportunity to see in the dark, to detect targets by their self-emission, and to communicate by secure means.

Military organizations began to experiment with infrared sensors soon after 1900. By the time of World War I there were experimental blinker signaling systems usable at ranges of up to 30 km, voice communication systems with ranges of 3 km, and detection sets that could detect aircraft at 1.5 km and people at 0.3 km. Neither side put any infrared equipment into production but the experience gained with the experimental equipment was promising enough to assure continued support of its development [1, pp. 8, 9, 464–510], [4].

Germany was the first country to deploy infrared equipment on the battlefields of World War II. Early in the war, German intelligence thought that the Allies were using infrared sensors to detect U-boats and aircraft. This conclusion was erroneous but it caused Germany to concentrate much of its research and development effort on infrared sensors and on the means of countermeasuring them. The Allies, on the other hand, concentrated their efforts on the development of radar. Germany lost the war but she clearly won the battle of the infrared [1, pp. 8, 9, 464–510].

German troops made effective use of an infrared communication system, called the Lichtsprecher, in the African desert during the major tank battles from 1941 to 1943. The maximum effective range of this system was 8 km. The existence of the Lichtsprecher remained a secret until the British captured one in October 1942 at the battle of El Alamein. In 1943, the Germans integrated image converters into fire control systems for tanks. These were used on the eastern front in 1944 and they proved to be remarkably effective in nighttime battles. Why these devices were never used on the western front remains a mystery. Night driving systems containing image converter tubes saw extensive field service. When the Allies gained air superiority over the continent, these night driving systems made it possible for the German Army to move its V-2 weapons across Germany and Holland to their launching ramps. The speed with which this was done puzzled Allied intelligence who did not know, at the time, of the existence of the German night driving capability. An experimental aircraft detection set, which was probably the first to use a cooled detector, could detect bombers (at night only) at a distance of 12 km. In 1943, development was completed on Madrid, an infrared seeker intended for the guidance of small air-to-air missiles. This seeker used an uncooled lead sulfide detector and there is some evidence that there were plans to incorporate a cooled detector [1, pp. 8, 9, 464–510].

The best known U.S. infrared equipment of World War II was the sniperscope, which consisted of an image converter and an illuminator mounted on a carbine. With it a soldier could fire accurately, in complete darkness, at targets that were as far away as 75 m. The sniperscope was first used in combat during the invasion of Okinawa, Japan, in April 1945. Night driving systems using image converters were under development but were not yet ready for field use when the war ended. Sensors f[illegible] as early as 1935. The SS Mauritania was detected at a distance of 21 km and the SS Normandie at 28 km. Other developments included infrared communication systems, both voice and blinker, for naval use and a simple viewer, called the Metascope, for detecting the sources that were required by active viewing systems. False-color film was perfected for the detection of camouflage from the air. It remains, to this day, one of the most important tools available for multispectral analysis [1, pp. 8, 9, 464–510], [4]–[6].

In the United Kingdom, an infrared aircraft detection set was tested as early as 1936. It could detect an aircraft at a distance of 1.6 km during the daytime and 3.2 km at night. (Most infrared sensors of this time period were bothered by reflected sunlight and they usually performed much better at night. They used either a thermal detector, with no spectral filtering to remove short-wavelength solar radiation, or a short-wavelength photon detector such as thallous sulfide or, later, lead sulfide.) The British also flight tested one of their detection sets and were able to detect another aircraft at a distance of 0.5 km. This occurred in 1937 and it may be the first time that an infrared sensor was used to detect one aircraft from another, while both were in flight [1, pp. 8, 9, 464–510].

The Japanese were influenced by the German success with infrared sensors and there is some evidence to suggest that they were planning to produce night viewers and driving devices when the war ended. There is no evidence that the Russians used any type of infrared sensor during World War II.

Despite the relatively small production totals that were achieved during World War II, infrared sensors showed sufficient merit to justify a strong postwar development that was supported largely by military funds. The postwar period is remarkable for the rapid development of new and improved detectors and of infrared-transparent optical materials and their application to the solution of a host of military problems. Subsequently, many of the same techniques were applied to the solution of industrial, scientific, and medical problems. In the late 1950's the release of information on the Sidewinder and Falcon heat-seeking infrared-guided missiles caught the public fancy, and subsequent applications of infrared remote sensing techniques to the attitude stabilization of space vehicles, satellite reconnaissance of sea-ice conditions, area surveillance, and submarine detection have been eagerly reported in the news media.

IV. The Military Applications of Remote Sensing by Infrared

The applications matrix of Fig. 5 is intended to give the reader a perspective from which to view the full panorama of military applications of infrared remote sensing. The three functional elements of any military organization, strategic, tactical, and logistic, are listed across the top of the matrix where they represent the three classes of military users. At the side of the matrix are listed the characteristic properties of target-emitted and reflected radiation that can be sensed in the infrared. The result is a logical compact classification scheme in the form of a 3 by 9 element matrix.

A. Rationale for the Applications Matrix

Let us look more closely at the functional elements who are the military users of infrared remote sensing. *Strategists* are concerned with long-range planning for the allocation of a [illegible] its security, or its success in attaining the objects of war. *Tacticians* apply their skills to the deployment of troops and to the execution of plans in the

TYPE OF SENSOR		PROPERTY SENSED	STRATEGIC	TACTICAL	LOGISTIC
PASSIVE	RADIATION EMITTED BY TARGET	EXISTENCE, DIRECTION, MOTION	STRATEGIC WARNING, EARLY WARNING OF ICBM/SLBM LAUNCH ARMS CONTROL VERIF HORIZON SENSORS	MISSILE GUIDANCE PROXIMITY FUSES COLLISION WARNING INTRUSION DETECTION BOMBER TAIL DEFENSE	INTRUSION DETECTION COLLISION WARNING DETECTION OF FUEL TANK FIRES
		QUANTITY OR TEMPORAL VARIATION	TARGET IDENTIFICATION	TARGET IDENTIFICATION	MONITOR WOUND HEALING REMOTE BIOSENSORS
		SPECTRAL CHARACTERISTIC	TARGET & BACKGROUND SIGNATURES DETERMINE ATMOSPHERIC TEMPERATURE PROFILE	DETECT POISON GAS DETECT CLEAR AIR TURBULENCE TARGET & BACKGROUND SIGNATURES	DETECTION OF CONTAMINANTS IN LOX PIPING
		GEOMETRICAL OR SPATIAL DISTRIBUTION	STRATEGIC RECONN EARTH RESOURCES AGRICULTURE WEATHER & SEA ICE ARMS CONTROL VERIF.	BATTLEFIELD RECONN AND SURVEILLANCE SUBMARINE DETECTION DAMAGE ASSESSMENT	WOUND ASSESSMENT AND MONITORING STUDIES OF THE EFFICIENCY OF ARCTIC CLOTHING
SEMI-ACTIVE	REFLECTED RADIATION (FROM SOURCE NOT INTEGRAL WITH SENSOR SYSTEM)	SPECTRAL CHARACTERISTIC	TARGET & BACKGROUND SIGNATURES	TARGET & BACKGROUND SIGNATURES CAMOUFLAGE DETECTION	
		GEOMETRICAL OR SPATIAL DISTRIBUTION	STRATEGIC RECONN EARTH RESOURCES AGRICULTURE WEATHER & SEA ICE ARMS CONTROL VERIF.	TACTICAL RECONN DAMAGE ASSESSMENT TARGET ASSESSMENT CAMOUFLAGE DETECTION	STUDIES OF THE EFFICIENCIES OF CAMOUFLAGE MATERIAL
ACTIVE	REFLECTED RADIATION (FROM SOURCE INTEGRAL WITH SENSOR SYSTEM)	EXISTENCE, DIRECTION, MOTION		NIGHT RENDEZVOUS INTRUSION DETECTION COLLISION PREVENTION SHIP & AIRCRAFT REFUEL	INTRUSION DETECTION COLLISION PREVENTION SHIP & AIRCRAFT REFUEL
		GEOMETRICAL OR SPATIAL DISTRIBUTION		NIGHT DRIVING SMALL ARMS FIRE AREA SURVEILLANCE IFFN INTRUSION DETECTION	NIGHT DRIVING AREA SURVEILLANCE INTRUSION DETECTION MONITOR WOUND HEALING
		MODULATION		SECURE COMMUNICATION IFFN TARGET DESIGNATION COMMAND GUIDANCE FOR WEAPON DELIVERY	

Fig. 5. Typical military applications of remote sensing by infrared.

actual conduct of war. Strategy is the prelude to the battlefield. Tactics are the action on the battlefield. *Logistics* provides the means for the conduct of war. By long-standing tradition, logistics includes the elements of supply, transportation, personnel services, and facilities.

The left side of the matrix shows the characteristics of target-emitted and reflected radiation that can be sensed or, put another way, the functions for which infrared sensors are particularly well adapted. Starting with line 1, we see that for passive systems if the target radiates in the infrared, and virtually all targets do to varying degrees, an infrared sensor can detect the existence of the target, determine its direction with respect to some reference, and sense its motion. Such sensors are the heart of search and detection, tracking, and guidance systems. Having detected a target, the sensor can measure the total quantity of radiation received or examine the radiation for any temporal variations. As shown on line 2, this information can be useful for target identification and remote measurements of temperature. Alternatively, the spectral characteristics of the target [illegible] for use in target identification and poison gas detection, as shown in line 3 of the matrix. Finally, as shown on line 4, the sensor can sense the geometrical or spatial distribution of the target radiation. This leads to thermal imaging systems that produce imagery similar to a photograph, with the exception that brightness variations in the thermal image represent temperature differences in the scene whereas in a photograph they represent differences in reflectance.

With semiactive systems, i.e., those in which the sensor responds to target-reflected radiation from a naturally occurring source, the spectral characteristics of the illuminant are known and it is easy to sense target-produced changes in the reflected radiation. As line 5 shows, such systems are useful for target identification and the detection of camouflage. In line 6 we have imaging systems that result from sensing the geometrical and spatial distribution of the reflected flux. It is in this category that we find photographic systems using infrared or false color film for tactical and strategic reconnaissance.

With active systems, i.e., those in which the sensor responds [illegible]tor that forms an integral part of the sensor system, there are three properties of the reflected radiation that can be sensed. If reflected energy can be detected, the presence of a target can be inferred, its direction can be determined with respect to the sensor, and any target motion can be noted. Systems such as these are shown on line 7 and they are used for night rendezvous and collision prevention. The geometrical and spatial distribution of the reflected radiation can, of course, be sensed and used to produce some sort of imagery (line 8). Representative systems include those to permit small arms fire at night (like the sniperscope of World War II) and night driving systems. Finally, as shown on line 9, we can sense amplitude, frequency, or phase variations and use them for rangefinding, target designation, or communication. The most common communication system uses a voice-modulated source at both ends of the circuit and the system uses not reflected radiation but, instead, the radiation from *cooperative* sources. Some communication systems in which covertness is particularly desirable, use a source at one terminal to illuminate a reflective modulator at the other terminal.

The reader may have noticed that some applications appear in more than one element of the matrix. This is not surprising because there are many times when it is desirable to use several of the remotely sensed characteristics in order to increase the probability of a positive target identification. Who among us has not, at some time, encountered someone whose face was familiar but whose name we could not recall until we heard their voice? With the exceptions of lines 1 and 5, the applications shown in the matrix either require, or imply, both detection and identification. In the case of an imaging system, positive identification often results from recognition of a characteristic shape. Is it a truck? No, it is a tank. But other situations are not so easy. Is the crop in that field wheat or is it alfalfa? To answer this question by remote sensing requires the recognition of a target *signature*. A signature is any unique combination of spatial, temporal, or spectral characteristics of the emitted or reflected radiation that is peculiar to a specific target. Once a signature has been identified it must be catalogued and made readily retrievable so that it can be used to recognize a similar target at another time and place, i.e., wheat in Kansas today and in the Ukraine next month. One currently popular technique of searching for signatures is *multispectral analysis* in which a sensor, or sensors, record in a number of narrow spectral intervals the radiation reflected or emitted by a target.

B. The Dollar Value of the U.S. Market for Military Infrared Sensors

As infrared matured into a recognized technology, the annual sales of infrared sensors assumed significant proportions. The exact dollar value of the U.S. market for military infrared sensors is, of course, open to considerable speculation but there are some guidelines that make it possible to provide at least an order-of-magnitude estimate [1, pp. 9, 10]. For this estimate, we define the market so that it includes all U.S. military expenditures for the research, development, test, engineering, procurement, and field service of the infrared sensors that are implied by the applications matrix of Fig. 5. Notice that by this definition we have included laser infrared devices along with the more classical infrared sensors. On the basis of this market definition we estimate that the value of the market was about $195 million in 1960, $425 million in 1968, and $700 million in 1974. Herschel's discovery of [illegible] matured into an impr business.

