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3-D Analysis Framework and Measurement Methodology for Imaging System noise

by

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ABSTRACT

Modern imaging sensors incorporate complex focal plane architectures and sophisticated post-detector processing. These advanced technical characteristics create the potential for multi-component noise generation which can exhibit effects temporally as well as along the vertical and horizontal image directions. Such complex three-dimensional (time, vertical, horizontal) noise cannot be adequately treated by previous mathematical analyses developed for simpler system designs where detector noise was predominant. In a parallel sense, earlier methods for noise measurement are no longer satisfactory. A new methodology has been developed at C²NVEO to characterize the noise patterns exhibited by advanced thermal imaging systems. The method represents a significant expansion of the standard techniques to characterize thermal system noise. This paper explains the principles behind the 3-D noise methodology and the methods used. It also describes how this methodology is implemented in a laboratory measurement environment.

1.0 INTRODUCTION

Modern imaging sensors incorporate complex focal plane architectures and sophisticated post-detector processing and electronics. These advanced technical characteristics create the potential for the generation of complex noise patterns in the output imagery of the system. Unlike classical systems where "well behaved" detector noise predominates, these complex systems have the ability to generate a wide variety of noise types each with distinctive characteristics temporally as well as along the vertical and horizontal image directions.

Such complex three-dimensional (time, vertical, horizontal) noise phenomena cannot be adequately treated by previous mathematical analyses developed for earlier simpler systems. In a parallel sense, earlier methods for noise measurement at the detector pre-amplifier port which ignored other potentially significant system noise sources are no longer satisfactory. System components following that stage to include processing may generate significant additional noise and even dominate total system noise.

Efforts at the Center for Night Vision and Electro-Optics (C²NVEO) to analyze and measure the performance characteristics of advanced 2nd generation scanning thermal systems uncovered the need for a more comprehensive noise methodology. It was observed at the outset that the noise patterns produced by these systems exhibited a high degree of directionality. It was believed that this directionality was responsible for a poor subjective resolution or MRT in the vertical (cross-scan) direction as compared with the MRT in the horizontal (in-scan) direction. Since, prior to this time, emphasis in noise measurements and analysis was placed on detector noise, and directionality was not an issue, the need for a new broader methodology was indicated.

This paper describes a new methodology developed by C^2NVEO for the analysis and measurement of the noise effects produced by advanced thermal sensors. The objectives of this new methodology are to understand and quantify the complex noise effects produced in order to incorporate these effects in the Center's FLIR90 thermal performance model. Under the Army's ACQSIM research program, the Center is committed to the goal of accurately modeling advanced military FLIR performance.

The specific approach taken divides the total noise present into a set of eight components which have special properties related to the temporal and spatial dimensions which form a three-dimensional coordinate system. Analyzing noise in this manner has proven advantageous in several ways. Generally, it simplifies the understanding of a complex noise phenomenon by breaking it down into a manageable set of components which can be clearly defined. For the system designer, the distinctiveness and relative magnitudes of the 3-D noise components provides an insight into the possible hardware and software factors which are responsible for them. For the laboratory evaluator, the methodology provides the basis for new noise indices of merit which take into account the inherent directionality present and thus are more comprehensive than those currently in use. For the system performance modeler, the new method simplifies the incorporation of complex noise effects in the model formulations.

This paper summarizes the principles behind the 3-D noise methodology and describes how this methodology is implemented in a laboratory environment. Previously publications have also dealt with these subjects in some detail[1,2].

2.0 THE 3-D NOISE ANALYSIS METHODOLOGY

2.1 Data Requirements

3-D noise analysis requires an empirical data base of noise consisting of a consecutive sequence of digitized images captured while the system being evaluated is viewing a uniform constant background stimulus. This data set may be obtained from either the analog or digital output port of the imaging system to be studied prior to any display component. If the analog port is used, then the horizontal analog data must be digitized prior to analysis. The laboratory procedures which are used to obtain and calibrate this noise data base are similar to those used for the purposes of calculating the standard NET. The main differences are the quantity of data, its total digital nature, and its three-dimensional structure.

