Information Analysis and Uncertainty: Selected R&D and Commercial Activities

Presented to Sandia National Laboratories Networks Grand Challenge (NGC)

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This report contains a sampling of activities from industry and academia that specifically address uncertainty in the context of information analysis. While the information presented is by no means comprehensive, the intent is that reviewing these selected items will provide NGC with a useful point of view in gauging the overall maturity of the field.

A table of contents appears on the next page. A short summary of highlights is provided in Chapter I.

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I. Introduction

A. Background

Perspectives was asked by the Networks Grand Challenge team to review academic and commercial activities related to incorporating concepts of uncertainty into analysis of large sets of data. Perspectives was given broad leeway to look at areas of potential interest, with the general guideline of focusing on activities similar in some way to the approaches of the NGC.

We searched a variety of sources throughout the effort. A bibliography of scholarly publications provided by Tim Trucano was a useful starting point in understanding areas of possible interest, and while our efforts were mostly focused on areas other than academic literature, the bibliography was very helpful for seeding the search. We looked for work focused on NGC-like problems; at the request of team members, we searched specifically for work around visualization and work around ontologies; and we examined work that referenced concepts and keywords similar to what we have seen in NGC materials. We specifically excluded several areas where the NGC team already has expertise (e.g., V&V). The search was limited to open-source materials.

The effort was *not* intended as a thorough benchmark of all activities around uncertainty. This is a good thing, insofar as uncertainty plays a role in a large number of areas, and to catalog all of them would be an immense (and not necessarily enlightening) undertaking. Rather, our goal was to identify the most important activities and to gauge overall maturity for dealing with problems of uncertainty in intelligence analysis.

B. Observations and Highlights from the Material

First and foremost, Perspectives' review of work in uncertainty makes it starkly clear that approaches for incorporating uncertainty into systems for information analysis and visualization are basically immature. This is a problem that is sufficiently large and difficult that, in general, the approach seems to have been to focus on the more tractable issues, or to focus in quite narrow application areas. This is not to say that consideration of uncertainty is a neglected area. On the contrary, uncertainty is the subject of intense interest and activity, with targeted conferences, active discussion, theorizing, and research.

Part of the problem appears to be in the nature of uncertainty. Dealing with the issue is more akin to public health responses to the flu than to polio – that is, flu outbreaks can be mitigated and addressed (and should be), whereas polio can be "solved." This is in part the result of the fact that uncertainty as an overarching concept spans a variety of very different sub-types. Indeed, some of the more interesting work we identified focused on simply delineating the various phenomena that together comprise uncertainty. This work makes a strong case that the appropriate approach for dealing with uncertain information will depend upon the particular type of uncertainty involved. In other words, it appears unlikely that a unified model and a corresponding single approach will be productive in addressing the needs of uncertainty (in the context of the IC or otherwise).

We also note that the fact that productive research is being done on something as fundamental as a schema is itself indicative of the immaturity of the field. Having a firm grasp of constituent types of uncertainty, if not a consensus on the taxonomy, would appear to be a necessary precondition for developing robust solutions.

While operational and command-and-control and warfighter issues of uncertainty were not a primary focus of this report, we did come across a large body of interesting work relating to such issues, much of it motivated by Department of Defense needs (see SBIR projects listed in the Appendix). This problem is inherently real-time and is thus different – and arguably more difficult – than that typically envisioned for NGC tools (where analysts will typically have time to consider any given question). It appears to us that the operational uncertainty issues drive researchers towards focused approaches, as any advances must

be applied in real-time to streams of information. There is also an emphasis on geospatial issues relating to targeting. The realm of cyber defense as envisioned by NGC has some things in common with the operational realm of uncertainty, but in general it seems to us that the problems are fairly distinct.

There is significant activity around data visualization as a means for communicating uncertainty. We would characterize the various tools that have been developed as interesting, relevant, and potentially helpful, but intended more as widgets or demonstrations than any sort of unified solution.

Some of the highlights of the material include:

- We identified a group at the **Swedish Defense Research Agency** as important in the area of uncertainty and intelligence analysis. Pontus Svenson and collaborators are notable in that much of the work is focused on uncertainty in the IC context. The group has spent considerable time thinking about the issues; and Svenson and others in the group publish frequently. Svenson's work is excerpted in the first section of this report. Impactorium is a tool the group has developed that helps users estimate the probabilities of various events that might occur in the future and which will have an impact on the user. Another key paper reviews some of their approaches to **adding uncertainty-handling to network analysis for intelligence analysts**.

- Jason Schenk (Ohio State University) writes in his PhD thesis on a visual and systematic framework to convey and document **meta-uncertainty for intelligence analysis**.

- Jennifer Widom of Stanford University has just begun a **NSF-funded project** on a "novel and resizable" information integration system targeted at an environment where multiple sources have joining, overlapping and potentially conflicting information about the same or closely related real-world entities **that permits and exploits uncertainty as an integral part of data integration**.

- **21st Century Systems, Inc**., provides the Webster-ACE product to the IC community. This tool is an integrated information fusion dashboard with "a system that can fuse uncertainties from multi-source data sets using two distinct detection mechanisms." While Perspectives has not been able to examine the product directly, we did find one product screenshot indicating that analyst input and peer ratings of source reliability are incorporated.

- We identified a few other companies that may have done some innovative work around uncertainty. Like 21st Century Systems, most of these were initially funded by DOD but have since broadened into other applications. Notably, **Aptima, Charles River Analytics**, and **Secureboration** have research credibility and funding awards relating to uncertainty in information analysis.

- **Ontologies used by the IC** are now the subject of an annual conference ("Ontology for the Intelligence Community"). Detailed papers are available online, and uncertainty is a key focus for much of the work reported in this conference. Some of the papers from this and other sources, that caught our eye are focused on marrying formal ontology with probabilistic reasoning, an ontology of evidence (and the many varieties of uncertainty), interoperability between ontologies, ontologies of "substance-blind classes of items of evidence," uncertainty in ontology mapping, modular ontologies, and so on.

- The literature on visualization of uncertainty, as one researcher described it, must first focus on what and how uncertainty is expressed. Thus, much of the literature in this area attempts to enumerate the **various classes of uncertainty**, such as uncertainty in accuracy/error, precision, completeness, consistency, lineage, credibility, disagreement, inferences, uncertainty awareness, cyclic uncertainty, and so on. Researchers working in this area from Microsoft provide an interesting map of existing uncertainty visualizations to their own classification categories.

- Techniques for visualizing ancillary uncertainty information together with the data are reviewed on a useful site provided by the **UC-Santa Cruz Laboratory for Visualization and Graphics**. Techniques include adding glyphs, adding or modifying geometry, modifying attributes, animation, sonification, and psycho-visual approaches.

- **Alexander Streit** has written a fascinating thesis on modeling and visualizing information uncertainty. His goal was to present an integrated environment that, among other things, automates the propagation of uncertainty, where uncertainty information is "encapsulated and treated as a unit allowing users to think of their data model in terms of the variables, instead of the uncertainty details." He also explores a "Unified Uncertainty Model" for the purpose of visual mapping.

II. Uncertainty and Intelligence Analysis / Defense Applications

A. Pontus Svenson, Swedish Defense Research Agency

Pontus Svenson and the Information Fusion Group at the Swedish Defense Research Agency are actively working in the area of uncertainty and intelligence analysis.

> We do research on **high-level information fusion and management of uncertainty.** Our research interests include the theoretical and applied aspects of soft computing, belief functions, neural networks, particle filtering, swarm intelligence/complex systems, social network analysis, data mining, information management, mixed-initiative interaction and military applications of high-level information fusion and artificial intelligence, especially approximate reasoning, management of uncertainty, and machine learning applications for situation and threat assessment and high-level resource management and its use in decision support systems. Our application focus is on effects-based planning and information fusion methods for intelligence information processing in network-centric operations. The group was founded on 1 July 1986.

A 2009 paper on "Uncertainty modelling for threat analysis" is available (full text available at link). One interesting concept discussed in this paper is "negative information" or "the absence of any sensed data corresponding to expected information." The abstract of the paper is shown below.

> Accurate modelling of information and knowledge is central to the modern command and control (C2) process. Without models and a language for describing them, it is impossible to collaborate on C2. All information which enters a C2 system will be uncertain, and hence it is important to be able to model the uncertainty in a way that makes it possible for us to understand it. Some kinds of knowledge can be embedded into reasoning systems designed to help humans sense-making. In order to do this, it is necessary to obtain the relevant knowledge (from humans, sensors and databases of background information), to model it in an appropriate way, and to design computer tools that use these models. In this paper, we describe some aspects of knowledge and information that are important both for understanding the C2 process and for constructing computer tools that help humans achieve situation awareness. We describe positive and negative information, and the concept of indicators as well as how they can be used in a computer tool for threat analysis.

The conclusions of this paper are worth reproducing in full and may be a good indication of just how far we have to go in dealing with uncertainty in intelligence analysis:

> While the concepts introduced and presented in the text all contribute to understanding and tackling problems in the decision-maker's situation, **we have not operationalized them quantitatively, even less proposed a best practice for decision-making in C2-systems**. Therefore, the road ahead should aim for precisely that by investigating methods and experiments to learn about the variability in knowledge and information factors, and the changes in quality of decisions, and the organizational consequences for efficiency and effectiveness.
>
> **Background factors**
>
> - Experience – How can previous experiences be formalized in terms of similarity in operation, team, operational environment? What is the impact? Can experience be a negative factor?
> - Knowledge – How can different types of knowledge (e.g., facts, understanding, ability, expertise) be tested in a meaningful way? To what extent can they replace experiences from previous operation?
> - Learning – From moments of reflection about the situation picture, to acquiring expert knowledge, to following the situation development over long periods, what is the role of learning in decision making?

- Expectations – How do expectations help and limit our information space? What is the exact relationship to experience and knowledge in different situations? How can we proceed more efficiently by taking our own expectations into account?

Situation factors

- Uncertainty – What is the relative importance, common ways of overcoming, and potential use-cases for decision-aids with regards to different types of uncertain information (lack of, contradictory, uninterpretable, invalid, unknown source)? How is it related to lack of knowledge? How well do we know our current organizational status?
- Negative information – What is the usability of description logic to express NI in a formalized way to store and report important NI? How can it contribute to reasoning about the situation (e.g., pruning alternative courses of adversary actions or excluding reconnaissance areas)?
- Indicators – What is the relative importance of different types of indicators? Can we overcome subjective biases and shortfalls by including model-based conclusions in a decision aid?
- Insecurity – How will stress and experienced risks change the decision quality? Can we define situations where reasoning becomes so degraded that a decision-aid should be given higher authority?

Decision and action factors

- Planning – What types of long, mid, and short term plans guides decision-making in a quickly changing situation? How "general" can a plan be for both meeting the challenges of a changing environment and enable preparedness and relief for the decision maker?
- Organization design – What types of organizational structure will be most successful in agile responses, given the decision-aids that are available today and tomorrow? If authority is distributed, will decisions be made in more insecure (field) environments?
- Time factors - Are there known schedules, events and orders, intervals, and other time aspects in uncertainty and security related phenomena? To what extent can such knowledge guide information requests and change the space of opportunities for decision-making and acting? For instance, are perceived threats smaller or bigger, taking the time-factor into account? Further, are prognoses beyond a certain time horizon too complex? When is it better to postpone a decision?

For all these sets of factors interesting specific questions exist with respect to decision aids. Yet, perhaps most important is how the factors relate to each other and whether shortfalls in one (e.g., knowledge or certain information) can be overcome by another (e.g., automated reasoning tools). The way to proceed would need careful and deliberate investigations, in which methods may need to be

The Svenson group has developed a tool for analysts, **Impactorium**, that helps users estimate the probabilities of various events that might occur in the future and which will have an impact on the user. (From "Development of Computerized Support Tools for Intelligence Work," 2009, full text paper)

It is based on the Impact matrix concept, where events of interest are visualized in a 2 × 2 matrix where the axes represent a priori probability and impact, respectively. In [39], we described a dynamic Impact matrix that has a semi-automatic coupling to real-world events that change the probability that an event is occurring or will occur in the near future. This is done by coupling incoming HUMINT reports to indicators that give a high level description of what they are about. The indicators are assumed to be associated to the reports either automatically or, most likely, by human operators that monitor sensors and incoming reports.

