

# Navy Distributed Aperture Sensor Infrared Search and Track System Overview

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## ABSTRACT

Under the ONR Fleet and Force Protection Future Naval Capabilities program, the Naval Research Laboratory's Optical Science Division is developing a prototype distributed aperture staring infrared search and track sensor (DAS IRST) intended for both the new DDX class of ships and a planned retrofit of a variety of existing surface ships. Along with providing detection, tracking, and declaration of sub- and supersonic anti-ship missiles, the system will provide capability for close-in surveillance and protection against terrorist class threats. This paper discusses the technical approaches to the key sensor subsystems, i.e. optics, focal plane, detection, and track processing software. Preliminary performance data on the focal plane array technology and optical system is presented. A detailed description of the detection, discrimination, and threat declaration algorithms is provided. Sensor performance is described in terms of expected NEI and detection ranges for a variety of targets under selected atmospheric and clutter conditions. The performance of the data processing suite using pre-recorded imagery is demonstrated. The planned laboratory, land based, and ship-based testing program is also reviewed.

## 1. Introduction

The Navy has had a longstanding interest in shipboard infrared search and track systems for detection of anti-ship missiles for a range of surface platforms. Recent terrorist events have also highlighted the need for 24 hour 360 degree close-in surveillance against small surface craft. System cost and shipboard installation constraints result in there being a significant advantage to being able to fulfill both of these functions with a single set of sensors. The objective of the effort described herein is to develop such a system for installation on the next generation littoral combat destroyer, DDX, and the potential retrofit of existing CG Aegis cruisers, LPD-17 amphibious transport dock ships, LHD amphibious assault ships, and CVN aircraft carriers. The rationale for inclusion of an IRST system for protection against anti-ship missiles on legacy platforms may be clouded by the significant capabilities of existing RADAR systems, in particular the SPQ-9b, to perform this function. The additional close-in high resolution surveillance capability of the current design, along with the ability to fill in 'performance gaps' associated with the RADAR systems under certain conditions help make the case for retrofitting existing ships. The case for the DDX installation is much more straightforward given the desire for a covert anti-ship missile detection system that will allow operation without the use of a search RADAR.

Recent advances in a number of technical areas have made a high frame rate staring sensor suite that addresses both of the previously mentioned functions feasible. While equivalent sensitivity sensors can be built using a scanning approach, the enhanced reliability associated with the mechanical simplicity of the staring approach makes it a desirable approach. In addition, the significantly higher frame rate of the staring sensor allows for the exploitation of scintillation phenomena in the detection and discrimination of faint targets at long ranges.<sup>1</sup> In an application where the number of physical phenomena available for discrimination is limited, this is a decided advantage of the staring approach. A low cost flexible anamorphic optical system design has enabled performance optimization for both the IRST, where higher resolution in elevation is desired, and the surveillance mode where a larger vertical field of view is required achievable. High sensitivity very large format midwave IR focal plane technology based

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on MBE HgCdTe has made high-resolution wide field of view imagers achievable at viable costs. Gigabyte per second data rates for optical fiber interconnects has made remote operation of the sensor and the processing electronics possible. The continuing improvement in processing power and ease of programming of field programmable gate array (FPGA) technology has made it a viable approach to the implementation and iterative refinement of two dimensional image processing for clutter rejection and target detection at the very high throughput rates required by the high resolution video frame rate sensor. The increase in performance in all areas in personal computing ranging from internal buss speeds, processor speeds, and memory volume have made the handling of large exceedance rates from the high resolution high frame rate sensor straightforward. All of these advances have been exploited in the design of the system under development here. While the system under development is designed to have the dual function IRST/surveillance FLIR capability mentioned above, the remainder of the paper focuses on the key aspects of the system relating to the IRST function.

## 2. Sensor Design

Rather than presenting a detailed trade study of all the relevant sensor design parameters, this section discusses the general approach that was taken in developing the design, and highlights the parameters that were chosen. A detailed description of the sensor performance in different scenarios is presented in Section 3 of this paper, but in summary, from the sensitivity perspective, the sensor design is driven by long-range detection of subsonic anti-ship cruise missiles under poor atmospheric transmission conditions. From a spectral band selection perspective, trade studies have shown that the superior transmission characteristics associated with reduced aerosol scattering for the 'blue spike' band in comparison to 'red-spike' band in the 3-5  $\mu\text{m}$  window, overcome the apparent advantage associated with the larger blackbody there which dominates the signature for this target. A significant performance advantage may be still be realized for the longer wavelength band under high solar clutter conditions however, leading to the incorporation of externally selectable warm spectral filters and extension of the system cutoff wavelength to slightly beyond 4.8 microns. From the simple parametric dependence of noise equivalent irradiance (NEI) given below (Equation 1) one can assess the relative importance of a variety of system trades in achieving the required sensitivity.