The data set obtained is mathematically three-dimensional with the temporal dimension representing the frame sequencing and the two spatial dimensions representing the vertical and horizontal extent within the image. Figure 1 illustrates the discrete 3-D coordinate system. t, v, and h are integer indices attached to evenly spaced locations in time and space with t being the frame number, and v and h the row and column numbers respectively within a frame. All indices start from zero.

The overall size of the 3-D data set is important. Ideally a large quantity of data is desired. This means entire frames of data and a large number of consecutive frames. Hardware memory and bandwidth recording limitations as well as data processing time constraints will place practical limits on the size of the data set. The results obtained under conditions where the entire frame is not analyzed will tend to be localized and not necessarily representative of the entire image frame area. In addition the mathematical separation or resolution of the 3-D components will be degraded with extremely small data sets. When the region to be analyzed within the frame is less than the entire frame, the central portion of the image is preferred since this is the region used generally for system resolution measurements.

2.2 3-D Noise Effects Model

At the heart of the 3-D noise methodology is the representation of the raw image data set described above as a composite consisting of a global constant S, and the effects due to each of seven possible distinctive noise types. The random effects model assumed for this noise analysis is given by:

$$U(t,v,h) = S + N_T(t) + N_V(v) + N_H(h) + N_{TV}(t,v) + N_{TH}(t,h) + N_{VH}(v,h) + N_{TVH}(t,v,h)$$

U(t,v,h) represents the total magnitude of the noise data set obtained above (section 2.1) as a function of frame, row, and column. S is the grand mean of all points in the 3-D data set. It correlates to the effect of the signal input (a constant uniform background). All of the seven noise effects which follow S have a mean of zero and thus do not contribute to the grand mean.

The model includes three random variables and their interactions. Noise types are characterized by their specific behavior along the three dimensions, i.e., temporal, vertical and horizontal. The effects produced by these variables are grouped and characterized in the model using the symbols N_T, N_V, N_H, N_{TV}, N_{TH}, N_{VH}, and N_{TVH}. To a statistician, the 3-D analysis process is similar to a three factor components of variance analysis in which temporal (frame-to-frame), vertical (row-to-row), and horizontal (column-to-column) effects are partitioned from the total noise present in the data set. N_T represents noise effects based solely upon the differences among individual frames. Likewise N_V represents noise effects based solely on row location and N_H represents the effects based solely on column location. The next three terms represent interaction effects. For example, N_{TV} represents the effect based upon the coincidence of frame and row, i.e., a row effect influenced by frame-to-frame variation. Contrast this with N_V which represents the effect attributable only to row and is therefore fixed from frame-to-frame. The term N_{TVH} represents the three-way interaction effect based on the coincidence of frame, row, and column factors. In statistical analysis N_{TVH} may also be interpreted as the residual noise present after accounting for the other noise types.

The noise types in the noise effects model represent fluctuations about a mean of zero in the directions indicated by their subscripts. Thus the net contribution of each noise type to the composite data set in those directions has a zero value. Of course the noise type does contribute to the variability in those directions. In the directions where the noise type does not represent fluctuations the contribution to the composite data set is uniform. That is the presence of that noise type in the composite results in a constant being added to or subtracted from all pixel values in those directions. This has only the effect of raising or lowering the mean value of that pixel group. It has no effect on the variability in those directions. For example N_T represents a noise type which consists of fluctuations in the temporal direction only (T is present) affecting the mean of each frame (V and H are not present). N_{TV} represents a noise type consisting of fluctuations in both the temporal and vertical directions (T and V are present) affecting the mean of each row (H is not present). Since N_{TVH} contains all three subscripts it represents fluctuations in all three directions on a pixel basis. Each of the other four noise types in the model may be described in a similar manner.

Figure 2 summarizes the eight 3-D data types (signal + seven noise types) in the model. Figure 3 suggests characteristics of various thermal imaging systems which may give rise to noise components which relate to the 3-D noise types.