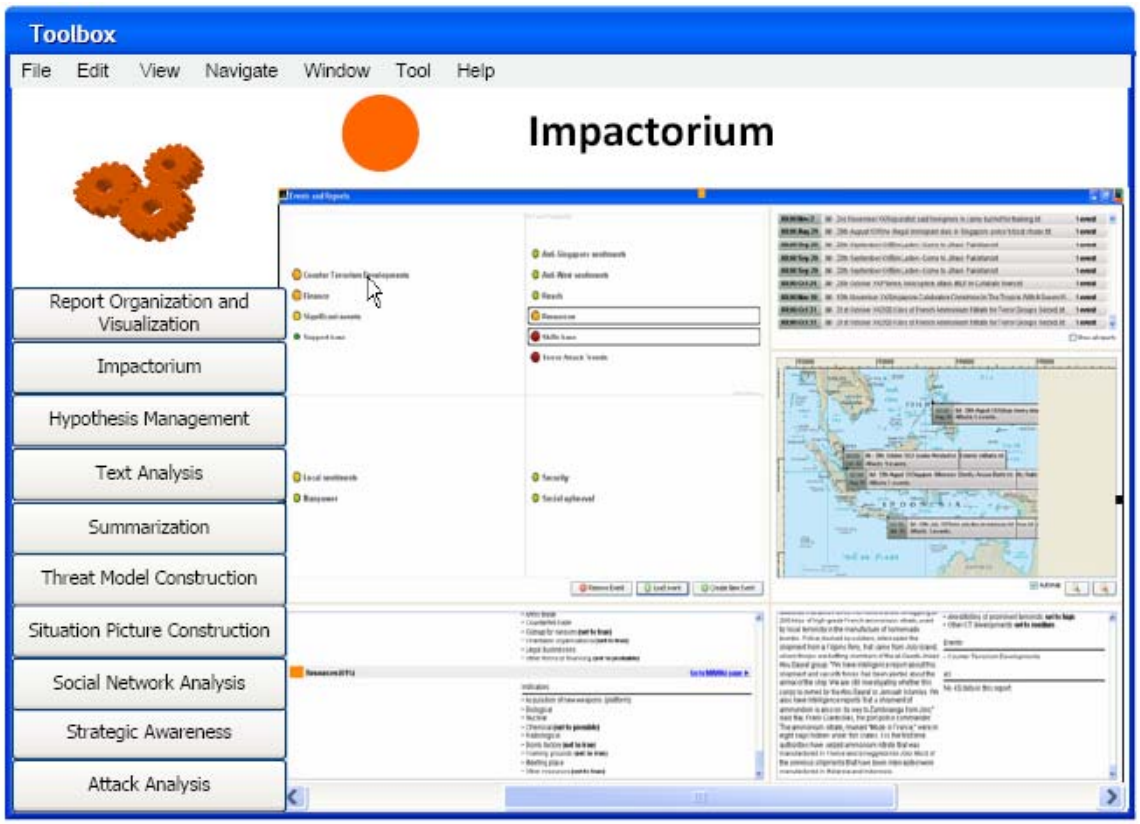


Figure 4: User interface of the Impactorium tool.

Indicators are generated using a Bayesian network linked to hypotheses about the realization of events; that is, the indicators, together, give different probabilities that a certain event will happen. When the probability of an event changes, it is indicated in the matrix by changing the color and size of the circle displayed next to the event. Thus, by looking at the matrix, it is possible for the user to immediately spot events that are about to occur, hopefully leading to increased situational awareness and giving the user the opportunity to act proactively.

Currently, Impactorium only supports model-based threat analysis. This means that the indicators as well as the Bayesian network used to calculate the event probability based on the values of the indicators must be **specified by a subject-matter expert beforehand**. Another approach to generating threat models for use in Impactorium would be to use statistical methods for learning accurate threat models from a large set of data. This, however, requires large amounts of data, which is not available for our problem domain of interest. There are two drawbacks to using the model-based approach: specifying the models requires a large amount of human effort, and it is not possible to automatically discover new threats for which there are no models. We are tackling these difficulties in several ways.

As outlined in Section 6.5, we will attempt to construct tools that help the users construct appropriate threat models. We are also **working on a method for automatically updating the Bayesian network used in a threat model if the user determines that the value calculated for the probability is wrong. Future versions of Impactorium will also include functionality for clustering observation reports that could be used to semi-automatically learn new threat models.**

Other publications of interest from this group include:

- "Social Network Analysis of Uncertain Networks," Svenson, P., in *Proceedings of the Second Skövde Workshop on Information Fusion Topics* (SWIFT 2008), University of Skövde, Sweden, November 4−6, 2008, pp. 2−4, Skövde Studies in Informatics (2008). (Full text)

  Analyzing networks (primarily social, but also computer networks or networks relating events to each other) is an important part of the intelligence analysis process. Currently, computer tools for network analysis lack functionality for adequately representing and reasoning with uncertain information. In this extended abstract, we outline some approaches to adding uncertainty-handling capabilities to network analysis.

- "System prediction combining state estimation with an evidential influence diagram," Schubert, J., Svenson, P. and Mårtenson, C., in Proceedings of the Twelfth International Conference on Information Fusion (FUSION 2009), Seattle, WA, July 6-9, 2009, pp. 428−435. (FOI-S--3158--SE, Swedish Defence Research Agency, 2008) (Full text)

  In this paper we develop a system state estimation model for combining partial information regarding the state of a system of interest. In addition we develop an evidential influence diagram representing our a priori knowledge of system relations. Both system state estimation and a priori knowledge are represented by belief functions. A predicted future system state is obtained by combining the fused estimated system state with the fused a priori knowledge. The predicted system state can be marginalized to give specific state predictions of all variables of interest of the system state estimation model. Finally, we may compare predicted system states with later actual states to highlight any deviations from expected developments.

- "An Overview of the Impactorium Tools 2008," Forsgren, R., Kaati, L., Mårtenson, C., Svenson, P. and Tjörnhammar, E., in Proceedings of the Second Skövde Workshop on Information Fusion Topics (SWIFT 2008), University of Skövde, November 4−6, 2008, pp. 74−76, Skövde Studies in Informatics 2008:1. (FOI-S--2975--SE, Swedish Defence Research Agency, 2008) [PDF]

- "A Vision of a Toolbox for Intelligence Production," Brynielsson, J., Horndahl, A., Kaati, L., Mårtenson, C. and Svenson, P., in Proceedings of the Second Skövde Workshop on Information Fusion Topics (SWIFT 2008), University of Skövde, November 4−6, 2008, pp. 77−80, Skövde Studies in Informatics 2008:1. (FOI-S--2976--SE, Swedish Defence Research Agency, 2008) [PDF]

A full list of publications from this group is available here.

B. Hybrid Uncertainty

Lewis Warren, a researcher at the **Australian Defense Science and Technology Organization**, has published information on what he describes as a new approach to fuzzy uncertainty representation with "more rigorous uncertainty management in aggregation operations." (Webpage; Full text paper)

"On modelling hybrid uncertainty in information" (2007) Report number: DSTO-RR-0325 [Australia]

Abstract: Numerical induction models are considered in this report to be models that aggregate lower-level information into higher-level measures for decision making. Various forms of uncertainty may be present in such models including hybrid uncertainties within the information elements being aggregated. After a review of some existing approaches for representing higher-order uncertainty in information, a new approach is presented to enable greater fidelity of uncertainty representation, and consequently more rigorous uncertainty management in aggregation operations. Several different applications then demonstrate the proposed procedures which have direct relevance to many Defence decision making models where higher-order uncertainty is ubiquitous. The overall objective of these procedures is to extract as much meaning from the input information as possible.

C. National Research Council

1. Committee on Intelligence Analysis

The National Research Council's Division of Behavioral and Social Sciences and Education has convened a **Committee on Behavioral and Social-Science Research to Improve Intelligence Analysis for National Security.**

> To better inform and improve the work of the IC, ODNI requested the National Research Council to convene a panel of experts to synthesize and assess the behavioral and social-science research evidence relevant (**1) to critical problems of individual and group judgment and of communication by intelligence analysts and (2) to kinds of analytic processes that are employed or have potential to address these problems.** To the extent the evidence warrants, the panel will recommend kinds of analytic practices that intelligence analysts should adopt or at least explore further. The panel will also recommend an agenda of further research that is needed to better understand the problems analysts face and to establish a base of evidence for current and potential solutions. Finally, the panel will identify impediments to implementing the results of such research, especially new tools, techniques, and other methods, and suggest how their implementation could be more effectively achieved.
>
> **Committee Membership**: Baruch Fischhoff (Chair), Carnegie Mellon University, IOM; Hal Arkes, Ohio State University; Bruce Bueno de Mesquita, New York University; Thomas Fingar, Stanford University; Reid Hastie, The University of Chicago; Edward Kaplan, Yale University, IOM/NAE; Steven Kozlowski, Michigan State University; Gary McClelland, University of Colorado; Kiron Skinner, Carnegie Mellon University; Barbara Spellman, University of Virginia; Philip Tetlock, University of California, Berkeley; Catherine Tinsley, Georgetown University; Amy Zegart, University of California, Los Angeles.

This committee routinely holds meetings of experts reporting on relevant research, and their presentations are available online. This source merits watching over the long term because they have identified dealing with uncertainty as one particular area of interest in their roadmap for modeling individual / organizational / societal behavioral modeling (see source).

One recent NRC presentation of interest is shown below (May 15, 2009 workshop).

Applied Behavioral Sciences in Support of Intelligence Analysis, Dr. David Mandel, Defence Scientist, Defence Research and Development Canada

SELECTED SLIDES BELOW

Outline

- Canadian perspectives – TRIG
- Study aimed at validating the effectiveness of training to improve probabilistic belief revision.
- Study aimed at validating the quality of predictive assessments from an intel assessment division.

Quantification of uncertainty in the division

- The IAS analysts are routinely directed to think first in terms of the numeric estimate on a 0/10 to 10/10 uncertainty scale.
- Only then for reporting purposes do they translate that estimate into a congruent verbal expression.
- An advantage of this approach is that accuracy of predictions can be assessed using precise measures of judgment quality.

PROBABILITY TERMS

Verbal Expression	Probability	Remarks
will is certain	[10/10]	where you can envisage no plausible scenario—however remote—where this event would not happen
almost certain extremely likely highly likely	[9/10]	there remains some conceivable scenario—albeit very remote—that this event would not happen
likely probable, probably	[7-8/10]	
slightly greater than even chance	[6/10]	use rarely, only when there is a specific reason to judge the probability at greater than even but cannot be categorized as "likely"
even chance	[5/10]	
slightly less than even chance	[4/10]	use rarely, only when there is a specific reason to judge the probability at less than even but cannot be categorized as "unlikely"
unlikely (only a) low probability probably not	[2-3/10]	
very unlikely highly unlikely extremely unlikely little prospect	[1/10]	there remains some conceivable scenario—albeit very remote—that this event could happen
no prospect will not	[0/10]	where you can envisage no plausible scenario—however remote—where this event could happen

2. A Note on NRC Reports on Uncertainty and Risk Analysis

Several reports from the National Research Council examine the issue of uncertainty and risk analysis. There is much discussion on uncertainty analysis in these reports, and strong cautionary statements about the possible downside of use of uncertainty analysis by federal agencies.

The first is a new report on "Science and Decisions: Advancing Risk Assessment" by the National Research Council's Committee on Improving Risk Analysis Approaches Used by the U.S. EPA" [online full text available]. This report has a **chapter devoted to uncertainty and variability**. According to a review of this report in *Science* (see "Five 'Easy' Questions" in the August 28, 2009 issue), uncertainty and variability are "explored along with many other concepts and practices of technical risk assessment so as to expose lingering problems – most of which are decidedly non-technical: 'The question is not often about better ways to do these analyses but about developing a better understanding of when to do these analyses.'"

Some important quotes from this Committee are shown below. The discussion of the level of uncertainty analysis needed is particularly interesting:

> Much has been written that addresses the taxonomy of uncertainty and variability and the need and options for addressing them separately (Finkel 1990; Morgan et al. 1990; EPA 1997a,b; Cullen and Frey 1999; Krupnick et al. 2006). There are also several useful guidelines on the mechanics of uncertainty analysis. However, there is an **absence of guidelines on the appropriate degree of detail, rigor, and sophistication needed in an uncertainty or variability analysis for a given risk assessment**. The committee finds this to be a critical issue. In presentations to the committee (Kavlock 2006; Zenick 2006) and recent evaluations of emerging scientific advances (NRC 2006a, 2007a,b), there is the promise of improved capacity for assessing risks posed by new chemicals and risks to sensitive populations that are left unaddressed by current methods. The reach and depth of risk assessment are sure to improve with expanding computer tools, additional biomonitoring data, and new toxicology techniques. **But such advances will bring new challenges and an increased need for wisdom and creativity in addressing uncertainty and variability. New guidelines on uncertainty analysis (NRC 2007c –** *see description below***) can help enormously in the transition, facilitating the introduction of the new knowledge and techniques into agency assessments. …**
>
> **Level of Uncertainty Analysis Needed:** The discussion of the variety of ways in which EPA has dealt with uncertainty—from defaults to standard QUA to expert elicitation—raises the question of the level of analysis that is needed in any given problem. **A careful assessment of when a detailed assessment of uncertainty is needed may avoid putting additional analytic burdens on EPA staff** or limiting the ability of EPA staff to complete timely assessments. … It is important to address the extent and nature of uncertainty analysis needed in the planning and scoping phase of a risk assessment).
>
> For many problems, a**n initial sensitivity analysis can help determine those parameters whose uncertainty might most impact a decision and thus require a more detailed uncertainty analysis. One valuable approach involves utilizing tornado diagrams,** in which individual parameters are permitted to vary while all other uncertain parameters are held fixed. The output of this exercise provides a graphical plot of parameters that have the largest influence on the final risk calculation. This both provides a visual representation of the sensitivity analysis, helpful for communication to risk managers and other stakeholders, and determines the subset of parameters that could be carried forward in more sophisticated QUA.
>
> "Tiers" or "levels" of sophistication in QUA in risk assessment have been discussed… the International Programme on Chemical Safety (IPCS 2006) has proposed four tiers for addressing uncertainty and variability in exposure assessment, from the use of default assumptions to sophisticated QUA. The IPCS tiers are shown in Box 4-4.

