REVIEW PAPER

Sensors for Desert Surveillance

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ABSTRACT

Various types of sensors-visible, passive night vision, infrared, synthetic aperture radar, etc can be used for desert surveillance. The surveillance capability of these sensors depends to a large extent, on various atmospheric effects, viz., absorption, scattering, aerosol, turbulence, and optical mirage. In this paper, effects of various atmospheric phenomena on the transmission of signals, merits and demerits of different means of surveillance under desert environmental conditions are discussed. Advanced surveillance techniques, ie, multisensor fusion, multi and hyperspectral imaging, having special significance for desert surveillance, have also been discussed.

Keywords: Thermal imaging, passive night vision sensors, image intensifiers, ICCD, infrared sensors, multisensor data fusion, multispectral imaging, hyperspectral imaging, synthetic aperture radar, automatic target recognition, atmospheric turbulence, optical mirage, search and track systems

1. INTRODUCTION

Surveillance is an important component of defence planning in strategic as well as in tactical environment. It refers to systematic observation of a particular area or target for an extended period of time with the purpose of locating, identifying, and determining its movement. The essence of surveillance is the continuous gathering of intelligence about the enemies' or potential enemies' preparedness/ movements/ possible intentions, vulnerable points, and vital targets. The platforms employed for surveillance are satellites, manned aircraft, unmanned air vehicles (UAVs), stabilised balloons, naval ships, and armoured fighting vehicles (AFVs). Sensors employed for surveillance work in the wavelength range from visible band to microwaves, and radio frequencies (RF) region,

There are various surveillance methods, formation of imagery being the most useful and easily interpretable one. Visible, infrared (IR) and synthetic aperture radar (SAR) systems provide characteristic advantages of their own. Visible sensors yield, under optimal conditions, the highest quality imagery in terms of resolution and easy interpretation but their effective operation is limited to daytime and under clear weather conditions. Night vision devices provide dusk-to-dawn observation capability but require some amount of ambient light. Infrared sensors operate through day and night and can even penetrate camouflage to some extent. While longer IR wavelength sensors can penetrate atmospheric haze better than their visible region counterparts, it is the SAR surveillance that provides almost all weather operation capability'-'.

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2. EFFECTS OF ATMOSPHERE ON TRANSMISSION OF SIGNALS

The objective of any surveillance system is to provide information about geographical terrain, coverage, and types of targets by directing the sensor to the desired area under surveillance. The main problem faced by any surveillance system is to negotiate the intervening medium between the system and the desired area to be covered[8-11].

The clear atmosphere contains gas molecules like oxygen, nitrogen, carbon dioxide, and water vapours. Other constituents exist as pollutants. These particles can either scatter or absorb the photons propagating through the atmosphere. The attenuation through the atmosphere due to absorption and scattering is given by Beer's law as

$$I_r / I_0 = \exp(-\gamma d)$$

where

I_r = Detected intensity at location d

I_0 = Intensity of source

γ = Attenuation coefficient

The attenuation coefficient is the sum of four individual parameters-molecular and aerosol scattering coefficients (α_m, α_a), and molecular and aerosol absorption coefficients (β_m, β_a) and is given by

$$\gamma = \alpha_m + \alpha_a + \beta_m + \beta_a$$

The scattering causes the radiation to be redirected and redistributed, which can lead to significant reduction of the received light intensity at the receiver location. Exact nature o.f scattering is highly complex and its effect depends on various factors, viz., type, orientation, size, and distribution of particles constituting the media as well as polarisation state, and direction of the incident light. Several scattering regimes exist depending on the characteristic sizes of the particles and wavelength of the radiation, viz., Rayleigh scattering, Mie scattering, etc.

