3.0 The Sensor Correlation and Fusion Process

3.1 Introduction

For many Air Force weapon and support systems employing sensors, performance requirements can be met only when data from multiple sensors or time sequenced measurements from a single sensor are combined. This process of combining data has been called sensor correlation and fusion, or simply data fusion. As the performance requirements increase (e.g., the demand for higher detection performance at lower false alarm rates) and targets become more difficult to sense (e.g., low observability), there is a greater demand to expand the dimensionality of sensed information acquired—driving the need for multiple sensors and the combination of that data. This demand to expand the time and space dimensionality of sensed data adds two important themes to *New World Vistas*: (1) sensors must be designed to be integrated and coordinated to maximize the overall system measurement process, and (2) processes are required to efficiently and accurately correlate and fuse data from a variety of sensors.

For purposes of this report, data fusion is defined as follows:

> Data fusion is a multilevel, multifaceted process dealing with the registration, detection, association, correlation, and combination of data and information from multiple sources to achieve refined state and identity estimation, and complete and timely assessments of situation (including threats and opportunities). (Based on the standard definition developed by the Department of Defense [DoD] Joint Directors of Laboratories)

Sensors produce individual observations or measurements (raw data) that must be placed in proper context first to create organized data sets (information) and then evaluated to infer higher-level meaning about the overall content in the information (knowledge). Consider, for example, a data fusion system that combines SAR and hyperspectral (HS) data. The SAR and HS sensors produce time-sampled data. The SAR data is processed to form an image, and the HS data is processed to form multilayer imagery: these images are registered and combined to produce information in the form of an image database. The image database is evaluated to infer the presence of transportation networks, facilities and targets; this is the knowledge (or intelligence) that is sought by the warfighter.

3.2 The Data Fusion Process

Notice that the data fusion process includes functions normally considered to be included within individual sensor pre-processing and even encompasses the functions traditionally included within single sensor ATR. These functions, enumerated within the definition above, include:

- **Registration**. Registration (or alignment) is the process that places all sensor data in a common time and space coordinate system. This corrects for the different time sampling, viewing perspective and image planes of different sensors.
- **Detection**. The decision regarding the presence or absence of an entity (e.g., target or aggregate of targets) or event (e.g., missile launch) may be based upon the evaluation of multiple individual sensor decisions, or it may be based upon

the combination of raw data from multiple sensors (often referred to as pre-detection fusion).

- **Correlation and Association**. The process of fusion which partitions data into associated categories (also referred to as labeling) includes correlation and association stages. In a typical problem, the data from different sensors are partitioned to associate all measurements from common targets into individual target categories. Sensor measurements are compared with correlation metrics that use temporal, spectral or spatial properties to score each alternative assignment hypothesis. The sensor data are then associated with the corresponding data from other sensors and are assigned to categories (e.g., track files, targets, entities, events).
- **Combination**. The process of combining data from all sensors to derive a refined estimate of state and identity must manage the uncertainty in sensor measurements and provide estimates with associated measures of estimate uncertainty.
- **State and Identity Estimation**. The output product from the data fusion process includes estimates of state (kinematic behavior, often in the form of a track file including track history and a state model to predict short term dynamic behavior) and identity of the entity or event.
- **Assessments of Situation and Threats**. At a higher level of abstraction, the process also evaluates the meaning of the data to assess the situation, including potential threats (defensive) and opportunities (offensive). This process incorporates intelligent reasoning functions including iterative search operations to assess the meaning of entire data sets at the highest level of abstraction.