C. Sources of Information for this Paper

The reader will, we hope, realize that much of the informa tion about military infrared sensors is protected by security classification and cannot be discussed here. The line between what is classified and what is not is often blurred and poorly defined. *Our criterion is that publication of an item in the readily available open literature of the world is a clear indica tion that the item is not, or, perhaps, is no longer, classified* By repeating such information we do not necessarily imply anything about its credibility. The source of each such item meticulously cited so that the reader, if he so desires, can to the original source and judge its validity for himself. personal files, which were used extensively for this paper, culled from the open literature and they reflect more years of worldwide "infrared watching." We find invalu much of the intelligence-like information that appea *Aviation Week and Space Technology*. This source is often cited in technical journals, but we believe it eminently proper for this paper. If the reader notices in this paper, they merely reflect our inability to loc source for the desired information in the open literature

In the remainder of this paper we will discuss some major military applications of infrared remote sensing. applications include the detection and early warning intercontinental ballistic missile (ICBM) launches, the tion of atmospheric contaminants, such as poison gas, or battlefield, aids for the precision delivery of weaponry, sensor systems for reconnaissance and surveillance.

V. STRATEGIC SYSTEMS FOR EARLY WARNING OF ICBM LAUNCHES

The detection of ICBM launches appears to be a pri application for infrared sensors. In the United States this is handled by the Early Warning Satellite System (EWSS) The infrared sensor on board the satellite (currently said in synchronous orbit) detects the radiation from the hot of the exhaust plume during the missile's boost, or pow phase. Information about the motion of the satellite derived from the sensor is fed to a high-speed ground computer that calculates the point of impact of the within about one minute from the initial detection Although the system was designed for the detection of launches it also appears to have a considerable capability the detection of ship-launched ballistic missiles (SLBM). capacity of the EWSS to detect and track multiple launc is said to be high enough so that system saturation would indicate a full scale attack against the U.S. [8].

Very few measurements of ICBM radiation have been lished. Seymour [9] models the radiation from the plume as being equivalent to that from a blackbody temperature of 2000 K with a radiant intensity[2] of 10^3 W He estimates that actual missiles emit within an order of nitude either side of this value. Rosenberg *et al.* [10] rep measurements of the emission spectrum of a kerosene missile (not further identified). Their measurements sho fairly continuous emission similar to that of a blackbody temperature of 2000 K. The peak emission from a 20

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[2] Radiant intensity is a measure of the flux leaving a point per unit solid angle.

blackbody occurs at 1.45 μm. From Planck's law we can calculate that three-fourths of the flux lies at wavelengths longer than 1.45 μm, one-half at wavelengths longer than 2.06 μm, and one-fourth at wavelengths longer than 3.08 μm. Interestingly enough, less than 0.8 percent lies in the visible. We conclude from our calculation that the detection of a powered ICBM is probably best done in the near infrared, but we hold the reservation that there may be a problem due to competing signals caused by the reflection of sunlight from clouds and other terrestrial backgrounds. Further information on the modeling of a variety of targets has been published [1, ch. 3].

A. System Development

In 1958, the U.S. Air Force initiated Project MIDAS (an acronym derived from *m*issile *d*etection *a*nd *s*urveillance) [1, pp. 471-474], [11], [12]. By the fall of 1961, MIDAS sensors had apparently demonstrated, from orbit, the ability to detect the launch of a Titan ICBM [1, pp. 471-474]. But the sensors were reported to be plagued by an inability to differentiate between missile exhaust plumes and sunlight reflected from high-altitude clouds [8], [13]. The roots of the problem appeared to stem from insufficient data on the characteristics of the radiation from targets and backgrounds when they are viewed through the earth's atmosphere and to a lack of data on the transmission characteristics of the atmosphere. Because of these troubles, the program was reduced to an experimental status early in 1963 [1, pp. 471-474], [12]. Program efforts over the next several years seem to have been devoted to measurements of the infrared signatures of ballistic missiles in the boost phase and to improvements in sensor reliability [12].

Apparently these efforts were successful because in June 1966 the Air Force asked for bids on the development of an operational EWSS [12]. By the end of 1966, satellite and sensor contractors had been selected for what was, by then, known by code number 949. The sensor package, estimated to weigh about 450 kg, was to contain both an infrared sensor and a camera for surveillance purposes. It was estimated that the infrared detector would be cooled by liquid hydrogen and that the objective lens of the sensor would be about 1 m in diameter [14]. It was expected that the first operational satellite could be launched before the end of 1968.

Experimental satellite launches, beginning in August 1968, were used to test system prototypes. In March 1971, the Secretary of the Air Force testified before Congress that the system had proven its capability to detect missile launches [15]. By now the system was known by the code number 647. The first launch of an operational satellite is reported to have occurred in November 1970. Plans were to put it in a synchronous orbit but this was not achieved because of a booster problem. Had the satellite reached orbit, the plan was to keep it over the U.S. for verification testing and then shift it to a longitude from which it could observe missile tests in the Peoples Republic of China [16]. On May 5, 1971 a satellite was successfully placed in a near synchronous orbit over the Indian Ocean, and the 647 system was considered to be operational. From this satellite position the infrared sensors were said to be able to detect any massive launching of Soviet ICBM's and it was also possible to get occasional verifications of system performance by detecting missile launches from Russian missile-test sites [illegible] believed that this initial satellite carried two types of sensors. The first [illegible] sense the radiation from the exhaust plume as the missile rose up out of the atmosphere. This sensor was said to use a 2000-element detector operating in the 3- to 5-μm atmospheric window. The second sensor was thought to be a television-camera type of device. The television camera was apparently included to detect false alarms caused by sunlight reflected off of high altitude clouds that might trigger the infrared sensor [15]. On March 1, 1972 an additional satellite was placed in a geosynchronous orbit and stationed over the Panama Canal to warn of SLBM launches from surrounding Atlantic, Pacific, and Caribbean areas [17].

It was later revealed that the EWSS successfully orbited in 1971 and 1972 were developmental models intended for test and measurement purposes. Since their performance was excellent, they were not replaced. In early 1973 it became known that the infrared sensor in the satellite orbited on May 5, 1971 had suffered a gradual loss of sensitivity [18]. No explanation has been offered for this degradation. In February 1973 the first of an improved model (phase 2) early warning satellite was delivered to the Air Force. On June 12, 1973 an early warning satellite was successfully orbited and stationed over the Indian Ocean. Although no confirmation has been given it is thought that this was a phase 2 system emplaced so as to supplement, or replace, the original system whose sensors had begun to lose sensitivity [19]. A total of 8 phase 2 systems were to be delivered on a schedule extending through 1974.

As yet, very little information has appeared in the literature about the causes of performance degradations in spaceborne sensors. One detailed report has appeared and it discusses in-orbit degradation of the multispectral scanner (MSS) that was launched in July 1972 on the Earth Resources Technology Satellite (ERTS-1) [20]. This system works in the visible and the near infrared whereas the 647 sensor is reported to work on the 3- to 5-μm region [15], so that one should probably not place too much reliance on effects extrapolated from one to the other. In the MSS, calibration signals generated during the scan retrace interval have shown a decrease from their expected values. The decrease is a function of both time in orbit and spectral interval. It is known that during spacecraft thermal vacuum test some Mylar insulating tape was overheated and this caused a milky deposit to appear on some of the MSS optical elements. Since there seemed to be no degradation of sensor performance, the optics were not cleaned before launch. It is postulated that this coating was polymerized by exposure to solar ultraviolet while in orbit. Such a mechanism could explain both a spectrally selective and a time-dependent sensor degradation [20]. Since most organic materials show characteristic absorption bands in the 2- to 5-μm region, a similar contamination would probably have an observable effect on systems operating in the middle infrared.

The EWSS has been operational for several years and the concept of boost-phase detection from synchronous orbit seems to have been proven. The Air Force has requested fiscal year 1975 funds for the purchase of an additional spacecraft, technical support, and the completion of a survivability retrofit on three satellites [21]. In October 1972, the Air Force contracted for the development of a stabilized satellite to carry several special defense experiments. Among these experiments was a test of an infrared "staring" sensor th[illegible] later versions of the 647 system [22], [23]. A "staring" sensor uses a two-dimensional array, or mosaic, of detectors to stare constantly at its total field of view. As a result, no scanning motion is required. The "staring" sensor to be tested uses a mosaic of about 1000 lead sulfide detectors combined with compact metal-oxide-semiconductor (MOS) circuitry. Apparently, other detector materials, such as mercury cadmium telluride, can also be used so that the technique can be applied at longer wavelengths. The absence of the moving parts usually found in mechanical scanners may increase system reliability but the use of a mosaic puts a much greater premium on achieving reliability in the detector. As a final vote of confidence in the use of infrared sensors for early warning, we note that the Air Force is seeking industry ideas for a new multimode ballistic missile EWSS that could replace the present 647 system in about 1980. The new system would be equipped with infrared sensors for the detection of ICBM launches as well as other sensors for detecting nuclear explosions and space tracking [24].

B. *New System Concepts*

With the success of the EWSS, it has been evident for some time that improved infrared sensors will be developed and that they may, in turn, open the door to new system concepts. One of the most important trends in infrared technology, of the past decade or two, is the introduction of new and improved long-wavelength infrared detectors [3]. Moving to longer wavelengths offers two advantages: 1) a reduction of the interference by sunlight reflected from the background, and 2) the ability to detect cooler targets. It would appear that one of the principle changes in the 647 sensor between 1963 and its reappearance in 1968 may have been the shift to a detector operating in the 3- to 5-μm atmospheric window [15]. Such a shift could have been one of the principal reasons for the new sensor's reduced susceptibility to false alarms triggered by sunlight reflected from high clouds.

As early as 1969, the Air Force asked for proposals for the development of a midcourse surveillance system using a low-altitude satellite with infrared sensors to track ballistic missiles after burnout [25]. Such sensors were to use infrared detectors operating in the 10-μm region in order to detect relatively cold bodies, such as satellites and ICBM's, during the midcourse phase of their flight [26]. The development of such a midcourse detection and, presumably, tracking system would be of great significance for an improved defensive system.

One of the most useful methods for monitoring the testing of long range missiles is to observe the missile reentry from ships or aircraft located near the impact point. U.S. ships have reportedly monitored Russian missile shots into the Pacific since 1961 [13]. Such observations should have provided an extensive collection of reentry signatures. In mid 1970, it was reported that tests of Soviet ballistic missiles in the South Pacific were being observed from high-altitude aircraft using special long-wavelength infrared sensors [27]. The sensors were said to be able to track the missiles against the cool sky background after the heat resulting from the powered portion of the flight had dissipated. In May 1971, the Air Force conducted a space flight evaluation of long wavelength infrared detectors operating in the 8- to 14-μm region. The reported purpose was to further test the ability of infrared sensors to track ICBM's during midcourse flight [28]. At about the same time a contract was let for the development of two special test vehicles for measuring the infrared radiation from ICBM's during midcourse flight. The unusual aspect was that the test vehicle would be carried aboard the ICBM. It would be ejected after launch so that it would fly along with the ICBM and make measurements of its infrared radiation throughout the ballistic portion of its flight [29]. Such measurements would be useful for the design of midcourse detection, tracking, or intercept systems.

The long-wavelength infrared sensors envisioned for use in a midcourse system would be relatively immune to reflected sunlight, but they would have to contend with the new problem of possible sensor saturation if the earth entered the sensor's field of view. The various measurement programs already discussed used look-up measurements made against the cold background of outer space. The implication was that any midcourse system would require a low-altitude satellite [illegible] incompatible with the 647 system which [illegible] synchronous altitudes. Apparently the next [illegible] ation of the feasibility of a midcourse system [illegible] how close to the earth an appropriate [illegible] a midcourse ICBM before the sensor [illegible] from the earth intruding into its field of view. In [illegible], the Air Force announced plans for a background measurement satellite. Measurements were to be made of long-wavelength infrared radiation near the earth's limb [illegible] an earth limb sensor [30]. Two earth-limb measurement satellites (ELMS) are scheduled to be launched into [illegible] circular orbits during 1975 and 1976 [31]. A radiometer for measuring the radiance[3] of the earth's limb from a meteorological satellite has been described [32]. It uses an array of 4 mercury cadmium telluride detectors cooled to 65 K by a two-stage solid ammonia-methane cryogenics unit.

Long-wavelength infrared sensors for space use will almost certainly use detectors operating in a background-limited condition. In this condition the noise from the detector is due to fluctuations in the rate at which carriers are generated by photons from the background and subsequently recombined. The design principles for background-limited systems are well known [1, pp. 421-423], [33]. In addition to cooling the detector and providing it with radiation shielding, the entire optical telescope assembly is usually cooled. Some idea of the complexity that this introduces into sensor design can be gleaned from a description of a liquid-helium-cooled infrared telescope assembly designed for rocket-borne astronomical measurements [34].