Rayleigh Scattering

Different wavelengths of light are scattered differently by atmospheric particles. Over the visible spectrum, Rayleigh's law of atmospheric scattering provides the relationship between the scattering coefficient and the wavelength as

$$a(A) \propto 1/\lambda^{\gamma}$$

where $0 \le \gamma \le 4$, depending on the exact particle size distribution in the atmosphere. For pure air, $\gamma = 4$, thuss hort er wavelength radiation suffers from larger scattering. For fog, $\gamma = 0$, and, so radiations of all wavelengths are scattered equally. A wide gamut of atmospheric conditions arises from aerosols whose particle sizes range between the minute air molecule (10^{-4} μm) and the large fog droplets (1-10 μm). Such aerosols (eg, mild haze and mist) show a significant wavelength selectivity ($0 < \gamma < 4$).

Mie Scattering

This regime is applicable for particles about the size of the wavelength. Therefore in near-IR wavelength region, rain/fog/haze and pollutant (aerosol) particles are major contributors to Mie scattering process. For aerosols, this distribution further depends on location, time, relative humidity, and wind velocity. As 'regards absorption effect, atoms and molecules are characterised by their indices of refraction. The imaginary part of index of refraction k is related to the absorption coefficient by

$$\beta = 4\pi k / \lambda = \sigma_a N_a$$

where σ_a is the absorption cross-section and N_a is the concentration of the absorbing particles. In other words, the absorption coefficient is a function of the absorption strength of a given particle as well as of the particle density.

In the near-IR wavelength region, water vapour is the primary source of molecular absorption, having many absorption lines to attenuate the signal, and, beyond 2.0 μm band, both water vapour and carbon dioxide play a major role. The vibration and rotation transitions determine the energy, which is easily absorbed.

Aerosols mainly comprise meteorite dust, sea-salt particles, desert dust, and volcanic debris. Further, man-made chemical conversion of trace gases to