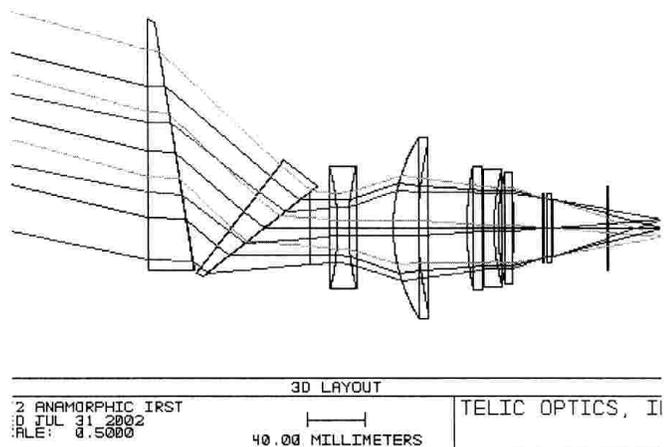
$$1) \quad \text{NEI} = 1.4h \cdot v \cdot \sqrt{\frac{X_{\text{opt}} Q}{\frac{\pi}{4} \cdot T_{\text{opt}} \eta_{\text{cs}} \eta_{\text{det}}}} \cdot \frac{1}{\sqrt{\tau_{\text{int}}}} \cdot \frac{F \Omega}{N W d}$$

Minimizing the detector IFOV through maximum sampling of the required field of view with a large number of detectors, while maintaining a low F number for the optical system that effectively matches the optical blur to the detector dimension clearly provides the optimum system sensitivity. Providing sufficient well capacity to allow maximum integration time within the required frame time also is seen to be an important, but secondary consideration in achieving system sensitivity. If one restricts the number of sensors utilized to cover the required 360 degree field of view to 8 sensors based on installation considerations associated with having a stabilized sensor, then a single sensor FOV of 45 degrees is required. General considerations for optical system design restrict the smallest practically achievable F number for such a wide field of view to approximately F/2. Given the desire to operate in the midwave spectral band for the reasons cited above, then to match the detector size to the diffraction limited blur one arrives at a detector dimension of approximately 25  $\mu\text{m}$ . The maximum number of detectors achievable in the long linear dimension of an array is limited by the largest detector material wafers that are available, and the desire to be able to process more than a single detector die per wafer. MBE grown HgCdTe on Si at a 4" diameter currently provides the largest wafers available for midwave

detectors.<sup>2</sup> At this wafer, size up to 4 2500x500 element arrays may be fabricated per wafer, a reasonable number from a throughput, yield, and cost perspective. The target radiance from a small Mach 0.75 anti-ship cruise missile in the 3.7-4.2 micron spectral band is approximately  $1.5 \times 10^{-2}$  W/ster. Given the desire to detect that target at a range of approximately 10 km, a sensor noise equivalent irradiance of approximately  $1 \times 10^{-15}$  W/cm<sup>2</sup> is required. A block diagram depicting the major components for the entire system is shown in Figure 1.

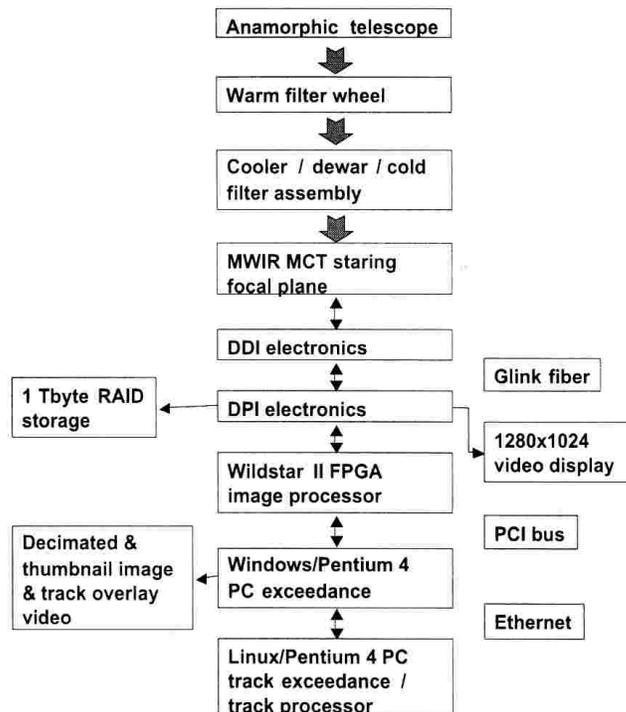
## 2.1 Optics

The optics for the DAS IRST sensor are being built by Telic Inc.. The design consists of a non-reimaging f/2.49 x 9 degree field of view 5 element telescope for operation in the close-in surveillance mode, with a 2 prism element anamorphic front end that is switched in to compresses the vertical field of view to 3.9 degrees for sensing in the IRST mode. The telescope front element is a ZnSe diffractive asphere



