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Silent-Mode Air Surveillance

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Summary

A new approach to ground-based air surveillance will be outlined. This concept makes use of passive electro-optical sensors for panoramic surveillance in silent mode. Based upon infra-red Focal Plane Array (FPA) detector technology this system is designed to scan the complete hemisphere with a high search frame rate. Surface as well as airborne threats will be detected, tracked and classified with high probability of detection. As opposed to Infra-Red Search and Track (IRST) systems known so far, this new system approach uses a laser range finder to verify its alarms, once these have been pre-classified. With this additional verification process, which provides 3-dimensional target trajectories, the system's False Alarm Rate (FAR) is improved considerably. A powerful signal processing is running in real-time at the system's high search frame rate. Accurate target designation is possible with low data latency to perform fire control for an associated weapon System. Though designed for stand-alone tactical reconnaissance, this system can be interfaced fluidly with long-range radar surveillance systems to use cueing information from every area of the electromagnetic spectrum. Under contract to the German Ministry of Defense (MoD), an Advanced Technology Demonstrator (ATD) of such a silent-mode air surveillance system has been built and field-tested.

1 Introduction

In general, ground-based air defense is a multi-layer concept. Its strategy is to face an incoming threat with graded countermeasures of different intercept ranges. An approaching warhead that leaks through must pass the multiple shields of intercepting fighters, surface-to-air missiles and eventually the high-rate barrel firing of a low-level air defense system, leaving little chance for the threat to home in on its intended target.

In a conventional battlefield situation, this defensive strategy is applied successfully. If a coordinated raid from a pre-known direction is to be expected, medium-range air defense systems such as PATRIOT and HAWK massively deployed near the frontline provide forward protection. In the rear zone, short-range (SHORAD) Surface to Air Missile (SAM) systems such as ROLAND or gun-based systems such as the German GEPARD or the Russian ZSU-23 are deployed along the last line of defense.

Associated with these weapon systems, radars of graded surveillance range early alert to an approaching threat. Relying on a complete wide-area air picture, operations can be conducted as preplanned missions.

However, in today's environment of out-of-area missions, the situation of orderly military forces is no longer given. For forces deployed in regions of limited conflicts and crisis, as well as in peace-keeping missions, the forward line of one's own troops is more likely to resemble a patchwork of hostile areas distributed arbitrarily among areas of friendly troops.

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With modern, short-range, easy to deploy man-pad weapon systems, which have been proliferated vastly all over the world, enemy threat is found to be co-located nearby one's own troops. An air picture as produced by upper level air reconnaissance is not able to provide the situational awareness necessary in a distributed battlefield like this, because this information is useless since it takes too much time to reach the platform under attack.

Even more, the capability of radar-based air defense systems to counter cruise missiles (CM) or unmanned aerial vehicles (UAV) becomes more and more insufficient. These kinds of missiles show improved performance with regard to maneuverability and stealth to run a surprising attack. Following the hiding contours of the terrain and with radar cross-sections considerably faint, these targets are hardly to detect by radar systems.

The use of ground-based radar systems turns out to be questionable, because active systems would cue enemy attacks.

As opposed to the preplanned missions in the past, today there is a need for immediate reaction when information about the enemy's position or about a surprising hostile attack becomes only available at short notice. As a consequence, air surveillance must not rely exclusively on radars, but has to look for other means to provide situational awareness without the drawback of active cueing of enemy detectors. Strategies have to be developed which are able to get along with fractional air pictures. Yet means have to be developed, that are capable of alerting reliably against all kinds of threat on short notice, but with the chance to counter successfully.

2 A New Quality Air Surveillance

An air surveillance system, able to cope with the challenges of a future highly dynamic battlefield should have the following main features:

- Providing an air picture in real time to report sudden actions without delay.
- Operating covertly, since many missions require silent-mode surveillance to avoid cueing of the enemy.
- In situations of an incomplete air picture there is a need for a 24-hour gapless coverage since surprising attacks from anywhere and at any time may be encountered.
- To ensure fire control data quality, the performance provided by radar systems has to be improved in terms of
  - high-precision target coordinates
  - target velocity
  - data output latency.
- The radar problem at low altitudes has to be overcome by a look-down capability into areas of high-level clutter return.
- Rapid overseas and immediate on-site deployment call for an air-mobile and vehicle-transportable system design
- If other sources of surveillance are available, the new system should be able to use this information to improve its own air picture.