C. *Additional System Applications*

An interesting additional use that has been proposed for the EWSS is to verify Soviet compliance with the arms control agreements signed as a result of the first round of the strategic-arms-limitation talks (SALT I) [13]. The agreements contain sections dealing with the problems of verification. In Article XII of the treaty limiting anti-ballistic missile (ABM) systems, it states: "1. For the purpose of providing assurance of compliance with the provisions of this Treaty, each Party shall use national technical means of verification · · ·. 2. Each Party undertakes not to interfere with the national technical means of verification of the other Party · · ·." Among the "national technical means of verification" available to the U.S. are the infrared sensors of the EWSS. Although their

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[3] [illegible] at a given point, in a given direction, per unit solid angle, and per unit of surface area projected orthogonal to that direction.

primary mission is to provide early detection and warning of an ICBM attack, they also provide a capability to monitor Soviet missile tests [13]. Additional SALT agreements may extend to a limit on the number of missile tests allowed per year [35]. Keeping track of such launches would be simple for the satellite borne infrared sensors. Since the infrared sensors, in conjunction with a ground-based high-speed computer are said to provide missile trajectory information it seems possible that the sensors could also detect the development and testing of terminal maneuvering systems [7], [13].

VI. THE DETECTION OF POISON GAS UNDER FIELD CONDITIONS

One of the most frightening aspects of war is the possibility that an enemy may use poison gas. Gas was used extensively by both sides during World War I. It has been noted that in 1918, German factories were producing equal quantities of chemical and high-explosive munitions and that by 1919 the war would have been predominantly a chemical one [36]. The principal chemical agents of that era were chlorine, phosgene, and mustard gas. Their general physiological action was irritation of the respiratory tract and lungs after inhalation and irritation of the skin and eyes upon contact.

The use of poison gas is prohibited by the Geneva Protocol that was prepared by the League of Nations in 1925. Not all nations are signatories to this protocol and it has, unfortunately, not had the desired result of completely banning the use of gas.

By the time of World War II advances in chemical technology had led to systemic poisons which would affect the entire body. These systemic poisons became known as the nerve gases. The first of the nerve gases, Tabun, was discovered in Germany in 1937 during a search for more potent insecticides. Other members of the family, Sarin and Soman, were discovered shortly thereafter. Tabun was put into production in Germany in the spring of 1942 and by April 1945 a total of 12 000 tons had been produced. After World War II a German Tabun plant was dismantled and moved to Russia. Subsequent work in the United States concentrated on Sarin because it is several times more lethal than Tabun. In the U.S. nerve gases are given the prefix "G". Tabun is designated as "GA", Sarin as "GB", and Soman as "GC" [36], [37].

The gases of World War I generally gave some warning of their presence by smell or irritation but the nerve gases are colorless, odorless, and tasteless. An antidote for the inhalation of a small quantity of nerve gas is an injection of atropine tartrate. It has been reported that all U.S. soldiers in a battle area carry a 2-mg tube of the substance that can be injected automatically by pushing it against a large muscle [37]. Masks offer an effective defense against nerve gases but there must be some means of providing a sufficiently early warning so that they can be donned prior to gas inhalation.

A method for the battlefield detection of very small amounts of Sarin appeared some years ago in the patent literature [38]. The detection method involves the sensing of changes in the spectral characteristics of radiation that has been transmitted through an atmosphere containing the gas. Sarin exhibits a characteristic absorption band at a wavelength of 9.8 μm. The principle used for its detection is to monitor the transmission in three narrow spectral intervals, one is centered in the Sarin absorption band [illegible] centered in absorption-free regions at 9.25 and 10.4 μm. A beam from an infrared source is projected across the area under surveillance and is returned by a retroreflector. The 3 chosen wavelength intervals are separated out of the return beam, by a diffraction grating or narrow bandpass filters, and sequentially delivered to an appropriate infrared detector. The ratios of the three signals are noted for a clear atmosphere, i.e., one in which there is no Sarin along the line-of-sight. If Sarin is subsequently introduced in the area, the signal ratios will change, triggering an automatic alarm. Concentrations of Sarin as small as 10^{-2} mg/m^3 could be detected with the sensor described in the patent. The median lethal dose for active men is about 25 mg/m^3 (an inhalation dose lasting one minute). A single inward breath at a concentration of 250 mg/m^3 is fatal [36], [37].

This detection equipment is called LOPAIR (an acronym for *long path infrared*). A comparison of the numbers given in the preceding shows that it can detect Sarin concentrations that are more than 3 orders-of-magnitude below lethal doses. The LOPAIR sensor described in the patent was not used over path lengths longer than 200 m. The limitations imposed by such a short path and the need for a retroreflector make the equipment unsuitable for any tactical situation. However, there seems to be no reason why an improved version should be subject to the same limitations. The detectivity of a modern cooled photon detector, such as mercury cadmium telluride, is about 2 orders-of-magnitude higher than that of the thermocouple used in LOPAIR. With this change, it should be possible to eliminate the retroreflector and source and replace them with a naturally occurring terrestrial source, such as a distant hillside or bluff. With these improvements, several LOPAIR sensors suitably deployed should be capable of monitoring an entire battlefield.

The general principle described for the operation of LOPAIR, comparison of the transmission in two or more narrow spectral intervals, one of which contains an absorption band of the substance to be detected, is used widely for industrial process control and for the precision determination of water vapor in air [1, pp. 524–527, 596–598].

VII. AIDS FOR THE PRECISION DELIVERY OF WEAPONRY

The military system designer is constantly on the alert for new techniques to enhance the precision and speed with which weapons can be delivered. Not too long ago it could take months, or even years, to carry firepower to an objective. After delivery, additional days or weeks were often needed to apply the firepower in sufficient quantity to achieve the desired results. Introduction of the airplane compressed the delivery time to hours. Missiles have compressed the time to minutes or seconds. A steady increase in the precision of delivery has accompanied this time compression. Infrared guidance techniques have played an important role in this improved delivery accuracy. There have been three quite independent stages in the utilization of infrared for this task. These stages included infrared guidance for small air-to-air missiles, battlefield support missiles that use infrared as an element of their command guidance systems, and laser guidance for the delivery of a variety of weaponry.

A. Passive Infrared Guidance for Air-to-Air Missiles

Of all the military applications of infrared, probably none [illegible] infrared-guided heat-seeking missile. Missiles thought to use passive infrared

COUNTRY	MISSILE	STATUS	MAX. RANGE, km	NOTES
AIR TO AIR MISSILES				
FRANCE	MATRA 511	OPERATIONAL	—	
	MATRA 530	PRODUCTION	21	
	MATRA 550 (MAGIC)	DEVELOPMENT	2	DOGFIGHT MISSILE DETECTOR COOLED WITH LIQUID NITROGEN.
ISRAEL	SHAFRIR	PRODUCTION	20	OPERATIONAL CEILING 18 km
ITALY	C 7 (RIGEL?)	DEVELOPMENT	10	
JAPAN	AAM 1	OPERATIONAL	—	
	AAM-2	DEVELOPMENT	—	USES INDIUM ANTIMONIDE DETECTORS IN 3–5 μm REGION, PLUME HOMING CAPABILITY
SWEDEN	Rb 28(FALCON)	OPERATIONAL	9	
UNITED KINGDOM	FIRESTREAK	OPERATIONAL	9.3	HAS INFRARED PROXIMITY FUSE. USES PYRAMIDAL IRDOME. MINIMUM RANGE 1.4 km
	REDTOP	PRODUCTION	15	CAPABILITY TO ATTACK FROM ALL ASPECT ANGLES.
	SRAAM 75	DEVELOPMENT	1.5	DOGFIGHT MISSILE
UNITED STATES	AGILE (AAM-95)	DEVELOPMENT	—	DOGFIGHT MISSILE
	FALCON (AIM 4C)	OPERATIONAL	9	
	FALCON (AIM 4D)	OPERATIONAL	>9	
	FALCON (AIM-4G)	OPERATIONAL	13	
	SEEK BAT	DEVELOPMENT	—	TO COUNTER MiG 25 TO ALTITUDES ABOVE 24 km. PLUME-HOMING CAPABILITY.
	SIDEWINDER 1A (AIM 9B)	OPERATIONAL	3.6	
	SIDEWINDER 1C (AIM 9D)	OPERATIONAL	18	
	SIDEWINDER 1C (AIM 9J)	OPERATIONAL	—	
	SIDEWINDER 1C (AIM 9K)	DEVELOPMENT	—	USES COOLED INDIUM ANTIMONIDE DETECTOR. COOLING BOTTLES IN LAUNCH RAILS.
	SUPER SIDEWINDER (AIM 9L)	DEVELOPMENT	—	COOLED DETECTOR. INTERNALLY STOWED COOLING MECHANISM. INTERIM DOGFIGHT WEAPON.
USSR	ANAB	OPERATIONAL	—	
	ASH	OPERATIONAL	—	
	ATOLL	OPERATIONAL	6.5	RESEMBLES AIM 9B CARRIED ON MiG-21
	AWL	PRODUCTION	—	
WEST GERMANY	SIDEWINDER	PRODUCTION	—	WITH MODIFIED SEEKER USING COOLED DETECTOR.
	VIPER	DEVELOPMENT	—	
AIR-TO-SURFACE MISSILES				
UNITED STATES	MAVERICK (AGM-65A)	DEVELOPMENT		IMAGING INFRARED SEEKER UNDER DEVELOPMENT AS ALTERNATE TO NORMAL TV SEEKER.
SURFACE TO AIR MISSILES				
JAPAN	KAM 9	EXP. PRODUCTION	20	
SWEDEN	REDEYE (Rb69)	PRODUCTION	3.2	
UNITED STATES	CHAPARRAL (MIM 72A)	PRODUCTION		MODIFIED SIDEWINDER 1C FIRED FROM TRACKED VEHICLE.
	REDEYE (FIM 43A)	PRODUCTION	3.2	
	STINGER (XFIM 92A)	DEVELOPMENT	—	PLUME HOMING CAPABILITY.
USSR	GOA (SA-3)	PRODUCTION	27	INFRARED SEEKER FOR TERMINAL HOMING
	GAINFUL (SA 6)	PRODUCTION	—	SAME
	GRAIL (SA 7)	PRODUCTION	9.5	EFFECTIVE TO 3 km ALTITUDE
	SAMOVAR	OPERATIONAL	4.8	
SURFACE TO SURFACE MISSILES				
NORWAY	PENGUIN	PRODUCTION	27	INFRARED SEEKER FOR TERMINAL HOMING
USSR	SCRUBBER (SSN 1)	PRODUCTION	180	SAME
	STYX (SSN 2B)	PRODUCTION	36	SAME
	SWATTER (AT 2)	PRODUCTION		SAME

Fig. 6. [illegible]

sensors for guidance are shown in Fig. 6 (missiles thought to use active infrared guidance techniques will be discussed later). Since a total of 10 countries are listed in Fig. 6, it is clear that no country enjoys a monopoly on infrared guidance techniques [1, p. 480], [39]-[43].

The basic concept of the infrared-guided missile was explored during World War II but the state-of-the-art in detectors and other components was not capable of supporting production of such a missile [1, pp. 466–469]. While only limited applications of infrared techniques appeared on the battlefields of World War II (and these were almost entirely active systems) great progress was made in the development of photon detectors. The thallous sulfide detector, responding to 1.4 μm, was put into production. This, for the first time, gave the military system designer an infrared detector with a response time short enough to permit its use for missile guidance. By the end of the war the lead sulfide detector, responding to beyond 3 μm, had been developed to the point where it too was ready for production [3], [44].

By the late 1940's, the development of infrared guided air-to-air missiles had started in the United States, France, United Kingdom, and the USSR [1, pp. 479-486], [45]. By the mid 1950's, these programs had borne fruit; the U.S. had its Sidewinder and Falcon, the U.K. had its Firestreak, France had its Matra 511, and the USSR had its Atoll (which, it has been noted, bears a striking resemblance to the Sidewinder [1, pp. 479–486], [46]). The effectiveness of these new missiles could only be assumed until a tragic accident in April 1961 in which a U.S. Air Force B-52 bomber was shot down by a Sidewinder missile inadvertently fired from an F-100 during a training flight. The typical behavior of heat-seeking missiles was, for the first time, revealed in the public press when it was reported that the missile entered the exhaust section of an engine, causing it to explode and buckle the wing [47]. It is not certain that the missile contained a live warhead but, whether or not it did, the high speed entry of the missile directly into the engine exhaust was sufficient to bring about the kill (a Sidewinder 1A missile has an overall length of 2.83 m, a body diameter of 0.13 m, a fin span of 0.56 m, a launch weight of 72 kg, and attains a maximum speed of Mach 1.8 [39], [42], [45]). The resulting crash killed 3 of the crew members of the B-52 while the others were able to parachute to safety [47].