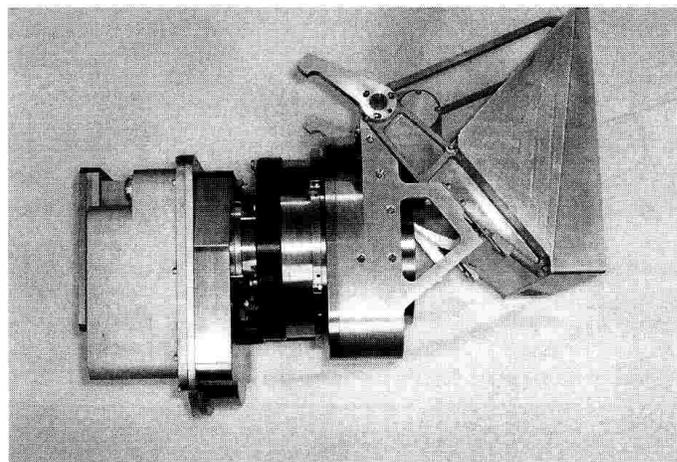
**Figure 2 Ray trace diagram for DAS IRST anamorphic telescope**

Due to the wide field of view of the sensor, the telescope possesses approximately 10% barrel distortion without the prisms in place. The design includes passive athermalization to provide constant focus over the temperature range of 0 to 40C. The optics assembly also includes two electronically controlled 4 position filter wheels that hold 50 mm diameter warm spectral bandpass



**Figure 0 Block diagram showing major subsystems of DAS IRST system**

and the remaining elements are a combination of ZnSe, Ge, and Si spherical surfaces (Figure 2). The anamorphic prisms are both Si with the front element having a clear aperture of 210x170 cm. The telescope has an 84 mm diameter clear aperture and the nominal transmission from 3.8 to 4.8 microns for the system is 80%. The encircled energy is near the diffraction limit for a 25 micron diameter (86%), and ranges from 77% at the field corners to 86% near the center of the field.



**Figure 3 Side view of fully assembled DAS IRST optical system**

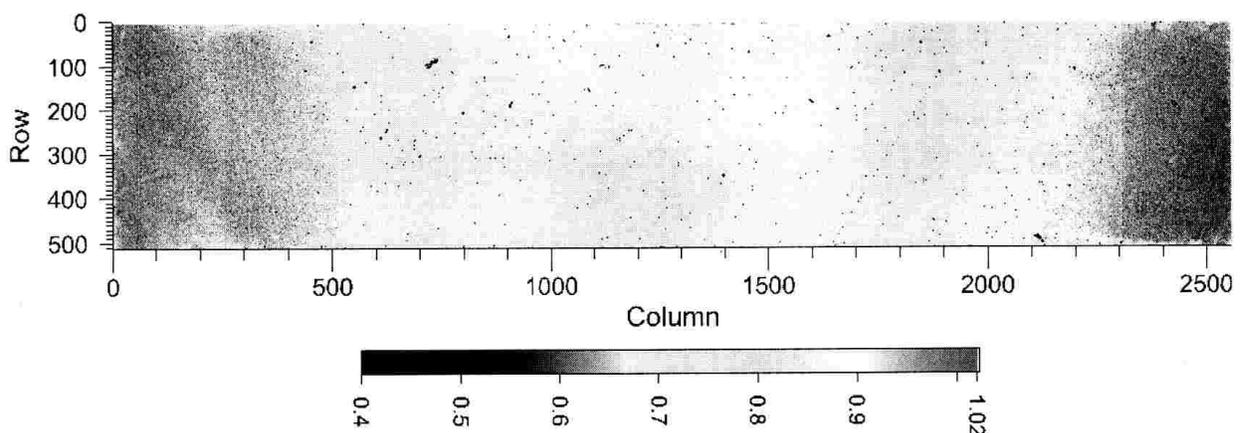
filters for the 3.7-4.2 and 4.6-4.8 spectral bands, a thermoelectric thermal reference source for nonuniformity correction, a polarizer, a cylindrical defocusing element for potential adaptive nonuniformity correction, and a clear aperture. The total weight of the optical system is xx pounds. A side view of the completed assembly is shown in **Figure 3** with the anamorphic elements switched into operational position. Initial test data on the completed assembly shows performance in all areas that closely matches the design parameters.

## 2.2 Sensor Engine

The focal plane, integrated cooler-dewar assembly, focal plane drive and data digitization electronics for the sensor are being built by Raytheon Vision Systems. Delivery of the first of three of these units is planned for late May 2004, with subsequent units due three months later. Focal plane hardware has been built and preliminary test results on these parts are reported here and in additional detail elsewhere<sup>3</sup>. Cooler and dewar components have been fabricated and are currently being built up into subassemblies for focal plane integration.