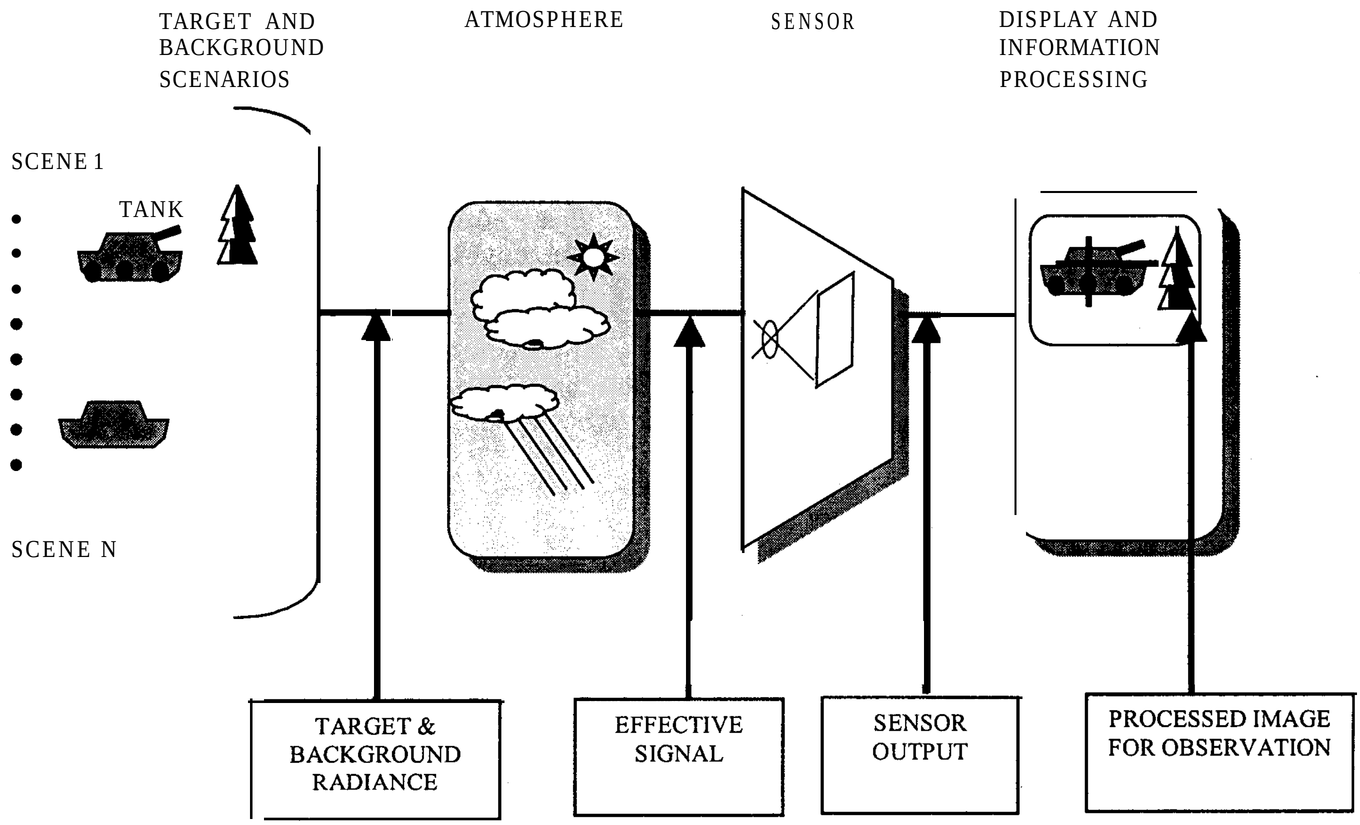

Figure 1. Target acquisition system

The atmosphere and optical instrument attenuate images of distant objects. A true target acquisition model accurately estimates the probability of detection, recognition or identification. Imaging systems have two sensitivity thresholds, ie, the sensitivity threshold of human eye (which is the ultimate receptor) and the sensitivity threshold of the electro-optical detector. The maximum usable frequency ($f_{C\max}$) of imaging system being the frequency at which overall system MTF curve intersects the threshold contrast curve demanded by the observer[14-16].

The contrast-limited systems have contrast limitation derived from the overall system MTF and threshold contrast of the observer at the output. An object or target can be resolved if contrast between it and the background is greater than the threshold contrast required at the output. The maximum usable frequency ($f_{C\max}$) determines the size of the blur radii recorded in the image. Contrast-limited images are thus blur-limited images as well.

The sensitivity threshold of electro-optical (EO) detector depends directly on the noise level of the imaging system. When the sensitivity threshold of electro-optical detector is high, the imaging system is considered to be noisy, which is characterised by random snow. Such a system is called noise- limited system as the system resolution is limited by threshold caused by noise. As the signal-to-noise ratio (SNR) increases, the snow gradually is less evident and smaller details are resolved. The highest spatial frequency $f_{N\max}$ is determined from the point where both the system and the threshold SNR curves meet. Various target acquisition models, ie, atmospheric transmission-based noise-limited model, atmospheric MTF-based noise, and contrast-limited models, have been discussed[12]. As is evident, the atmosphere has variable effects at different spatial frequencies. This indicates that target acquisition is limited more by atmospheric blur rather than by transmission.

Table 1. Evolution of image intensifier tube

Image intensifier tube	PC material	PC sensitivity		QE of PC (%)	Long wavelength cutoff of PC (nm)	Dark current (Acm^{-2})	Applications
		Luminous (µA/lm)	Radiant (mA/W)				
Zero	*Ag-0-Cs*	25	2.3	1	1200	$1x10^{-11}$	Active IR devices
First generation	Na_2KSbCs	250	25.0	20	900	$1x10^{-16}$	Military (long range), medical, astronomical
Second generation (ESI)	Na_2KSbCs	250	25.0	20	900	$1x10^{-16}$	Weapon mount, HH devices, study of nocturnal behaviour of animals
Second generation (wafer)	Na_2KSbCs	250	25.0	20	900	$1x10^{-16}$	Goggles
Super generation	Super generation trialkali	600	43.0	≈ 40	900	$1x10^{-16}$	Night vision devices
Third generation (wafer)	*GaAs Cs*	1000	100.0	40	1000	$1x10^{-14}$	Goggles
Fourth generation	*GaAlAs*, *InP*, *GaAsP*, etc	>1000	>100.0	> 40	>1500	1x10-s	Possibility for various applications if cooled to -100 °C or below