Infrared-guided air-to-air missiles made an early, and effective, appearance in Vietnam. The first MiG-21 to be downed by a U.S. aircraft in combat over North Vietnam was reported to be the victim of a Sidewinder missile fired from an F-4C. The MiG carried a pair of Atoll missiles but apparently never got in position to fire them [48]. Numerous similar accounts have appeared [1, pp. 479–486]. In June 1967, during the six-day Arab-Israeli War, Atoll missiles were used successfully by the Arabs. On the second day of the war, an Iraqi MiG-21 fired an Atoll at an Israeli Mirage 3CJ. The Atoll characteristically homed on and detonated near the tailpipe. Although the explosion mangled the aft end of the Mirage and damaged its engine, the pilot was able to lose the MiG by diving into a bank of clouds over the Sea of Galilee and eventually land at an emergency base. On another occasion an Egyptian MiG-21 fired a salvo of Atoll missiles that passed an Israeli aircraft within what was thought to be normal kill range, but they failed to expl[illegible]

In September 1973, on the eve of the October Middle Eastern war, it was reported that a total of 13 Syrian MiG-21 fighters were destroyed by Shafrir missiles fired from Israeli F-4 aircraft [49]. The Shafrir is an infrared-guided missile developed and produced entirely in Israel. Development of the missile started in the early 1960's and it was declared operational in 1969. The firing sequence is described as being extremely simple. An automatic technique is used for achieving target acquisition. A blinking signal light alerts the pilot to an impending acquisition and an accoustic signal in his headset announces its achievement. The Shafrir can be fired at altitudes up to 18 km and has a maximum range of about 20 km [39].

Despite these successes, infrared-guided missiles were not without their problems. It sometimes happened that the missile seekers were decoyed by sunlight reflected from clouds in the background. In addition, the apparent limitation to a tail attack became an increasingly serious factor in their tactical usage [45], [50], [51]. Both of these problems were a consequence of seeker operation in the near infrared. At the time these missiles were developed, lead sulfide (uncooled) was the obvious choice for a detector [52]. As shown in Fig. 4, these detectors do not respond much beyond 3 μm. For this reason, the seekers were designed to use the 2- to 2.5-μm atmospheric window. Since there is no emission from the exhaust plume in this window, these seekers could only home on the hot metal tailpipe of jet aircraft [1, ch.3]. Hence, the limitation to a tail attack. Interference by reflected sunlight has always been a problem in the near infrared. Many of the infrared sensors that were developed during the 1940's and 1950's were so plagued by sunlight that they were used only at night. For a while it looked as if infrared sensors would be permanently relegated to nighttime-only operation [1, pp. 8, 9, 464–510], [6]. Most missile seekers used a reticle (optical modulator) to generate the error signals that fed their tracking loops. Reticles are an effective means of eliminating much of the interference from backgrounds because they discriminate against sources, such as clouds, that subtend large angles [1, ch.6]. Even the best reticle technology, however, could not guarantee background immunity for these early seekers.

These seeker problems were alleviated by the adoption of improved photon detectors, such as indium antimonide and lead selenide, that appeared in the late 1950's [52]. The response of these detectors extends to beyond 5 μm so that seekers equipped with them can use the 3- to 5-μm atmospheric window [3]. The price paid for the longer-wavelength response is the necessity to cool these detectors to the temperature of liquid nitrogen (77 K). When one examines the effect of this shift to longer wavelengths, he finds that there is more target radiation and less interference from solar radiation. The radiation from the hot metal of a jet aircraft tailpipe is similar to that from a blackbody at a temperature of about 900 K. From equation (2), the maximum of the radiation distribution lies at about 3.2 μm. A more complete analysis of the tailpipe radiation shows that nearly 5 times as much energy is radiated in the 3- to 5-μm window as in the 2- to 2.5-μm window. In addition, the energy in the sunlight reflected from the background is lower by at least a factor of two for the longer wavelength window [1, pp. 85–98 129–136, 438–452]. Thus the availability of detectors for the 3- to 5-μm window offered the system designer an order-of-magnitude increase in the ratio of desired target, to undesired background radiation.

[illegible] a shift to the longer wavelength window. This is the ability of the sensor to home on the radiation from the plume of hot exhaust gases that extend do[illegible] processes result in the formation of carbon dioxide and water vapor. Heated carbon dioxide radiates strongly in a narrow region near 4.4 μm which is, in turn, conveniently located within the 3- to 5-μm atmospheric window. Since an exhaust plume may extend for 0.1 km, or more, behind the aircraft, a seeker that can sense plume radiation will not be limited to a tail attack but will, instead, have an all-aspect attack capability [1, pp. 85–98, 129–136, 438–452]. Missiles believed to have plume-homing capability are so noted in Fig. 6. Another clue to such a capability is, of course, the use of a cooled detector [53].

The next group of problems encountered with infrared-guided missiles were more fundamental in nature and required considerably more effort for their solution. The problem was, in short, that the missiles were not being used in the type of war for which they had been designed [54]. The missiles, developed as they were in the 1950's, were designed for the deterrence-and-massive-retaliation scenario in vogue at that time. Under this scenario, interceptor aircraft carrying long-range missiles would be matched one-on-one with single bombers that had been programmed to hit specific targets. When these missiles were finally used it was in the close-order combat of limited war. Such combat required a missile that could be fired at short ranges from a violently maneuvering aircraft and one that could not be eluded by target maneuvers [45].

The Sidewinder 1A probably came closest to meeting the demands of the times in which it was used. It was developed by the U.S. Navy for use by fighters providing air superiority for fleet protection. The Navy scenario envisioned engagements between two fighters, rather than between an interceptor and a bomber. Tactically this meant a continuation of the dogfight tactics used in previous wars. Dogfight tactics call for short-range weaponry and highly maneuverable aircraft. The prime tactic in any dogfight is to maneuver into a position on the tail of a target. What, then, makes more sense than the development of a missile that will home on the engine heat so copiously available at the rear of a jet aircraft [45], [51]?

In order to launch a Sidewinder properly, the launch aircraft had to be pointing at the target at the time the missile was fired. There were times in a dogfight when this requirement could not be met. If the missile was fired while the launch aircraft was maneuvering, the high-g loading could seriously degrade the performance of the missile. A lateral loading of 3 g's at launch would, it was said, have made the missile worthless [51], [55].

Sidewinder had a minimum launch range of about 1 km which is also about the maximum limit for accurate gunfire [51]. Pilots in the heat of a dogfight had to make the difficult estimation of target range before they could make a choice between firing a gun or launching a missile. At long range, in a standoff situation, identification, friend, foe, or neutral (IFFN) problems arose because pilots were naturally hesitant to launch a missile without a positive target identification. The appearance of N for neutral in IFFN symbolizes another new problem that has been handed the pilot. With the permissive environments often found in limited wars it is not at all uncommon for combat pilots to encounter commercial airliners. Visual identification of targets is said to be effective out to 2 or 2.5 km. In the absence of any other IFFN procedures, it was this visual limit that dictated the maximum launch range for Sidewinder [51].

The correction of these missile problems required a basic redesign of both the missile and its seeker. In early 1969, it was announced that the Air Force and the Navy were exploring the design of dogfight missiles. These missiles were to be infrared guided by seekers having an all-aspect attack capability, they were to have a short minimum-firing range, and they were to be capable of very high maneuvering rates [1, pp. 479–486], [56]. The current result of these programs is Agile, a thrust-vectored missile capable of turning 180° in less than 1.5 s while traveling at a speed of nearly 1 km/s [57]. The seeker is said to be housed in a pillbox-shaped nose section which enables it to look "over-the 'shoulder'" for tracking targets that are maneuvering at high angular rates [59]. It is evident from Fig. 6 that the U.S. is not alone in the development of this type of high capability missile.

Among the surface-to-air missiles that are shown in Fig. 5 are Redeye, its probable replacement Stinger, and Grail. These missiles will have a radical effect on close air support and tactics of the future. For the first time, these missiles make the individual foot soldier a lethal match for armed helicopters and close support aircraft. The Redeye concept is to make an infrared guided missile small enough to be carried by one man and light enough so that he can fire it from his shoulder on very short notice. The first public firing demonstrations were held in October 1964. Targets included a drone F9F moving at 750 km/h across the line of sight and a drone OH-13 helicopter. Average firing ranges were about 1.5 km [1, pp. 479–486]. Stinger is an improved version of Redeye that is said to have a plume-seeking capability [39].

Very little is known about the Soviet program that led to the development of the SA-7 Grail missile. It is probably a descendent of the Samovar missile, which was described in 1959 as an infrared-guided surface-to-air missile for use against low-altitude supersonic aircraft. The useful range of Samovar was said to be about 4.8 km [1, pp. 479–486]. The existence of Grail has been known since 1969 and it was, until recently, called Strella. It was given to the Egyptian Armed Forces in 1970 and introduced into Vietnam in the spring of 1972. It remains to be seen whether it will be generally deployed within the Warsaw Pact countries [43].

Both the Redeye and the Grail system consist of the [illegible] missile and an expendable launcher. Initial aiming is done visually and it is believed that both systems signal the operator when there is sufficient energy to permit missile tracking. The operator must determine visually whether the target is within the flight envelope of the missile. IFFN is a major problem. During the October Middle Eastern war in 1973, the Arab forces launched the SA-7 Grail in batteries from radar-equipped tracking vehicles (which represents an interesting evolution from the original shoulder-fired concept). Hundreds of missiles were launched within short periods of time but only relatively few Israeli aircraft were downed, even though many of the missiles scored direct tailpipe hits. This may indicate that the warhead carried by Grail is too small to cause lethal damage in most encounters with jet aircraft [58].

The Redeye story has a fascinating sequel; it has been added to the arsenal of weapons used to guard the White House [59]. Early in 1974, two attempts, one of them successful, were made to penetrate the restricted air space surrounding major public buildings in the Washington, D.C., area. In the successful attempt, a stolen helicopter was actually landed on the White House lawn. The known presence of Redeye may deter future landing attempts but it remains to be seen whether

COUNTRY	MISSILE	FUNCTION	STATUS	RANGE, km	NOTES
FRANCE	ACRA	ANTI TANK	DEVELOPMENT	3	INFRARED BEAM RIDER
	AS.20	AIR-TO-SURFACE	PRODUCTION	7	
	AS.30	AIR TO SURFACE	PRODUCTION	12	NOTE 1
	CROTALE	ANTI AIRCRAFT	PRODUCTION	8.5	RADAR TRACKED WITH ACQUISITION BY AN INFRARED TRACKER USES INFRARED PROXIMITY FUSE.
	HARPON	ANTI AIRCRAFT	PRODUCTION	3	NOTE 1
INTERNATIONAL	HOT	ANTI TANK	PRODUCTION	4	NOTE 1
	MILAN	ANTI TANK	DEVELOPMENT	2	NOTE 1
	ROLAND	ANTI AIRCRAFT	DEVELOPMENT	8	NOTE 1
ITALY	SEA INDIGO	ANTI AIRCRAFT	DEVELOPMENT	9.5	USES AN INFRARED TRACKER AND AN INFRARED PROXIMITY FUSE.
UNITED KINGDOM	RAPIER	ANTI AIRCRAFT	PRODUCTION	3	
UNITED STATES	DRAGON	ANTI TANK	PRODUCTION	--	
	SHILLELAGH	ANTI TANK	PRODUCTION	16	COMMAND GUIDANCE BY INFRARED LINK

NOTE 1: INFRARED FLARES ON MISSILE ARE AUTOMATICALLY TRACKED BY AN INFRARED SEEKER AT THE FIRING SITE.

Fig. 7. Battlefield support missiles thought to use active infrared guidance [1, pp. 508–510], [41], [42], [60].

official will dare to approve its firing over the heavily populated metropolitan area.

B. Active Infrared Guidance for Battlefield Support Missiles

Combat troops have their own group of battlefield support weapons. Among these are relatively short range missiles that can be used against tanks and other armor, fixed objectives, and low-flying aircraft. As shown in Fig. 7, many of these make use of infrared techniques for missile tracking, command guidance, and beam riding. An early forerunner of a system widely deployed today used an optical sight to acquire and track the target, after which the missile was fired [1, pp. 508–510], [41]. When the missile entered the field of view of the sight, the operator, using a miniature job stick, generated steering signals that would direct the missile toward the target. The steering signals were, in turn, transmitted to the missile over a trailing wire or via a radio command link. In effect, the operator became part of a servo loop. Such a system has a number of human engineering problems associated with it as well as the fact that in bad weather, under adverse lighting conditions, or at night, it may be difficult or impossible to see and follow the missile. The logical solution to this problem is to mount a pyrotechnic flare on the rear of the missile to improve its visibility. Since most pyrotechnic flares emit more energy in the infrared than they do in the visible the next step was to add an infrared sensor that would automatically acquire and track the flare-augmented missile. The system must still have an optical sight, but the operator's only function is to keep the target centered on its cross hairs. Steering signals are generated by a simple computer that compares the line of sight of the infrared tracker with that of the optical sight. A further refinement is to give the flare its own signature, a unique spectral or temporal characteristic, that can be recognized by the infrared tracker [1, pp. 509–510], [41], [42]. The analysis and optimization of such a system has been described [61].