## 2.2 Focal Plane Array Technology

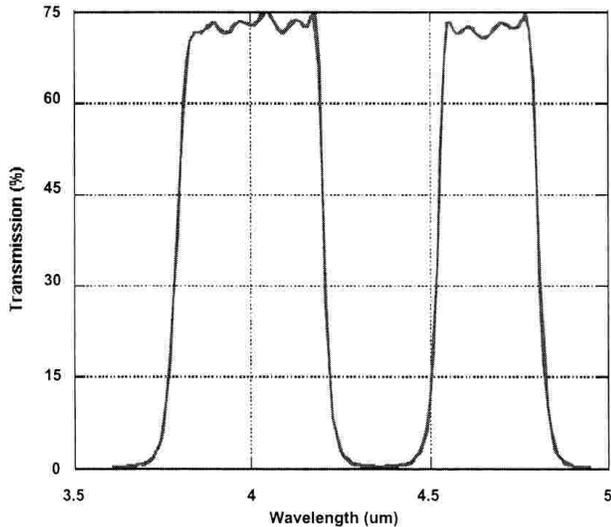
The focal planes for the sensor are being fabricated by Raytheon Vision Systems. As indicated in a previous section, MBE grown HgCdTe on Si was chosen as the detector material approach given its compatibility with producing high performance very large format arrays. The mesa isolated detector structure with the appropriate compositional grading of the detector material results in good detector MTF, consistent with the desire to match blur size and pixel dimension. Quantum efficiencies of approximately 85% have been achieved. Because of the high quality of these diodes and the system flux levels, a simple direct injection readout circuit was adequate to meet sensor performance requirements. The design includes a well capacity of 20 million carriers, sufficient to support integration times up to 20 msec under 40 C background temperatures. The design goal for the input referred noise level for the focal plane is 500 electrons, or 50  $\mu$ V, resulting in predicted noise equivalent photon flux at the focal plane of  $5 \times 10^{10}$  photons/cm<sup>2</sup>-sec, or a noise equivalent temperature difference of 12 mK for a resolved target. Units cell outputs are read into programmable variable gain column CTIA amplifiers. These are multiplexed to at a 4 MHz clock rate through 10 outputs to support the 30 Hz frame rate requirement. The outputs are high speed, low power, differential current mode drivers. This provides excellent immunity to supply noise and external EMI pickup in the dewar. Preliminary responsivity data typical of the arrays built to date is shown in Figure 4. Array operability defined using a  $\pm 50\%$  of the mean criteria



**Figure 4 Responsivity map for DAS IRST focal plane based on 300K-280K flood illumination difference.**

have exceeded 99%. Array noise data to date have been limited by test set noise to values of approximately 900  $\mu\text{V}$  as a consequence of testing in a laboratory test dewar. This makes assessment of the ultimate noise equivalent flux performance or NEDT of the arrays impossible. A significant reduction in noise is expected upon integration in the system dewar assembly and testing with the sensor electronics.

## 2.3 Supporting subsystems / electronics

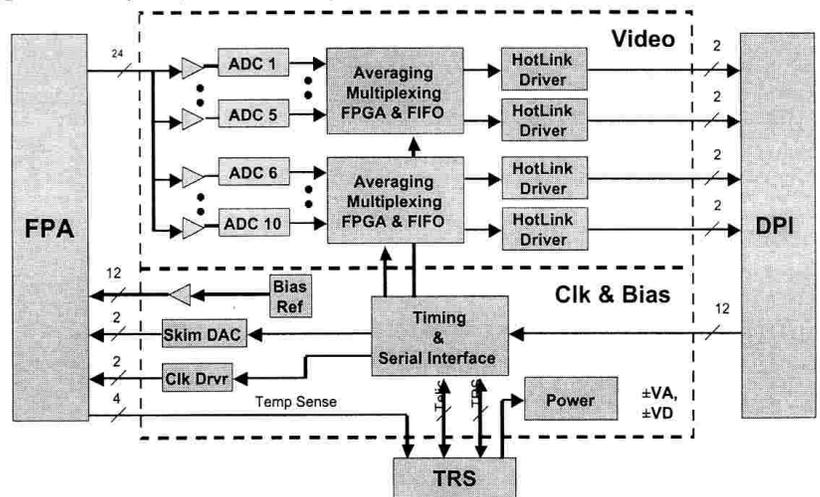


**Figure 5 Transmission characteristics for DAS IRST cold filter**

The large dimensions of the focal plane coupled with the relatively fast optical system present particular challenges for the design of the dewar assembly. The desire to minimize  $\cos^4$  cold shielding effects at the focal plane has resulted in a roughly 3" tall cold shield. This structure supports a 2" diameter cold double band pass filter with the transmission characteristics shown in **Figure 5**. Structural rigidity and thermal mass considerations have led to the use of magnesium for the cold shield. The dewar is designed to accept a 20,000 hour MTBF 1.5 watt cryocooler from Thales that was chosen for its ability to meet the continuous operation requirements for the DAS IRST system.