3.3 Categories of Data Fusion

Four categories of data fusion application that must be mastered to achieve the objectives of *New World Vistas* include:

- **Target Data Fusion**. The fusion of point target data from multiple co-located or dispersed sensors to develop target state (tracks) and identities for C^4I systems.
- **Multisensor ATR Data Fusion**. The fusion of imaging (two-dimensional) and non-imaging data to perform automatic target recognition.
- **Image Data Fusion**. The fusion of multiple sources of image (two-dimensional) and non-image data to generate enhanced image products that present the full information content from all sources.
- **Spatial Data Fusion**. The fusion of more general spatial data (three-dimensional representations of real-world surfaces and objects that are imaged) combines multiple data views into a composite set incorporating the best attributes of all contributors.

This paper describes the motivations for sensor fusion before defining both image and spatial data fusion as a subset of the more general fusion process. Then, the state of the art in three major application areas is described.

The taxonomy in Figure 3-1 illustrates the functions of each form of data fusion and the distinctions between the output products for each of the four.

These four categories are required throughout the seven representative operational tasks of the *New World Vistas*, as demonstrated in Table 3-1.

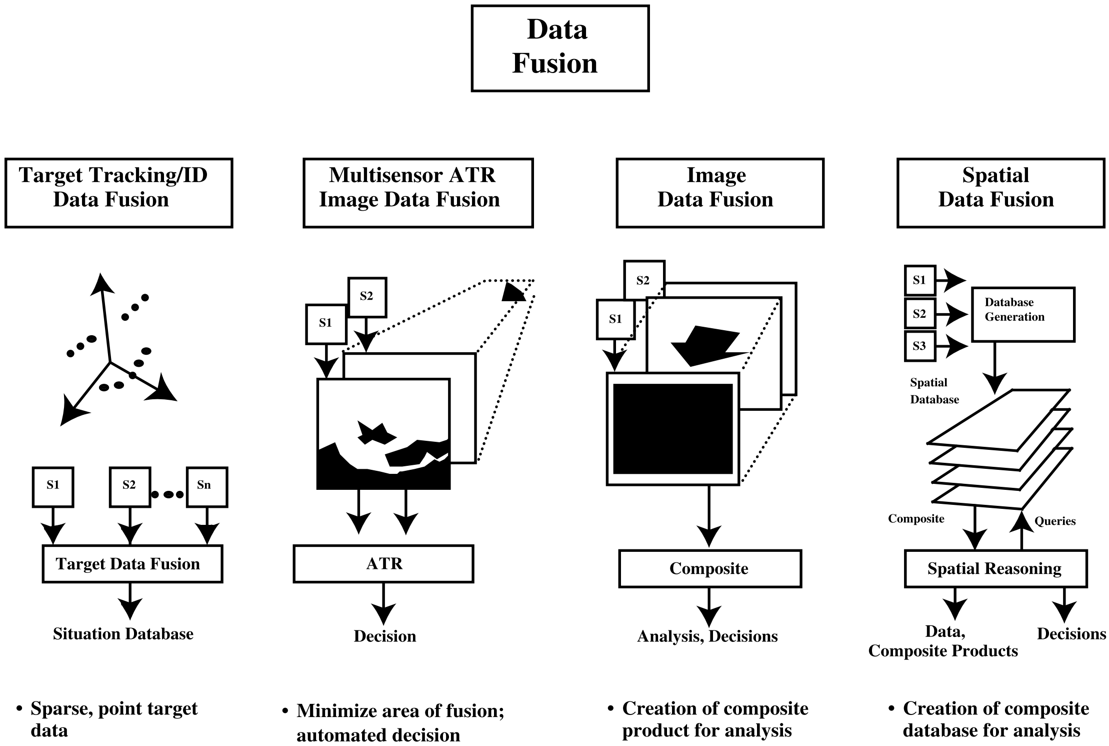

Figure 3-1. Four Categories of Data Fusion are Required for New World Vistas

Table 3-1. Representative Roles of the Four Categories of Data Fusion Across the Seven Air Force Operational Task Areas