2.4 The Directional Averaging Operators D_t, D_v, & D_h

The fact that each 3-D noise type represents a random fluctuation about zero in the directions indicated by its subscripts provides a clue to reducing or eliminating the presence of that component in the composite. Any filtering in those directions to reduce the variability will reduce the magnitude of that component. The ultimate filter which reduces that magnitude to zero will be one that performs a perfect averaging in any of the appropriate directions. This is the nature of the 3-D noise types - they are amenable to reduction or complete deletion by simple averaging in any of the directions where they exhibit effects. Implementation of the 3-D noise analysis is therefore accomplished by processing the original data set using the three basic directional averaging operations defined below. As will be shown, when the directional averaging operations are used in various combinations they serve to isolate systematically each of the eight 3-D data types.

$$D_t\{U(t,[v],[h])\} = 1/T \sum_{t=0}^{T-1} U(t,[v],[h])$$

$$D_v\{U([t],v,[h])\} = 1/V \sum_{v=0}^{V-1} U([t],v,[h])$$

$$D_h\{U([t],[v],h)\} = 1/H \sum_{h=0}^{H-1} U([t],[v],h)$$

The original unprocessed 3-D image data set is represented again by U(t,v,h). T, V, and H represent the total number of samples present in each direction. The averages are obtained for each line of pixels in the direction indicated. Under the summation sign the variables not being summed over (those contained in brackets), are constant during the summation. For example, with D_h, the operator averages each row of pixels in the horizontal direction and 0 and H-1 signify the limits over which the averaging takes place.

Each D operation has the expected simple averaging effect. For each line of pixels averaged, all variations about the mean in the direction indicated are integrated out (removed). Mathematically, this effectively collapses the dimensions of the resulting data set by one. As described earlier, the noise effects model represents any arbitrary 3-D image data set as a composite of eight separate distinctive components. If any of these 3-D component data types present in the composite represent variations about a mean of zero in the direction filtered (indicated by the <u>presence</u> of the respective subscript), then that operator has the effect of deleting those data types from the original set. On the other hand, if any of the 3-D component data types present in the composite represent a lack of variation in the direction filtered (indicated by the <u>absence</u> of the respective subscript), then the operator leaves those components intact. The operations $1-D_t$, $1-D_v$, and $1-D_h$ have the opposite effect. They extract from the original composite data set all 3-D component data types which do not represent a variation in the appropriate direction.

It is easy to see how the successive use of the direct *D* operators and/or the corresponding opposite operations defined above make isolation of any of the individual 3-D data type relatively straightforward. Figure 4 illustrates graphically the effects of the directional averaging operators and their opposite counterparts on an original composite data set. With the *D* operator in hand the 3-D noise types can now be defined on the basis of the operator process used to extract them from the original composite data set.

NOISE FUNCTION	CORRESPONDING D PROCESS
N_{TVH}	$[(1-D_t)(1-D_v)(1-D_h)]\ \{U(t,v,h)\}$
N_{VH}	$[\ D_t\ (1-D_v)(1-D_h)]\ \{U(t,v,h)\}$
N_{TV}	$[(1-D_t)(1-D_v)\ \ D_h\ ]\ \{U(t,v,h)\}$
N_V	$[\ D_t\ (1-D_v)\ \ D_h\ ]\ \{U(t,v,h)\}$
N_{TH}	$[(1-D_t)\ \ D_v\ (1-D_h)]\ \{U(t,v,h)\}$
N_H	$[\ D_t\ \ D_v\ (1-D_h)]\ \{U(t,v,h)\}$
N_T	$[(1-D_t)\ \ D_v\ \ D_h\ ]\ \{U(t,v,h)\}$
S	$[\ D_t\ \ D_v\ \ D_h\ ]\ \{U(t,v,h)\}$

With any arbitrary image data set U(t,v,h), the operations outlined above will isolate the seven 3-D noise data types. In each case the operations represent the systematic removal from the original data set of all data types which are not desired. The definition of N_{TVH} is special in this regard since it represents the removal from the original data set of all data types (signal and noise) except that due to a three-way interactive effect. Interpreting the operations left to right and consulting figure 4., the process $(1-D_t)$ removes both the signal S and all noise types which do not exhibit a temporal effect (i.e. N_{VH}, N_V, and N_H). Similarly the operation $(1-D_v)$ subsequently removes all remaining noise types which do not exhibit a vertical effect (i.e. N_{TH} and N_T). Lastly the operation $(1-D_h)$ removes all remaining noise types which do not exhibit a horizontal effect (i.e. N_{TV}). After all operations are completed the only noise type defined in this methodology which remains is the desired N_{TVH}.