power the focal plane and a video chain that includes ten 14 bit A/D converters, multiplexers, and HotLink fiber channel drivers that transmit the data to the DPI board being built by SmartLogic Inc.. FPA operational modes and parameters are controlled over a serial data link. The A/D converters double sample each pixel each clock cycle for noise reduction purposes. The DPI is a VME chassis board that serves as the interface between the RVS electronics and the data processing for the system. It has the capability to collect and store in real time up to 1 Gbyte (300 frames) of data at a 30 Hz frame rate. It performs nonuniformity correction and bad pixel replacement and provides a full resolution corrected 2560x512 image through two 1280x1024 video outputs. The board is controlled through software running on a VME PC in the same chassis. This software provides a GUI for collecting and storing data, controlling all focal plane operating parameters, generating nonuniformity coefficients, positioning the filter wheel, controlling the thermal reference sources, and positioning the anamorphic optical elements.

The functional block diagram for supporting sensor electronics being built by RVS is shown in **Figure 6**. They include clock and DC bias supplies to



**Figure 6 Block diagram for detector /dewar interface electronics.**

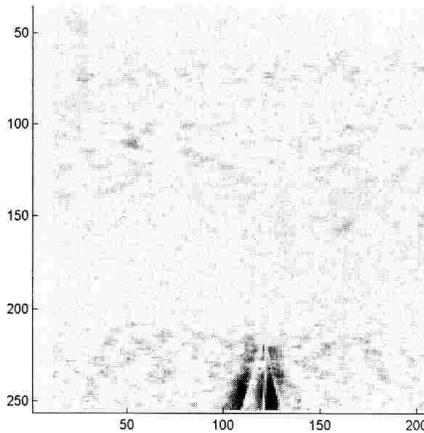
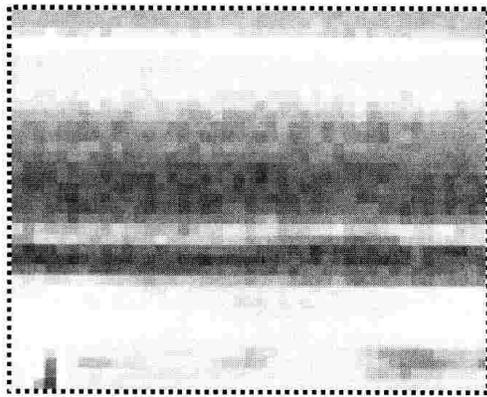
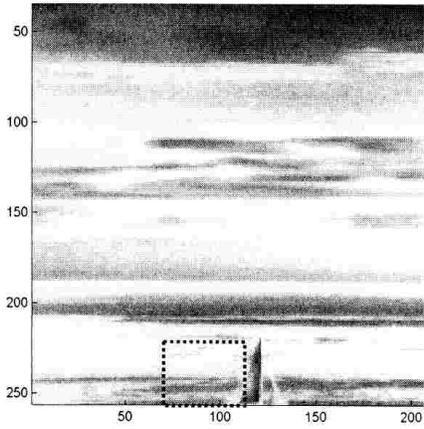
## 2.4 Data Processing

Real time sensor data processing functions are broken down into two primary subdivisions, the first being referred to subsequently as front end processing. It consists of two-dimensional spatial image processing and iterative operations on sequential frames in the temporal domain. Through thresholding operations it generates exceedance data that is passed via an Ethernet connection to the second processing level, referred to hereafter as the back end processing. The back end encompasses processing of the exceedance data for the generation and maintenance of tracks, and the declaration of threats and minimization of false alarms.

### 2.4.1 Front End Processing

The front end processing is implemented using FPGA technology incorporated on the WildStar II PCI board from Annapolis Microsystems. It incorporates two 6 million gate XILINX XC2V6000 FPGAs, each of which includes six 2Mbyte banks of SRAM and 64 Mbytes of DDRAM. This hardware is being programmed using the Annapolis Corefire development software that includes standard math and logic libraries, as well as a variety of fast FFTs and FIR filters.

