New Infrared and Systems Technology for Enhanced Vision Systems

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August 2002

1. Introduction

The present work was motivated by the following issues:

- Of all available technologies, what is today's best choice for infrared Enhanced Vision System (IR-EVS) sensors?
- What is the performance of such a system, and what will it accomplish?
- What will be the ultimate system configurations?

The ground rules for approaching the first issue were that there be no vested interest in any particular technology, such that we be guided only by effectiveness and cost. The resultant choices were to be implemented in a manner that is entirely tailored to EVS, using lessons learned by our team on such programs as Boeing's Enhanced Situation Awareness System, DARPA's Autonomous Landing Guidance, NASA's High Speed Research and EVS Definition activities, and a Cooperative Research and Development Agreement (CRADA) with the U.S. Air Force for use of the C135 "Speckled Trout" aircraft.

The purpose of this paper is to review the decisions that were made, including their rationale, and to briefly describe our strategy regarding the employment of EVS and the evolution of integrated EVS systems.

2. Infrared Sensor Technology

2.1 Baseline Imager

Uncooled, microbolometer focal plane array technology has continued to improve to the point that its basic measure of sensitivity, the Noise Equivalent Temperature Difference, rivals that of cryocooled units such as those based on InSb photodetector arrays. In order to reach these performance levels, a microbolometer requires low-f/# optics. However, EVS by its nature involves wide-field optics; this implies short focal lengths and small overall sizes even for such "fast" optics. Hence, this technology is made-to-order for EVS.

The absence of a cryocooler endows this sensor with a number of critical advantages:

- compact and lightweight for ease of installation – thus addressing a major challenge for EVS
- reliable and maintenance-free – thereby confronting another major issue
- instant-on/no cool-down period; operational use need not be anticipated in advance
- low power requirement
- economical

Furthermore, uncooled microbolometers operate in the long-wave (LWIR, or 8-14 micron wavelength) band, while the commonly-used, cryocooled InSb operates at mid wave (MWIR, or 3-5 microns). LWIR is ideal for background scenes such as runways, terrain, traffic, structures, and obstacles. It performs very well at night, and/or in obscurants such as haze, smoke, and rain. In more challenging, colder scenarios, the ambient thermal energy shifts to LWIR, representing a further advantage for uncooled sensors. Finally, as discussed later, LWIR is generally a superior choice for penetrating fog.

The advantages of microbolometer imagers are sufficiently compelling that U.S. Defense Department support is continuing to push the performance as far as possible toward the theoretical limit. This limit, represented by thermal fluctuation noise, is roughly one order of magnitude below currently obtained sensitivities. Rapid evolution is also continuing in such areas as resolution, the elimination of thermal-electric stabilization, and the elimination of calibration for non-uniformity correction.

A microbolometer "sensor engine" is shown in Figure 1, and typical terrain imagery in Figure 2.

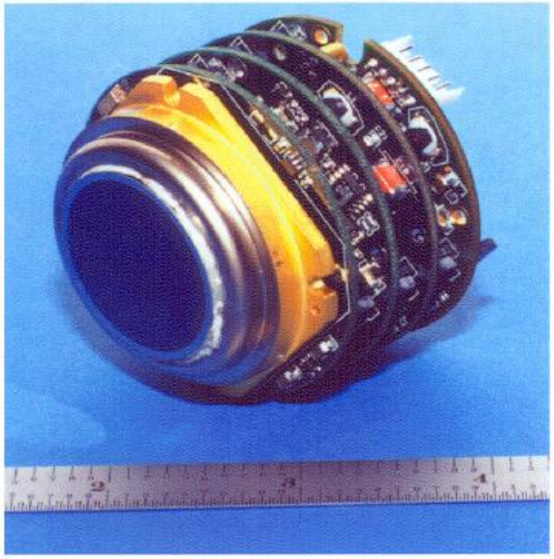

Figure 1
Microbolometer Sensor Engine for EVS

2.2 Detection of Lights

In addition to the general ambient scene, the pilot needs to see approach and runway lights. The housings of these lighting units may not be particularly elevated in temperature, and their glass lenses cut off their LWIR emissions. However, they are better short wave infrared (SWIR) sources than they are visible lights. In addition, at SWIR wavelengths (e.g., in the vicinity of 1.5 microns), solar energy is substantially reduced, so that lights/solar background contrast is markedly improved in daytime fog. The cumulative advantage is approximately 20X in a typical daytime fog scenario.