In the past, defense industry has made many approaches to meet these requirements by designing surveillance systems based upon infra-red (IR) technology. Those IRST systems did not, however, fulfill the performance requirements for reliable air surveillance and target acquisition. The main drawback associated with these systems was their poor performance with regard to false alarms.

To enlarge the technological basis for the development of improved passive surveillance systems in future, the German MoD started a demonstrator program some years ago. This program became known under the title "ABF" which is the German abbreviation for "Reconnaissance and Engagement of Air Targets". Bodenseewerk Gerätetechnik (BGT), a business unit of the Diehl VA Corporation, was awarded the contract to build an Advanced Technology Demonstrator for a silent-mode air surveillance system.

In this program, a new approach to tactical air surveillance is made, evolving from BGT's core business, which is the development and production of IR missile seeker heads. Mastering the latest technology of imaging IR seekers, the idea behind it is to transfer this know-how to the field of passive air surveillance. Real-time image processing as it is used successfully in IR seekers, is intended to give the missing impetus to passive reconnaissance systems with improved false alarm performance.

3 Demonstrating Silent-Mode Air Surveillance

For a passive surveillance sensor to perform wide-area search and target acquisition autonomously and with high reliability in real time, a two-step signal processing concept is applied, based upon fused multi-sensor information.

In this concept (Figure 3-1), the sensor suite of the demonstrator system includes a panoramic search sensor platform with passive IR sensors and a tracking and verifying sensor platform with a high-resolution IR sensor and a laser range finder.

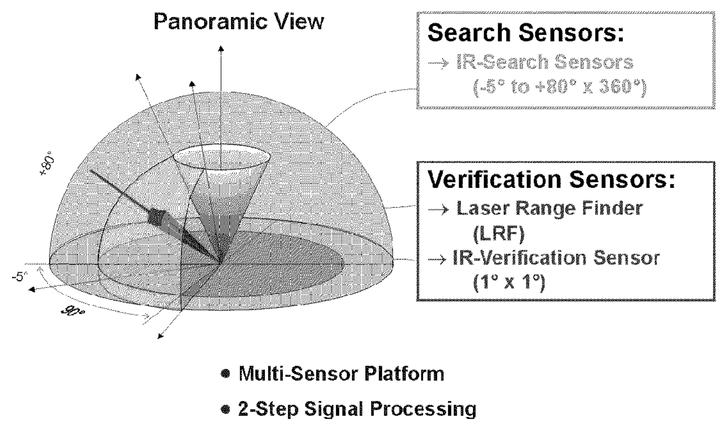

Figure 3-1: Surveillance Volume

3.1 Search sensor platform

The task of the search sensors is to frequently scan the hemisphere looking for inbound threats, whereas the verification sensors are used to check whether a tentative track seen by the search sensors is a real target or a false alarm.

As targets may approach from any direction, the search sensors' field of regard (FOR) has to extend from ground to almost zenith. In particular, a look-down capability will be required to detect targets approaching from low altitudes in a terrain-following mode. In azimuth, full panoramic coverage is necessary. This results in a wide FOR of 85° by 360°.

With the demonstrator, modern matrix Focal Plane Arrays (FPA's) are used to image the panoramic search volume. To achieve a good signal-to-clutter ratio, the spatial resolution of the search sensors has to be adapted to the problem of detecting point targets in front of a radiating background. For the detection of distant objects, high spatial resolution is a prerequisite. However, the total amount of detector elements rises intensively with increasing geometrical resolution. To give an example, if a resolution of 1 milliradian were to be achieved using currently available IR FPAs with 256^2 elements per detector, a minimum of 95 detectors would be needed to cover the FOR in a staring mode.

Therefore, a design has to be chosen which is able to get along with an affordable number of detectors: The solution is given in Fig. 3-2 where only 4 FPAs are shown, being multiplexed onto a set of distributed optical channels, each pointing in a different elevation direction.