The primary purpose of the front end processing is to remove spatial clutter from the image, and through a spatial filtering and thresholding process identify pixels that are likely to be associated with point source like targets. To accomplish this, the primary functions incorporated into the front end are single frame spatial demeaning, point spread function matched filtering, local neighborhood calculation of the spatial variance, and sequential frame iterative exponential weighted moving average (stack and add) and temporal variance calculations. The demeaning filter is a (1x21) finite impulse response (FIR) filter intended to remove low frequency and pedestal features from the image while passing the high spatial frequency information associated with the point like targets. Three different point spread function filters based on different assumptions for the power spectral density for the clutter are incorporated. The first being the matched filter assuming a uniform power spectral density for the clutter, the second assuming a slight modification of this reflecting weak nearest neighbor correlation for the clutter, and the final referred to as the LMS filter<sup>4</sup> based on the assumption of a low frequency dominated power spectral density function for the clutter. For each of these, there is a set of four different (5x5) kernels representing different spatial phasing of the peak location, i.e. at the center, bottom edge, left edge, and corner of the pixel. The local spatial variance for each pixel is calculated in a (5x5) region. The output of the 'demeaned' and 'point spread function' filtered data is normalized by the local variance and subjected to a threshold process to select the output that results in the largest signal to clutter ratio for generation of an exceedance. The intensity of the signal for the selected pixel, the mean background signal in its local neighborhood, the local variance, and the temporal variance for that pixel, are then associated with the pixel location to define the exceedance. The front-end processor also serves to provide a display of 30 Hz full frame decimated imagery and zoomed region of interest images selected by the operator. Track symbology passed from the back end processor is also overlaid on this imagery. The front end receives and processes inertial measurement sensor data that allows conversion of all pixel coordinates into an inertial coordinate system. The processing described above has been



demonstrated real-time at 30 Hz using synthetic 2560x512 imagery constructed by mirroring and tiling 256x256 data. Examples of an unfiltered image, demeaned image, point spread function filtered image, local variance, and background normalized signal image are shown in **Figure 7**.

## 2.4.2 Back End Processing

Back end processing is hosted on a Pentium 4 PC running under LINUX. Some legacy tracker code is currently written in Ada, but all other code is in C.

(In the final implementation the tracker code will be ported to C).

Spatio-temporal tracking is accomplished using a constant velocity Kalman filter. Tracks are initiated on exceedances having a threshold to clutter ratio greater than 6.4.

Subsequent to initiation, tracks are maintained if a predefined exceedance occurrence density and consecutive dropout criteria based on the age of the track are satisfied.

In the absence of exceedance data for a frame, the Kalman filter will 'coast' the track assuming these criteria are met. If not, in the

**Figure 7 Sample imagery showing front end processing steps : a) raw data, b) demeaned image, c) point spread filterd, d) local variance, e) normalized signal**

absence of exceedance data the track will be killed. For each new frame the tracker attempts to associate exceedances with

existing tracks prior to establishment of a new track. Tracks are evaluated with respect to their spatial origin, radiometric intensity, angular rate, and short (few frames) and long term (large fraction of a second and longer) temporal behavior in order to classify them as threats or 'false' detections. Currently the formalism for classification is based on a heuristic multi-branch decision tree approach that uses the expected characteristics of a target and false detections to perform discrimination. The back end processing has been demonstrated to handle 4000 exceedances per frame leading to the processing of approximately 100 tracks on a continuing basis. Track maintenance and declaration for five simultaneous artificially inserted targets has also been demonstrated. Additional discrimination/threat declaration approaches based on Bayesian techniques, fuzzy logic, and neural networks will be investigated as part of the system development and test program.

### 3.0 System Performance Modeling

The performance of the DAS IRST sensor has been modeled using a code referred to as IRSTAT that was developed by the NAWC Dahlgren Division under previous shipboard IRST programs<sup>5</sup>. It includes a number of modules depicted in **Figure 8** that together allow the calculation of the probability of declaration as a function of range for a given sensor either under one well defined set of meteorological conditions, or the performance averaged over large weather databases. Key elements of the model include a sensor noise equivalent radiance module based on sensor optics, detector, electronics, and signal processing parameters, a target signature module based on aerodynamic heating of the target and geometrical cross section as seen by the sensor, a MODTRAN4 module for calculation of atmospheric transmission, and a module containing meteorological data bases. The tool has been used to predict performance under specific conditions of interest, and to get a sense of the overall operational availability