Small, uncooled photodetector array technologies are available that are extremely sensitive at SWIR. In particular, InGaAs arrays have high quantum efficiency, and D* values that are nearly background (shot noise) limited. The approach that we have adopted[1] is to boresight and electronically scale the SWIR and LWIR images for precise coincidence, and then to use image processing to separate the lights and other objects of interest from the SWIR background and to fuse these items onto the LWIR scene. With judicious use of spectral filters and image processing techniques, the desired airport and landmark lighting can be derived while avoiding background illumination clutter.

The cryocooled alternative is to open the InSb imager to SWIR wavelengths in addition to MWIR, thereby detecting both the background and the lights in the same focal plane array. The problem with this approach is that there exists a large dynamic range between SWIR lights/solar input and MWIR ambient-scene

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[1] This dual-sensor approach is the topic of the following U.S. patents:
US 6,232,602 and US 6,373,055, "Enhanced Vision System Sensitive to Infrared Radiation", issued May 15, 2001 and April 16, 2002 respectively.

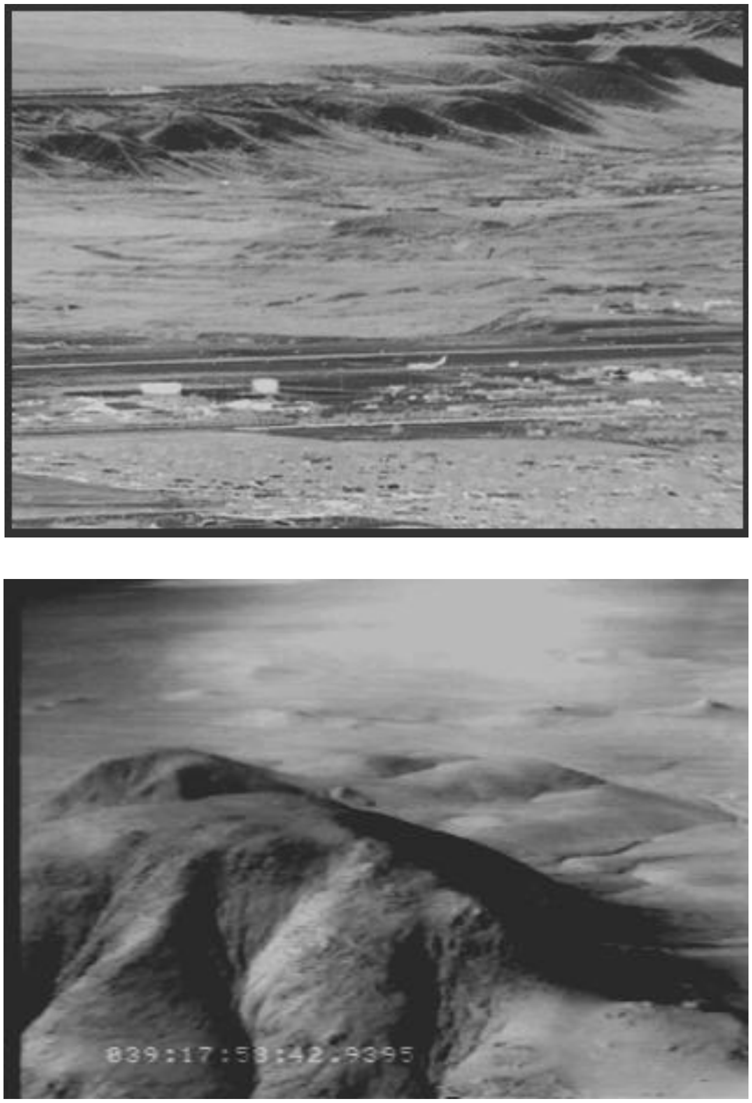

Figure 2
Terrain Imagery with Uncooled LWIR EVS

thermal energy. The result tends to be saturation and blooming of the SWIR data, combined with non-optimum (washed-out) gain and levels for the MWIR. Consequently, both functions (lights and background) are compromised. The uncooled dual-sensor approach, on the other hand, permits both functions to be separately optimized.

If desired, the dual-sensor configuration may be implemented in a single aperture, utilizing a dichroic mirror and suitable optics. It is also interesting to note that the U.S. Defense Advanced Research Projects Agency, in recognizing the broad advantages of the uncooled SWIR/LWIR combination, is supporting work to combine the two focal plane arrays (InGaAs and microbolometer) in a single, stacked structure.

Compact, economical image processing hardware utilizing microprocessors, field programmable gate arrays, digital signal processors and memory chips can now achieve autogain and level, image enhancement, and fusion on a local-image-area basis.

The combined SWIR/LWIR imagery as taken during a night approach to Boeing Field (Seattle) is shown in Figure 3. A runway incursion (Boeing 737) can be seen at the far end of the field.