4. SENSORS FOR DESERT SURVEILLANCE

Electra-optical systems provide the capability of covert observation and support desert operations in gathering information for target acquisition and situation awareness. Except for lasers, all EO/IR sensors are passive, these do not emit electromagnetic waves, and, are, therefore, very difficult to detect, which is an important advantage for surveillance and reconnaissance. The different types of surveillance sensors developed have been described.

4.1 Day Vision & Night Vision Sensors

Charged-couple device (CCD)-based cameras provide high resolution, good contrast, and sensitivity under clear weather during day time. The performance gets impaired as the light level decreases and the target is camouflaged.

Image intensifier-based night vision devices and thermal imagers can be used for night operations. The evolution of image intensifier has been linked with the gradual advancements in the development of photocathodes (Table 1). The improved photo- cathode results in better SNR, the most important system performance criterion. The improved SNR reduces the ambient light requirement for target detection, identification or recognition.

First-/second-generation as well as super generation image intensifier tubes employing S-20 and S-25 photocathodes, third-generation image intensifier tubes, using *GaAs* photocathodes have been evolved over the time and a number of passive night vision devices have been developed based on these image intensifier tubes. Further development in photocathodes employing *InP*, *GaAsP*, *InGaAs*, having much better longer wavelength threshold (promising up to 1500 nm), better photocathode sensitivity and quantum efficiency, would be the photocathodes of the future[2]. However, the main problem with these photocathodes is the simultaneous increase in thermoionic emission. As such, their use is restricted unless the photocathode is cooled.

The ICCD night vision camera based on image intensifier coupled to area array CCD imager by demagnifying fibre optics, with dusk-to-dawn capability, offer low-cost solution in numerous defence/para-military applications.

Table 2. Parameters affecting the outcome of an imaging system

Target	Atmosphere	Platform	Sensor	Display	Observer
♦ Type	♦ Visibility	♦ Vibration	♦ Type	♦ Screen size	• Training
♦ Clutter	♦ Cloud cover	♦ Environment	• Spectral band	♦ Colour	♦ Motivation
♦ Size	♦ Sun angle	♦ Stabilisation	• Field of view	♦ Resolution	♦ Experience
♦ Camouflage	♦ Solar loading	♦ Speed	• Resolution	♦ Gray-scale	♦ Pre-briefing
♦ Reflectance	♦ Range	♦ Target exposure time	♦ Dynamic range	♦ Phosphor persistence	♦ Stress
♦ Emittance	♦ Attenuation	♦ Crew Size & interaction	♦ Sensitivity		♦ Task load
• Contrast	♦ Temperature		♦ Magnification		• Fatigue
♦ AT	♦ Humidity				♦ Age
♦ Motion	♦ Scattering				♦ IQ
	♦ Turbulence				

4.2 Thermal Imagers

Thermal imagers convert the heat (Infrared) energy into a real-time picture, where the temperature and emissivity differences of targets wrt the background determine the contrast and contour of the target. Various parameters affecting the performance of a thermal imaging system, for that matter of any imaging system, are depicted in Table 2 and a basic target acquisition system in Fig. 1. The IR sensor system incorporates the IR optics, transducer/detector, and suitable electronic processor to translate the signal in the desired format. Thermal imagers can be used during day and night. It is partially affected by smoke, dust or haze; can detect any object even through camouflage nets, and cannot be blinded by search lights, flares, fires. It can reveal details, which cannot be achieved using other sensors.