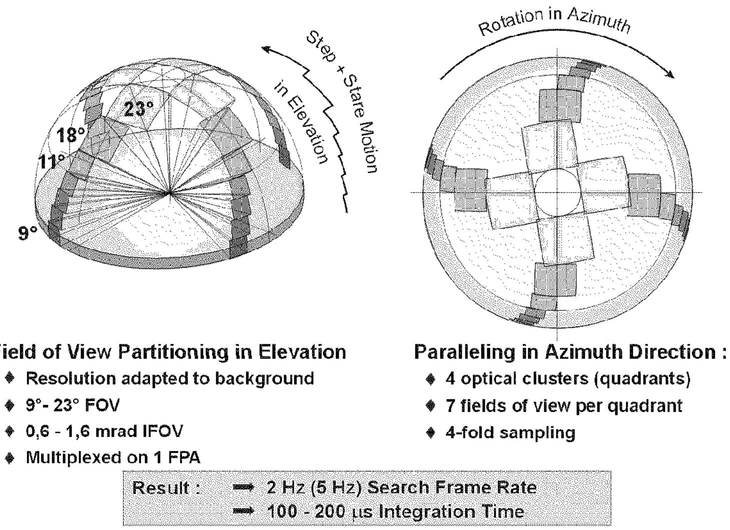

Figure 3-2: Hemispherical Sampling with FPAs

To achieve a 360° coverage of the panorama in azimuth, the whole platform is rotated slowly, including 4 quadrants with their respective detectors and elevation optics clusters. Due to the 4-fold optics, the search volume is sampled 4-times during one revolution of the platform. The slow rotation in turn allows a longer integration time of the FPAs, resulting in a longer dwell time on target for a better detection range.

If image distortion is to be less than the size of one pixel element, a 100 – 200 µs integration time is possible by sampling the hemisphere with a 2 – 5 Hz search frame rate.

Given these parameters, the search sensor platform is well suited for detecting in time any target entering its search volume. Good radiometric sensitivities are achieved, by using high aperture optics. Depending on the amount of energy radiated from the targets, this results in comfortable detection ranges. As an example, Fig. 3-3 shows different layouts of the sensors in terms of their Noise Equivalent Irradiance (NEI).

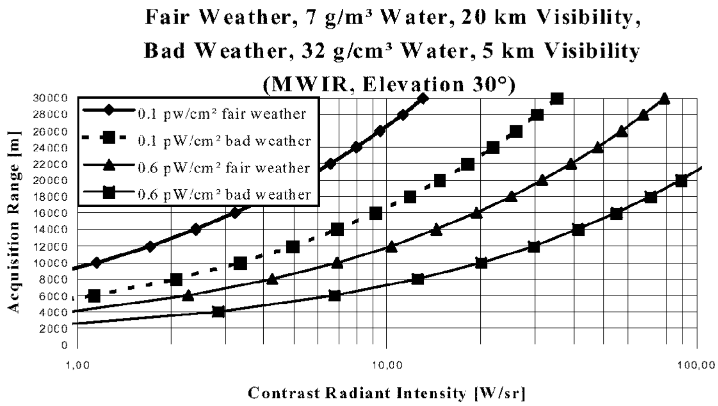

Figure 3-3: Typical IR Acquisition Ranges

Detection at a signal-to-noise (S/N) ratio of 5 has been assumed. As an obvious performance issue of any IR sensor, their viewing range limits with weather conditions have been depicted in the plots, too.

3.2 Track and verification sensors

The passive search sensors have to detect possible target events and establish first tracks of tentative targets. However, the ability to separate threatening targets from clutter, noise and other non-hostile targets is, in general limited for passive IR sensors. Operating on 2-dimensional images only, the amount of information provided is insufficient, as commonly used IRST systems show.

To improve the false alarm rate of the ABF demonstrator beyond the IRST level, additional information is acquired by the track and verification sensor unit.

This unit includes a high-resolution IR sensor boresighted to the line of sight of a Laser Range Finder (LRF). Once a tentative track has been established by the search sensors, the verification sensors' line of sight is directed instantaneously to the track coordinates indicated by the search sensors with the help of a rapidly steerable mirror gimbal. A closed loop control using the verifier's IR image locks the LRF's line of sight onto the target for precise laser ranging. The target in-range velocity is determined by means of consecutive range measurements.