BOX 4-4: Levels of Uncertainty Analysis (Source: IPCS 2006)
Tier 0: Default assumptions—single value of result.
Tier 1: Qualitative but systematic identification and characterization of uncertainty.
Tier 2: Quantitative evaluation of uncertainty making use of bounding values, interval analysis, and sensitivity analysis.
Tier 3: Probabilistic assessment with single or multiple outcome distributions reflecting uncertainty and variability.

> The committee does not endorse any specific ranking approaches but favors the up-front consideration of levels of sophistication in uncertainty analyses and notes that there is a **continuum of approaches** rather than a number of discrete options. T**he characterization of uncertainty and variability in a risk assessment should be planned and managed and matched to the needs of the stakeholders involved in risk-informed decisions**. In evaluating the tradeoff between the higher level of effort needed to conduct a more sophisticated analysis and the need to make timely decisions, EPA should take into account both the level of technical sophistication needed to identify the optimal course of action and the negative impacts that will result if the optimal course of action is incorrectly identified.

An earlier NRC report (2007), "Scientific Review of the Proposed Risk Assessment Bulletin from the Office of Management and Budget" (access page), addresses uncertainty in risk assessment as well. In January of 2006, OMB issued a draft bulletin on Risk Assessment, which included a new definition of risk assessment and proposed standards aimed at improving federal risk assessments. OMB also requested that the Research Council review the bulletin. The NRC report concluded that the draft bulletin issued by OMB was "fundamentally flawed" and should be withdrawn.

This report provides significant discussion of uncertainty in risk assessment. Some key quotes from this document:*

> The difficult problem of uncertainty analysis is well-described in *Understanding Risk* (1996): Much attention has been given to quantitative, analytic procedures for describing uncertainty in risk characterizations. Participants in decisions need to consider both the magnitude of uncertainty and its sources and character: whether it is due to inherent randomness or to lack of knowledge; and whether it is recognized and quantifiable, recognized and indeterminate; or perhaps unrecognized. Unfortunately, the unrecognized sources of uncertainty – **surprise and fundamental ignorance about the basic processes that drive risk** – are often important sources of uncertainty, and **formal analysis may not help if they are too large**. Thus, uncertainty analysis should be conducted with care and in conjunction with deliberation and in full awareness of its limitations, especially in the face of unrecognized sources of uncertainty. It is best to focus on uncertainties that matter most to ongoing processes of deliberation and decision. The users of uncertainty analysis should remember that both the analysis and people's interpretations of it can be strongly affected by the social, cultural, and institutional context of the decision (NRC 1996, p. 5).
>
> These cautionary notes regarding the descriptions of uncertainties in risk assessments are echoed in other cited studies, but **none offers explicit guidance on the analytic methods best suited to evaluate and express uncertainties in specific contexts**. Although the cited studies generally do not offer explicit guidance on the conduct of uncertainty analysis, much work has been done in probabilistic risk assessment (PRA) to develop standards that explicitly incorporate such analysis. *[pp.18-19]*
>
> ***

* Also of interest from this report are statements from various agencies (including DOD and DOE) in response to these questions (although most of these responses are related to uncertainty in risk assessments for chemical toxicology and health issues): Please provide a brief overview of your current risk assessment practices. Specifically, do you conduct **probabilistic risk assessment**? Is there a common approach to both risk assessments and **uncertainty analysis**? How do you currently address uncertainty and variability in your agency's risk assessments?

> The committee is not suggesting that risk characterizations ignore uncertainties or omit reasonable depictions of the ranges of risk that might be suggested by the data. Indeed, as stated above, the committee urges the use of defaults and, when possible, alternatives to them. But the bulletin seems to go well beyond these modest approaches and can be read as calling for more fully quantitative expressions of the uncertainties in risk than have been offered in most applications of risk assessment. **In the absence of clear guidance regarding the conduct of uncertainty analysis, there is a danger that agencies will produce meaningless and confusing ranges of risk estimates and that the development of risk assessments will be delayed to no clear benefit. The possibility of large inconsistencies in risk assessments between and even within agencies is also increased in the absence of explicit and peer-reviewed guidance on this issue.** *[p. 24]*

D. Other Items of Interest

Some additional items that we identified as being of particular interest are:

- "Fuzzy set methods for uncertainty management in **intelligence analysis**," International *Journal of Intelligent Systems,* 21(5): 523-544 (May 2006), **Ronald R. Yager**, Machine Intelligence Institute, Iona College, 10.1002/int.v21:5

  > Considerable concern has arisen regarding the quality of intelligence analysis. This has been, in large part, motivated by the task of determining whether Iraq had weapons of mass destruction. One problem that made this analysis difficult was the uncertainty in much of the information available to the intelligence analysts. In this work, we introduce some tools that can be of use to intelligence analysts for representing and processing uncertain information. We make considerable use of technologies based on fuzzy sets and related disciplines such as approximate reasoning.

- "Meta-uncertainty and resilience with applications in **intelligence analysis**," (PhD thesis) Jason Robert Schenk, Ohio State University, Industrial and Systems Engineering, 2007 (Advisor: Theodore T Allen). Release of the full-text document has been delayed until December 2010. (Source)

  > Uncertainty plays a major and inevitable role in human decision-making. Meta-uncertainty about the uncertainty can also be important but it is generally less studied. Such meta-uncertainty has arisen in medical contexts as researchers and practitioners strive to improve conceptualizations of efficacy and mortality related data. Similar but less studied issues arise in the study of human conflicts, in related intelligence analysis, and in responding to business crises. For any given year, the chance of a new conflict arising between a pair of nation states or "dyad" is generally small even if those nations are "politically relevant" to each other. Predicting "no conflict" is almost always correct. Yet, the probabilities of conflict and their meta-uncertainty can be of great interest to military and civilian planners. This dissertation reviews and synthesizes methods available for both conflict probability prediction and meta-uncertainty estimation. It also proposes Bayesian mixture modeling approaches for these purposes and clarifies their potential advantages in relation to actual human conflict data. Intelligence analysis involves gathering and synthesizing a multitude of different data sources into a coherent explanation of events using adductive reasoning. The outputs often involve predicted probabilities of events, which are commonly used in real time briefings and after action reviews (AARs). Given a variety of time, data quality constraints, it can be important to convey the "rigor" or meta-uncertainty associated with probability prediction. For the context of intelligence analysis, this dissertation provides a visual and systematic framework for convey and document meta-uncertainty for intelligence analysis. This framework is based on the proposed "consequence likelihood" diagrams and can be referred to as "hypothesis scrubbing." Resilience engineering offers new ways to conceptualize responsiveness and reserve capacity. This dissertation reviews and synthesizes many quantitative measures of system resilience. It also explores the application of a recently proposed "master" stress-strain model to evaluate response alternative to crises at a major call center. A main conclusion is that resilience

engineering can be viewed as a response to high levels of meta-uncertainty. Also, the synthesis has illuminated a potentially important concept called the "graceful degradation angle" which rates the system's ability for self-diagnosis.

- "ICI Uncertainty & Predictive Analysis Teams," presentation by Shilo Anders, Lisa Fern, Akilah Hugine, Rachael Pasini, and Daniel Zelik (Ohio State), 2007. According to the author:

  … [The] document details some of the directions explored by the uncertainty and predictive analysis team. The problem of uncertainty in information analysis describes the difficulties inherent in coping with indeterminate information—particularly the challenges of estimating, evaluating, synthesizing, and acting upon it. Our approach to addressing the issue of uncertainty—driven by the perspective of maintaining adaptive capacity in the face of change—explores alternative ways to capture, represent, and understand uncertain information. This exploration focuses on technology forecasting and predictive analysis as a manifestation of future-oriented uncertainty and as an interesting case for the study of uncertainty. [See also "Hedging Against Uncertainty" poster, which provides an "overview of a model for how analysts hedge against uncertainty. We use an accepted model of intelligence analysis as a framework to consider uncertainty throughout the iterative process."] *[For more on the activities of the* ***Ohio State CSEL Cognitive Engineering Laboratory,*** *see this webpage and this summary of work in* ***Analytical Rigor in Information Analysis****.*]

- "100 Books on Risk, Uncertainty, and Intelligence," from a research blog on "risk, uncertainty, and everything else," by William McGill of Penn State. McGill is working his way through the list and has provided a review of one book thus far.

  … I happened upon one hundred books covering a variety of topics spanning the fields of risk and decision analysis, uncertainty modeling and intelligence. This is a lot of books. So, I decided to perfect the art of the "10-minute" review by offering the community my thoughts on each title, to include a bit of personal meta-data on the subject, title, author and so on. And in the spirit of speaking to the risk community, I will call this series "The Security Risk Professional's Bookshelf" (I borrowed the title from the "Intelligence Officer's Bookshelf" published in each issue of the CIA's journal Studies in Intelligence).

- ***Uncertainty and risk: multidisciplinary perspectives*** (book), Gabriele Bammer, Michael Smithson (2008). Limited online preview available. Book summary:

  The most thorough examination of 'uncertainty,' the core concept in risk theory and management. Covers a wide range of perspectives, practice and problems including environmental risk, emergency planning, terrorism, law enforcement, communicable disease and public health. Develops an integrated view of the nature of uncertainty, examines uncertainty as a motivating force and provides strategies for coping and managing under uncertainty governs our lives. …

- "Verbal Probability Expressions in National Intelligence Estimates: A Comprehensive Analysis of Trends from the 50s through post 9/11" (Master's thesis), Rachel Kesselman, Mercyhurst College, full text available here.

- "Evaluating Intelligence," K. Wheaton and D. Chido, *CI Magazine*, 10:5 (2007). (Full text) The article deals with the difficult issue of evaluating intelligence processes and products.

- "A scenario-driven decision support system for serious crime investigation," Shen, Q, Keppens, J., Aitken, C., Schafer, B., and Lee, M., *Law, Probability and Risk,* 5:2:87-117(31), (June 2006).

  Consideration of a wide range of plausible crime scenarios during any crime investigation is important to seek convincing evidence and hence to minimize the likelihood of miscarriages of justice. It is equally important for crime investigators to be able to employ effective and efficient evidence-collection strategies that are likely to produce the most conclusive information under limited available resources. An intelligent decision support system that can assist human investigators by automatically constructing plausible scenarios, and reasoning with the likely best investigating actions will clearly be very helpful in addressing these

challenging problems. This paper presents a system for creating scenario spaces from given evidence, based on an integrated application of techniques for compositional modelling and Bayesian network-based evidence evaluation. Methods of analysis are also provided by the use of entropy to exploit the synthesized scenario spaces in order to prioritize investigating actions and hypotheses. These theoretical developments are illustrated by realistic examples of serious crime investigation.

- "A Multinomial-Dirichlet Model for Analysis of Competing Hypotheses," Duncan K. A., Wilson J. L., San Diego State University, *Risk Analysis* 28:6, 699-1709 (December 2008).

  Abstract: Analysis of competing hypothesis, a method for evaluating explanations of observed evidence, is used in numerous fields, including counterterrorism, psychology, and **intelligence analysis**. We propose a Bayesian extension of the methodology, posing the problem in terms of a multinomial-Dirichlet hierarchical model. The yet-to-be observed true hypothesis is regarded as a multinomial random variable and the evaluation of the evidence is treated as a structured elicitation of a prior distribution on the probabilities of the hypotheses. This model provides the user with measures of uncertainty for the probabilities of the hypotheses. We discuss inference, such as point and interval estimates of hypothesis probabilities, ratios of hypothesis probabilities, and Bayes factors. A simple example involving the stadium relocation of the San Diego Chargers is used to illustrate the method. We also present several extensions of the model that enable it to handle special types of evidence, including evidence that is irrelevant to one or more hypotheses, evidence against hypotheses, and evidence that is subject to deception.

In addition, this NSF award to Jennifer Widom of Stanford University is interesting:

Better Information Integration through Uncertainty
Start Date: July 1, 2009 Expires: June 30, 2013 Awarded Amount to Date: $1,184,825

The problem of providing seamless, integrated querying over multiple interrelated sources of information has been plaguing the database, information management, information retrieval, and artificial intelligence research communities for decades. There have been successful lines of research addressing specific components of the data integration problem, and large "one-off" systems have been built that successfully integrate specific information sources in specific domains. However, a completely general solution to the data integration problem is thought not to be realizable. The investigator is developing a new type of information integration system that is both novel and realizable. It is based on the following premises and components.

1) The system provides a general data integration solution targeted for a certain type of environment: when multiple sources have joining, overlapping, and potentially conflicting information about the same or closely related real-world entities.

2) The system permits and exploits uncertainty as an integral part of data integration: Uncertainty may be present in source data, source schemata, the integration process, integrated schemata, and integrated data. In fact, uncertainty can play a key role successful information integration.