3.0 MEASUREMENT PROCEDURE AND ANALYSIS

3.1 Equipment and Setup

The laboratory setup for the 3-D Noise Analysis is similar to the setup for the Noise Equivalent Temperature Difference (NETD)[2,3]. The system responsivity, *R*, is determined as the known input differential temperature of the target and the resulting output intensity for a given gain and level setting. This responsivity value *R* (input Temp/output intensity) is used to characterize the 3-D image function types in terms of temperature similar to that of the Noise Equivalent Temperature Difference (NETD).

It is imperative that the integrity of the original composite data set not be corrupted as a result of the data acquisition. For this reason a frame grabber of sufficient bandwidth is used to acquire an integral composite data set. For the acquisition of digital data the analog to digital converter of the frame grabber is bypassed which allows for direct digital frame acquisition. Analog signals should be sampled sufficiently by the frame grabber such that aliasing due to undersampling does not occur.

3.2 Data Analysis

The process of extracting the eight 3-D image function types from the composite data set, time averaged data set or any other intermediary data set is performed by a combination of two basic processing operations.

The first operation is the Directional Averaging Operator, D (see discussion above). The result of this operation is a data set in which all variations about the mean in the direction of the operation are integrated out. For instance, D_h is a horizontal averaging of the pixels of each individual line to form a data set containing N_{TV}, N_V, N_T and S (see Figure 5). Essentially this would result in a two dimensional data set in which the standard deviation of data points along the axis of the directional averaging equals zero.

The second process is a simple point for point subtraction of corresponding pixels of one data set from a second data set. These data sets may be the composite data set or the resultant of another operation (i.e. D_t). The data set resulting from this subtraction contains the difference of the two data sets. For example, subtraction on a point for point basis of the time averaged data set (comprised of N_{VH}, N_V, N_H and S) from the composite data set (comprised of all 3-D function types) would result in a data set of only temporally varying 3-D image function types (N_{TVH}, N_{TV}, N_{TH} and N_T). The subtraction of the time averaged data set from the composite data set would be defined in D Operator terminology as $(1-D_t)$. In essence, all spatial components have been removed from the resulting data set leaving only temporally varying components.

3.3 Statistical Analysis

An important application of the 3-D noise measurement methodology is to quantify statistically the value of each noise component in the image for the purpose of modeling the Minimum Resolvable Temperature (MRT)[2]. These statistical values are expressed in terms of standard deviations, σ, or variance, σ^2, in units of temperature (degrees C) similar to Noise Equivalent Temperature Difference (NETD). A value representing the standard deviation corresponding to each 3-D noise type is obtained by calculating the average standard deviation along pixel streams in any direction where the noise function is variable. This shortcut procedure assumes a type of ergodicity in each 3-D noise type such that the standard deviation will be approximately equal regardless of the direction used.

3.4 Data Examples

The following section will present data that has been generated from two systems using operations similar to those described above. The two systems are one second generation thermal imager and one developmental staring array. For each system a Horizontal and Vertical Minimum Resolvable Temperature Difference (MRTD) test was performed in addition to the 3-D Noise Analysis.

The values of the 3-D Noise Analysis displayed in Figure 6-b and 6-d have been normalized to their respective values of S. In actual practice such a normalization would not be performed. Thus, comparison of the 3-D Noise results of one system to another in Figure 6-b and 6-d is not valid.

Figure 6-a and 6-b show the MRTD and 3-D noise analysis results of an advance scanning thermal imager, System A. Analysis of the MRTD curves of Figure 6-a show a substantial increase in the temperatures of the vertical MRTD curve. Values obtained for the vertical MRTD curves are factors of 5 to 9 times higher then that of the horizontal curve. Analysis of Figure 6-b shows that the σ_{TVH} term is not the dominant term. The vertical components σ_{TV} and σ_V are far greater than their horizontal counterparts. System A has a large contributing component of σ_T indicating a great deal of system frame bounce.