4 Signal Processing

When the system is running in its search mode, a pattern of some hundred single FOVs covers the hemisphere. Given a 256^2 matrix detector and assuming a 2 Hz search frame rate, the data rate accumulates up to the order of gigabits per second. Image-processing algorithms have to translate this stream of pixels into useful data for a combat system.

On each FOV, real-time image processing is running, permanently looking for possible targets hidden in noise and clutter. In Fig. 4-1, a single frame is enlarged for illustration.

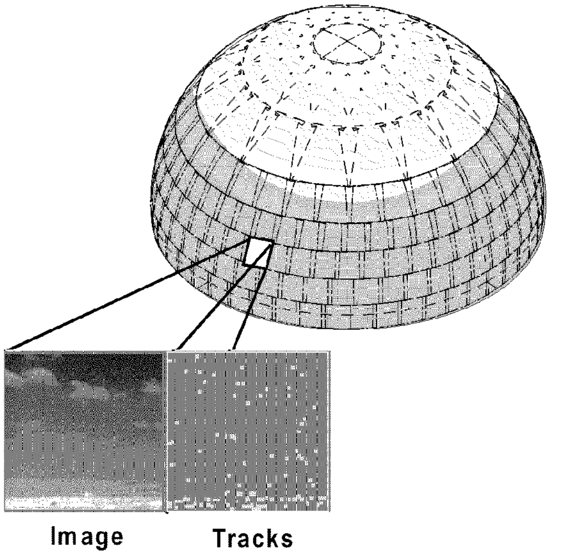

Figure 4-1: Multiple Frame Event Detection

Compared with a missile seeker FOV of, say, 4°x 4°, a hemispherical FOR of a surveillance system consists of roughly 1,200 missile FOVs. If only the FAR of a single missile seeker were to be achieved, the image processing of an IR surveillance system would have to be improved at least 1,200-fold. Moreover, since the baseline operation of a surveillance system is for 24 hours, compared to the few seconds' mission of a missile, the necessary improvement in the suppression of false alarms is tremendous.

To work-off this huge amount of data in real time, a powerful signal processing hardware is required.

Real-time image processing of this kind is found in imaging IR (IIR) seeker heads where BGT has acquired experience for many years. As a key element for fast front-end computing, BGT has developed a special-to-type parallel processing computer called Systolic Array Processor (SAP). This computer is designed to do pixel data processing of FPAs row by row, in parallel and at high speed. Meanwhile, this hardware is a proven design used in several military full-scale development an production programs such as IRIS-T or IR-RAM.

5 Target Classification at Weapon Interface

Every single event in the FOR showing a measurable contrast to its surrounding neighborhood is tracked for a sequence of image frames. Image processing algorithms are designed to hold in memory hundreds of tracks simultaneously. Most of the tracks turn out to be unstable because their events have been created by noise. Some tracks, however, will remain persistent as they belong to a possible threat or clutter.

Stationary image events will be eliminated by high-pass filtering. This is equivalent to forming a clutter map of the stationary background and suppressing this information.

The remaining tracks produced by the search sensors are analyzed further. Evaluating the statistical correlations of a moving background such as drifting clouds, moving trees or sea glint flicker, provides a powerful means to sort out targets mixed with such background, because of their different statistical significance.

This kind of prioritization which uses the statistics of target dynamics as opposed to ratings based upon the comparison of target colors is stable with variations of signal amplitudes which is a problem in a weather-dependent changing environment.

To verify whether a stable track is clutter or a target, additional information about its dynamic behavior is provided by the verification sensors. The track and verification sensors provide

- range
- in-range velocity
- high-resolution IR features, e.g. helicopter rotor frequencies

with a high frame rate governed by the LRF pulse rate.

Using Kalman filtering techniques, a higher dimensional state vector of the target is calculated. For example, a 6 degrees of freedom (6-DOF) model of the dynamic behavior of a track, turns out to produce stable and reliable target features which allow a reliable distinction between false and true alarms.

As a result of this discrimination, which runs in real-time, too, threatening targets are classified and their dynamical state vector is available at the weapon interface.

Precisely measured target data such as

- class of target, e.g. helicopter, aircraft, missile, subsonic or sonic
- target bearing and elevation in the order of less than a milliradian
- target range and velocity vector
- target acceleration
- type of target trajectory
- time to target impact

are transmitted with high frequency to the weapon system. Real-time signal processing provides low data latency which is an indispensable prerequisite for fire control.