Operational Tasks	Target Data Fusion	Multisensor ATR	Image Data Fusion	Spatial Data Fusion
1. Real-Time Situation Awareness	Target Tracking and ID	Non-Cooperative Target ID, Recognition	Surveillance Imagery Enhancement	Terrain Visualization, Planning
2. Global NBC Capability Surveillance	Equipment, materials Detection, tracking	Equipment, Materials ID	Surveillance Imagery Enhancement	Facility Visualization
3. Hardened/ Underground Facility Surveillance			SAR/HS Detection	
4. Recon and Deliver Weapons to Air-Ground Targets	Netted Target Tracking	Non-Cooperative, Lethal Target Recognition	Target Map Generation	Ground Target Precise Geo-Location
5. Detect, Track, Intercept Theater Ballistic Missiles	Detect and Track Via Air, Ground, Space Sensors	Radar/IR/LADAR Missile Typing		
6. Acquire, Maintain, Disseminate Info for MOOTW	All-Source Intel and Traffic, Personnel tracking	Non-Cooperative, Non-Lethal Target and Personnel recognition	Personnel (Facial) Recognition: Intel and Security	Terrain Visualization, Planning
7. Force Sustainment and Product Assurance			Non-Destructive Testing Image Analysis	Robotic Handling of Complex Components

3.4 General Model of Data Fusion

A general model of the data fusion process can be used to define the functional elements and the stages of the fusion process. We use the Joint Directors of Laboratories (JDL) general model[3] to compare target data fusion with multisensor ATR data fusion in which imagery data is fused (Figure 3-2). The JDL model distinguishes three processing levels: Level 1 processing performs the sensor-to-sensor data registration, correlation-association, and state/identity estimation, Level 2 performs situation assessment based on all data, and Level 3 assesses the threat content of the data. (A Level 4 is not shown, which includes management of the sensors and the internal fusion processes to optimize the process. Objective functions for optimization include: sensor emissions, target update rates, estimation accuracies, computation load utilization, etc.). The following paragraphs describe data fusion in the context of three of the four categories of data fusion.

Target Data Fusion—The generic JDL data fusion model (top sequence in Figure 3-2) illustrates the target data fusion process sequence in which multiple sensors (the collection assets) report the detection (or pre-detection raw measurements) of targets with associated state measurement data. The stages of processing include:

- **Preliminary Filtering**. Performed to remove noise and apply sensor-specific corrections (e.g., bias, gain and non-linearity corrections) to the data.
- **Alignment**. All measurements are placed in a common temporal and spatial reference frame by: (a) applying dynamic target models to extrapolate all state

3. Franklin E. White, Jr., "Data Fusion Subpanel Report," in *Proc. Fifth Joint Service Data Fusion Symp.*, October 1991, Vol. I, pages 335-361.

measurements to a common sample interval, and (b) applying spatial transformations to bring all measurements into a common coordinate system.

- **Association**. New measurements are correlated with predicted states of all known targets to determine if each measurement can be assigned to update an existing track, used to start a new track, or eliminated as a false alarm measurement.
- **Tracking**. Sequences of data for any target are used to develop a dynamic target model which is used to predict the future location of targets (at time t+1) for association with new sensor observations and for correction of motion distortions.
- **Identification**. All of the associated data for a given target are used to perform automatic target recognition and to provide an assignment of the target to one or more of several target classes.
- **Levels 2 and 3 Processing**. The entire scene context is considered (terrain, target mix and spatial arrangement) to derive an assessment of the "meaning" of the scene in terms of threats, opportunities for engagement and probably intent of the targets present.