3) The system relies on general-purpose entity-resolution as a fundamental building block of the integration process and the integrated information. Furthermore, the system retains both the uncertainty and the lineage associated with the entity-resolution process.

4) The system incorporates powerful lineage capabilities, tracking where, when, and how data was produced, how it has evolved over time, and how it has been combined and manipulated as part of the integration process. Lineage is used to enhance the integration process, and it is offered to the end-user in a variety of forms for data understanding and conflict-resolution purposes. Further information may be found at: http://infolab.stanford.edu/udi/. *[This is currently a non-working link, but may function in the future. However, the webpage on "Trio - A System for Integrated Management of Data, Uncertainty, and Lineage" shows related work.]*

III. Ontologies and Uncertainty

A. "Ontology for the IC" Conferences

Proceedings of the "Ontology for the Intelligence Community" conferences are available online (2008; 2007). Several papers are of particular interest, although many others touch on uncertainty:

- A paper by Rensselaer's AI & Reasoning Laboratory on "Toward Automated Provability-Based Semantic Interoperability Between Ontologies for the Intelligence Community" (extended abstract, 2007 conference) The introduction to the extended abstract:

  > The need for interoperability is dire: Knowledge representation systems employ ontologies that use disparate formalisms to describe related domains; to be truly useful to the intelligence community, they must meaningfully share information. Ongoing research strives toward the holy grail of complete interoperability, but has been hindered by techniques that are specialized for particular ontologies, and that lack the expressivity needed to describe complex ontological relationships. In the sequel, we describe provability-based semantic interoperability (PBSI), a means to surmount these hindrances; **translation graphs**, one of our key formalism for describing the complex relationships among arbitrary ontologies; and **ways in which these techniques might be automated**.

- A paper by researchers at the University of South Carolina's Information Technology Laboratory on "Ontological Support for Bayesian Evidence Management" (see 2007 proceedings). Abstract:

  > This paper describes our work on an integrated system that can assist analysts in exploring hypotheses using Bayesian analysis of evidence from a variety of sources. The hypothesis exploration is aided by an ontology that represents domain knowledge, events, and causality for Bayesian reasoning, as well as models of information sources for evidential reasoning. We are validating the approach via a tool, Magellan that uses Bayesian models for an analyst's prior and tacit knowledge about how evidence can be used to evaluate hypotheses.

- "Ontologies and Probabilities: Working Together for Effective Multi-INT Fusion" by researchers at D'Youville University, George Mason University, and Lockheed Martin (see 2007 proceedings for full text paper). From the introduction:

  > … Until recently, there has been little research on marrying the fields of formal ontology and probabilistic reasoning. However, this situation is changing (e.g., [6]). This paper will address the question of how formal ontologies can best be combined with probability theory to provide theoretically sound and practically useful semantic technology for multi-INT fusion. We will investigate theoretical concerns associated with the connections between logics associated with formal ontology (e.g., description logic, common logic, first-order logic) and those of probabilistic mathematics. The goal is to provide a high-level discussion of the issues involved with combining ontologies and probabilistic systems as a basis for dialog between these two communities, and to identify a broadly construed research agenda for their mutual development and interaction. The authors of this paper argue the necessity of articulating a clear theoretical foundation as a basis for later development of specific methodologies and languages.

- "Ontology of Evidence," by researchers at George Mason University and Lockheed Martin (see 2008 proceedings for full text paper). Abstract:

  > Intelligence analysts rely on reports that are subject to many varieties of uncertainty, such as noise in sensors; deception or error by human sources; or cultural misunderstanding. To be effective, intelligence analysts must understand the relationship between reports, the events or situations reported upon, and the hypotheses of interest to which those events or situations are evidential. Computerized support for intelligence analysts must provide assistance for

managing evidential reasoning. For this purpose, computational representations are needed for categories and relationships related to evidential reasoning, such as hypotheses, evidence, arguments, sources, and credibility. This paper describes some of the entities and relationships that belong in an ontology of evidence, and makes the case for the fundamental importance of a carefully engineered ontology of evidence to the enterprise of intelligence analysis.

The 2009 OIC Conference, to be held at George Mason University in October, issued a call for papers including the following topics:

- Ontologies and reasoning under conditions of uncertainty
- Ontological issues related to source credibility and evidential pedigree
- Ontological issues related to the use of images and other kinds of sensing devices
- Creating an **interoperable suite of public-domain ontologies relevant to intelligence analysis** covering areas such as: Social networks; Ethnicity, religion and politics; Spatial and temporal phenomena; Conditions that foster or inhibit outbreak of violence; Infrastructure; Biology and health; Emergency response
- Usability issues relating to semantic technology

B. Other Materials on Intelligence Analysis and Ontologies

- "Policies for Public Domain Ontologies for the Intelligence Community," Kendall E. F., Jacobs, J., McGuinness, D. L., and Schwab, S., (Sandpiper Software, SPARTA, and Rensselaer Polytechnic Institute) (2007) (full text paper is available here). Abstract:

  Numerous RDF vocabularies and OWL, KIF, and other knowledge representation language ontologies have been contributed to the growing body of ontologies available in the public domain over the last ten years. Many of these were created with government-funded research support in the US and EU. Only a small subset is reusable, and fewer are appropriate for use in applications supporting evolving Intelligence Community requirements. This is partly due to decreasing funding available in the US in particular, but also because of lack of well-specified policies for vocabulary management, metadata, and provenance specification. In this paper we will highlight some of the challenges we have faced in developing and attempting to reuse ontologies in support of DARPA and US Department of Defense initiatives, and provide fodder for discussion of requirements for public domain ontologies.

- "Intelligence Analysis Ontology for Cognitive Assistants," Boicu, M., Tecuci, G. and Schum, D., (George Mason University), in *Proceedings of the Conference "Ontology for the Intelligence Community: Towards Effective Exploitation and Integration of Intelligence,"* (December 2008) (full text available here). Abstract:

  This paper presents results on developing a **general intelligence analysis ontology which is part of the knowledge base of Disciple-LTA**, a unique and complex cognitive assistant for evidence-based hypothesis analysis that helps an intelligence analyst cope with many of the complexities of intelligence analysis. It introduces the cognitive assistant and overviews the various roles and the main components of the ontology: an ontology of **"substance-blind" classes of items of evidence**, an ontology of **believability analysis credentials**, and an ontology of actions involved in the chains of custody of the items of evidence.

C. Other Material on Ontologies and Uncertainty

- "Dealing with Uncertainty Issues in Complex Ontology Matching," Wang, Y., Liu, W., and Bell, D., (Queen's University, Belfast), 2009 WMM conference paper. Abstract:

  Ontology mapping is one of the most important tasks for ontology interoperability and its main aim is to find semantic relationships between entities of two ontologies. However, most of the current techniques suffer from some kind of drawbacks as listed below: (a) most of them only consider 1:1 mappings; (b) most of them do not consider the importance of uncertainty in ontology mapping. In this paper we consider the following two issues that have been the focus of our ongoing research: (a) how to produce complex mappings (m:1 or 1:m and m:n) and (b) how to deal with uncertainties in the process of ontology mapping.

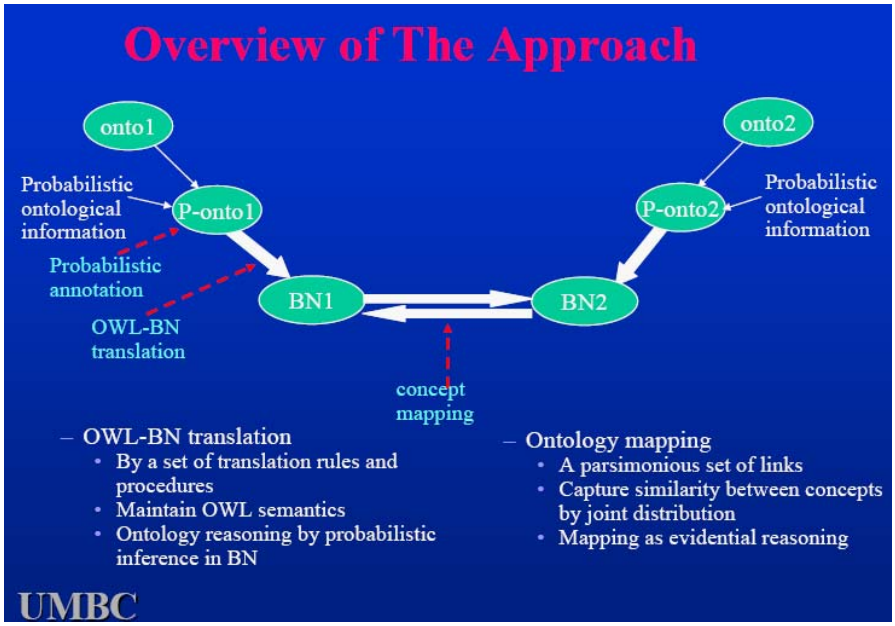
- "Integrating Uncertainty Into Ontology Mapping," Wang, Y., ISWC 2007. (Full text) Abstract:

  This paper gives an outline of my PhD thesis which describes the integration of managing uncertainty into ontology mapping. Ontology mapping is one of the most important tasks for ontology interoperability and its main aim is to find semantic relationships between entities (i.e. concept, attribute, and relation) of two ontologies, However, in the process of mapping, uncertainty and incompleteness of semantics in the syntactic representation and description of relations between entities in ontologies will lead to imprecise results. If we want to obtain better results, it becomes more significant for the ontology mapping to be able to deal with uncertainty.

- "Ontology Mapping Discovery with Uncertainty," Prasenjit Mitra, Noy, N. F., and Jaiswal, A. R., (Penn State and Stanford) in *Lecture Notes in Computer Science* (2005): 537-547. (Full text) Abstract:

  Resolving semantic heterogeneity among information sources is a central problem in information interoperation, information integration, and information sharing among websites. Ontologies express the semantics of the terminology used in these websites. Semantic heterogeneity can be resolved by mapping ontologies from diverse sources. Mapping large ontologies manually is almost impossible and results in a number of errors of omission and commission. Therefore, automated ontology mapping algorithms are a must. However, most existing ontology mapping tools do not provide exact mappings. Rather, there is usually some degree of uncertainty. We describe **a framework to improve existing ontology mappings using a Bayesian Network**. **Omen, an Ontology Mapping ENhancer** uses a set of meta-rules that capture the influence of the ontology structure and the semantics of ontology relations and matches nodes that are neighbors of already matched nodes in the two ontologies. We have implemented a protype ontology matcher using probabilistic methods that can enhance existing matches between ontology concepts. Experiments demonstrate that Omen successfully identifies and enhances ontology mappings significantly.

- "Uncertainty in Ontology Mapping: A Bayesian Perspective," a 2004 presentation by Yun Peng, Zhongli Ding, and Rong Pan of the University of Maryland Baltimore County (full text available here). Overview slide presented below.



- An ARDA Challenge Workshop, "Interoperable Knowledge Representation for Intelligence Support (IKRIS)" (a project ending in 2006, homepage), addressed the following challenge problems:
  - How to enable interoperability of knowledge representation and reasoning (KR&R) technology developed by multiple organizations in multiple DTO (Disruptive Technology Office) programs and designed to perform different tasks, and
  - How to practically represent knowledge that is relevant to intelligence analysis tasks in a form that enhances *automated support* for analysts.

    Goals include: 1) Specify a knowledge interchange formalism that enables interoperability of KR&R systems across DTO and IC programs; 2) Evaluate the interchange formalism by testing whether it can be used to effectively interchange the knowledge bases developed for sample analysis tasks between the knowledge representation and reasoning modules of prominent analyst support systems being developed in ongoing DTO programs; and 3) Actively seek opportunities to transfer IKRIS-derived specifications and technologies to operational users.

- "Uncertainty Reasoning for the Worldwide Web" (final report, published in March of 2008, of the **WC3/UR3 Incubator Group**, whose mission is to better define the challenge of reasoning with and representing uncertain information available through the World Wide Web and related WWW technologies). Part of this group's activities included constructing an **uncertainty ontology**. A briefing on the URW3 group is available here.

- "Which Role for an Ontology of Uncertainty?" presentation by Paolo Ceravolo, Ernesto Damiani, and Marcello Leida of the Universita degli studi di Milano at the 4th International Workshop on Uncertainty Reasoning for the Semantic Web (URSW) (2008). The presentation covers uncertain information representation and reasoning, classification of uncertainty, reasoning with uncertainty, ontology of uncertainty, and a use case in data integration semantics-aware matching strategy.

- "BayesOWL: Uncertainty Modeling in Semantic Web Ontologies," by Zhongli Ding, Yun Peng, and Rong Pan; in *Soft Computing in Ontologies and Semantic Web* (Date: October 28, 2005). (Full text available here). Abstract:

  It is always essential but difficult to capture incomplete, partial or uncertain knowledge when using ontologies to conceptualize an application domain or to achieve semantic interoperability

among heterogeneous systems. This chapter presents ongoing research on developing a framework which augments and supplements the semantic web ontology language OWL for representing and reasoning with uncertainty based on Bayesian networks (BN), and its application in ontology mapping.