Mission success of the engagement action could be monitored and tracked by help of this system, if required. Therefore, the feasibility shown by the demonstrator program will shorten the distinction between surveillance devices and fire-control devices.

With its highly dynamic pointing capability, the verifier unit is capable of a simultaneous multiplexed tracking of multiple targets.

6 Target Acquisition and Engagement Sequence

The overall functional sequence starting from first detection to weapon handover takes place within a few seconds. In Fig. 6-1, the timeline plots of typical air targets are shown to illustrate the course of target acquisition, weapon alignment and engagement by an example.

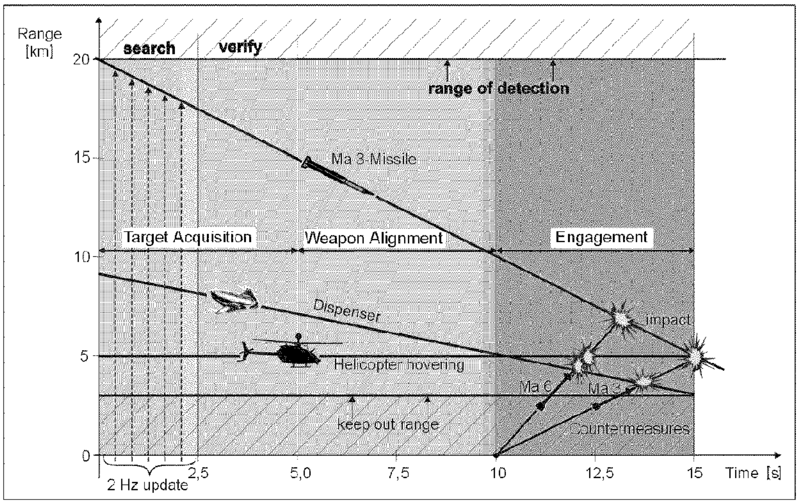

Figure 6-1: Surveillance and Engagement Timeline

First, the system is operating continuously in its search mode. A clutter map has been established, having raised the system's sensitivity for the detection of suddenly changing events. Once a missile's signature has crossed the search sensor's threshold of detection, only few additional detections are necessary to establish a track. Within a few seconds, the system is able to decide whether this track might be a candidate of a possible threat or if the track was simply caused by noise. Potential threat tracks are handed over to the verifier to form 3D tracks and for threat classification. This step lasts one or two seconds, depending on the verifier's mechanical slew rate and the LRF pulse frequency.

As can be seen from the diagram, roughly 5 seconds after its first detection, the system is able to "declare target" to the associated weapon system.

The weapon has to be pointed to the designated target coordinates and weapon release is possible immediately, if the firing rules allow this.

Considering a certain time to go for the engagement, a comfortable keep-out range can be achieved in this example, even in the case of an attack by a Mach 3 missile.

7 Demonstrating New Technologies

With the ATD, the feasibility of new technologies in passive surveillance devices is to be investigated.
For an improved FAR suppression, the spin-off from missile seeker technology is a new approach to be applied.

The most prominent feature in this field is the application of SAP chip processing which allows fast filtering techniques to weed out in real time the things that are target like from the things that are really targets.

In conjunction with the SAP, modern IR technology is applied which uses matrix FPAs for frequent sampling of the total search volume. Their high frame rate allows multiplexing of more than one optical channel on one detector without degradation of the remaining hemispherical scanning efficiency.

Within the optical channels, mirror arrays fabricated by means of micro-mechanical techniques are used to mechanize this optical MUX function. With Micro-Mirror Arrays (MMAs), fast and arbitrary switching of optical channels is possible. Switching is electronically addressable which allows any switching sequence required. This offers the possibility to sample certain areas of the search volume adaptively.

Under this condition, each IR sensor of a quadrant would normally be running with its basic frame rate of 200 Hz, resulting in a 2 Hz sampling rate of the full FOR. If tentative targets were identified by the SAP processor, it would send a command back to the MMA to switch such optical channels pointing to the areas of interest more frequently. Additional image samples are provided by the FPA's spare capacity of up to 400 frames per second.