The last system compared is a developmental Staring Array system to be referred to as System B. This staring array was equipped with square detectors such that the resolution in the vertical is equal to that of the horizontal. As illustrated in the MRTD results of Figure 6-c, the curves of the Horizontal MRTD are equal to that of the Vertical MRTD. Analysis of the 3-D Noise Analysis of Figure 6-d show what would be expected of a staring array. The bi-directional terms σ_{TVH} and σ_{VH} are the dominant components. This is expected in a staring array where each pixel in the output is a result of an individual detector. The σ_{VH} term represents the pixel to pixel non-uniformity of the array. σ_{TVH} represents the random noise of each detector. There is little contribution due to vertical or horizontal noise components because there is no scanning of the detectors. The larger value of the column to column component, σ_H, compared to that of line to line, σ_V, is possibly a result of gain balance adjustment in the readout electronics. Each column of the array is read out serially by independent readout electronics. It is possible that the gain balance of the readout electronics for each column is not adjusted well causing column to column nonuniformity. These components were very hard to detect visually because of the substantially greater bidirectional components.

4.0 CONCLUSION

An analysis methodology and procedure has been developed which appears to be ideally suited to the characterization of the noise present in advanced thermal imaging systems. The methodology divides the total noise present into a set of eight separate function types which have unique relationships to the temporal and spatial directions. The individual noise types are isolated both mathematically and in the laboratory with the use of directional averaging image processing operations.

Analytical software has been developed which provides a basis for noise component assessment using the "D" operator process as well as providing a tool for application of related noise assessment/reduction techniques. The inherent capability of the software to reduce primary image function types and save the resulting image frames provides an additional tool for the research of image quality improvement techniques related to the "D" operator process. In addition, recent equipment improvements and the integration of advanced frame grabbers into the facilities at C^2NVEO now make it easy for complete full frame data acquisition and analysis.

The paper also has presented data examples in which the horizontal and vertical MRT results are more easily understood using the data obtained from the 3-D noise analysis of those systems.

5.0 ACKNOWLEDGEMENTS

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6.0 References

1.J. D'Agostino, The Modeling of Spatial and Directional Noise in FLIR90, IRIS Passive Sensor Imaging Symposium, March 1991.

2.C. Webb et. al., Laboratory Procedure for the Characterization Of 3-D Noise in Thermal Imaging Systems, IRIS Passive Sensors Imaging Symposium, March 1991.

3.ARPA Order 1938 - DOD Advanced, Image Evaluation Program (Phase 1 Report), June, 1974.

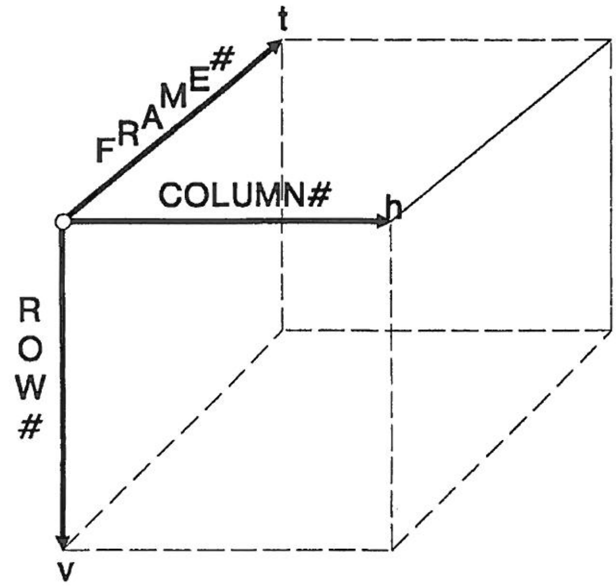

Figure 1 "TVH" Coordinate System

TOTAL NOISE IN THE VERTICAL

	BI-DIRECTIONAL (PIXEL)	VERTICAL (ROW)	HORIZONTAL (COLUMN)	(FRAME)
TEMPORAL	N_{TVH}	N_{TV}	N_{TH}	N_T
FIXED	N_{VH}	N_V	N_H	S