- Iowa State researchers are involved in a project, "Algorithms and Software for Collaborative Development and Use of Modular Ontologies" funded by NSF. They claim that their modular ontologies approach has led to:
  - The development of modular variants of description logics that provide mechanisms for semantic importing of names (including concept, role and nominal names) across ontology modules and contextualized interpretation of reused knowledge . The resulting family of ontology languages, namely, package-based description logics (P-DL), frees the ontology designer from the burden of ensuring the reusability of an ontology module in contexts that are hard to foresee at the time of construction of the module in question. A natural consequence of contextualized interpretation is that **inferences that are drawn are always from the point of view of a witness module.** Thus, different modules might infer different consequences, based on the knowledge that they import from other modules.
  - Development of a framework for answering queries against a knowledge base that contains both public and private information, whenever it is possible to do so, without revealing private information, and development of algorithms for privacy-preserving query answering under the open world assumption.
  - The development of distributed tableaux-based reasoning algorithms for P-DL which provide support for inference from the point of view of an ontology module, using knowledge that is imported from other modules, without the need for complete integration of multiple ontology modules.
  - Design and implementation of a prototype software for collaborative construction of ontologies; distributed reasoning with P-DL ontologies; and privacy-preserving reasoning in the special case of hierarchical ontologies. (Source)

IV. Uncertainty and Visualization

Approaches to visualizing uncertainty, while discussed at length in the literature, are still emerging. Much of the work appears to be heavily focused on basic issues, such as enumerating the types of uncertainty that need to be handled. In addition, many of the attempts to do so have been confined to individual applications. A recent paper, "Information and Knowledge Assisted Analysis and Visualization of Large-Scale Data" (full text), noted this about uncertainty and visualization:

> Assess the Uncertainty. Dealing with and accounting for uncertainty is an important topic in scientific experiments. Uncertainty comes with various forms and has multiple facets throughout the simulation and data understanding pipeline. **Thus, a comprehensive framework is necessary for tracing the sources of uncertainty and the following propagation throughout the entire simulation, analysis, and visualization process.** Uncertainty representation and quantification, uncertainty propagation, and uncertainty visualization techniques need to be developed in order to provide scientists with credible and verifiable visualizations. Information as well as knowledge gathered from the process can be used to handle the uncertainty where the different sources of uncertainty are identified, quantified, represented, tracked, and visualized together with the underlying data.

A. Microsoft

Authors from Microsoft Research Group and University of Washington recently published "Revealing uncertainty for information visualization," in *Information Visualization.* (Full text of this 2008 paper here)

> Abstract: Uncertainty in data occurs in domains ranging from natural science to medicine to computer science. By developing ways to include uncertainty in our information visualizations, we can provide more accurate depictions of critical data sets so that people can make more informed decisions. **One hindrance to visualizing uncertainty is that we must first understand what uncertainty is and how it is expressed.** We reviewed existing work from several domains on uncertainty and created a classification of uncertainty based on the literature. We empirically evaluated and improved upon our classification by conducting interviews with 18 people from several domains, who self-identified as working with uncertainty. Participants described what uncertainty looks like in their data and how they deal with it. We found commonalities in uncertainty across domains and believe our refined classification will help us in developing appropriate visualizations for each category of uncertainty. [Journal reference]

The authors note that experts in different domains do not even have consistent definitions of uncertainly and attempt to improve on the definition as well as to graphically represent uncertainty awareness:

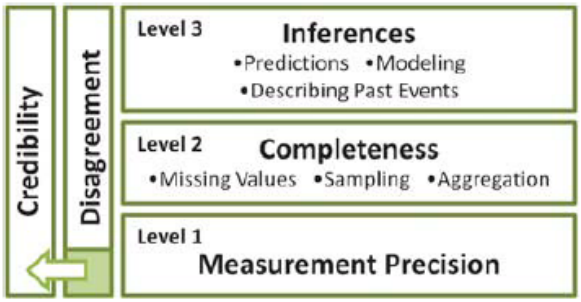


Figure 2: Improved classification. Credibility and Disagreement uncertainty span levels and sometimes disagreement results in credibility uncertainty.

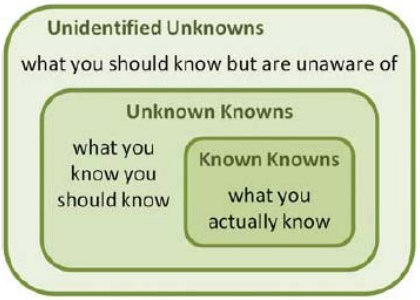


Figure 3: Level of uncertainty awareness: (1) Known Knowns: what you know; (2) Unknown Knowns: what you need to find out; and (3) Unidentified Unknowns: what you don't even know you need to find out. Participants described the unidentified unknowns, or unrecognized information needs, as the worst case.

The authors also discuss **cyclic uncertainty**:

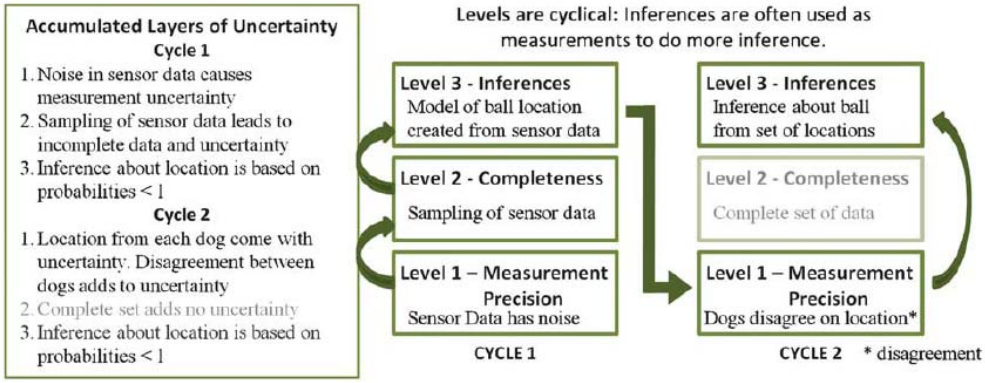


Figure 4: Example of Cyclic Uncertainty: when dogs disagree about the location of a soccer ball. By the time a ball location is predicted we have several layers of uncertainty below this one assertion.

The improved topology they had developed is shown below, with examples from several domains.

Table 2: Examples of uncertainty from three different domains

Domain	*Ecology*	*Computational Biology*	*Medicine*
Goal	Identifying species diversity in different regions of the world	Modelling viral evolution	Diagnosis of disease
Data types	List (and numbers) of species and maps	Evolutionary tree and RNA sequences	Variety of formats such as written/verbal descriptions, numerical values and images
Inference	Predicting future populations based on past events or current states is imperfect	Models of evolution are imperfect so inference about past viral sequences based on evolutionary models is uncertain	Signs and Symptoms are used to infer diagnosis when often there is not a clear line between one set of signs and symptoms and one diagnosis
Completeness	Lack of data for some parts of the world leaves an incomplete data set	Do not have sequences for all strains of the virus, which would be required to have a complete data set	Decisions must often be made with incomplete medical records or without running all possible tests
Measurement precision	Identification of a species within a specific geographic region could be wrong because location data is imprecise	Errors can occur in lab processes for identifying sequences	Many diagnostic procedures (for example laboratory tests) are not perfectly precise
Credibility	Data gathered from some sources may be trusted over others based on source's qualifications	Viral sequences from one data source might be trusted over another	Some expert opinions (for example radiology) may be trusted over others
Disagreement	Different sources may disagree about the presence or absence of a species in a region	Different evolutionary models render different results	Two different tests might contra-dict one another or two doctors might disagree on a diagnosis

And finally, the Microsoft researchers map other visualization approaches to their own classifications:

Table 3: Mappings of existing visualizations to our classification

Visualization	*Classification*
Vis by Pang and Freeman	Disagreement uncertainty (inference level)
CandidTree	Disagreement uncertainty (inference level)
LISTEN	Disagreement uncertainty (inference level)
DaVis	Disagreement uncertainty (measurement precision level) and Completeness uncertainty
MANET	Completeness uncertainty
Restorer	Completeness uncertainty
Vis by Djurcilov and Pang	Completeness uncertainty
Vis by Collins and Penn	Inference uncertainty
Error bars by Olston and Mackinlay	Inference uncertainty
Ambiguation by Olston and Mackinlay	Measurement precision uncertainty

*CandidTree developed by Microsoft (see for example this paper – also discussed later in this report in the section on companies); LISTEN (data sonification) reference (1996);DaVis (tool for visualizing data uncertainty [full text paper from 1995]); MANET – may be referring to the iNSpect tool for **M**obil **A**d Hoc **Ne**twork **T**opology, see this reference and this one; Restorer 1994 reference here and NASA webpage here on color visualization for missing data in restorer.)*

The visualization techniques in the above table are described as follows:

> There is a limited amount of research on visualizing uncertainty and much of it is in the field of geographic visualization, geographic information science and scientific visualization. **The main techniques developed include adding glyphs, adding geometry, modifying geometry, modifying attributes, animation, and sonification.** These techniques have been applied to a variety of applications such as fluid flow, surface interpolants and volumetric rendering. … [discusses each of the approaches above] … **Unfortunately, most of these uncertainty visualizations were isolated efforts designated for a specific purpose**. … Although Table 3 may not cover all the currently available uncertainty visualizations, we notice that visualizations for disagreement uncertainty mainly from the **inferences level and completeness uncertainty mainly for missing values have**

> **been investigated the most**. Furthermore, **visualizations for credibility uncertainty have not been investigated yet**. We suspect it is because, compared to the disagreement uncertainty and completeness uncertainty, credibility uncertainty is much more difficult to quantify. … We may need to develop ways to express credibility uncertainty as categories or numbers that are meaningful to end users before we try to design new visualizations for credibility uncertainty. The **'subjective probability' or 'personal probability' judgment commonly used in intelligence analysis** can be used as a starting point. We then can either apply existing visualizations or develop new visualizations to reveal uncertainty about the credibility of data difference between geometric quantities obtained by two interpolants.

The source references for this paper are well worth looking at on their own.

B. Penn State ARDA Project

The GeoVISTA Center (est. 1998) – the Pennsylvania State University Geographic Visualization Science, Technology, and Applications Center – conducts information and cognitive science research focused on five themes:

- Geographic Representation: To understand the world, we must represent it. Cartography has addressed this challenge for centuries and we extend that tradition through innovative research on multivariate, space-time, and multiscale representation. This research is complemented by development of new strategies for database representation.
- Geovisual Analytics: To cope with increasing geospatial data profusion one focus for our research is to integrate visual, statistical, and computational methods for representation, analysis, knowledge construction, and sensemaking using both multivariate and heterogeneous geospatial information.
- Knowledge Management & Geocollaboration…
- Spatial Cognition & Human Factors ….
- Risk Assessment & Spatial Decision Support: Our work here leverages our basic research in the other four areas to develop methods and tools that are particularly relevant to integrating and using geospatial information for risk assessment & **decision support**.

An ARDA-funded project on uncertainty (not an active grant): (source)

> **Fundamental Approaches to Task-Oriented Visualization of Uncertainty** (based on work supported by the Geo-Spatial Intelligence Information Visualization Program (GI2Vis) BAA Number: NMA401-02-BAA-0005)
>
> > The goal of this project is to **improve the quality of decisions under uncertainty**. Because very few decisions by the intelligence community are ever made under complete certainty, the quality of the complex decisions analysts make depends critically on their ability to incorporate significant, task-relevant uncertainties. The abstractness, complexity, and volume of real-world information can overwhelm analysts. Consequently, various tools for visualizing intelligence information have been developed that significantly improve the analysis of complex intelligence. Though examination of uncertainty is critical, it is most important when judgment is difficult or contentious, when adequate multi-source perspectives do not back up data, or when information is subject to potential deception. **Despite this, current visualization methods and tools do not help the analyst consider or take successful advantage of explicit or tacit knowledge about information uncertainty.** To overcome this, we are developing novel methods for depicting the degree of uncertainty and its influence and for supporting the manipulation of these factors by the analyst in order to strengthen analytical reasoning.

Narrative Scenario: The outcome of the project is a set of methods that significantly improve the quality of analytic products relying on "deep analysis" of geospatial data embodied in image intelligence (IMINT) and measurement and signature intelligence (MASINT) and fusions of each by making uncertainty, and reasoning within the presence of uncertainty, explicit. In particular, the objective is to provide the analysts with tools that enable them to incorporate uncertainty into their cognitive processes. Because uncertainty in IMINT and MASINT has many different facets or elements, including position, latency, identification, classification, and so forth, and the importance of these facets varies with the data, sources, inferences, their fusion, and the current task or goal that the analyst needs to satisfy, this research is critical to aiding deep analysis of geospatial data.

Summary: Information visualization provides a powerful mechanism for helping analysts make sense of complex, multifaceted collections of information contaminated with a range of different uncertainties. **Although failing to account for uncertainty can lead to intelligence failings, few present-day tools express this information at all. Instead, during the sense-making process, analysts often have no way to incorporate explicit knowledge about uncertainty (that is encoded with data), nor are tools available to assist them to incorporate their own individual tacit knowledge of a source's credibility (or other facets of uncertainty) into the analysis.** We are developing an approach for exposing uncertainty information based on the needs for that information within specific tasks of deep analysis.