This feedback would be accomplished on line. The region of interest within the search FOR would then be converted to a higher frame rate, while the other areas would remain under the basic sampling rate. The update at a higher rate would enable a faster track generation resulting in an adaptively improved system reaction time.

8 Field Testing of the Demonstrator System

Incorporating the main technology items described, a hardware demonstrator has been built which is able to show the main functional principles of passive surveillance in real time. To save cost, compromises had to be made with regard to the physical size of the demonstrator and no effort was made on miniaturization and packaging.

In autumn 1999, first field tests were carried out with the ABF demonstrator at a German test range in Meppen. In a realistic scenario, the entire spectrum of air targets such as SAM's, drones, helicopters and jets as well as countermeasures was engaging the ABF system. In more than 100 sorties, all kinds of attack missions such as dive, loft or pop-up maneuvers with attack aircraft and low level ground attacks with helicopters were flown. SA-7 missiles were fired ballistically in a head-on but offset attack mode for safety reasons. These tests carried out over a period of several weeks allowed the system to be evaluated in various situations, different clutter environments and with changing weather conditions.

Figure 8-1 shows a photo of the sensor suite on the Meppen test range.

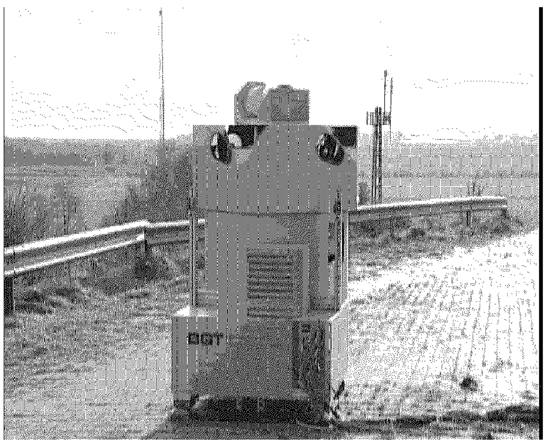

Figure 8-1: ABF Demonstrator Sensor Suite

In Figure 8-2, a plot of the man-machine interface (MMI) is shown indicating the information displayed for the operator.

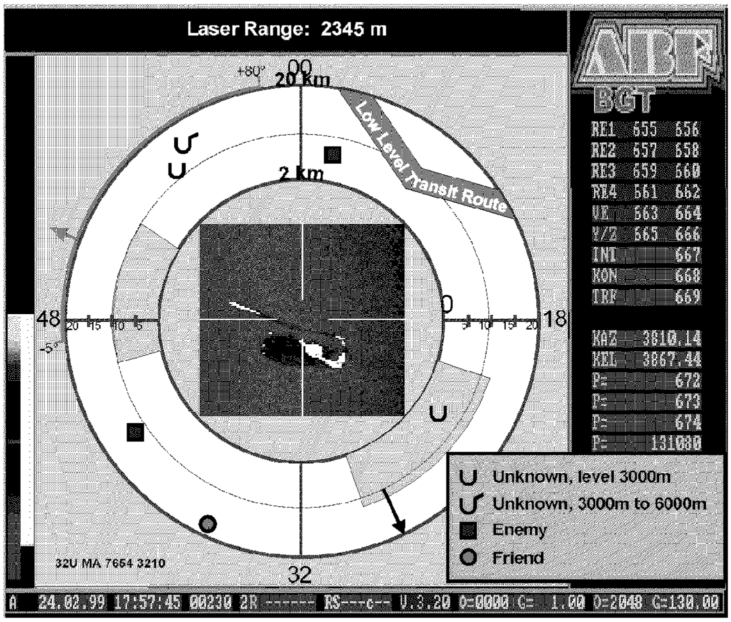

Figure 8-2: ABF Demonstrator MMI

The area which is kept under surveillance is plotted as two concentric circles indicating the 2 km and the 20 km bounds with the ABF sensor suite in the center. Reported alarms are marked by symbols, their position showing range and bearing of the target inbound. In the center of the plot, the instantaneous IR image of the verification sensor is visualized.

During the extensive field trials it was shown that the verifier was able to discriminate targets from clutter and noise with high reliability. Target alarms were reported within the range and time limits necessary to assure a sufficient keep-out range for a virtual engagement. The target plots reported by the demonstrator showed no false alarms, confirming the superiority of the 2-step system concept using the verification principle.