TOTAL NOISE IN THE HORIZONTAL

Figure 2. The 3-D Noise Components

	SERIAL SCAN SYSTEM	PARALLEL SCAN SYSTEM	STARING SYSTEM
N_{TVH}	BASIC DETECTOR NOISE	BASIC DETECTOR NOISE	BASIC DETECTOR NOISE
N_{VH}	---	PIXEL PROCESSING	DETECTOR-DETECTOR NON-UNIFORMITY 1/f
N_{TV}	1/f	LINE PROCESSING 1/f	READOUT LINE PROCESSING
N_V	---	LINE-LINE NON-UNIFORMITY 1/f	---
N_{TH}	---	SCAN EFFECTS	---
N_H	---	SCAN EFFECTS	---
N_T	1/f	FRAME PROCESSING	---

Figure 3. Sources of 3-D Noise

[D_t]

N_{TVH}	N_{TV}	N_{TH}	N_T
0	0	0	0
1	1	1	1
N_{VH}	N_V	N_H	S

[$1-D_t$]

N_{TVH}	N_{TV}	N_{TH}	N_T
1	1	1	1
0	0	0	0
N_{VH}	N_V	N_H	S

[D_v]

N_{TVH}	N_{TV}	N_{TH}	N_T
0	0	1	1
0	0	1	1
N_{VH}	N_V	N_H	S

[$1-D_v$]

N_{TVH}	N_{TV}	N_{TH}	N_T
1	1	0	0
1	1	0	0
N_{VH}	N_V	N_H	S

[D_h]

N_{TVH}	N_{TV}	N_{TH}	N_T
0	1	0	1
0	1	0	1
N_{VH}	N_V	N_H	S

[$1-D_h$]

N_{TVH}	N_{TV}	N_{TH}	N_T
1	0	1	0
1	0	1	0
N_{VH}	N_V	N_H	S

Figure 4. Illustrates the Effect of the Directional Averaging Operator on a 3-D Data Set. A [0] in a box adjacent to a 3-D data component indicates that the operator or opposite operation above has the effect of deleting that component from the data set. A [1] adjacent to a box indicates that the operator or opposite operation above has no effect on that component.