Image Data Fusion for Multisensor ATR—When image data must be fused to create a composite image for automatic target recognition, similar stages are performed, but the processes are different. Consider the process flow in which two dynamic imaging (video) sensors and a non-imaging (RF direction finding) sensor are fused to recognize a tactical target (lower sequence in Figure 3-2):

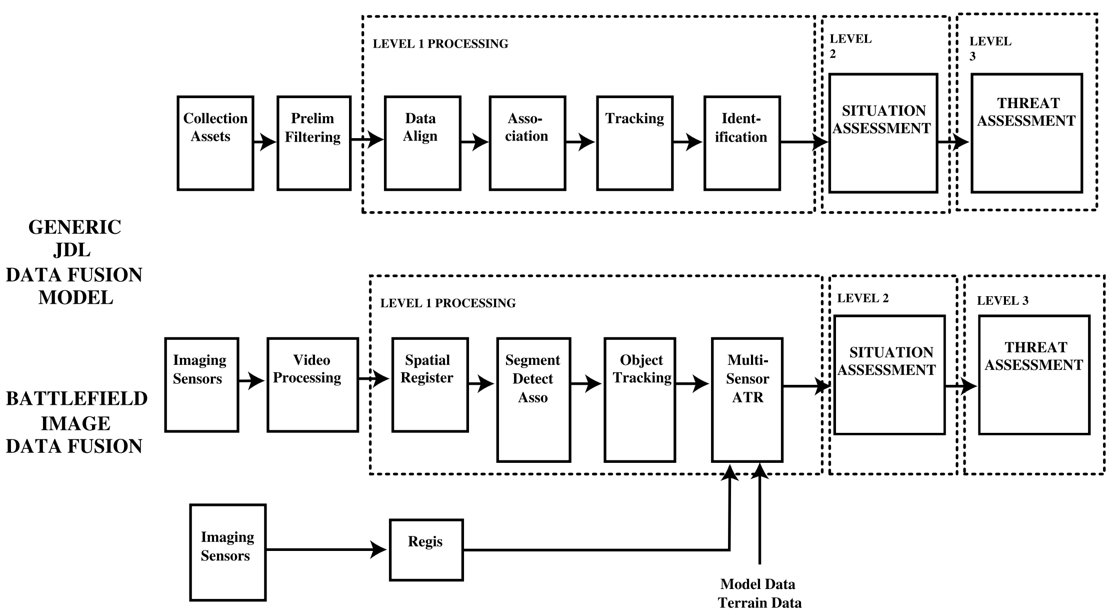

Figure 3-2. Data Fusion Functional Model is Shown for Target Data Fusion and Multisensor ATR Data Fusion Applications

- **Video Processing**. Frequency domain filters limit noise bandwidth and remove narrow-band noise content.
- **Alignment**. The alignment of video data involves the application of spatial transformations to warp the image data to a common coordinate system (e.g., projection to an earth reference model or three-dimensional space). The non-imaging data are spatially referenced, not to a point in the image, but to a region with a specified uncertainty, from which the detected emission occurred.
- **Association**. First, target candidates are detected and data regions encompassing the candidates are segmented. Then, the current target candidates (at time t) are associated with previously detected objects (at time t-1) by scoring the likelihood of each hypothesis pairing. Based upon the likelihood of each pairing, assignments (of new measurements to existing targets) are made, or multiple assignment hypotheses are created and maintained for latter updating or deleting when reinforcing or contradicting data are found in subsequent images.
- **Tracking**. The objects are tracked in video by modeling the dynamics of target motion to predict the future location of targets (at time t+1) for association with new sensor observations and for correction of motion distortions.
- **Multisensor ATR Identification**. The segmented target data from multiple sensors are combined (at any one of several levels) to provide an assignment of the target to one or more of several target classes.
- **Levels 2 and 3 Processing**. The entire scene context is considered (terrain, target mix and spatial arrangement) to derive an assessment of the "meaning" of the scene in terms of threats, opportunities for engagement and probable intent of the targets present.

Spatial Data Fusion—Perhaps the most complex form of data fusion for *New World Vistas* applications is spatial data fusion to create a spatial model of a region of the earth, with spatial associations to all available intelligence data in the region. This process requires the combination of diverse sets of imagery [spatially referenced non-image data sets, two-dimensional (2-D) images and three-dimensional spatial data sets] into a composite spatial data information system. The most active area of R&D in this category of fusion problems is the development of geographic information systems (GIS) by combining earth imagery, maps, demographic and infrastructure or facilities mapping data (geospatial data), and textual intelligence reports (spatially referenced) into a common database.