In spite of the challenges posed by uncertainty in information, information analysts currently have no model or framework for describing the kinds of uncertainty that affect their work. Conversely, the field of scientific computing in general and geographic information systems in particular, includes significant research and proposed frameworks for understanding uncertainty. Such frameworks can form the foundation for organized methods of dealing with the many issues involved. As a step toward the goals of this project, we have drawn on past frameworks to provide a typology that can be applied to uncertainty aspects in intelligence analysis. The background for this work and the **preliminary typology** is presented in a draft paper that has been accepted for publication in the Proceedings of the Conference on Visualization and Data Analysis 2005 (here) – the draft paper is available here. (Bibliographic information and some tables from the paper are shown below)

Thomson, J., Hetzler, B., MacEachren, A., Gahegan, M., & Pavel, M. in press, "Typology for visualizing uncertainty." *Conference on Visualization and Data Analysis 2005 (part of the IS&T/SPIE Symposium on Electronic Imaging 2005)*, San Jose, CA, January 16-20, 2005.

Table 1. Typology Categories

Category	Definition
Accuracy/error	difference between observation and reality
Precision	exactness of measurement
Completeness	extent to which info is comprehensive
Consistency	extent to which info components agree
Lineage	conduit through which info passed
Currency/timing	temporal gaps between occurrence, info collection & use
Credibility	reliability of info source
Subjectivity	amount of interpretation or judgment included
Interrelatedness	source independence from other information

Table 2. Domain Examples for Typology

Category	Attribute Examples	Location Examples	Time Examples
Accuracy/error	counts, magnitudes	coords., buildings	+/- 1 day
Precision	nearest 1000	1 degree	once per day
Completeness	75% reporting	20% cloud cover	5 samples for 100
Consistency	multiple classifiers	from / for a place	5 say M; 2 say T
Lineage	transformations	# of input sources	# of steps
Currency/timing	census data	age of maps	C = Tp - Ti
Credibility	U.S. analyst; informan	knowledge of place	reliability of model
Subjectivity	fact <…> guess	local <…> outsider	expert <…> trainee
Interrelatedness	same author	source proximity	time proximity

A key difference between the typology for geospatially referenced information and past efforts is the focus on the task of the information analyst. This typology has been developed to specifically address the types of uncertainty intelligence analysts face. The categories in this typology represent the types of uncertainties previously identified as having significant influence on analytical decisions. Indeed, analysts routinely keep track of these types of uncertainties manually, in an attempt to incorporate that knowledge into any product they make. We believe that the finished typology will provide a guide for the methodical development of visual representations that incorporate and identify the uncertainties most important to the analyst for the task at hand.

This is a second key difference between the typology presented here and other previous efforts. The typology geospatially referenced information is presented as a general typology that must be instantiated to define the s uncertainties relevant to a particular type of task. As illustration, Table 3 gives an instantiation of the uncerta typology for the task of intelligence analysis with the goal of creating analytic product. The table shows the subcategories of each of the main categories that are particularly relevant to the selected task along with exan when that type of uncertainty might occur.

Table 3. Analytic Uncertainty Typology

Category	Subcategories	Examples
Accuracy/error	• Collection Accuracy • Processing errors • Deception	• Documents that are translated into English may contain translation errors. • A report may note that 50 tanks were observed although the tanks may in fact be dummy placements.
Precision	• Precision of collection capability	• resolution of satellite imagery
Completeness	• Composite completeness • Information completeness • Incomplete sequence	• images of a site may not be available on a particular day, due to adverse weather conditions. • an intercepted conversation may have words that were not clear • the lack of confirming information might signal incompleteness
Consistency	• Multi-INT Conflict • Model/observation Consistency	• multiple sources may actually conflict • models of events may differ from observations
Lineage	• Translation • Transformation • Interpretation	• Machine translation is more uncertain than human linguist translation • Measurements or signals may have been transformed • Information that comes directly from the collection capabilities has a different lineage than an interpretive report produced by an analyst
Currency/timing	• Temporal gaps • Versioning	• Images that show new objects do not show when the object first appeared • Time between when events occurred, when they were reported, and when the information is available to analysts • Reports may have multiple versions, sometimes with major changes.
Credibility	• Reliability • Proximity • Appropriateness • Motivation (of the source)	• Possibility of deliberate disinformation • Source may not have expertise on this subject • Information may be second hand
Subjectivity	• Analytic judgment	• Amount of interpretation added rather than pure facts
Interrelatedness	• Source independence	• Likelihood that the source derives from other reported information (such as repeated news stories)

6. SUMMARY: USING THE TYPOLOGY

We have presented a typology that provides a general categorization for the types of uncertainty present in geospatially referenced information along with a specification of the typology describing the specific uncertainties faced by intelligence analysts when tasked with creating an analytic product. We are currently evaluating the applicability of the typology to practical visualizations aimed at increasing the accuracy of decisions that are based on visual representations of geospatially referenced information. We believe that the typology will be a valuable framework for use by persons who construct visualizations for analysts. The graphical components of the visualization that are related to information uncertainty can be linked to specific aspects of the typology. This allows the visualization to use the model underlying the typology to combine and propagate uncertainties as well as information about the types of visual components that are most suited for representing specific types of uncertainty. The next step in this work is to identify visual metaphors that are particularly effective for each of the different types of uncertainty, as well as for uncertainty that is a composite of two or more types. We have begun evaluations to identify suitable glyphs for annotating geospatial visualizations, and are exploring the use of manipulative icons and glyphs for representing composites

Our belief is that a visualization that maps each type of uncertainty into a different visual dimension will permit the analyst to express the implications of each dimension separately and to perform cognitively the fusion of the different type of uncertainties. At the same time the system will estimate the parameters of the underlying model and be ready to present the fusion that results from applying the model to the known uncertainties. In that way the analyst can make comparisons between their own conclusions and the systems, which provides an appropriate check on the consistency of the analysis.

Other Publications:

MacEachren, A.M., Robinson, A., Hopper, S., Gardner, S., Murray, R., Gahegan, M., Harap, and Hetzler, E (2005); "Visualizing Geospatial Information Uncertainty: What We Know and What We Need to Know." *Cartography and Geographic Information Science*, 32: 139-160 [Full text]

Abstract: Developing reliable methods for representing and managing information uncertainty remains a persistent and relevant challenge to GIScience. Information uncertainty is an intricate idea, and recent examinations of this concept have generated many perspectives on its representation and visualization, with perspectives emerging from a wide range of disciplines and application contexts. In this paper, we review and assess progress toward visual tools and methods to help analysts manage and understand information uncertainty. Specifically, we report on efforts to conceptualize uncertainty, decision making with uncertainty, frameworks for representing uncertainty, visual representation and user control of displays of information uncertainty, and evaluative efforts to assess the use and usability of visual displays of uncertainty. We conclude by identifying seven key research challenges in visualizing information uncertainty, particularly as it applies to decision making and analysis.

Grant awarded to: Battelle-Pacific Northwest Division
Partnering with: OGI School of Science and Engineering, Oregon Health and Science University; and GeoVISTA Center, Pennsylvania State University

Other interesting papers from the GeoVISTA Center:

- Roth, R.E. (accepted 2009). "A qualitative approach for understanding the role of geographic information uncertainty during decision making" *Cartography and Geographic Information Science*. (2009) [Full text]
- Roth, R.E., 2009. "The impact of expertise on geographic risk assessment under uncertain conditions" *Cartography and Geographic Information Science*, 36(1):29-43. [Full text]

FYI, this center makes the GeoVIZ toolkit (see here for more detail). Potential applications, according to the developers, range from research in public health (e.g., infectious disease dynamics or cancer etiology, surveillance, and control), through analysis of socioeconomic and demographic data in support of both research and public policy, to exploration of patterns of incidents related to terrorism or crime.

C. UC-Santa Cruz Laboratory for Visualization and Graphics

The UC-Santa Cruz Laboratory for Visualization and Graphics (laboratory homepage) presents a webpage (undated) with a rather extensive list of research work in the development of methods and tools for visualizing ancillary uncertainty information together with the data. It is interesting because of the broad variety of types of visualizations shown, as well as different kinds of data. Examples of uncertainty visualizations included on this page are verity visualizations, uncertainty glyphs, IFS fractal interpolation, methods of comparing 3D surface attributes, comparative streamflow visualization, uncertainty disks, reconfigurable disk trees, 2D distribution data sets, scalar volumetric uncertainty, and so on.

The first item on the webpage is a paper on "Approaches to Uncertainty Visualization": This paper surveys techniques for presenting data together with uncertainty. These uncertainty visualization techniques present data in such a manner that users are made aware of the locations and degree of uncertainties in their data so as to make more informed analyses and decisions. The techniques include **adding glyphs, adding geometry, modifying geometry, modifying attributes, animation, sonification, and psycho-visual approaches**. "We present our results in uncertainty visualization for environmental visualization, surface interpolation, global illumination with radiosity, flow visualization, and figure animation. We also present a classification of the possibilities in uncertainty visualization, and locate our contributions within this classification."

D. DOD's VACET

The Visualization and Analytics Center for Enabling Technologies (**VACET**):

> … focuses on leveraging scientific visualization and analytics software technology as an enabling technology for increasing scientific productivity and insight … The vision of VACET is to adapt, extend, create when necessary, and deploy visual data analysis solutions that are responsive to the needs of DOE's computational and experimental scientists. Our center is engineered to be directly responsive to those needs and to deliver solutions for use in DOE's large open computing facilities. The research and development directly target data understanding problems provided by our scientific application stakeholders. VACET draws from a diverse set of visualization technology ranging from production quality applications and application frameworks to state-of-the-art algorithms for visualization, analysis, analytics, data manipulation, and data management. Our

goal is to respond to the urgent needs of the scientific community by providing significant, production-quality technology to aid in data understanding.

VACET institutions include: University of Utah: Scientific Computing and Imaging Institute; University of California, Davis: Institute for Data Analysis and Visualization; Lawrence Livermore National Laboratory; Oak Ridge National Laboratory; and Lawrence Berkeley National Laboratory. Note the applications below to which they apply uncertainty visualization (last column).

Applications	Technical Point of Contact	Techniques: Visualization							Techniques: Analytics						
		Integration of Basic Tools for Visualization and Analysis	Publication Quality Images, Illustrations, and Movies	Project-Wide Visualization Tools	Flow Techniques	Scalable Tools	Remote Data Access and Streaming Techniques	Collaborative Tools	Query Driven Visualization	Statistical Displays	Feature Detection (topological analysis, semantic range queries)	Temporal specific issues (feature tracking, events, ...)	Multiple Fields	Comparative Visualization and Analytics	Uncertainty Visualization
Fusion	Utah ORNL LBNL	●●	●		●	●		●●	●●●	●●●	●●	●●●	●●●	●●●	●
Combustion	LBNL LLNL ORNL	●	●●●		●●●	●●●	●●●	●●●	●●●	●●	●●●	●●●	●●●	●●	●
Acclerator	LBNL	●	●	●	●	●	●●		●●●	●●	●●●	●●●	●●	●●	●
Astrophysics	ORNL LBNL	●	●●	●	●	●●	●●		●●●	●●	●●	●●	●●●	●●	●
Turbulence	LLNL	●	●●●		●	●●●	●●			●	●●●	●●●	●	●	
Climate	LLNL ORNL	●			●	●●	●●		●●●	●●	●●	●●	●●	●●	●●
Environmental Management	LBNL	●	●●	●●		●●●	●●●	●●							

● Number of dots indicate the level of need in a given application area for that technique.

What VACET says about their work in uncertainty visualization:

> With few exceptions, visualization research has ignored the visual representation of errors and uncertainty for three-dimensional visualizations. This lack can be attributed in part to the inherent difficulty in defining, characterizing, and controlling comparisons between different data sets and in part to the corresponding error and uncertainty in the experimental, simulation, and/or visualization processes. In addition, visualization researchers have developed few methods that allow for easy comparison and representation of error and uncertainty in data for visualizations. To make current and proposed visualization and analytics techniques and software more useful to SciDAC researchers, we propose to incorporate visual representations of error and uncertainty within a set of the most often used visualization techniques for scalar, vector, and tensor fields. In some cases this could be as simple (but virtually non-existent in most visualization techniques and software) as adding to an existing display some indication of the level of statistical error that is present in the data. We would also leverage our work in comparative visualization to allow the ability to overlay and compare two-dimensional and three-dimensional visualizations and

uncertainty (automating the so called "view-graph norm"). Additionally, we will explore better visual representation of, and interaction with, statistical data within three-dimensional visualizations and leverage existing work in information visualization and analytics methods applied to three-dimensional scientific visualization data. Finally, we would leverage our latest research in statistically quantitative methods for volume visualization techniques to adapt and deploy these new methods for SciDAC applications. (Source)

A 2009 brochure on visualizing uncertainty with climate data, "Visualization of Uncertainty and Ensemble Data: Exploration of Climate Modeling Data with integrated ViSUS-CDAT Systems, " is available here.