Figure 3
Combined SWIR/LWIR Imagery

2.3 Practical Embodiment

A dual-sensor EVS system is shown in Figure 4. The resultant imagery may be utilized on a head-up display (HUD), or head-down on a video-capable Flight Management System, Multifunction Display, or dedicated, flat-panel EVS display. Using electronic zoom, a 40x30 degree field of view sensor may be used with a corresponding head-down display, while simultaneously scaled and projected on a 30x22.5 degree HUD.

Figure 4
Dual-Uncooled SWIR/LWIR EVS Imager

Basic specifications appear in Table I.

Table I
Summary Specifications for Dual-Uncooled EVS Imager

SENSOR HEAD	6x5x8 inches, 7 pounds
PROCESSOR/POWER MODULE	2.3x7.6x12.7 inches, 9 pounds
FIELD OF VIEW	30x22.5 or 40x30 deg
RESOLUTION	320x240 elements
LWIR SENSITIVITY	25-60 mK (export-dependent)
SWIR SENSITIVITY	NEI < $3x10^9$ photons/cm^2-sec
VIDEO OUTPUT	RS170, SERIAL DIGITAL
INTERFACES AVAILABLE	ARINC 429, MIL-STD-1553 Fiber optic serial video available
ENVIRONMENTAL/SOFTWARE QUALIFCATION	DO-160D, DO-178D, DO-254
OPERATING TEMPERATURE	-65 to 71 deg C
PREDICTED MTBF	> 15,000 hrs

A number of installation options are available for the sensor LRU, facilitated by its small size. A favored approach, with minimum parallax on a HUD, is to mount it above the radome, with a faired-in enclosure and window. It may also be mounted within the radome, using a conformal window. Other configurations include the eyebrow window region or above.

3. Applications of EVS

3.1 IR-EVS in Fog

From the standpoints of both consistency and predictability, it is well known that infrared imagery is not a panacea for low-visibility flight operations. However, it is important to put this matter in perspective, particularly in view of the new availability of highly sensitive, LWIR staring array imagers. Because of the extreme variability of fog droplet size dispersions, and the complex nature of the theory, data tend to be highly anecdotal. The observed existence of a substantial "infrared advantage" in many fog scenarios may be explained by the following considerations.

A frequently used – albeit oversimplified – means of describing fogs is in terms of two archetypes: 1) inland (radiative), and 2) coastal (advective) fogs. The nominal droplet radii span approximately 3-14 microns and 6-15 microns respectively.[2] Real fogs tend to be a hybrid of these two descriptions.