In the *New World Vistas*, the Air Force must develop such spatial databases for intelligence preparation of the battlefield (IPB), mission rehearsal and use as the base map for target data fusion. (The Terrain Feature Generator component of the Advanced Research Projects Agency [ARPA] War Breaker project is one example of a major spatial database and fusion system developed to automate the functions of IPB and geospatial database creation from diverse sensor sources and maps.)

Figure 3-3 illustrates the basic functional flow of such a system, partitioning the Level 1 (Spatial Data Integration) functions that perform database generation from the Level 2 (Scene Assessment) function. The functional stages parallel the functions in the earlier applications.

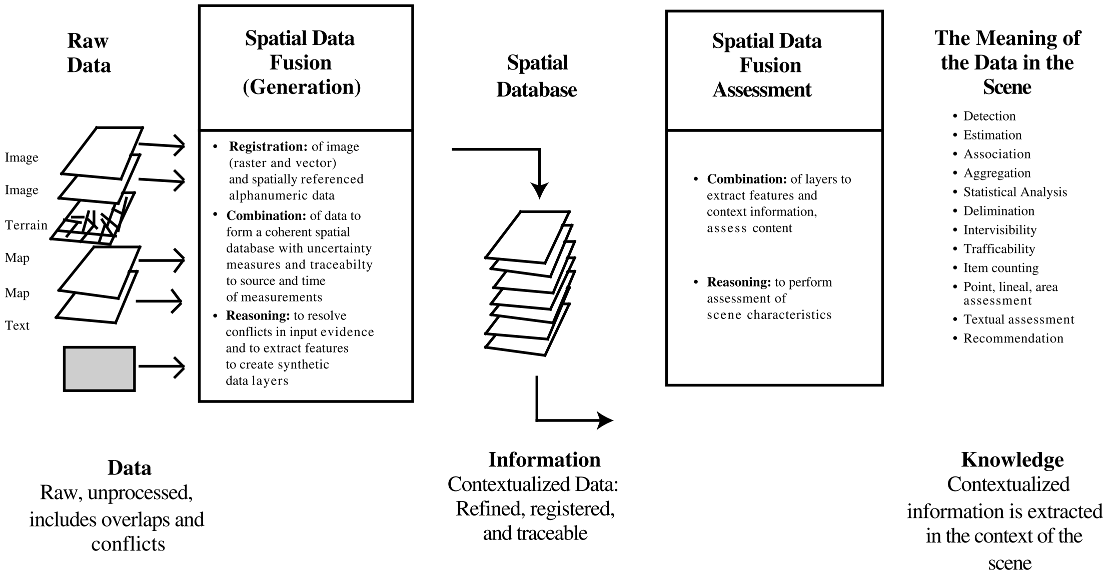

Figure 3-3. Spatial Data Fusion Process Generates and Maintains a Geospatial Database

- **Raw Data Preprocessing**. Data are accepted in a wide variety of physical and logical formats, all requiring conversion to acceptable raster or vector data formats. Maps are scanned, text messages are natural language processed, key words and spatial references are extracted, and raster (image) and vector (graphic) data are formatted. All data are augmented with metadata (data about the data sets) descriptors.
- **Registration (Alignment)**. Incoming data of varying accuracies and resolutions are spatially registered and linked to a common spatial and temporal reference.
- **Association and Combination**. Higher-level spatial reasoning is required to resolve conflicting data and to create derivative layers of extracted features. Data layers are combined (mosaicking, creation of composite layers, extraction of features to create feature layers, etc.) to produce registered, refined, and traceable spatial data.
- **Reasoning (for Tracking Changes)**. Changes in the data (e.g., road modifications, buildings, water levels, etc.) are identified in the data sets collected over time and are recorded. Configuration management is maintained on time tracked data.
- **Reasoning (for Identification of Features)**. Features in the data are extracted and identified using the multiple layers of sensed data on any particular object. This process may require statistical pattern recognition over a single pixel or region (as in multispectral analysis), spatial analysis, or higher-level spatial reasoning.