C. Infrared Laser Guidance for Weapon Delivery

The development of laser-guided weapons may be the most important advance in precision weapon delivery since World War II. Such systems use a laser target designator to illuminate a specific target while a sensor on the weapon homes on the reflected laser illumination. Apparently, most designators use a neodymium yttrium aluminum garnet (Nd:YAG) laser that emits in a very narrow infrared band at a wavelength of 1.06 μm [62], [63]. At this wavelength the system can be considered only partially covert.[4] In addition to possible detection by the eye, the infrared image converters in the night driving viewers found on many military vehicles respond at 1.06 μm as does the Metascope [1, pp. 296–300, 498–502]. Of course, these methods of detection are far too casual to be considered adequate for warning purposes. It has been reported that a microminiature infrared alarm has been developed that will alert the bearer when he has been illuminated. The device is said to be small enough to be attached to a soldier's uniform. Estimates are that it will provide an aural warning as well as indication of the direction to the illuminator [65].

The addition of a receiver to the basic laser designator allows the determination of slant range to the target to be done simultaneously with the designation function. Because it is usually desirable to know slant range, the multifunction laser designator/rangefinder, or illuminator/rangefinder, has become increasingly popular. Some of the newer designator/rangefinder units are programmed to calculate range on every nth pulse. Laser designators weighing only 4 kg have been designed for use by ground troops. An optional clip-on receiver adds a rangefinding capability when desired. The device is configured so it handles like an M16 rifle. A photo of the device in action indicates an effective range of several kilometers [63].

The use of an airborne designator may bring with it the requirement for a stabilized mount. One of the few

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[4] Very few people are aware that the response of the human eye extends to beyond 1 μm. Griffin *et al.* [64] measured the spectral response of the eye out to a wavelength of 1.05 μm, where the eye's response is 3×10^{-13} times its peak value. They calculated that at wavelengths beyond 1.15 μm the response of the eye would be less than that of the skin, so that radiation of this and longer wavelengths would be more readily felt as heat by the skin than perceived as light by the eye. [illegible], a person should, under certain conditions, be able to visually perceive the radiation from a Nd:YAG laser. The result, however, might well be a permanent impairment of the individual's sight.

designators that has been described in detail in the open literature is the AVQ-18 [63]. It was produced for use on Air Force gunships. It uses a Nd:YAG laser and produces 10 pulses per second. Each pulse has a duration of 10 ns. The beam width is only 0.6 mrad, i.e., at a distance of 1 km the diameter of the beam and, hence, of the illuminated spot is only 60 cm. It seems evident that use of such a narrow beam from an aircraft would be nearly impossible without a stabilized mounting.

To further enhance the versatility of the laser designator it is often packaged in conjunction with a low-light-level television camera or a forward looking infrared (FLIR) imaging sensor (which will be discussed in a later section). In such arrangements the designator and the sensor generally share the same optics and stabilization. The operator can identify targets seen on the sensor display, select the desired one, illuminate it with the designator, and launch the laser-guided weapon. One such system, the Pave Knife, is said to be able to detect targets and achieve acquisition at ranges of from 5 to 11 km [62]. In the Pave Spot System, which is intended for use by a forward air controller, it has been reported that an illuminator/rangefinder is combined with an image intensifier for the nighttime acquisition of targets. The Nd:YAG illuminator weighs 12 kg and its associated rangefinder can range on targets as far away as 20 km [62]. The Long Knife system consists of a pod-mounted laser designator and a low-light-level television camera, both of which share a stabilized mounting. With this system, it is reported that ground targets can be designated at standoff ranges of up to 48 km, with twice the accuracy of the earlier Pave Knife system that was used extensively over Vietnam [66]. Excellent photographs have been published showing a pod-mounted targeting and laser designation system mounted on the wing stub of an attack helicopter. The pod is said to contain a precision stabilized sight, a laser designator/rangefinder, a laser spot tracker, a FLIR, and a television camera. The laser spot tracker is said to be able to detect and track ground targets that have been designated for helicopter attack by virtue of being illuminated by a forward air or ground controller [67]. It has also been reported that laser designators can be used successfully from unmanned drones. In one such demonstration, the drone was fitted with a special nose section that contained 3 windows. One window was for a daytime television camera or a nighttime FLIR, one for the designator, and one for a laser receiver [68].

The designer of a laser seeker should be able to use much of the technology that already exists for the longer wavelength passive infrared seekers that were discussed earlier. Silicon photodiodes are one possible choice for a detector. Unfortunately, their quantum efficiencies drop rather sharply at about 1.0 μm and their performance at 1.06 μm leaves much to be desired. Cooling (to about 150 K) increases their detectivity but it is doubtful that the increase is worth the effort required to provide the cooling. A much better choice is the silicon or germanium avalanche photodiode. Substantial current gain can be achieved in solid-state photodiodes through avalanche carrier multiplication. Although excess noise is introduced by this multiplication process, significant improvements in detectivity result [69]. Optical materials present no problems for a 1.06-μm seeker since a wide variety of suitable glasses are available. A very good account of efforts to develop a triservice seeker for use with close air support missiles has been published [70].

The laser-guided "smart bomb", introduced into Vietnam in 1969, is said to have demonstrated an astounding increase in

delivery systems. puzzling to note, however, that a former Assistant Sec of the Air Force has revealed that the laser-guided bomb available as early as 1967 but they failed to excite any m interest [71]. It was after the bombing halt of March 19 when the prime focus was on the interdiction of supply rout that pilots found the new "smart bombs" were superbly ade at hitting trucks and other small targets.

The idea of a guided bomb has been explored, but vainly, f many years, Centervall [72] patented a guided aerial torp in 1921 (applied for in 1916) and others, including a gro from Sweden [73], have tried to adapt infrared sensors to guidance of bombs [1, p. 466], [74]. None of these prior tempts met with much success. The performance of the guided bombs has been phenomenal. Of the first thou that were dropped in Vietnam, more than 70 percent reported to have struck their intended targets [62]. Th capability for precision delivery made it possible to dest military targets, such as bridges, petroleum tanks, and h defended point targets, with "surgical neatness," and significant reduction in inadvertent damage to nearby ci activities. Kits, designed in 1966, were used to c conventional iron bombs into the "smart" variety. Co involved mounting a laser seeker on the bomb's movable steering vanes on its body. The total cost verting a bomb was said to be about $3500 [71].

The basic concept of designation and guidance by laser has opened a host of new opportunities for of bombs, missiles, and gun-fired projectiles. ploitation of the concept has only begun and reading about additional new developments for come.

VIII. Imaging Sensors for Reconnaissance and Surveillance

Tactical military forces are constantly faced with the lem of finding the enemy and keeping track of his The remote sensing systems we have discussed relatively little use for such reconnaissance and because they are non image forming. They, in essence, the centroid of the energy emitted by or reflected target. This is all that is needed for detection and tracki it is rarely adequate for recognition and identification. tasks require an imaging sensor, i.e., one that provides fo operator an indication of the geometrical and spatial dis tion of the energy from the target.

A. *Aerial Photography with Black and White Infrared F*

Reconnaissance by means of aerial photography has practiced by the military since the time of the Civil War. first recorded usage was in June 1862 when the Union under General McClellan, used the tethered balloon "Intr as an aerial photography platform. Photos taken from tude of 450 m were used to assess the defenses of Rich Cameras designed specifically for use in aircraft production by the end of 1915 and saw extensive u World War I. The story of aerial photography has been elsewhere [75], [76] and our concern in this paper limited to the use of infrared film in aerial photography.

A photographic film or plate consists of a light-sensi emulsion coated on a suitable transparent support (if on a flexible support product is called a *film*, if the support is glass the pro called a *plate*). The emulsion consists of very fine crystals halide of silver dispersed [illegible] only to blue, violet, and ultraviolet wavelengths and the emulsions made with them have a long wavelength cutoff at about 0.5 μm. Response to longer wavelengths is accomplished by the addition of sensitizing dyes that are adsorbed at the surface of the silver halide grains. The principle of dye sensitization was discovered in 1873 by Vogel but its application to long wavelength sensitization was slow until major advances in dye synthesis occurred in the 1930's. The majority of modern day black and white aerial reconnaissance photography is done with panchromatic film that has an extended-red response [77]. This film responds fairly uniformly to all colors of the visible spectrum and has a long wavelength cutoff at 0.7 μm (panchromatic films sold for general pictorial use do not have the extended-red response and their long wavelength cutoff occurs at 0.65 μm).

Infrared-sensitive black and white film for aerial reconnaissance is sensitized so as to have a long wavelength cutoff at [illegible] μm. Since this film also responds to all colors of the visible spectrum as well as to the ultraviolet, it is normally used with a red filter that absorbs all wavelengths shorter than 0.6 or 0.7 μm. By the proper choice of sensitizing dye it is possible to produce emulsions having a cutoff as long as 1.35 μm. Such emulsions are used in spectroscopy and other laboratory applications. They have a relatively short lifetime and must be stored at dry ice temperatures until used. It seems unlikely that the photographic long wavelength cutoff will be extended beyond 1.35 μm. As shown in Fig. 3, atmospheric water vapor absorbs strongly between 1.3 and 1.5 μm. Beyond 1.5 μm the transmission is quite good until 1.8 μm is reached. A new problem, however, arises because at these wavelengths there is sufficient radiation from the normal 300 K ambient surroundings to fog the film and render it useless in a very short time.

The Air Corps was experimenting with the use of black and white infrared film for aerial reconnaissance as early as 1936 and had acquired considerable experience with it before the start of World War II [76, p. 236]. There are two reasons for using black and white infrared film[5] for aerial reconnaissance. The most important reason is its unusual tonal rendering of scenes containing green foliage and water. The second reason, an improved ability to penetrate haze has been much overemphasized. On a positive print made from a panchromatic negative,[6] foliage is rendered as a dark shade of gray while lakes and streams are rendered in a much lighter tone. On an infrared photo of the same scene, foliage is rendered in a very light tone, so light, in fact, that it often appears to be covered with snow. Lakes and streams are rendered a deep black. The reasons for this unusual tonal rendering are a consequence of the spectral reflectance characteristics of water and of chlorophyll, the universal coloring matter of green vegetation. We shall examine this "chlorophyll effect" in greater detail to see the part it plays in camouflage detection and, ultimately, in multispectral analysis.

The green color that characterizes the leaves of most vegetation is due to the presence of chlorophyll. Chlorophyll is a pigment that plays an essential role in the life of the plant by facilitating the absorption of carbon dioxide from the air and the subsequent formation of a starch from it. Other pigments, notably carotene and xanthophyll, which are yellow in color, generally accompany chlorophyll. When the green chlorophyll is destroyed by, for instance, a change in climate or soil chemistry, it is these other pigments that cause the color of the foliage to change from green to yellow or orange [78]. Chlorophyll shows strong absorption bands in the blue at about 0.44 μm and in the red at about 0.66 μm. There is a slight residual absorption between these two bands but there is virtually no absorption in the near infrared beyond 0.7 μm [78], [79].

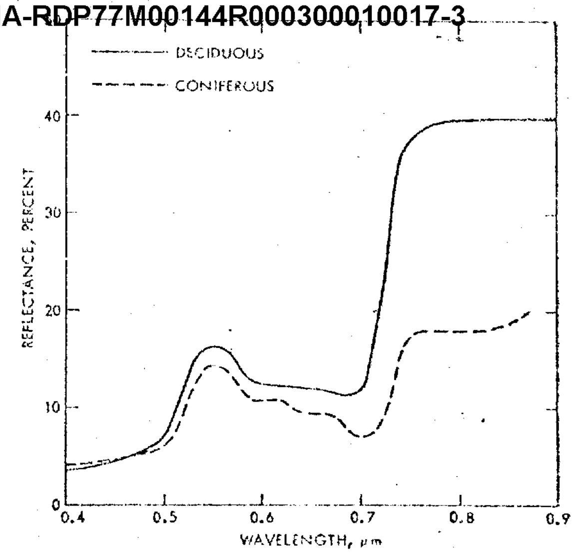

Fig. 8. Typical reflectance spectra of leaves from deciduous and coniferous trees [78], [80], [82].

When light is incident on a leaf, part of it is reflected, part is absorbed, and part is transmitted into the body of the leaf. From 2 to 15 percent of the light is reflected directly from the surface (the reflectance of the lower surface may be twice this amount). The reflectance is greatest in the green region of the spectrum and considerably less in the blue and red where the absorption of the chlorophyll is high. Light transmitted into the leaf encounters a very complex structure and it is scattered by multiple reflections and refractions at the many structural elements. The long path lengths that result give ample opportunity for absorption by the pigments of the leaf and any of this light that ultimately escapes from the leaf is quite green in color. As a result, the human eye perceives the leaf as a strong shade of green. Even though the total reflectance of the leaf in the green rarely exceeds 15 percent, it is these wavelengths that the human eye is most sensitive to and we perceive leaves as brightly colored objects that have a strong contrast with their surroundings.