E. Additional, Recent Reviews of Uncertainty Visualizations

"Visualisation of Information Uncertainty: Progress and Challenges," Pham, B., Streit, A. and Brown, R. in *Trends in Interactive Visualization,* Chapter 2, (2009) (abstract)

> Information uncertainty which is inherent in many real world applications brings more complexity to the visualisation problem. **Despite the increasing number of research papers found in the literature, much more work is needed.** The aims of this chapter are threefold: (1) to provide a comprehensive analysis of the requirements of visualisation of information uncertainty and their dimensions of complexity; (2) to review and assess current progress; and (3) to discuss remaining research challenges. We focus on four areas: information uncertainty modelling, visualisation techniques, management of information uncertainty modelling, propagation and visualisation, and the uptake of uncertainty visualisation in application domains. [Full text images for scanning are available online at Google books, here. The authors conclude: "In summary, the advance and uptake of uncertainty visualization **does not rely on how many more new visualization techniques that can be devised, but on the development of a rigorous framework for evaluation on how useful and usable visualization techniques are, with respect to the objectives of the users and the specific tasks they have to perform**. To this end, it is imperative to develop good schemes for management of uncertainty modeling, uncertainty propagation and visualization. Furthermore, the understanding of human behavior and preferences has to play a crucial part in the design of the techniques and software tools."]

"Visual Representations of Meta-Information," Bisantz, A. M.; Stone, R. T.; Pfautz, J.; Fouse, A.; Farry, M.; Roth, E.; Nagy, A. L.; Thomas, G., *Journal of Cognitive Engineering and Decision Making*, 3(1):67-91(25) (2009) (abstract).

> We conducted two studies that investigated display characteristics related to color (hue, saturation, brightness, and transparency) and contrast with a background for displaying information qualifiers (termed meta-information) such as **uncertainty, age, and source quality**. Level of detail (or granularity) of the meta-information and task demands were also manipulated. Participants were asked to rank and rate colored regions overlaid on different map backgrounds based on the level of meta-information the regions displayed. Results from Study 1 indicated that participants could appropriately rank and rate levels of meta-information across saturation, brightness, and transparency conditions, and results from Study 1 and Study 2 showed that the natural direction of ordering is complex and dependent on the relevance of different information to the task and the contrast of the overlay region with the background.

F. Integrated Information Modeling and Uncertainty Visualization Environment

Australia has a service that pulls papers from a variety of sources, including universities and government agencies (e.g., Defense). This search pulls up quite a number of interesting papers: http://search.arrow.edu.au/main/results?keyword=visualization+AND+uncertainty .

Here is one example:

Encapsulation and abstraction for modeling and visualizing information uncertainty (Streit, Alexander) **Australasian Digital Theses Program** (2008).

Information uncertainty is inherent in many real-world problems and adds a layer of complexity to modeling and visualization tasks. This often causes users to ignore uncertainty, especially when it comes to visualization, thereby discarding valuable knowledge. **A coherent framework for the modeling and visualization of information uncertainty is needed to address this issue**. In this work, we have identified **four major barriers to the uptake of uncertainty modeling and visualization**. Firstly, there are numerous uncertainty modeling techniques and users are required to anticipate their uncertainty needs before building their data model. Secondly, parameters of uncertainty tend to be treated at the same level as variables making it easy to introduce avoidable errors. This causes the uncertainty technique to dictate the structure of the data model. Thirdly, propagation of uncertainty information must be manually managed. This requires user expertise, is error prone, and can be tedious. Finally, uncertainty visualization techniques tend to be developed for particular uncertainty types, making them largely incompatible with other forms of uncertainty information. **This narrows the choice of visualization techniques and results in a tendency for ad hoc uncertainty visualization. The aim of this thesis is to present an integrated information uncertainty modeling and visualization environment that has the following main features**: information and its uncertainty are encapsulated into atomic variables, the **propagation of uncertainty is automated**, and visual mappings are abstracted from the uncertainty information data type. Spreadsheets have previously been shown to be well suited as an approach to visualization. In this thesis, we devise a new paradigm extending the traditional spreadsheet to intrinsically support information uncertainty. Our approach is to design a framework that integrates uncertainty modeling techniques into a hierarchical order based on levels of detail. **The uncertainty information is encapsulated and treated as a unit allowing users to think of their data model in terms of the variables instead of the uncertainty details.** The system is intrinsically aware of the encapsulated uncertainty and is therefore able to automatically select appropriate uncertainty propagation methods. A user-objectives based approach to uncertainty visualization is developed to guide the visual mapping of abstracted uncertainty information. Two main abstractions of uncertainty information are explored for the purpose of visual mapping: the **Unified Uncertainty Model** and the **Dual Uncertainty Model**. The Unified Uncertainty Model provides a single view of uncertainty for visual mapping, whereas the Dual Uncertainty Model distinguishes between possibilistic and probabilistic views. Such abstractions provide a buffer between the visual mappings and the uncertainty type of the underlying data, enabling the user to change the uncertainty detail without causing the visualization to fail. Two main case studies are presented. The first case study covers exploratory and forecasting tasks in a business planning context. The second case study investigates sensitivity analysis for financial decision support. Two minor case studies are also included: one to investigate the relevancy visualization objective applied to business process specifications, and the second to explore the extensibility of the system through General Purpose Graphics Processor Unit (GPGPU) use. A quantitative analysis compares our approach to traditional analytical and numerical spreadsheet-based approaches. Two surveys were conducted to gain feedback from potential users. The significance of this work is that we reduce barriers to uncertainty modeling and visualization in three ways. Users do not need a mathematical understanding of the uncertainty modeling technique to use it; uncertainty information is easily added, changed, or removed at any stage of the process; and uncertainty visualizations can be built independently of the uncertainty modeling technique.

G. Other

- William McGill (Penn State) has submitted a variety of risk and uncertainty terms to the Cymbolism project (an attempt to quantify the association between words and colors), and has reported the results in a blog posting.
- "Visualizing Uncertainty and Making Comparisons on Maps Using Simple Uncertainty Classes," presentation by Daniel B. Carr of George Mason University (2007).
- "Faction Display: Visualizing the Spectrum of Risk Estimates in a Terrorist Attack," conference paper by Michael W. Smith, Emily S. Patterson, Daniel Zelik, and David D. Woods (Ohio State) (2007). Abstract:

  > Detecting biased information, and deriving an accurate assessment of issues or situations from a pool of information representing multiple factions, are challenges for which intelligence analysts have developed strategies. These include researching sources, submitting products for peer review, explicitly contrasting pro vs. con positions, and comparing predictions along a spectrum of optimism/pessimism. We explore the concept of a Faction Display as a means to use visualization to support **awareness of the location of a source along a spectrum of opinion**. It can be used to place estimates or other assessments in the context of the source's position among the set of factions in play. The Faction Display concept is illustrated as a "design seed" placed within the context of a safety analysis case study; the concept displays relative estimates for safe distances from Liquefied Natural Gas (LNG) pool fires resulting from a terrorist attack.

- "A Framework for Uncertainty-Aware Visual Analytics," technical report by Carlos D. Correa, Yu-Hsuan Chan, and Kwan-Liu Ma (UC-Davis) (2009). Abstract:

  > Visual analytics has become an important tool for gaining insight on large and complex collections of data. Numerous statistical tools and data transformations, such as projections, binning and clustering, have been coupled with visualization to help analysts understand data better and faster. However, data is inherently uncertain, due to error, noise or unreliable sources. When making decisions based on uncertain data, it is important to quantify and present to the analyst both the aggregated uncertainty of the results and the impact of the sources of that uncertainty. In this paper, we present **a new framework to support uncertainty in the visual analytics process, through statistic methods such as uncertainty modeling, propagation and aggregation**. We show that data transformations, such as regression, principal component analysis and k-means clustering, can be adapted to account for uncertainty. This framework leads to better visualizations that improve the decision-making process and help analysts gain insight on the analytic process itself.

V. Commercial Activities

A. DOD Support of Companies via SBIR/STTR Topics

In January of 2004, the Office of the Secretary of Defense (OSD) made SBIR awards to a number of companies for several uncertainty topics (solicitation text, see topics 027, 028, and 029):

- Information Fusion System for Counter-Terrorism Operations: Developing "a novel system for the fusion of intelligence information that arises from multiple sources, e.g., humans, signals, imagery, open-source, news stories, etc. that **explicitly accounts for the uncertainty in the data**."
- Information Uncertainty Portrayal: "innovative methods for **portraying information for decision makers so that data uncertainty as well as content is readily understood.**"
- Portraying Uncertainty in Battlefield Weather Situational Awareness

Some 15 awards were made for the first two topics. A number of the companies profiled below received awards under this solicitation, which no doubt helped create a certain capability in small commercial companies.

In further researching this topic, we discovered that DOD has made a number of SBIR and STTR awards related to information uncertainty. Some of the more interesting ones are included in the Appendix or with the company descriptions below. (Searches for "uncertainty" were made from this page http://www.dodsbir.net/Awards/Default.asp)

B. 21st Century Systems, Inc.

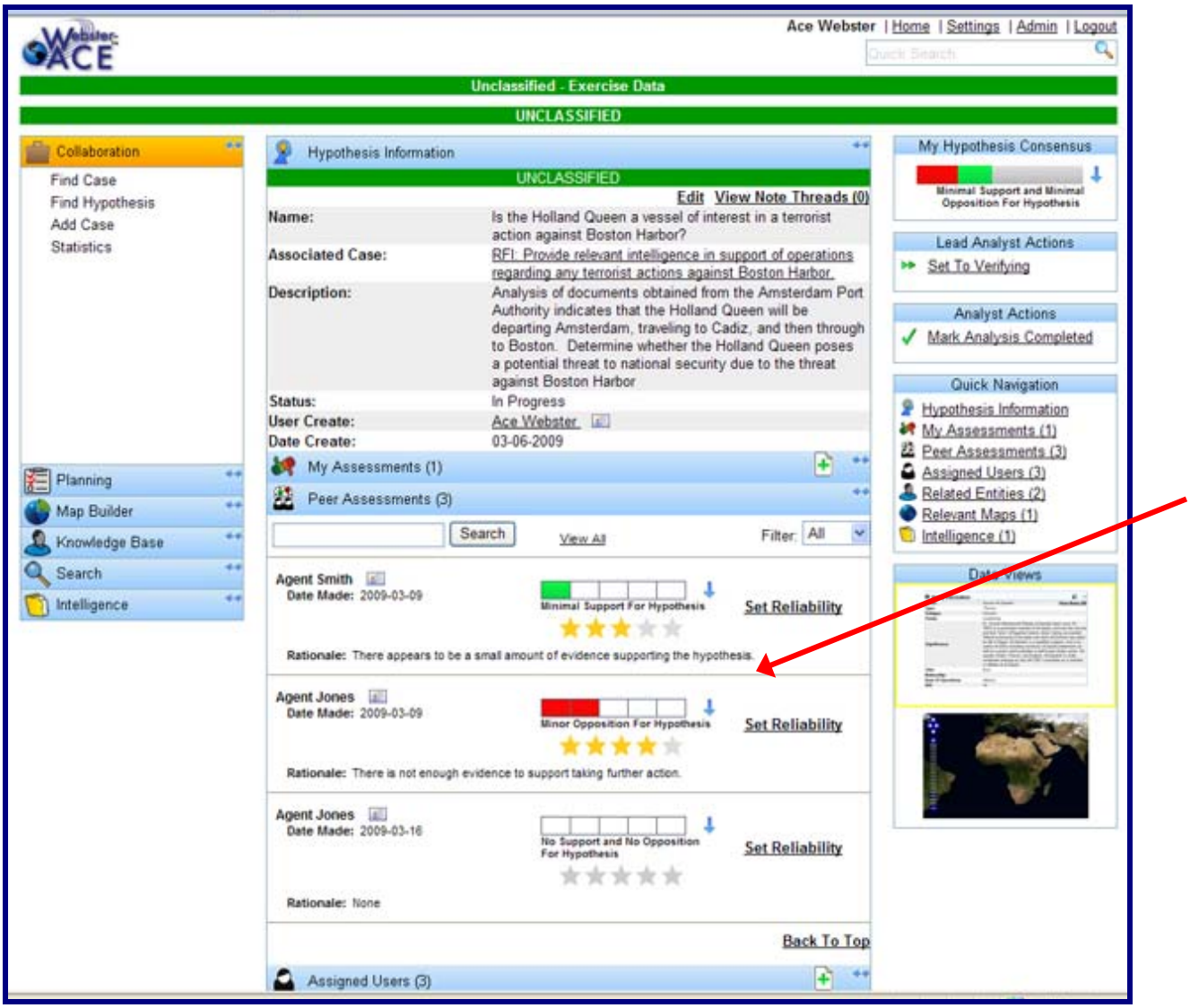
21st Century Systems (21CSI) offers an information fusion product called "Webster-Ace" for intelligence analysts. In late 2008, this product was deployed for use in the DOD department-wide federated web system. It appears that 21CSI may have incorporated some type of uncertainty considerations into this product.