- **Scene Assessment.** The final step is scene assessment, which can be performed for a variety of application functions (e.g., further feature extraction, target detection, quantitative assessment, creation of vector layers, etc.) by a variety of user disciplines. This stage extracts information in the context of the scene and is generally query driven.

All of the data fusion models have a common set of processing problems which give rise to a taxonomy of design issues and system alternatives that are summarized in the next section.

3.4.1 Processing Taxonomy

Because of the wide range of applications for data fusion, the choice of system structural and functional processing architectures varies widely. The principal performance requirement parameters and operational considerations that impose constraints on data fusion system designers are summarized below:

- **Sensing Phenomenology**. The physical phenomena that are sensed, the discriminating characteristics of target classes, and interference phenomena (natural clutter, camouflage, concealment and deception) set ultimate limits on the achievable performance of the data fusion process.
- **Sensor Dimensionality**. The number of independent measured parameters (often referred to as observables) define the dimensionality of the total multiple sensor suite. The overall sensor load on the fusion process is quantified by the product of dynamic range (bits/sample) and sample rate (samples/second) for each dimension, summed over all contributing sensors.
- **Detection Performance**. The composite fusion detection performance is defined by the $P_{detection}$-to-$P_{false\ alarm}$ operating characteristic function (for single-sensor systems this is the well-known receiver operating characteristic). This composite performance requirement influences the choice of sensor pre-processing, uncertainty representation and inference approaches selected.
- **Information Accuracy**. The required accuracies for combined measurement estimates of state (three-dimensional location, velocities, etc.) and of identification parameters dictate the performance of individual sensors and the methods for representing and combining measurement uncertainty.
- **Information Currency and Latency**. Search rates, target revisit rates and processing speed are dictated by the requirements for currency (update rate) and latency (delay between sensor visits and delivered decisions) of fused information.
- **Security**. Requirements for multiple level security influence the combination processes and the methods chosen to assign security levels to data products that derived from multiple levels of secure data.

The taxonomy of processing alternatives that are influenced by these and other parameters are enumerated in Table 3-2. The taxonomy is based on five cardinal design trades that must be considered in any system design.

Table 3-2. Taxonomy of Fundamental Data Fusion Processing Alternatives

Processes	System and Processing Design Issue	Alternative Approaches
Representation and Management of Sensor Data Uncertainty	Level 1 - Select the most effective means to measure, represent and combine values of sensor uncertainty across all sources of data.	• Certain data (Boolean logic) • Uncertainty or confidence intervals • Probabilities (Bayesian inferencing) • Multi-Valued probabilities (Dempster-Shafer evidential reasoning) • Fuzzy sets (Fuzzy logic) • Random Sets (Combinatorial Algebras) • Multiple Hypothesis Maintenance
Representation of Knowledge	Level 2 - Represent and store information in a manner that permits efficient access, linkage and retrieval.	• Rules or Frames • Semantic Networks • Neural Networks • Graphical Relationships (space, time, spectrum) • Vector/Raster Spatial Data
Inference, Reasoning and Evaluation	Levels 2 and 3 - Partition (associate) and combine raw data to optimize the estimates of parameters about the source of data, and infer higher-level information about the source and its context.	• Induction • Deduction • Exhaustive or incomplete search • Default Inference - Boolean - Bayesian - Evidential Reasoning - Fuzzy
Processing Control	Level 4 - Control the sensing and processing functions in accordance with a defined objective function.	• Control Theory • Monotonic Reasoning • Non-monotonic Reasoning • Opportunistic Reasoning
Architecture	Interconnect sensors and sources in accordance with network bandwidth, security, distribution and processing constraints	• Centralized fusion processing at a common node in a network • Distributed fusion processing throughout a heterogeneous network