Beyond 0.7 μm, in the near infrared, the situation is quite different because at these wavelengths chlorophyll has negligible absorption. As a result, these wavelengths are readily reflected from the surface of the leaf. Because of the transparency of the chlorophyll, any light transmitted into the leaf suffers little absorption and a significant fraction is scattered back out of the leaf. The result is that the reflectance of the leaf is very high, from 40 to 60 percent, in the near infrared. This, then is the reason for the extremely light tonal rendering of foliage on infrared photos.

Typical spectral reflectance curves for the leaves of deciduous (hardwood) and coniferous (softwood) trees are shown in Fig. 8. Both show relatively high reflectance in the near infrared but that of the conifer is noticeably lower. It is this

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[5] Hereafter, we will refer to this simply as infrared film. In order to avoid confusion, a non-black-and-white type to be discussed in the next section will be called false color infrared film.

[6] Hereafter, we will use p[illegible] made from a negative. When necessary, we will indicate the type of negative material by using it as a modifier, i.e., a panchromatic photo signifies a positive print made from a panchromatic negative.

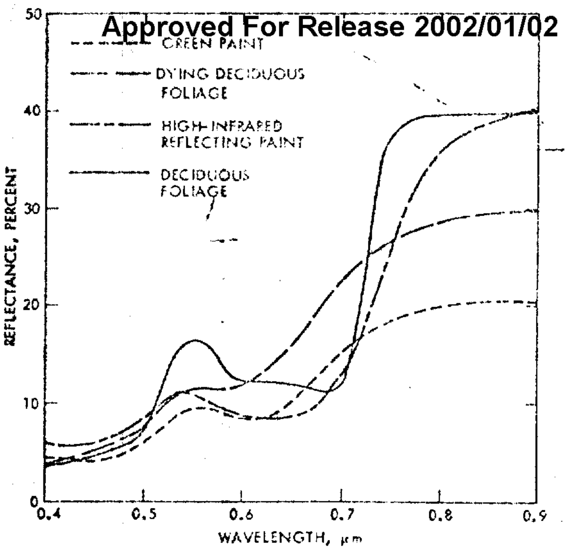

Fig. 9. Spectral reflectance of foliage and paints [78], [80], [81].

difference in reflectance that enables a photointerpreter to differentiate between the two on an infrared photo. Here, then, is a simple example of multispectral analysis. On a panchromatic photo, deciduous and coniferous trees are rendered in similar shades of gray and an interpreter trying to differentiate between the two must fall back on such subsidiary clues as texture and shape. On an infrared photo the two types are readily separated on the basis of their different tonal rendering. A side-by-side comparison of the two photos makes the differences even more apparent.

Camouflage is used in a military situation to confuse or deceive an observer. The techniques of camouflage include complete concealment, dummies, nonfunctional structural additions to make the object look like something else, and coverings to blend the object with its surroundings.[7] Among the means used to blend an object with its surroundings are the direct application of paints, the use of overlying nets supporting strips of variously painted fabrics, and simply covering the object with foliage cut from the surroundings. The camouflager works on the thesis that the more closely an object can be made to resemble its environment, the more difficult it will be to detect and identify it. The introduction of infrared film for aerial reconnaissance made the attainment of this goal much more difficult because it forced the camouflager to achieve a resemblance in the near infrared as well as in the visible portion of the spectrum. Fig. 9 shows the spectral reflectance of deciduous foliage, both living and dying, ordinary green paint, and a special infrared-reflecting green paint. If the object to be concealed is painted with the ordinary green paint it is unlikely that the eye will perceive a difference between it and a background formed by the deciduous leaves. On an infrared photo the deception will be obvious. The object, because of the low reflectance of the paint in the near infrared, will appear as a dark shade of gray in front of a very light background. This problem with paints was recognized during World War II and it led to the development of camouflage paints having a high reflectance in the near infrared [80], [81]. [illegible] the reflectance curve of this camouflage paint with that of the leaves shows that neither the eye nor the infrared photo are likely to differentiate between the paint and the leaves. The curve for dead foliage represents foliage that was cut approximately one day prior to having its reflectance measured. The decreased reflectance in the near infrared and the increased reflectance in the yellow and red (due to the carotene and xanthophyll) are obvious and it is unlikely that use of such foliage would fool either the eye or an infrared photo. When foliage is cut it may retain its green color for several days but the decrease in infrared reflectance occurs very quickly. In some cases it can be detected within 2 h on an infrared photograph [80]. As a result, foliage is a poor choice as a camouflage material unless one is prepared to replace it every few hours and has, in addition, a secure place to hide the telltale used material.

A closer examination of Fig. 9 shows that there are significant differences in reflectance of the materials that could be detected by examination in a narrow spectral interval. The reflectance of high-infrared-reflecting paint is, for example, noticeably different from that of the leaves in the 0.68-μm chlorophyll absorption band, and between 0.7 and 0.75 μm where the leaf reflectance increases abruptly. Limiting the observation to either of these spectral regions will quickly show the mismatch. We mentioned earlier that panchromatic film for aerial reconnaissance has an extended-red response. It is evident now that this is done so as to extend the film's response into the chlorophyll absorption band. Because of this extended-red response, panchromatic film with a red filter can detect some of the commonly used camouflage materials [78, ch. 13], [82].

Water is rendered as a deep black tone on infrared photographs because water absorbs strongly in the near infrared. A water-filled stream or ditch need be no more than 30 cm deep to record as completely black on an infrared photo. This characteristic enhances the contrast between green vegetation and water on infrared photos whereas they often record in quite similar tones on panchromatic photos. If a stream is carrying a heavy load of sediment it may be shown quite dramatically on an infrared photo.

The ability of infrared film to penetrate haze is often misunderstood and overstated. Brock [83] and Clark [78, ch. 15] have reported detailed analyses of photographic haze penetration. From their analyses, it is possible to state several general conclusions about the possibility of penetrating haze, mist, and fog by infrared photography.

1) In the case of a haze consisting of small particles, relatively large gains can be achieved. Such hazes scatter principally in the blue end of the spectrum and, hence, appear blue to the eye.

2) The lower the visibility in haze, the smaller is the chance of increasing it by infrared photography.

3) In the case of mists, fogs, or clouds which are white or neutral gray in color, no useful increase in penetration may be expected.

4) Much of the observed "haze penetration" is, in fact, due simply to the enhanced contrast caused by the unusual rendering of foliage and green vegetation in the infrared photograph.

Infrared film rarely finds any military application in the [illegible] emission. The lowest temperature blackbody that can be detected with infrared

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[7] Numerous examples of these techniques can be found in *Aviation Week and Space Technology*. It is interesting to note that during the October Middle Eastern War in 1973 [illegible] of plywood and cardboard dummies of antiaircraft missiles, tanks, and aircraft.

film is one having a temperature of 250°C (482°F) [84]. At this source temperature the required exposure time may be from 10 minutes to several hours.[8]

B. Aerial Photography with False Color Infrared Film

The Air Corps began the experimental use of color film as early as 1926 and by 1939, when World War II started, the value of color film for aerial reconnaissance had been well established [76]. Most, but not all, color films for reconnaissance use yield a positive color transparency. They are a trilayer type of film consisting of 3 emulsion layers coated on a common base. The emulsion next to the film base is sensitive to red light, the middle emulsion is sensitive to green light, and the top emulsion is sensitive to blue light. Each layer contains a dye coupler which, during development of the film, reacts with components of the developer to form an appropriately colored dye.[9]

In 1938, a modified color film was produced for the detection of camouflage [85], [86]. It is a trilayer film consisting of the normal green- and red-sensitive layers but the blue-sensitive layer has been replaced with a layer sensitive to the near infrared (0.7 to 0.9 μm). Because all three layers show some response to blue light, which is not to be recorded, a yellow filter is used over the lens to absorb the unwanted blue light. Unlike normal color film, the dyes formed in each layer do not produce the color to which the layer responds. Green objects appear blue, red objects appear green, and objects having a high reflectance in the near infrared appear red. It is this combination of infrared response and false color rendition that gives the film its designation of false color infrared.

False color infrared film is valuable for the same reasons that have already been described for black and white infrared film. Deciduous foliage and grasslands appear as bright red. Conifers, which have a lower reflectance in the near infrared, appear in purplish red tones. Dying foliage appears bluish or cyan against the reddish healthy foliage. Diseased vegetation has a reduced reflectance in the near infrared and it shows as a darker shade of red or, sometimes, even black. Plants stressed by moisture loss show up as a light red or white. In many cases, plants under stress show up on false color before the symptoms of disease or death are visible to the eye. As a result, the airborne camera, which may be miles away, can detect a condition that the ground based observer cannot perceive even if he has the plant in his hand. Ordinary green paint appears blue while the high-infrared-reflecting green paint appears purplish.

During World War II, false-color infrared film revealed, for the first time, the extensive camouflage system over the German V-1 preparation area north of Arras, France, by making it appear as a large blue fan. This complex had escaped detection for many weeks despite intensive reconnaissance with panchromatic film [85].

There is also a Russian-produced false-color film. It is a two-layer type and is referred to as spectrazonal film. One layer has a panchromatic-type response extending to 0.65 μm. The response of the second layer extends to 0.80 μm. Different dye colors are produced in spectrazonal film than are produced in the previously described false-color film. On the spectrazonal film, conifers appear green, deciduous foliage appears yellow, orange, or red, and high-infrared-reflecting camouflage paints appear nearly white [80], [87].

The reader who wishes to see examples of the truly beautiful photographs that can be made with false color film, is urged to examine those found in [77], [85], and [88]. Brock [83] shows a series of excellent aerial photos taken with a twin camera arrangement in order to allow direct comparison of panchromatic and black and white infrared imagery.[10]

C. Image Converters for Night Vision

The image converter was developed on the eve of World War II, first in Germany and somewhat later in the United States. It was of prime interest to the military because it offered an effective means for man to see in the dark. An image converter tube is a photoemmisive device that converts an infrared image into a visible image. An optical system is used to form an image of the scene onto the cathode of the tube. The cathode is a semitransparent silver-cesium-oxide-cesium film with a maximum response at 0.85 μm and a long wavelength cutoff at about 1.3 μm. Photoelectrons leaving the cathode form an electron image of the scene that is reimaged onto a fluorescent screen. When struck by an electron, this screen emits visible light. In this way the original infrared image is converted into a visible image. A magnifying eyepiece increases the apparent size of the image without appreciable loss in its brightness [1, pp. 296–297, 498–502, 531–532, 547–548], [89], [90]. Because very few military targets are hot enough to radiate appreciably in the spectral region covered by image tubes it is necessary to provide some means of illuminating the target. The most common illuminator is the tungsten lamp fitted with a filter that passes the near infrared while blocking the visible so as to insure covertness. Since most military vehicles are equipped with tungsten head lamps, the simple addition of a snap-on filter converts them into covert illuminators for night driving.

Military applications for image converters include weapon firing (the sniperscope), surveillance (the snooperscope), night driving of jeeps, trucks, and tanks, detection of homing beacons, air-to-air IFF, ship docking, aircraft landing, fire control systems for tanks, camouflage detection, and station keeping. Fig. 10 shows the performance characteristics that have been reported for typical night viewing equipment that

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[8] It is interesting to compare this temperature with the minimum temperatures that the eye can perceive. Objects at a temperature of 600°C (1112°F) are clearly visible in a well lighted room. Objects at 500°C (932°F) can be seen in a darkened room with little or no dark adaptation by the observer. A completely dark adapted observer can just detect an object at a temperature of 420°C (788°F). At this level the object appears colorless.

[9] The film is developed by a reversal process and the colors of the dyes are complementary to the colors to which the various layers respond, i.e., there is a positive yellow dye image in the blue-sensitive layer, a positive magenta dye image in the green-sensitive layer, and a positive cyan dye image in the red-sensitive layer. The final images are formed by a subtractive color mixing process when the transparency is viewed or projected by transmitted light. By this process an image of a red object, for example, forms a positive yellow dye image in the blue-sensitive layer, a positive magenta dye image in the green-sensitive layer, and in effect, no positive cyan dye image in the red-sensitive layer because the density of the dye images is inversely proportional to the exposure of the resp[illegible] transmitted light, the yellow and magenta dye images subtract blue and green from the white transmitted light and the lack of a cyan dye permits the remaining red light to be transmitted to the eye.

[10] If any reader is interested in experimenting with either of these infrared films in his own camera he should know that they are available in most of the larger camera stores. The commercial names for each are Kodak High Speed Infrared Film and Kodak Ektachrome Infrared Film [88].