The ability of a fog droplet of a given radius (r) to scatter and therefore attenuate the point-to-point transmission of a given wavelength is given by its "scattering efficiency" (K). This is the ratio of the effective scattering area to the physical cross section of the droplet. The resultant, exponential "extinction coefficient" (σ) is simply the total effective scattering area resulting from a volume density of n drops per cubic meter:

$$\sigma = nK(\pi r^2) \qquad (1)$$

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[2] C. Tomasi and F. Tampieri, "Infrared Radiation Extinction Sensitivity to the Modified Gamma Distribution Parameters for Haze and Fog Droplet Polydispersions," *Applied Optics*, vol. 15, Nov. 1976.

The fractional transmission over pathlength L is then

$$T = e^{-\sigma L} \qquad (2)$$

The value of K, vs radius/wavelength ratio, is calculated from the Mie theory and shown in Figure 5 as follows[3]:

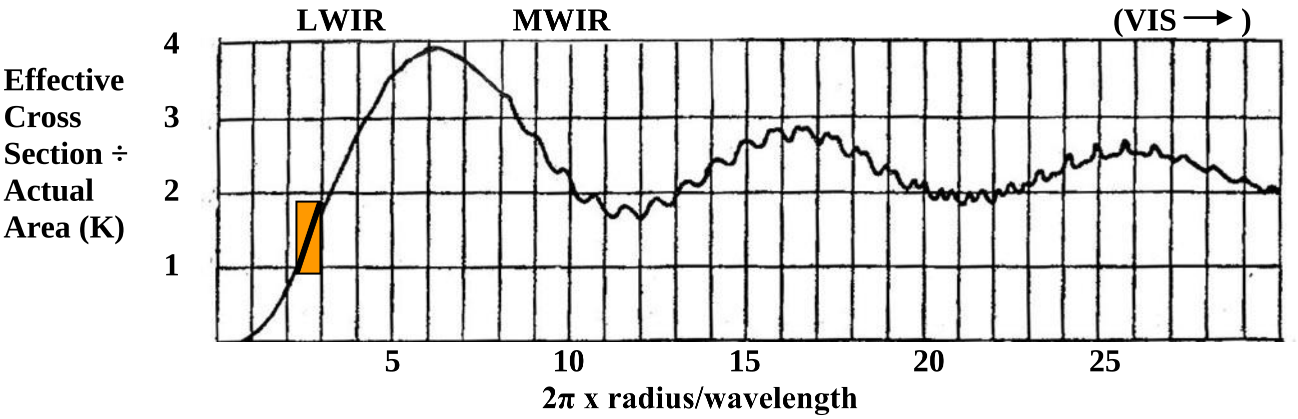

Figure 5
Scattering Efficiency of a Fog Droplet

For large radius/wavelength ratios, the asymptote is two. I.e., at visible and ultraviolet wavelengths, each droplet scatters with twice the effective area of its physical cross section; this represents the equal contributions of diffractive and geometric scattering[3]. For droplets whose diameter is on the order of a wavelength, a "resonance" is exhibited (Figure 5), and since these K values appear in the exponent of Eq. (2), the effects are quite large. Similarly, for droplets with diameter smaller than the wavelength, K is less than two and substantially better transmission results. In fact, since the standard ("Koschmieder") visible range[4] is defined by T = 2%, then for the same range but half the scattering efficiency (infrared K=1), the transmission improvement is 7X.

In any real scenario, it is necessary to integrate over both the droplet polydispersion and the wavelength passband of the sensor. For the nominal droplet sizes cited above, the position of the infrared bands is roughly indicated in Figure 5. It is important to note that, for the upper (11-14 micron) bandpass region of the microbolometer, a fraction of droplets that are well within the size range for a radiation fog offers scattering efficiencies below the visible-wavelength value of 2 (see colored block in Figure 5); and the same is somewhat true of advective fog.