3-D IMAGE ANALYSIS FRAMEWORK

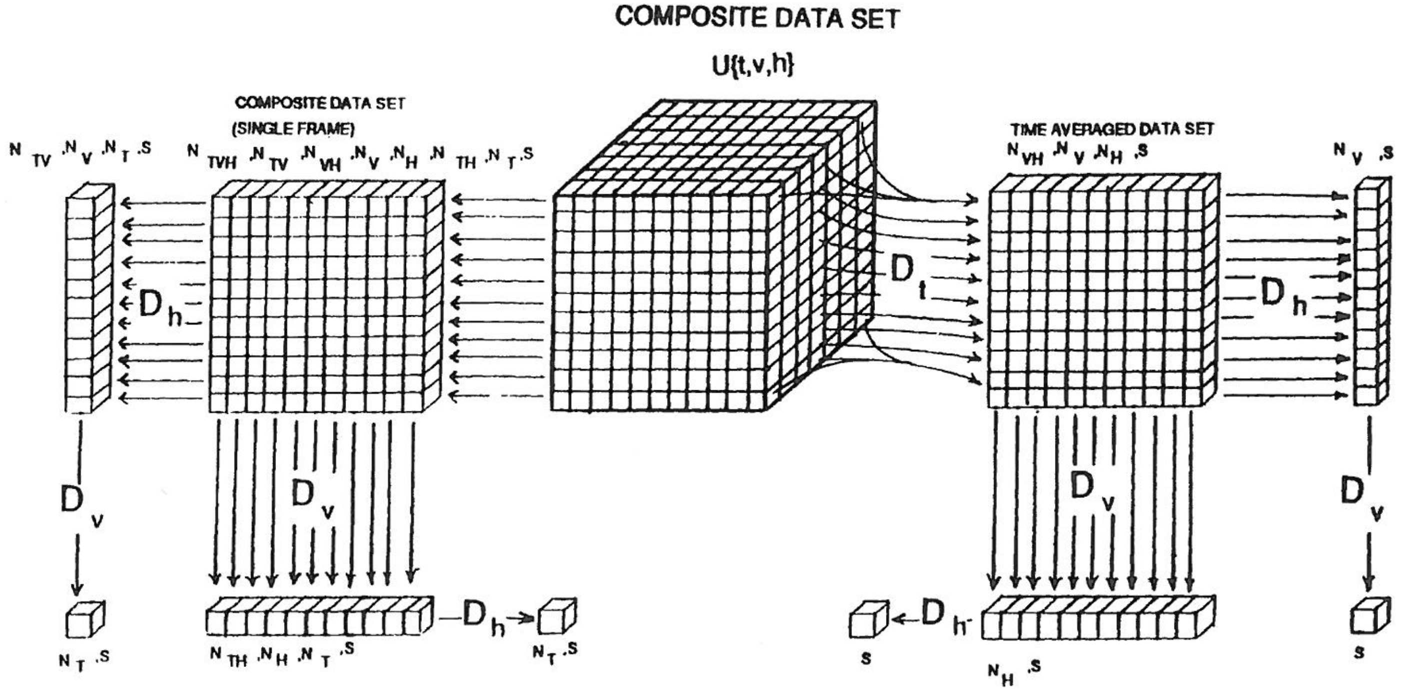

FIGURE 5

MRT OF SYSTEM A
HORIZONTAL VS. VERTICAL
ADVANCED SCANNING SENSOR

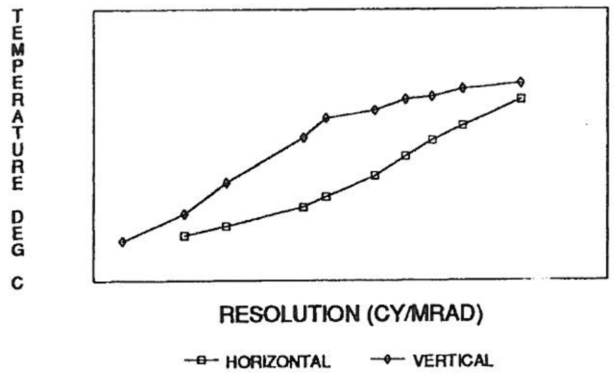

Figure 6-a

MRT OF SYSTEM B
HORIZONTAL VS. VERTICAL
STARING ARRAY

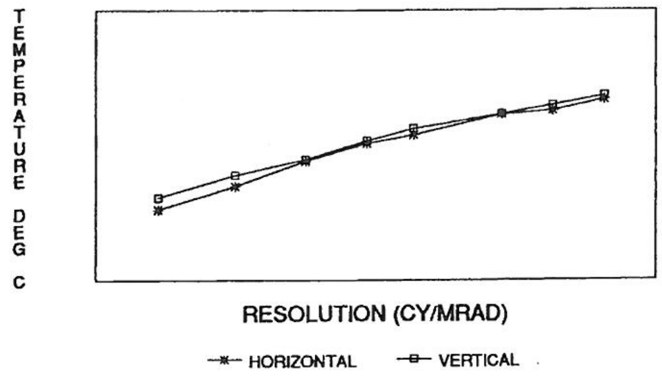

Figure 6-c

3-D NOISE OF SYSTEM A
ADVANCED SCANNING SENSOR

BIDIRECTIONAL	VERTICAL	HORIZONTAL	FRAME
σ_{TVH} 0.0534	σ_{TV} 0.0822	σ_{TH} 0.0136	σ_{T} 0.0793
σ_{VH} 0.0064	σ_{V} 0.0913	σ_{H} 0.0153	S 1

Figure 6-b

3-D NOISE OF SYSTEM B
STARING ARRAY

BIDIRECTIONAL	VERTICAL	HORIZONTAL	FRAME
σ_{TVH} 0.0659	σ_{TV} 0.0172	σ_{TH} 0.0083	σ_{T} 0.0165
σ_{VH} 0.0373	σ_{V} 0.0097	σ_{H} 0.0180	S 1

Figure 6-d