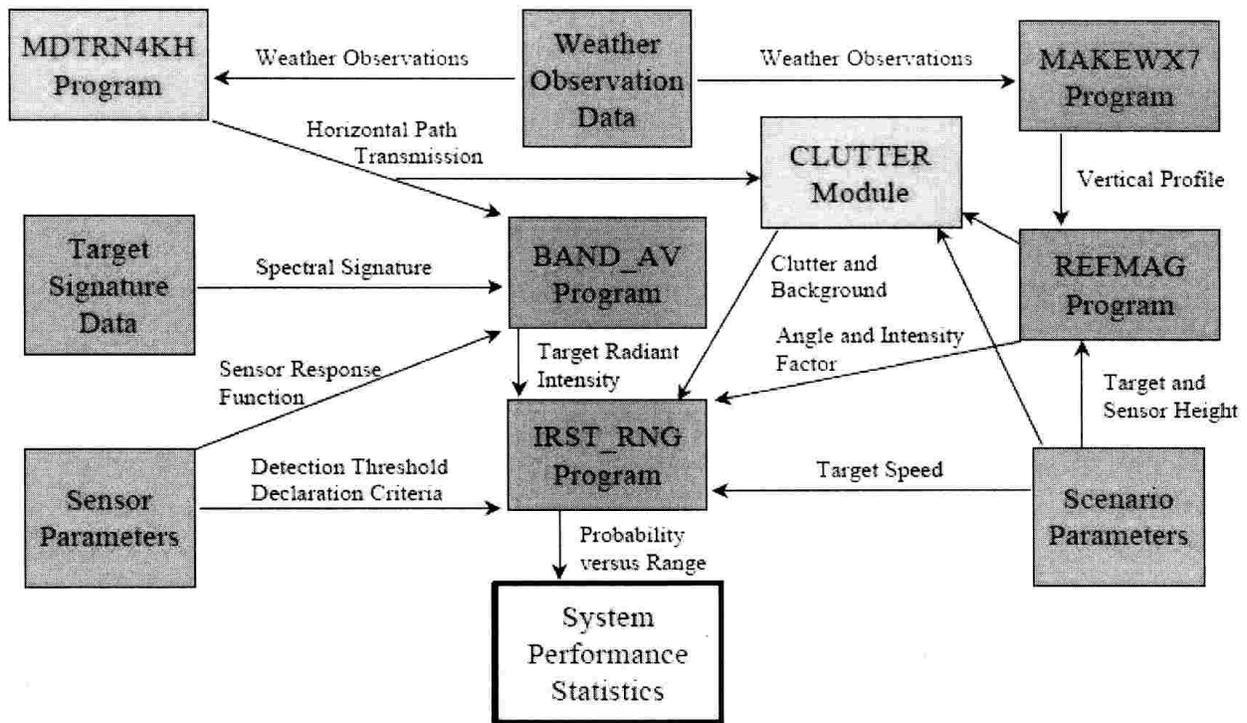
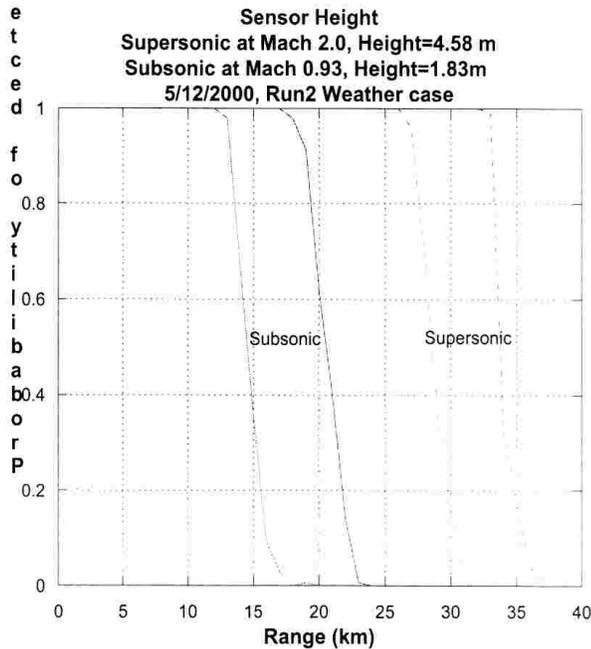


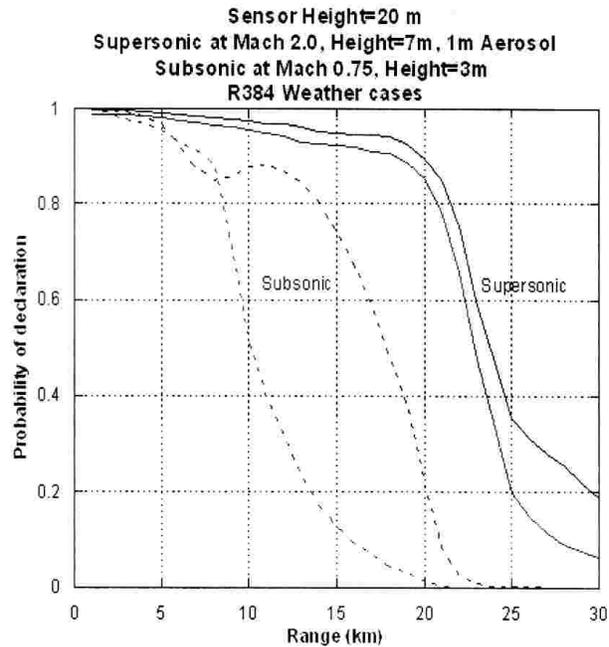
Figure 8 Block diagram showing IRSTAT modules

of the sensor against different classes of targets under broad weather conditions. Declaration probability

as a function of range for the BQM-74 cruise missile surrogate at Mach 0.75 and for a nominal mach 2.0 large diameter cruise missile, is shown in **Figure 9** for the R384 meteorological data base and the two spectral bands. The missile heights were assumed to be 3 and 7 meters respectively, and the sensor height was 20 meters. Declaration distances are seen to be in 10 and 20 km ranges respectively. **Figure 10** shows a calculation of declaration probability as a function of range for at Mach 0.93 small anti-ship missile, and a large Mach 2 class anti-ship cruise missile under a set of meteorological conditions that had resulted in significantly degraded performance for the SPQ-9b and SPY1 RADAR systems. The long declaration ranges clearly show the utility of theIRST as an adjunct to RADAR systems.