APPLICATION	MAXIMUM USEFUL RANGE, m	POWER INPUT TO ILLUMINATOR, WATTS
CARBINE AIMING (WW2)	100 – 150	10 – 30
CARBINE AIMING (1965)	– 200	–
NIGHT DRIVING	50 – 200	10 – 100
BATTLEFIELD SURVEILLANCE	200 – 800	200 – 1500
TANK FIRE CONTROL	600 – 2000	1000 –
SHIP SURVEILLANCE	1600 – 13000	1000 –
BEACON DETECTION	– 16000	–

Fig. 10. Reported performance for typical night viewing equipment using image converter tubes [1, pp. 296–297, 498–502, 531–532, 547–548].

uses image converter tubes [1, pp. 296–297, 498–502, 531–532, 547–548].

In 1943, when the Germans introduced their first tank fire control systems incorporating image converter tubes, they were clearly a case of the tactician's dream come true—a weapon possessed by one side and not the other! In numerous instances, German tank crews badly mauled Russian tank units during nighttime strikes on the eastern front in 1944. The German success was simply due to the fact that they could see at night and the Russians could not. It has not been explained to this day why the Germans did not use this equipment against the Allies on the western front. Guderian, the brilliant German tank tactician, however, has very few complimentary things to say about image converter equipment in his autobiography [91].

One might assume that the presence of the easily detected illuminator with each image converter system would make these systems so vulnerable to counterattack that their use would be abandoned. The Metascope, in fact, was developed expressly for detecting these sources. It was a small hand-held device that used an infrared-sensitive phosphor. It was simple to use, weighed less than 0.25 kg, could be pocketed by any soldier, and cost about $40 to produce [1, pp. 296–297, 498–502, 531–532, 547–548], [5], [6]. But survive they did and image converter systems are alive and well today. An examination of one of the standard references on military equipment [41] shows more than 50 examples of image converter devices on tanks, armoured personnel carriers, and scout cars. The applications include viewers for tank commanders, sights for gunners, and viewers for night driving (some being affixed to the vehicle and some being helmet mounted). Among the countries listed as using this equipment are France, India, the Netherlands, Sweden, United Kingdom, United States, and the USSR. It is also significant to note that two excellent books on night vision devices, written by and for the military, have been published and widely distributed in the Warsaw Pact countries [80], [92]. The book by Kapeller [80] is unusual for its treatment of camouflage detection with image converters. The author was a captain in the Hungarian Army Engineer Corps and his discussion is in such depth that it even advises the individual soldier on means of avoiding detection by image converters.

D. Imaging Scanners and Multispectral Sensing

The basic principles of multispectral imaging so elegantly ex- [illegible] tended to provide imagery in more than three regions [illegible] spectrum. As we do this the dividing line between milita [illegible] civilian applications becomes increasingly hard to defin [illegible] military strategist intent on detecting signs of an ima [illegible] crop failure in another country may use the very same [illegible] niques as the county agricultural agent intent on detecti [illegible] fungus in neighboring citrus groves.

An early multispectral sensor used a special 9-lens aeria camera to make 9 simultaneous black and white photograph in narrow spectral bands extending from 0.40 to 0.90 μm [93], [94]. At about the same time, a 4-lens camera wa developed but it differed in that additive color technique were used to produce a color positive from the black an white negatives. In essence, 4 negatives were made [illegible]taneously, one each in the blue, green, red, and near infrare Each negative was printed to yield a positive black an [illegible] transparency. The four positives were then placed in a [illegible] viewer that illuminated each transparency with colo [illegible] and optically superimposed the four to yield a colo [illegible] Photo interpreters often find that it is easier to inte [illegible] color rather than a black and white photograph of [illegible] subject. The designers of this 4-lens sensor system [illegible] that the eye can perceive about 200 shades of [illegible] over a million color differences (black and white [illegible] vary in brightness only while color processes vary in bri [illegible] hue, and saturation [95]). The Skylab Orbital W [illegible] carried a multispectral photographic facility [illegible] matched cameras. Two of the cameras used panch [illegible] film, two used black and white infrared film, one [illegible] color infrared film, and one used color film [96]–[98].

The multispectral sensors that we have been describ [illegible] limited in their coverage of the spectrum by the [illegible] response of available films. To remove this limitation [illegible] use a scanning sensor which combines a mechanical or [illegible] scanning mechanism with an infrared detector. The [illegible] many ways of generating a desired scan pattern [1, pp. [illegible] 209], [99]. In essence one takes a sensor with a sma [illegible] of view and arranges to move the field of view in some [illegible] priate manner so as to cover a much larger search field. [illegible] time required for one complete scan of the search fi [illegible] called the *frame time*. Many infrared scanners gener [illegible] rectangular scan pattern or raster similar to that [illegible] television. For special applications, however, conical, sp [illegible] rosette, and circular scan patterns may be used.

The simplest way of generating a scan pattern is to mo [illegible] entire sensor so as to create the desired pattern. If the se [illegible] and its mounting are designed expressly for this meth [illegible] angular scanning rates as high as 250°/s can be achieve For those applications where it is not practical to scan th entire sensor, various optical techniques must be used. A rotating scanning mirror is a good example of these techni [illegible] Assume that we wish to design a sensor to provide a map [illegible] image of the terrain beneath an aircraft. A simple sensor wou [illegible] consist of a lens and a single small detector. We will mo [illegible] this sensor so that its axis (the line joining the lens and [illegible] detector) is parallel to the direction of flight. A mi [illegible] inclined at an angle of 45° to the sensor axis, and placed [illegible] front of the lens, will allow the sensor to "see" the grou [illegible] If the mirror is rotated about the axis of the sensor it [illegible] cause the sensor to scan a line on the earth's surface that [illegible] [illegible]ection of flight. The [illegible] the detector and the focal length of the lens determ [illegible] *instantaneous field of view* of the sensor (most com [illegible] of view and the altitude of the aircraft we can determine the linear size of the patch on the ground that just fills the sensor's field of view. Since the detector integrates the radiation from all objects within this ground patch it determines the *ground resolution* of the sensor. Successive scan lines are displaced along the surface of the earth by virtue of the forward motion of the aircraft. A visual record of the scene beneath the aircraft can be reconstructed if the output of the detector is used to modulate the brightness of a small lamp and the lamp is, in turn, imaged onto a photographic film via a scanning mirror synchronized with that of the sensor. Alternatively, the output of the detector can be used to modulate a cathode ray tube so as to form a television-like picture. If the scanning was done in the intermediate or far infrared the resulting image is often called a thermal image.

There are many ways of controlling and changing the spectral region utilized by the scanner we have just described. A filter placed in front of the detector can be used to select any desired spectral interval. Gross changes in spectral coverage can be made by changing the type of detector. In many cases it is desirable to provide simultaneous scanning in several spectral intervals. This can be accomplished by replacing the single detector with a number of fiber optic bundles, each of which leads to a different detector. Alternatively, the single detector can be replaced with a spectrometer or other dispersing device. Still another way is to replace the single detector with an array of detectors, each with a different spectral response. Further information on the design and performance of scanners can be found in [1, pp. 428–432, 494–497, 528–531, 541–547, 599–607], [100]–[105].

A particularly versatile design of a multispectral scanner has been described. It uses a spectrometer to define the various spectral bands (channels) that are covered. A 15-channel version, having spectral coverage from 0.4 to 13.5 μm, forms the airborne data acquisition subsystem of a complex agricultural remote sensing system [106]. All data are handled by a computer complex [107]. An 18-channel version has been flown extensively in aircraft for various ecological studies. Its spectral coverage extends from 0.32 to 14 μm [108]. A 24-channel version has been designed for use in a NASA earth-resources survey aircraft. Its spectral coverage extends from 0.34 to 13 μm and the angular resolution of each channel is 2 mrad. During the inactive scan time the mirror rotates through an angle of 280°. This time is used for roll compensation and to insert calibration signals from two thermoelectrically controlled blackbodies whose temperatures are known to within 0.25 K. The visible channels are calibrated by a tungsten halogen lamp or by a skylight-illuminated diffusing screen in a hole through the top of the fuselage [109].

Multispectral scanners have also been used from space. Again the line between military and civil application is not easy to define. Observing from space, for whatever reason, violates no international law and infringes on no territorial boundaries. Many efforts have been made to have such a concept formalized for inclusion in the recognized body of international law but, unfortunately, little progress is evident [110], [111]. The general principles of observation from space have been particularly well described in [112].

The ERTS carries a multispectral scanner that provides imagery in four chann [illegible] The first three channels are each 0.1 μm wide and use photomultiplier tubes as detectors. The fourth channel extends

Six scan lines are imaged in each spectral band with each sweep of the scanning mirror. The scan lines are defined by the ends of fiber optic bundles arrayed in a 6×4 element matrix in the image plane of the scanner's optics. During scan retrace the scene is blanked out by a rotating shutter and the output of an internal calibration lamp is swept across the fiber optic bundles. The optical system is a two-mirror type with a 23-cm diameter primary mirror. Ground resolution is about 70 m. The entire scanner weighs about 55 kg [113], [114]. Many spectacular examples of ERTS imagery have appeared in the literature. An especially fine color portfolio appeared in [114].

The Skylab Orbital Workshop also carried the S-192 multispectral scanner. It provides 13 channels of imagery over two spectral intervals extending from 0.41 to 2.35 and 10.2 to 12.5 μm. The all reflective optical system employs a 60-cm diameter, nickel-coated, aluminum primary mirror. A conical scan is generated but only the front 120° are used for sensing radiation from the earth. The remaining 240° are used for sensor calibration. The use of a conical scan has the advantage that the length of the line-of-sight path is essentially constant throughout the full length of the scan line. Hence, variations in atmospheric transmission, due to varying lengths of the line-of-sight path, do not occur. An unusual dichroic beam splitter that provides 80-percent reflectance from 0.4 to 2.5 μm and 80-percent transmittance for longer wavelengths is used to divide the incoming radiation into two broad bands. The short wavelength band is fed to a prism spectrometer that provides the dispersion necessary to separate the 12 spectral bands before they reach a 12-detector array [32], [96], [97]. All detectors are cooled to cryogenic temperatures by a Stirling cycle cooler. The ground resolution is 80 km. A color portfolio of imagery from this scanner appeared in [93].

Obscuration by cloud cover has been a problem since the very beginnings of aerial reconnaissance and the problem is even more critical for reconnaissance from space. No longer is it sufficient to argue that since the average cloud cover of the earth is about 40 percent, about 60 percent of all earth observations will be free of clouds. What is needed by the military or earth resource user is a statement of the probability that a particular area will be clear enough for observation at a particular time. A large body of worldwide cloud statistics exist and considerable work has been done in applying them to planning for optimum satellite application [115]–[117].

E. Thermal Mapping Sensors

Thermal mapping sensors were originally developed to produce thermal imagery of the terrain beneath an aircraft. Most thermal mappers are scanners and their operation and implementation is similar to that already described for multispectral scanners.

Thermal mappers were discussed during World War II, but it was not until the 1950's that any were flown. These very early mappers used a "pushbroom" scanning technique. The sensor consisted of optics and a linear array of detectors and it was mounted vertically in the aircraft, so that it pointed toward the ground. The detector array was arranged so that its axis was at right angles to the flight direction. In this way, each detector defined a scan line that was moved forward over the earth's surface by the forward motion of the aircraft. The [illegible] not result in a very high information rate with this scanning arrangement and relatively slow responding thermal detectors could be used.

most scanner designs from the later 1950's on used the cross-course arrang[illegible] [5].

In 1959, it was reported that a U.S. Navy patrol plane was shot down over international waters while carrying infrared equipment designed to detect submarines [118]. Less than a year later, an article in a Russian journal, by a major in the Soviet Engineering Corps, described the detection technique [119]. The article stated that modern airborne infrared sensors could detect submarines submerged as deep as 40 m by the temperature difference of 0.05 to 0.5°C that exists between the surface wake and the surrounding water. In 1967 it was claimed that infrared sensors for the detection of submarines had the capability of detecting a temperature difference of 0.005°C but further development of the equipment was uncertain because of the way its operation was affected by high seas, rain, and fog [120]. Other similar reports have continued to appear [1, pp. 494–497]. A recent article on the U.S. Navy S-3A Viking anti-submarine warfare aircraft lists an infrared sensor among the onboard quipment [121].

It has been speculated that an infrared scanner should be able to detect buried objects, either by slight thermal patterns evident at the surface or by some sort of persistent thermal scar left by the excavation and subsequent backfilling required to bury the object. In 1963, it was claimed that an infrared sensor had been developed for the detection of buried land mines [122]. Tests were described in which a simulated mine, buried at a depth of 45 cm, was readily detected by the sensor for at least a week after burial. In 1970, it was reported that an infrared scanner being flown under contract to the Kansas State Highway Department had detected abandoned underground mines down to support pillars. The purpose of this program was to determine the underlying structure of potential interstate highway routes [123]. A short time later, it was reported that the West German Navy in test flights of infrared scanners had been able to detect bunkers buried deep in the ground [124].