In the infrared region, the absorption of radiation by gas molecules is often the most significant attenuation process. Strong absorption by water vapour and carbon dioxide molecules restrict atmospheric transmission to two windows at 3-5 μm and 8-12 μm. The 8-12μm band has higher sensitivity for ambient temperature objects, while the 3-5 μm band has the greater contrast. In general, 8-12 μm band is preferred for high performance thermal imaging because of its greater sensitivity and better transmission through mist and smoke. However, 3-5 μm band may be more appropriate for hotter objects, or if sensitivity is less important than contrast. The 3-5 μm band also has the advantages that the diameter of the optics required to obtain a certain optical resolution is smaller and thermal imager operating in this band can be operated at a higher temperature than the 8-12 μm band thermal imager.

Thermal imagers can broadly be classified into three categories depending upon the type of detectors used, viz., first-generation, second-generation and third-generation thermal imagers (Fig. 2).

Important technological developments are being made worldwide in the area of uncooled infrared technology[17]. These developments are likely to have a major impact on the use of thermal imaging systems, both for military and civilian applications, at low manufacturing costs. Amorphous silicon has emerged as the preferred detector material for uncooled microbolometer, mainly because of its compatibility with CMOS silicon readout electronics.

Recent developments in detector technology are two-colour detectors and quantum well detectors[15]. The integrated two-colour detector combines both spectral bands separately in each pixel in a single focal plane and provides a target identification/recognition and clutter rejection capability required for wide ranging applications. quantnmwell detectors utilise technique of growing of alternate layers of $GaAs$ and $AlGaAs$ on silicon.