**Figure 9** Declaration probability as a function of range for sub (dashed) and supersonic (solid) targets for the short (blue) and long (red) spectral bands for the R384 database



**Figure 10** Declaration probability as a function of range for sub (dashed) and supersonic (solid) targets for the short (blue) and long (red) spectral bands for the R384 database

## 4.0 System Test Plan

The initial integration of the optics, sensor engine, and system software is scheduled for late spring 2004. Initial laboratory testing of the system is scheduled for completion in early summer of 2004. Determination of all relevant radiometric performance and image quality metrics will be performed as part of that test effort. A data acquisition system capable of storing up to 3.5 hours of full resolution 30 Hz frame rate data will be assembled to support this and all following test activities.

The first stage of the shore based test program will be performed at the Naval Research Laboratory's Chesapeake Bay Detachment (CBD) site near Chesapeake Beach, MD. That site provides a wide clear field of view over the bay from an elevation of approximately 30 meters to Tilghman Island at a range of 16 km. A xx meter high tower at that location enables viewing of calibrated sources at a variety of heights. Targets will also be deployed on small surface craft for observation at shorter ranges. The site also provides many targets of opportunity for viewing small craft and large commercial shipping vessels.

The CBD site is also the location for ongoing work on the effect of atmospheric turbulence on optical propagation over long maritime paths, and as such is well instrumented for characterization of such phenomena at visible and near infrared wavelengths. One of the primary objectives of the IRST testing at this site is the assessment of the utility of algorithms based on scintillation effects for discrimination of long range point sources from extended background clutter and nearer small targets, e.g. birds. Data from the other available sensors will be utilized to help compare measured results with existing meteorological data bases. This will also provide the first opportunity for testing the image processing, tracking, and target declaration algorithms.

Shore based testing is planned for 2005 at the Navy's Wallops Island Atlantic range facility. This site provides wide field of view observation across the open ocean from an elevation of approximately 20 meters. A multi-phase program consisting of approximately 8 different data collection events over the course of the year, to sample as many different meteorological conditions as possible, is currently being planned. Targets will include surface vessel deployed sources, low altitude air towed targets, and tactical aircraft acting as cruise missile surrogates. Coordination with the MFR test program in early CY05 will allow sharing of target assets and test range data. Continuous meteorological and sea surface condition data will be obtained from buoys deployed in the test area.

The technology transition agreement for the DAS IRST between the Office of Naval Research and NAVSEA calls for at-sea testing of the system in CY06. At this time no detailed plans have been made for this effort, but the intent would be to show the effectiveness of the system in the open ocean over a range of environments against representative threats.

## **5. Summary**

Hardware component development for the DAS IRST system is nearly complete. The system utilizes state of the art focal plane technology, signal processing hardware, and algorithms. Final integration and testing of the IRST sensor will be accomplished by early summer 2004. Prototype image processing, tracking, and discrimination/declaration software has been demonstrated operating at the full system resolution and frame rate. A phased test program to assist in the further refinement of algorithms and demonstrate the capability of the system against surrogate targets is planned for 2005-2006.

## **6. Acknowledgements**

The authors gratefully acknowledge the valuable contributions of Russ Smith (Smart Logic Inc), Leslie Smith, Ken Vilardebo, Ed Kaulakis(V-Systems Inc), Jim Howard (Telic Inc), Joe Griffith, Steve Black, and Alex Childs (Raytheon Vision Systems) to the DAS IRST program and their assistance in the preparation of this manuscript.

## **7. References**

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<sup>3</sup> D. J. Gulbransen, S. H. Black, A. C. Childs, C. L. Fletcher, S. M. Johnson, W. A. Radford, G. M. Venzor, J. P. Sienicki, A. D. Thompson, J. H. Griffith, "Wide FOV FPAs for a Shipboard Distributed Aperture System", Proceedings 2004 Specialty Group on Infrared Detectors.

<sup>4</sup> E.H. Takken, D. Friedman, A.F. Milton, and R. Nitzberg, "Least Mean Square Spatial Filter for IR Sensors", Appl. Optics, 18, 4210 (1979).

<sup>5</sup> The authors gratefully acknowledge Dr. Ken Hepfner and NSWC Dahlgren Division for providing this code as well as their valuable assistance in running it and interpreting the results.