Visible and thermal imagers respectively operate on very different principles, and the extinction coefficient cannot tell the complete story. The former senses reflected solar and artificial light and some direct lighting. The latter senses varying temperatures and emissivities from the scene objects. In this regard, a LWIR thermal imager is very well matched to its "source," i.e., the contrasts in ambient energy from the background scene. It may therefore perform well with significantly greater path extinctions than will a visible camera.

The ability of pilots to see runway/approach lights may also be significantly better than is suggested by simple extinction alone. This is recognized in the modern, dual definition of "runway visible range" whereby the lights may dominate over extinction through "Allard's Law"[4]. Similarly, although the SWIR does not realize any

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[3] H.C. van de Hulst, *Light Scattering by Small Particles*, Dover Publications, New York, 1981.

[4] David C. Burnham, et al, "United States Experience Using Forward Scattermeters for Runway Visual Range," U.S. Dept. of Transportation Report, No. DOT/FAA/AND-97/1, March 1997.

significant "fog attenuation advantage", it is better matched to the lights than are the pilots' eyes, and often "sees" the runway/approach lights well before the cockpit crew does.

In addition, the consideration of simple extinction omits another issue. The actual imaging of objects through fog involves the complexities of multiple-scattering modulation transfer functions (MTF's)[5]. These phenomena were extensively studied in the 1970's and 1980's. Again, visible-wavelength MTF's are more severely affected than is the case in IR.

The most authoritative support for the "infrared advantage" in fog is the U.S. Air Force MODTRAN modeling program. This program uses empirical data and analysis to determine the atmospheric transmission through a variety of atmospheres, and has been validated by over thirty years of use; it is also used in the calculation of infrared system performance by the U.S. Army thermal imaging model NVTHERM. Typical results are shown in Figures 6a and 6b below. Note that in these examples, whereas the MWIR and LWIR transmission over 2 km are quite good, the corresponding visible transmission is down many orders of magnitude. The LWIR and MWIR imager sensitivities where chosen as 40 and 15 mK respectively.