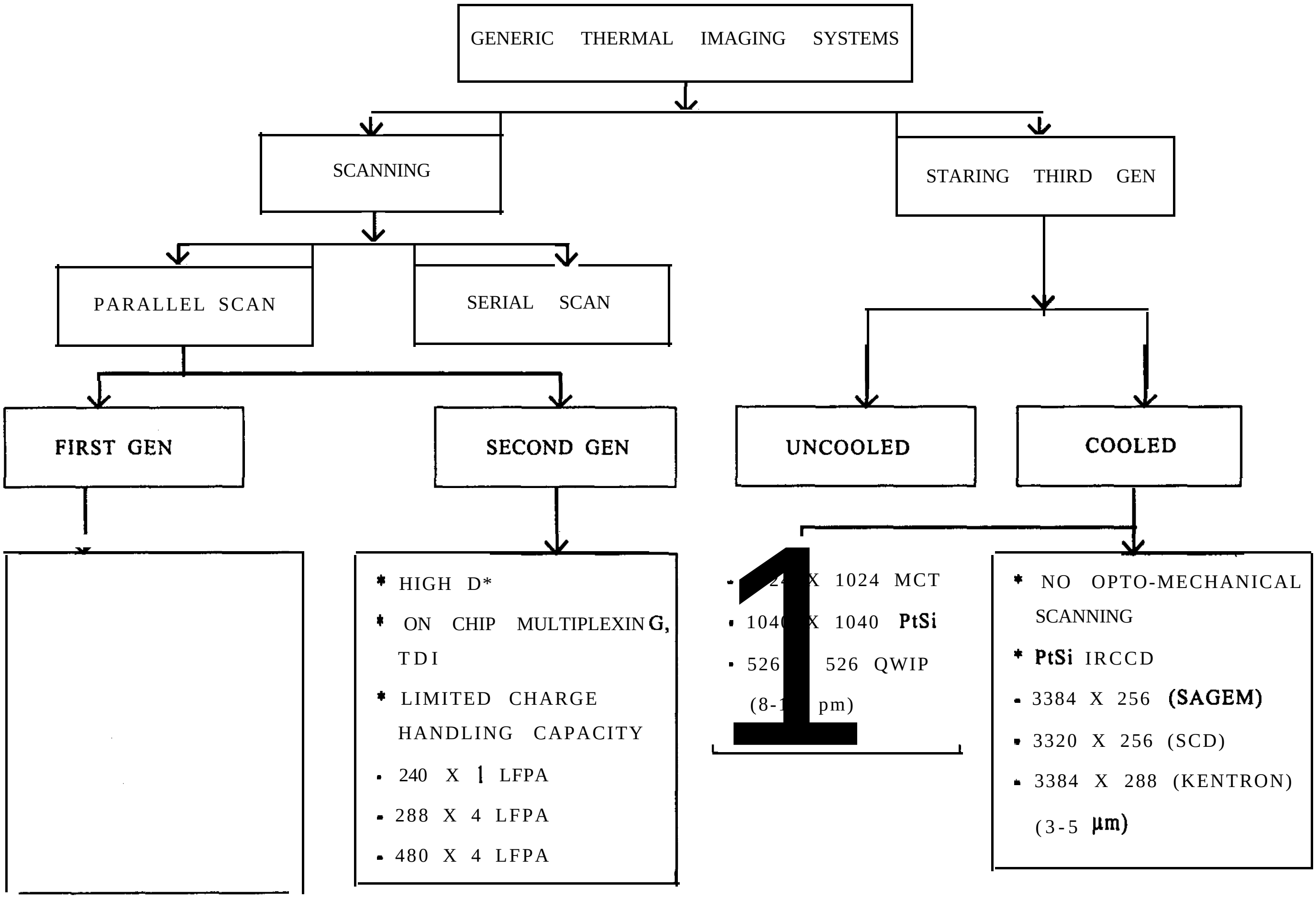

Figure 2. Thermal imaging systems-technology trends

4.3 Synthetic Aperture Radar Imaging System

The synthetic aperture radar (SAR) imaging system synthesises a large effective aperture or antenna size using the motion of a small radar dish or an array of small antenna spaced apart. This technique provides means to obtain high resolution without the need for large-sized antenna. Because of large wavelength, imaging radar can penetrate through jungle vegetation, ice, snow, dry sand, and soil, revealing concealed or buried objects hidden to human eyes, and, in many cases, hidden to infrared and ultra-voilet imaging systems.

Shorter wavelength in radio and microwave band (submillimeter wave, millimeter wave) are not as penetrating, but these can be used to generate images with much higher resolution as compared to radar imaging. Millimeter wave imaging has the additional advantage of much higher frame rates, therefore making real time, large wavelength synthetic vision available. Submillimeter wave imaging has the ability to see through thin, low-density material too cold to emit at shorter wavelengths*.

4.4 Radar Search & Track System

The surveillance radar can be used for target classification though not for target identification. The radar classification is based on distinct feature of scattered radar signals from the targets, which define the radar signatures of the targets. The targets are classified using a database of signatures of targets of interest.

Radar remains the prime long-range surveillance and target indication system. However, it suffers from major drawbacks, ie, it works using active radio frequency which can be detected and can possibly be jammed. Also, it cannot give positive visual target identification, and despite the improvements offered by Doppler techniques, radar performance in poor weather is significantly limited. It is also susceptible to multipathing and ducting effects.

4.5 Electra-optical Search & Tracking System

An electro-optical search and tracking system (EOST) offers the benefits of passive detection and identification at long ranges, highly accurate line-of-sight target tracking for small and medium-calibre gun control, low-jamming susceptibility, and other countermeasures at a price considerably less than its radar counterpart. It can also be used for navigational support, moored mine detection, and covert surveillance at night and in poor visibility'*. electro-optical sensors have the following advantages over radar:

- Being passive in nature, EO sensors offer surveillance capability even under electromagnetic interference (EMI) conditions and are insensitive to jamming.
- The imaging nature of the information is very useful in complex environment and offers simple kill assessment and unambiguous identification capability.
- The sensor's high resolution provides very good target discrimination capability and accurate target tracking as well as target characteristics.
- The detection capability of infrared/electro-optical system depends on target signature and not on its radar cross-section. The detection range against aircraft, missile, is thus speed-dependent.