From numerous reports it appears that thermal mappers were used in Vietnam and that they demonstrated a capability to detect Viet Cong cooking fires and truck engines [1, pp. 494–497], [125].

Satellite borne thermal imaging systems for meteorological observations have been in use for about a decade [1, pp. 603–605]. It has, however, not been so well known that the U.S. Air Force has operated the Defense Meteorological Satellite Program for nearly as long. In March 1973, the Under Secretary of the Air Force acknowledged the program and stated that it would be used to support all of the Air Force's worldwide missions [126]. The satellites carry both visible and infrared scanners capable of providing imagery with a ground resolution of either 3.7 or 0.6 km. The two sensors, thus, provide both a day and night capability for cloud-cover surveillance. An additional infrared sensor makes measurements of the vertical temperature profile of the atmosphere [126], [127].

The satellites are reported to be in a polar orbit at an altitude of about 9500 km and are placed so as to provide world wide data sensed at 7:00 A.M., noon, 7:00 P.M., and midnight (local times) [126], [127]. The Under Secretary described how, in a conflict situation, Unit Commanders need to have current data on weather conditions along the approach route and in the target area if they are to direct successful strike missions. A knowledge of cloud patterns and of cloudtop altitudes would be invaluable in the designation of refueling [illegible] planning the optimum approach to a target, and in estimating areas wherein strike aircraft might be especially vulnerable to attack by surface-to-air missiles [126].

Further reports indicate that a 2-channel scanner is used that has a 20-cm diameter primary mirror. A beam splitter separates the 0.4- to 1-μm band from the 8- to 13-μm band. A cooled mercury cadmium telluride detector is used for the long wavelength band and a silicon photodiode is used for the visible and near infrared band [128]. In the multispectral scanner that we described previously, the ground resolution was at its best at a point directly below the sensor and it gradually worsened as the ground patch approached the horizon. In the defense meteorological satellite scanner an almost constant ground resolution is achieved by limiting the scan angle to 58° either side of the vertical and by driving the scanning mirror at a nonlinear rate [114].

An excellent survey has been published that details the characteristics of infrared and visible imagery that can be obtained from orbiting meteorological satellites [129].

The sensor that measures the vertical temperature profile in the atmosphere is described as a 16-channel multispectral cross-track scanner. In addition to the atmospheric temperature profile it also measures profiles of water vapor and ozone. The temperature measurements are accurate to ± 0.5° and are derived from scanning the edge of the carbon dioxide absorption band from 14 to 16 μm. Water vapor content is measured to an accuracy of ± 2 percent by scanning in the water vapor absorption band at 25 μm. Ozone content is determined to an accuracy of ± 4 percent by scanning the ozone absorption band at 9.6 μm. The entire instrument is reported to weigh 14 kg [128]. Another technique for measuring atmospheric temperature profiles from a satellite has been described [130].

Clear air turbulence (CAT) is often associated with horizontal temperature gradients in the atmosphere. Many different types of sensors have been tested for their ability to detect CAT but only infrared sensors have shown any real promise [1, pp. 524–527]. The infrared techniques used for detection of CAT are, in essence, the same as those used to determine the vertical temperature profile in the atmosphere. Sensors were installed in three commercial jet airliners in regular passenger service and over 600 h of flight data were acquired. No severe turbulence occurred during the test period but many light turbulence encounters were detected as much as 130 km in advance. This is equivalent to giving the pilot as much as 8 minutes advance warning of the encounter. A high false-alarm rate was experienced because of atmospheric temperature gradients that were not associated with turbulence [131].

Horizontal atmospheric temperature gradients can also be measured by the infrared scanners on meteorological satellites. A recent study related temperature gradient measurements from Nimbus meteorological satellites to the probabilities of CAT as inferred from regular pilot reports. The most severe horizontal temperature gradients were found to be related to areas of large-scale vertical wind shear. The results of this study indicate that meteorological satellite data can be used to design flight paths so that the probability of encountering CAT is extremely low [132]. Such information would be extremely valuable to the Air Force and it seems reasonable to assume that data from its satellites will be used for this purpose.

EQUIPMENT DESIGNATION	PLATFORM	FUNCTION	MILITARY SERVICE	STATUS	NUMBER CONTRACTED
OR-89AA	S-3A	NIGHT TARGET CLASSIFICATION & PERISCOPE DETECTION	NAVY	PRODUCTION	66
AAR 37	P-3A-B	NIGHT ASW SURVEILLANCE	NAVY	PRODUCTION	13
	A-7E	TARGET ACQUISITION	NAVY	DEVELOPMENT	5
	A-6E	TARGET ACQUISITION	NAVY	DEVELOPMENT	5
	B-1	NAVIGATION DURING LOW ALTITUDE PENETRATION IN CLOSED CURTAIN ENVIRONMENT	AF	DEVELOPMENT	2
AAQ 6	B-52G-H	SAME	AF	PRODUCTION	324
AAS-26	B-57G	NIGHT SURVEILLANCE & TARGET ACQUISITION	AF	OPERATIONAL	14
AAS 28	A-6C	NIGHT TARGET ACQUISITION	NAVY	OPERATIONAL	22
	YOV-10D	TARGET ACQUISITION	NAVY	DELIVERED	2
BLACK SPOT	C-123K	NIGHT TARGET ACQUISITION	AF	OPERATIONAL	6
AAD 4,6	C-119, AC-130	NIGHT TARGET ACQUISITION	AF	OPERATIONAL	55
AAD 7	AC-130E	NIGHT TARGET ACQUISITION	AF	OPERATIONAL	30
LATIS		TECHNOLOGY PROGRAM	ARMY	COMPLETED	1
ACSTIS		TECHNOLOGY PROGRAM	ARMY	DEVELOPMENT	1
AUSTERE FLIR	OV-10	TECHNOLOGY PROGRAM	AF	COMPLETED	1
MAFLIR		TECHNOLOGY PROGRAM	AF	DEVELOPMENT	1
HIGH ZOOM DISCOID	BQM-34E	NAVIGATION & TARGET ACQUISITION	AF	DEVELOPMENT	2
	RPV	NAVIGATION & TARGET ACQUISITION		DELIVERED	2
AAS 25	AH-56A	GUNNER'S NIGHT SIGHT	ARMY	COMPLETED	3
AAS-29	UH-1	NIGHT TARGET ACQUISITION	ARMY	OPERATIONAL	5
AAQ 5	UH-1	NIGHT TARGET ACQUISITION	ARMY	OPERATIONAL	9
IRISH	MAVERICK	MISSILE SEEKER	AF	DEVELOPMENT	2
HIGH ZOOM DISCOID	F-4	TARGET ACQUISITION FOR NIGHT MAVERICK	AF	DEVELOPMENT	1
	WALLEYE	MISSILE SEEKER	NAVY	DEVELOPMENT	1
S-3A FLIR	A-7	TARGET ACQUISITION	NAVY	TEST	1
	CHAPARRAL	NIGHT TARGET ACQUISITION	ARMY	DEVELOPMENT	3
ASS 28A	MK-68	SHIPBOARD NIGHT TARGET ACQUISITION	NAVY	DELIVERED	10
TINTS	M60	TANK NIGHT SIGHT	ARMY	DEVELOPMENT	6

Fig. 11. FLIR sensors reported to be used by the U.S. military services in mid-1973. Adapted from Miller [133].

F. Forward Looking Infrared (FLIR) Sensors

The scanners and thermal mappers that we have been discussing were designed to view the terrain beneath an aircraft and to display the resulting imagery in a map-like display. This imagery is rarely presented or used in real time. Attack aircraft, however, need a sensor that can provide high resolution imagery in *real time*. The FLIR is such a sensor. It operates in the longer wavelength portion of the infrared, sensing the radiation emitted by targets and providing high-resolution real-time thermal imagery. The Deputy Chief of Staff for R & D of the U.S. Air Force, in testifying before the Congress, called the FLIR one of the three most significant sensors to emerge from recent U.S. technology [133]. In his testimony he noted that "The FLIR imagery available today from the most advanced systems is hardly distinguishable from a TV picture .... The FLIR can be used as a scene viewing device; however, it is particularly effective in locating targets that have a temperature significantly different from their surroundings, such as hot truck engines, hot gun barrels, generators, and so forth." Further statements indicated that FLIR sensors installed on gunships in Vietnam were instrumental in detecting the movement of supplies down the Ho Chi Minh trail.

The early forerunners of FLIR sensors were designed for fire-control use and usually did not provide imagery. They began to appear in the early 1960's and significant quantities were produced [1, ch. 14, pp. 477–479]. But, like the infrared-guided missiles, they were not designed for the type of war they were ultimately used in. Limited war placed a new premium on sensors versatile enough to detect not only airborne [illegible] of tactically interesting ground targets. FLIR sensors designed to meet this challenge began to appear in 1968 and were, of course, immediately tested in Vietnam [1, ch. 14 and pp. 477–479], [134].

Fig. 11 presents information on a wide variety of FLIR sensors that were operational, in production, or under development in mid 1973 for the U.S. military services.[11] Perhaps the most striking feature of Fig. 11 is the indication that a total of nearly 600 FLIR sensors are under contract with more than half of this number being in production or already operational. It is reported that U.S. Army planners project army needs at 7000 to 10 000 FLIRs for use as night vision devices on tanks, armored vehicles, crew-served weapons, and remotely piloted surveillance vehicles [133]. Many of the FLIR variants designed for the Army are hand-held or tripod-mounted devices that have their own built-in displays [133], [135].

IX. Conclusions

In this review we have tried to provide a perspective from which the reader can view the full extent of modern-day military involvement with the techniques of infrared remote sensing. Of necessity, we have been selective in our choice of topics to be covered. The choice of some topics was tempered by the necessary constraints of military security classification. Our choices run the full gamut from night viewing to missile guidance to reconnaissance from space. We hope that these topics, and our treatment of them, will help to convey some of the sense of excitement that pervades the infrared field today. Even a casual perusal of the literature of the infrared shows that the military communities of the world share a common awareness of the value of infrared techniques in accomplishing their assigned missions. Infrared is no longer on trial. It is a healthy, growing field with a fine heritage, a strong present, and a bright future.

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Geologic Applications of Thermal Infrared Images

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Invited Paper

Abstract—Thermal infrared images provide information about the near-surface physical state of geologic materials, particularly, the density, water content, and heat transfer. Nonterrestrial planetary studies, conducted at fairly coarse resolution, have been useful primarily in determining the distribution of rock fragments. Terrestrial studies, conducted from satellite and aircraft at coarse to fine resolutions, have been successful for monitoring effusive volcanism, delineating areas of steaming altered ground and hot-spring activity, detecting fractures expressed hydrologically and topographically, and distinguishing a variety of geologic materials with physical and compositional differences.

Interpretation of thermal images is complicated by the various types of physical processes involved and commonly requires an assessment of many different factors. A simple theoretical model was used in this analysis to provide quantitative assessment of some of these factors, to predict optimum times to acquire thermal data, and to determine quantitative values of various properties of terrain.

Two geologic applications were studied in some detail: geothermal mapping and thermal inertia mapping. Initial results indicate that both techniques have considerable potential, especially in reconnaissance studies. These data were acquired under optimal meteorological conditions and at sites where the geologic materials were well exposed. A realistic assessment of the limitations of these techniques must await future studies.

Introduction

OPTICAL-MECHANICAL scanners provide the means to monitor the temporal and spatial variations in the natural thermal emission from planetary surfaces. These variations, observed at a great variety of altitudes from low-flying aircraft to orbiting satellites, can be [illegible] physical properties of terrain materials and [illegible] geologic processes which have occurred. The [illegible] of these data can range from direct visual [illegible] photographic recordings of the measured sign[illegible] niques developed in photogeology) to sophisti[illegible] processing using modeling analysis and pattern [illegible] techniques. These investigations are limited, howev[illegible] complexity of the problem, in terms of both the [illegible] phenomena and the number of different factors that [illegible] the result. Of necessity, the interpretation of thermal inf[illegible] data has been based on quite simple theoretical model[illegible] volving very limiting assumptions and fairly ideal circ[illegible] stances (both meteorologically and geologically). Future [illegible] finements in observational technique and theoretical [illegible] will be required in order to apply the technique [illegible] the diverse terrain conditions found in nature.

This paper describes the development of one [illegible] model for analysis of the surface temperature distr[illegible] The results provide a quantitative estimate of the eff[illegible] various geologic, meteorologic, and topographic f[illegible] hence can be used as a basis for direct interpretation [illegible] thermal images. In addition, the model curves can [illegible] to predict optimum times to acquire the data in [illegible] enhance specific effects and features. Finally, the mo[illegible] be used to determine quantitative values of various [illegible] of the terrain. This last aspect of the model [illegible] impact in future geologic applications and receive[illegible] attention in this paper.

Manuscript received [illegible]

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