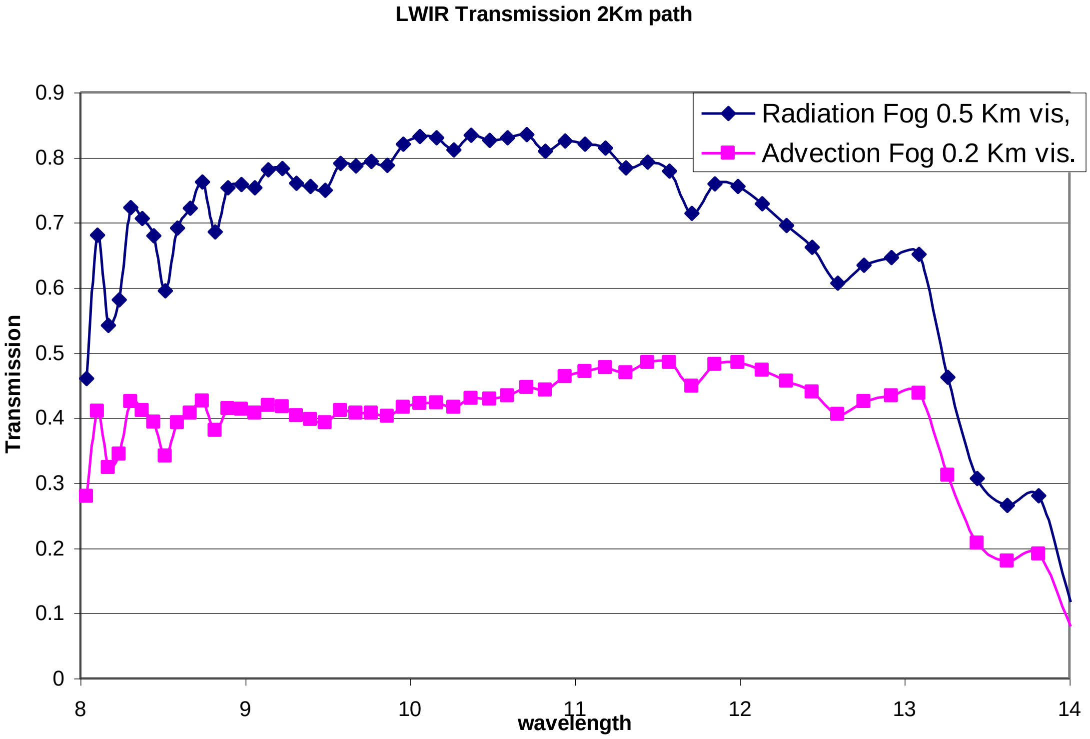

Figure 6a
LWIR Transmission vs Wavelength (microns)

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[5] Dan Sadot, G. Kitron, N. Kitron, Norman S. Kopelka, "Thermal Imaging Through the Atmosphere: Atmospheric Modulation Transfer Function Theory and Verification," *Optical Engineering*, vol. 33, March 1994.

[6] S. Greenwood, "Selection of FLIR Wavelength for Enhanced Vision System," Maryland Advanced Development Laboratory, internal publication, November 1990.

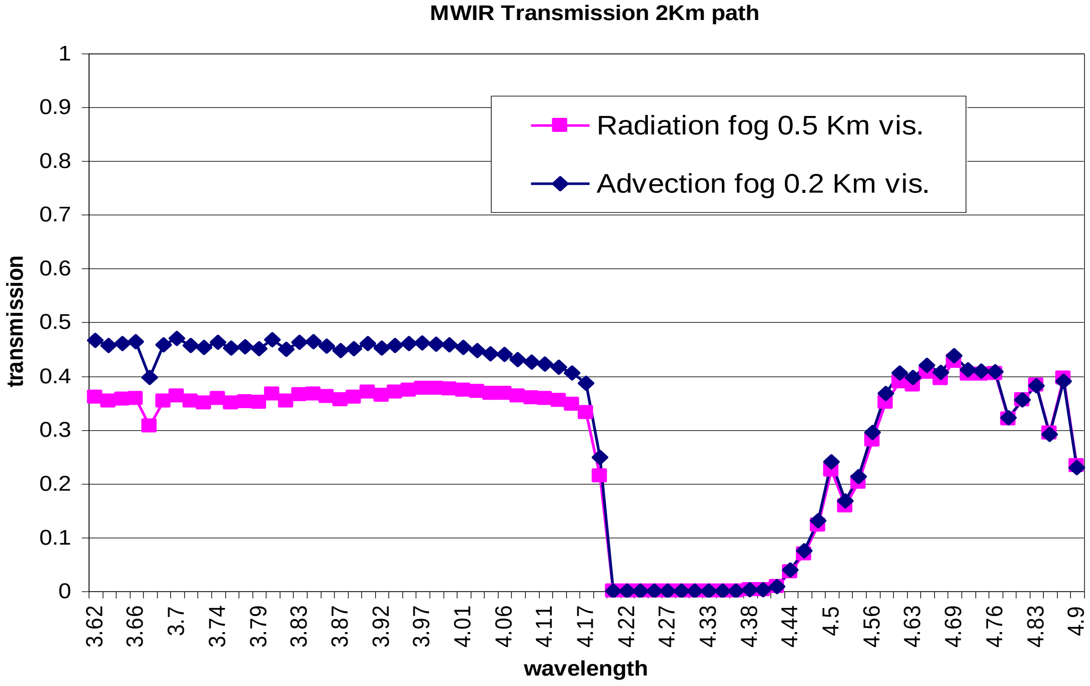

Figure 6b
MWIR Transmission vs Wavelength (microns)

Extensive references on IR in fog span more than 60 years, many of them predating modern infrared imagers. One concise review of the MWIR/LWIR/fog issue is contained in Ref. 6. The conclusions may be simply summarized as follows:

- IR does better with radiation fogs than with advection fogs
- LWIR is generally better than MWIR in most scenarios, and very much better in many
- There certainly are situations where IR is attenuated beyond usability; this poses a problem for IMC certification, but does not negate the frequent advantages that are obtained

Finally, a tentative conclusion that may be drawn from close examination of current LWIR sensitivities along with the above considerations is that “LWIR will always be useful over at least double the visible range, plus a margin”. As has been discussed, this does not require that the LWIR extinction average (over droplet size and sensor waveband) be only half that of the visible wavelengths, because other mechanisms are also involved. In any event, this hypothesis needs to be tested, in the most challenging scenarios.