5. ADVANCED SENSORS

Efforts are being made the worldover to use the advances in information technology, commercial and industrial products for military applications. Advanced low cost, lightweight sensors having all weather capabilities and providing better estimate of target parameters, are being developed[19-21]. The following are some of the advanced sensor technologies:

5.1 Multisensor Data Fusion

Data fusion techniques combine data from multiple sensors and related information to provide more specific inferences than could be achieved using a single independent sensor. The multisensors system consists of electro-optical, acoustic, RF, and meteorological sensors. It is used for automatic target recognition (ATR), identification of friend-or-foe(IFF) system, battlefield surveillance, and guidance and control of autonomous vehicles.

Sensor fusion can take place at three levels, viz., data, feature, and decision (low-level fusion, intermediate-level fusion, and top-level fusion) depending on the stage at which the information-processing fusion is contemplated. Data fusion from multiple sensors offers advantages like improved estimate of position and velocity, operability, quick reaction, full picture, all-weather and all-time capability, and, is cost-effective. Sensor fusion, combining sensors for optimal image display or automatic detection, is an emerging field and would provide the operator the opportunity to visualise the data from different electro-optical sensors in a single image[20].

5.2 Passive Multispectral & Hyperspectral Imaging Sensors

Colour variation provides useful information of objects (targets) as well as of natural backgrounds (clutter), as the ultimate receptor, ie, human eye, is very sensitive to slight differences in colour rather than brightness variations. Advanced systems will be multispectral with several relatively coarse bands (50-100 nm wide) spread over the visible to near-IR, to short wave IR (SWIR) spectral range. Spatial resolution of the system can be very high, of the order of few centimetres. The emerging airborne spectral imager would be multispectral having 5-20 bands with bandwidth of 100 nm and IFOV of 1 mrad providing high ground resolution of few centimetres from low altitude UAVs to 20 m for sensors placed at very high altitudes[20].

Further improvements in the sensing concept would be achieved using hundreds of narrow bands (of width say, 10 nm) in the same spectral region. This hyperspectral measurement technique has become possible by the advances in large focal plane array (FPA) technologies, and can support the sensing of very narrow spectral features for passive target discrimination task, and also enables adaptive measurement, depending on the application or mission of interest. This technology would bear special significance for desert surveillance. At present, very compact and efficient instruments are being developed in the visible spectral range; complexity grows as multiple FPAs are needed to span a broader spectral range.

5.3 Active Multispectral Imaging Sensor Systems

Active sensors make use of laser for illuminating the scenes at specific wavelengths to enhance their reflective spectral features. The primary reason for using active multispectral sensing is that, unlike passive sensors, the illumination and apparent reflectivity are no longer dependent on scene illumination. However, active sensor system has limitations like performing wide area search because of the limitation of available laser power level. Laser wavelength, that cannot be detected by the naked eye or by standard night vision instruments, could be used. The laser could be range-gated to avoid bias from backscattering from aerosols and fog. The active sensor would scan the ground with beam composed of light from a set of laser, where the specific wavelength would be tuned to detect a target of interest.

5.4 Laser-b ased Synthetic Aperture Imaging Systems

The laser-based synthetic aperture imaging systems provide high resolution images. Efforts are being made the worldover to image distant space objects through the earth's atmosphere. Laser provides the coherent illumination required for synthetic aperture at short wavelength. The use of synthetic aperture technique is today becoming increasingly widespread in a number of applications, ranging from satellite remote sensing of land and sea, target imaging from airborne radar, to satellite surveillance for military purposes. Using the precise tracking and high resolution imaging capability of CO, lidar, one can inspect surveillance satellite in space[21].

6. CONCLUSION

Surveillance is an important component of defence planning in strategic as well as in tactical environment. In a desert, atmospheric turbulence and optical mirage are the factors in addition to the atmospheric effects, viz., scattering, absorption, and aerosols, which affect the transmission of signals. Different types of surveillance sensors are effective for different atmospheric conditions. As no single sensor is capable to meet the all-weather, all-time capability in estimating accurately the target parameters like range, velocity, position, and, providing quick reaction time, multisensor, multi/hyperspectral imaging are being developed. These techniques will have automatic target recognition capability and would bear special significance for desert surveillance in the future.

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