First, is the selection of a means to represent the uncertainty in sensed data. If the signal strength in individual sensors is high, each sensor may independently perform detection decisions and measure target features for combination. In this case, detection data is reported as certain and a simple Boolean rule (AND, OR) is all that is needed for detection fusion. If, on the other hand, sensor measurements are weak, raw signals with uncertainty measures may be used to perform composite detection decisions (and classification decisions). Numerous alternatives (listed in the table) exist to represent signal uncertainty and to combine uncertain data to express composite uncertainty.

Second, are the alternative methods to represent *a priori* knowledge (target signatures, relationships between signatures and entities, behaviors of entities, etc.) and knowledge accumulated by the fusion process.

The third design alternative is closely related to the chosen knowledge representation scheme: the means to evaluate and infer new knowledge based on *a priori* knowledge and composite information compiled from sensor measurements.

The fourth design alternative is the selection of a control structure to manage the sensing process (e.g,. sensor tasking, sensor mode control and emission control) and the fusion process. The management of sensors and the associated reasoning process can be closely coupled to adapt to a time-varying target load and is heavily influenced by each unique application environment.

The fifth alternative is the overall system architecture, which may employ centralized or distributed data fusion processes, depending upon factors such as sensor-processor distances, available network bandwidth, security, distribution (display) and processing constraints.

3.5 Challenges and Opportunities

The same “grand challenges” that face the general sensor area (noted in Section 3, “The Sensor Correlation and Fusion Process”) apply to the fusion process because fusion is simply the process that allows a suite of sensors to be viewed as a single unit. These include: the ability to accept higher data rates and volumes, improved multiple sensor performance and improved multiple sensor operation. In addition to these, several additional challenges can be added:

- **Improved Integrated Sensors**. *New World Vistas* sensors will be designed from the ground up as elements of a multisensor suite, rather than as independent sensors with outputs that can be input to fusion. Integrated apertures, coordinated operating modes, synchronous sampling and common measurement reporting formats must be developed for these sensor suites to optimize the suite performance—both in management and collection efficiency.
- **More Robust Fusion Processes**. Fusion processes must be capable of accepting wider ranges of sensor data types (true “all-source” processes), accommodating natural language extracted text reports, precision-to-uncertain sensor measurements, historical data, and spatial information (maps, charts, images).
- **Improved Learning Abilities**. Fusion processes must develop adaptive and learning properties, using the operating process to add to the knowledge base

while exhibiting a sensitivity to “unexpected” or “too good to be true” situations that may indicate countermeasures or deception activities.

- **Enhanced Immunity to Information Warfare Threats**. Because the data fusion process is the node toward which all sensor data flows and information resides, it is the highest value target for information warfare attacks. System architectures must be designed to defend against: (a) active attacks (transmission or malicious code attacks), (b) deception, (c) disruption, or (e) exploitation.
- **More Robust Spatial Data Structures**. Efficient, linked data structures are required to handle the wide variety of vector, raster, and non-spatial data sources needed to perform global and regional spatial data fusion. Hundreds of point, lineal, and aerial features must be accommodated. Data volumes for global and even regional spatial databases will be measured in millions of terabits, and short access times are demanded for even broad searches.
- **Improved Spatial Reasoning Processes**. The ability to reason in the context of dynamically changing spatial data is required to assess the “meaning” of large volumes of spatial surveillance data. The reasoning process must perform the following kinds of operations to make assessments about the data: spatial measurements (geometric, topological, proximity, statistics, etc.), spatial modeling, spatial combination and inference operations in the presence of measurement uncertainty, spatial aggregation of related entities, and multivariate spatial queries.