3.11 Comment on Use of Ultraviolet in Fog

There has been some promotion of ultraviolet (UV) imagers for use in EVS. Of course, where practical, a UV-matched source would be of some efficacy for such a sensor. However, as explained above, the scattering efficiency for UV is at the asymptotic efficiency value of 2 and is essentially the same as for visible light. As is generally cited in such discussions, the directional scattering pattern does concentrate in the forward direction, which is a manifestation of the diffraction component as the droplet-size/wavelength ratio becomes large. However, the point-to-point transmission remains governed by the Mie extinction analysis. In addition, UV is subject to a heightened level of scintillations when compared with visible imagery.

3.2 Initial Applications of IR-EVS

Notwithstanding the limitations of IR in fog, the dual-sensor, infrared EVS offers greatly increased Situation Awareness (SA) at night and/or in obscurants such as haze, rain, and many fog scenarios. The advantages of heightened SA at night should not be underestimated. Also, in commercial operations, pollution in the form of haze and smog have become continental and even international issues.

The initial application that we are pursuing is therefore “autonomous safety insurance”. As such, it does not seek “extra credit” certification, but specifically addresses the following:

- Runway incursions – detection and prevention
- CFIT avoidance
- Approach and landing – safety enhancement
- Generally improved visual detection of terrain, traffic, structures, obstacles

Certification will be confined to issues of non-interference, both operationally and from the hardware. This basic level of SA enhancement will also have value with regard to increased reliance on Category I and non-precision airfields.

3.3 All-Weather EVS Sensor Suite

The availability of a compact, capable and affordable millimeter wave (MMW) imaging sensor remains a desirable component in an “all-weather” EVS system. Recent progress, particularly driven by missile seeker technology, has been substantial. With its lower resolution but unfailing ability to penetrate fog, MMW constitutes a natural complement to IR.

In conjunction with strategic partners, we will be including an all-weather capability. The imaging data will be “fused” in a seamless manner. More importantly, they will be processed in the context of an advanced, Integrated EVS configuration as briefly described in the following section.

3.4 Integrated EVS

Although the details are beyond the scope of this paper, we suggest that the use of EVS for IMC (including tactical) operational benefit will involve techniques that go well beyond the presentation of an enhanced image to the pilot. The EVS suite will be part of an integrated architecture to include DGPS, inertial sensors, and digital ground-map correlation. The use of correlation and feature extraction/object recognition technology will transcend subjective imagery: the resultant Integrated Enhanced Vision System will comprise a separate-thread, nav/attitude correction/guidance loop for both low-visibility approaches and takeoff. As such, it will contribute the required system integrity for such operations. In addition, it will provide a real-time, hazard-detection subsystem.

Under a U.S. Air Force Research Laboratories, Small Business Innovative Research (SBIR) grant, we are working on advanced algorithms and neural net implementations for key processing elements of Integrated EVS. Certification of such a system, to eventually Category IIIc levels, will require significant human factors efforts as well as proof of hardware/software integrity and operational accuracy.

Accordingly, EVS will complement a number of recent and emerging technologies, such as

- Head-up Display (HUD)
- Surface Guidance System (SGS)
- Synthetic Vision Systems (SVS)
- Integrated RNAV (IRNAV)
- FMS Approaches
- GPS Landing System (GLS)
- Required Navigation Performance (RNP)
- Terrain Alert and Warning System (TAWS)
- EGPWS
- ADS-B