9 Operational Outlook

Intended for tactical use, lightweight IR technology offers the basis for a mobile, easy-to-deploy surveillance system that provides protection against incoming air targets of all kinds.

To improve the range coverage with IR surveillance one could easily deploy several IR surveillance systems in the direction of the expected threat. Fig. 9-1 shows typical deployment situations depending on the concept of operations.

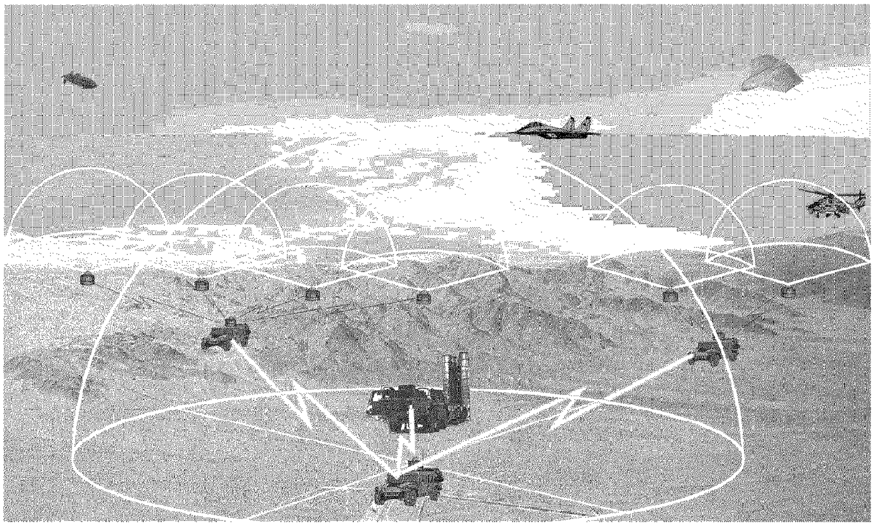

Figure 9-1: Deployment of Silent-Mode Air Surveillance Systems

In general, the deployment of an IR surveillance system will be embedded into existing command structures. Interoperability is required and a passive surveillance system has to be adaptable to commonly used interfaces such as Link 16 or JTIDS/MIDS (Fig. 9-2).

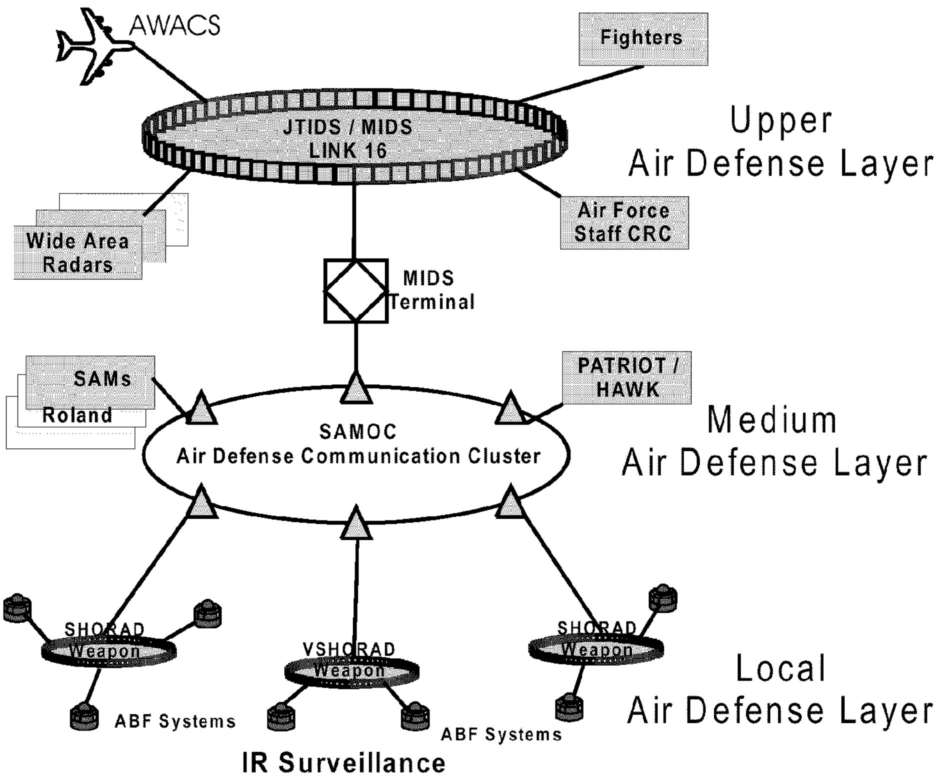

Figure 9-2: IR Surveillance Integrated into Existing Air Defense

In a joint operation of deployed forces as depicted in Figure 9-2, an IR surveillance system will make use of any information provided by the array of diverse sensors tapped to the information links. For example, the early warning radar plot of a distant threat could be used as a-priori information, as well as the cueing signals of Electronic Support Measures (ESM) to enhance the overall performance of the IR surveillance system.

In the command post of a Surface to Air Missile Operating Center (SAMOC) the sensor information of all distributed sensors will be displayed on the commander's display, including the situational air picture of the short range IR surveillance systems in real time. The SAMOC in turn will allocate firing rules to the (V)SHORAD weapon systems linked to IR-surveillance systems taking into account their requirement for immediate engagement.

Of course, ground-based use is not the only employment of passive surveillance technologies as demonstrated by ABF as an experimental system.

Ship defense is another possible application for IR surveillance. As an addition to other self-defense sensors, a shipboard IR surveillance system will have specific responsibilities for the low-elevation region where radar is least effective. Anti-ship cruise missiles are approaching barely above wave height where the ship's search radar is boggled by sea-clutter problems. If the environment is littoral, land clutter degrades the picture even more. Here is where an IR surveillance system comes in, which is able to cope with a very clutter-intense background scene.

Last but not least, aircraft have an even greater need for passive search capability. The technologies as applied with the ABF demonstrator also provide the background for a passive missile approach warning device based upon IR sensor technology and its real-time image processing capability associated with.

10 Conclusion

The ABF experimental system demonstrates the feasibility of a silent-mode surveillance and target acquisition system of high efficiency. Since IR sensors obviously are range-limited by physics, its use is constrained to the end-game of an engagement. This means that threatening targets are already on a closing-in track when detected for the first time by an IR surveillance system. Therefore, the only chance to survive lies in a fast reaction time of the system which is in the order of a few seconds. If this situation is compared to the task of conventional reconnaissance with radars, which is to provide long range air pictures, an IR system provides tactical reconnaissance for a local area only, but in an extremely high dynamic environment.

As a consequence, such a system will be operated nearby, and in tight conjunction with, a weapon system for short range air defense.

Its lack of range performance, if compared to radars, is compensated for by high speed signal processing providing precisely measured target data.

The demands for detection probability and FAR are extremely high since the silent-mode system will be deployed as an ultimate shield in the inner air defense layer. Detection, acquisition and target classification take place within a seconds' time-frame immediately before release of a countermeasure. In a timeline so tight, there is no chance to have a man in the loop. The only provision is for mission abort if there is an unforeseen event.

The accuracy of the data provided by high-resolution IR optics is suitable for cueing ground-based weapon track radars. A consequence of its real-time processing capability is its low data latency which offers the possibility to use those data for fire control. However, when closing the fire control loop, IFF (Identification Friend or Foe) information has to be taken into account.

Though silent-mode surveillance systems obviously could be used as stand-alone, normal operation will be somehow in connection with radar surveillance systems to form a synergic supplement. For example, IR surveillance could be employed to improve radar surveillance. Acting as a “gap filler”, an IR system could be deployed in areas of radar shadow in certain geographical terrains.

Since IR does not present any multi-path or ducting problems, an IR system with look-down capability in a cluttered background scenery could be used to improve the well-known radar degradation at low altitudes.

Of course, in adverse weather conditions radar is the only means to get an air picture. However, in today’s and in future conflicts there will be missions which forbid the use of active systems. With IR, 24-hour surveillance is possible, weather permitting, without revealing one’s own position.

The technological possibilities as demonstrated by the Advanced Technology Demonstrator ABF not only point out an alternative passive air surveillance system for ground-based use, but also will give impetus to the development of ship-borne systems as well as to airborne warning systems used for self-defense or for the protection of high-value targets.

11 Acknowledgements

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