21CSI was awarded several SBIR projects related to the development of Webster and work related to "fusing uncertainties from multi-source data sets." The abstract for these projects:

> In this Phase I SBIR, we shall demonstrate, the **Integrated Fusion Dashboard**, a system that can **fuse uncertainties from multi-source data sets using two distinct detection mechanisms**. To ensure that the fused product makes sense to the counter-terrorism analyst, … Mr. Craig Robinson, a decorated and retired 30 year veteran of the DIA, [will] evaluate the results. … two detection methods to detect possible terrorist activity …TMODS, Terrorist Modus Operandi detection system, contains **graph pattern matching and social network analysis** detection capabilities that has been developed on multiple projects for DARPA (EELD, Genoa II, TIA programs), and Rome Laboratories and inserted into operational facilities at the DIA, Terrorist Information Awareness Center (TIA), and NYPD Counter Terrorism Division. In this Phase I effort, we shall compute and fuse uncertainties from these detection mechanisms. In the Phase I effort, we shall focus on open source data as a proof of concept with later extensions to multi-source data sets.
>
> … pleased to propose continuing its successful Phase I research and development in refining the high-level Webster framework and expand the Webster software agent system to incorporate use of multiple existing systems into a high-level information fusion system. Webster combines multidisciplinary expertise for the integration and inference of information products extracted from the Internet (OSINT), with quantification of data certainty and source reliability. Webster retrieves, filters, analyzes, and fuses information that is time sensitive and critical to CTO. In order to handle incoming intelligence-based secure sources, Web data, and field data sources, potentially massive in amount, Webster will employ 21CSI's Hierarchical Collective Agent Network

(HCAN) architecture. HCAN agents, ultimately in thousands, will be responsible for overall supervision, scheduling, coordination, and execution of information retrieving, filtering, analysis, and fusion tasking. Intelligence information fusion and attendant uncertainty estimates are performed by a novel Hybrid Intrinsic Cellular Inference Network (HICIN) structure. HICIN is an information integration engine embedded with advanced reasoning and uncertainty handling mechanisms.

In looking at the screenshot of the Webster-Ace product, part of it appears that how this company ultimately links uncertainty is to include peer ratings on the reliability of sources:



C. Aptima

Aptima is a company that appears to be heavily involved in working with uncertainty in decision systems (modeling and visualization) for DOD customers. The company is a "leader in the field of human-centered engineering, solving the problems of human performance in today's complex, sociotechnical systems … our unique approach couples social science principles with quantitative, computational methods. … For the Intelligence Community, Aptima applies this expertise to design tools for diagnosing and disrupting adversarial networks."

Some of the interesting work this company has done in the area of uncertainty includes:

- "Information Fusion for **Intelligence Analysis.**" (2005) [Full text available from a link on this page.] The Infusion software tool described here may have eventually been supplanted by MUSE, see further information below, or something like it.

  > Ensuring the accuracy of intelligence assessments is made difficult by the pervasiveness of uncertainty in intelligence information and the demand to fuse information from multiple sources. This paper describes **Infusiun**, **a model-based software tool for information fusion and uncertainty assessment in intelligence analysis.**

  In addition, Aptima received a SBIR award in early 2004 for their work on Infusion:

  Topic#: OSD 03-027 **Awarded:** 21JAN04

  Title: Infusiun: A Decision Support System for Intelligence Fusion and Uncertainty Analysis

  Abstract: We propose to develop the Infusiun decision support tool to provide quantitative support to counter-terrorism analysts performing Level 3 information fusion (Threat Assessment) from open-source and human intelligence. The focus of our effort is on providing intelligence analysts with **methods to manage uncertainty of information and generate quantitative measures of the validity of their assessments.** We represent each intelligence source as providing evidence from which the analyst will, in combination with evidence drawn from other sources, seek to draw conclusions about the status and intent of a terrorist organization. Our method will provide the analyst with a multi-dimensional measure of the confidence level of these conclusions based on the following three properties: 1-Robustness: the extent to which the conclusions are based on multiple independent sources of information; 2-Reliability: the extent to which the conclusions are based on intelligence determined to be accurate and reliable; 3- Strength: the extent to which the conclusions are supported by the evidence reported in the intelligence sources. We propose an innovative approach that draws upon techniques from social network theory, reliability theory, fuzzy logic, and belief theory to integrate empirical measures of validity with the judgment and expertise of the analyst.

- Aptima, working with Lockheed Martin, has a current SBIR, titled "**LUCID: Limiting Uncertainty in Command Information Displays**." The project description (source) states how they plan to use their uncertainty modeling and visualization in a combat system. An example of a visualization from MUSE is shown on the next page, from an earlier paper.

  > Modern military systems employ a variety of models to realistically represent warfighting capabilities and the environment in which these capabilities operate. However, these models rarely represent the uncertainty inherent in real-world domains. Further, the systems rarely visualize uncertainty in decision-makers' command displays. This proposal outlines a research and development program to identify and remedy deficiencies in the portrayal of uncertainty in military decision support systems. Aptima working with its partner, **Lockheed Martin, will modify and expand Aptima's MUSE (Modeling Uncertainty in Shifting Environments)** model for Aegis command displays and design visualization techniques for representing individual information reliability and the aggregate uncertainty to the decision maker in an intuitive manner. Further we will conduct assessments of the model and the visualization techniques. LUCID (Limiting Uncertainty in Command Information Displays) will provide the commander of Navy ships greater situational awareness for making decisions.
  >
  > **Benefit:** By the end of Phase II, Aptima and Lockheed Martin will design, develop, and demonstrate a production-scalable prototype of LUCID that can be implemented to Aegis

software standards and integrated with the Aegis combat system. LUCID will represent the reliability of shipboard sensors using the MUSE model, aggregate this data, and the present visualizations of the uncertainty in the command information displays. LUCID will lead to significant improvements in the situational awareness of the commander by providing a more complete picture of unreliable, ambiguous, or complex data

- "Visualization Techniques for Revealing Uncertainty to Decision Makers," see this 2007 paper for an impressive taxonomy of uncertainty (Full text available here). Abstract:

  Modern military simulations employ a variety of models to realistically represent warfighting capabilities and the environments in which these capabilities operate. However, these models rarely represent the uncertainty inherent in realworld domains, and simulations rarely depict uncertainty in decision-makers' battlespace displays. In this paper, we describe a research program to identify and r**emedy deficiencies in the portrayal of uncertainty in military decision support systems**. We address the issue of multiple sources of uncertainty in military systems by presenting a theoretical model of uncertainty, which builds on cutting-edge research in cognitive decision theory, human psychology, mathematics, and information systems design. **We demonstrate some general strategies for visually conveying the complexity that resides within uncertain data without overly increasing the user's cognitive workload**. Our visualizations aim to incorporate the knowledge of the application domain that is necessary for the tasks so that information is provided in context, highlighting critical information, and alerting the user to the predominant aspects of uncertainty within the simulation environment. We also discuss the key quantifiable effects of this approach on human-system performance, such as reduced decision time and increased situational awareness, decision accuracy, and user confidence.

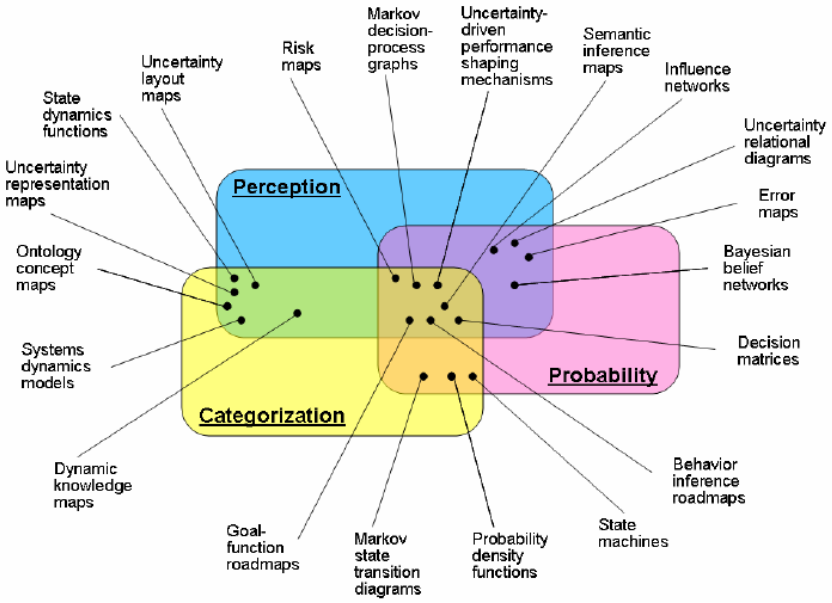


Figure 2. Different models of uncertainty resulting from applications of probability theory, categorization theory, and perception theory.

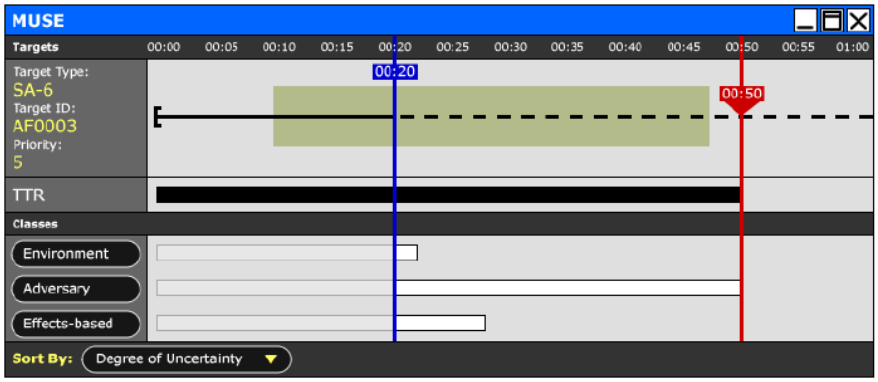


Figure 3. MUSE visualization of uncertainty timeline for a single target.

- "Improving the Display of River and Flash Flood Predictions Project ..." – This 2008 presentation also deals with uncertainty (for NOAA). (Full text available here)
- "Identifying the Enemy – Part I: Automated Network Identification Model" (2007) (Full text available here).

Aptima also has received a number of DOD SBIR awards for the development of uncertainty analysis, as shown below:

D. Charles River Analytics

Since 1983, Charles River Analytics has been delivering intelligent systems that turn our customers' data into decision-quality information they can use to accomplish their missions. … Its research and development work for the US Federal Government has resulted in a series of successful products that have also served the commercial sector. … "We develop mixed-technology architectures that integrate a diverse range of algorithmic, subsymbolic, and symbolic techniques. …" Products include the BNet Builder and BNet EngineKit.

BNet™.Builder is a desktop application for rapidly creating Belief Networks, entering information, and getting results. Use it to:

- Quickly create graphical models of cause and effect
- Easily incorporate past experiences
- See the results of entering evidence about the current situation or hypothetical cases as you enter it
- See how incoming data affects results in real-time
- Clearly communicate how your model works

BNet™.EngineKit: is a developer toolkit for researchers and engineers to use to embed belief networks in software applications. Unique in its focus on clear APIs with the right functionality, BNet.EngineKit offers software developers who aren't inference algorithm specialists a chance to use Bayesian networks without spending years learning about them.

Case study: PUMA: The US Army Research Laboratory sponsored this project using its BNet™ belief network modeling tool to help Army meteorological scientists better **manage and visualize uncertainty in weather prediction.**

… To address the problem of clarifying uncertainty in weather forecasts based on NWP information, the Army Research Laboratory at White Sands Missile Range in New Mexico sponsored the Weather Prediction Uncertainty Management and Representation (PUMAR) project. The goal of the PUMAR project was to create a user-friendly software tool that can be used to effectively communicate weather forecasts and their associated uncertainty, resulting in better and faster decision-making based on numerical weather prediction information. Artificial Intelligence Scientists at Charles River Analytics, Inc. and Meteorologists affiliated with the Air Force and Army used BNet.Builder to model uncertainty in a NWP forecast for a real weather event that occurred over New Mexico in April 2004. The BNet.Builder model incorporated both the judgments of meteorological experts and the NWP data from the Air Force Weather Agency (AFWA). By capturing the experts' knowledge and combining it with the NWP data, the BNet model allowed Army Research Meteorologists to graphically interact with the NWP information to represent and thus understand the types and sources of uncertainty in the forecast process.

The company also has received a number of DOD SBIR awards for their work with uncertainty for analysts. For example:

Topic#: OSD 03-027 **Awarded:** 16JAN04

Title: Decision Aid for Counter-Terrorist Analysts (DACTA)

Abstract: We propose to develop and demonstrate a **Decision Aid for Counter-Terrorist Analysts (DACTA)** by fusing and aggregating information from distributed sources. The DACTA architecture integrates a key decision aiding module with two supporting modules for information visualization and scenario simulation. The decision-aiding module provides the key decision-support functionalities at multiple levels: 1) low-level fusion of data into task-relevant information, supporting skill-based processing; 2) aggregation of information providing high-level abstraction of task-relevant knowledge, supporting rule-based processing; and 3) response recommendations based on the current context and prior knowledge, supporting knowledge-based processing. **Robust performance is assured through the use of complementary artificial intelligence (AI) techniques (e.g., fuzzy logic, belief networks, probabilistic argumentation), thus providing strong foundations for quantifying uncertainty associated with terrorist threat assessment results from DACTA.** The visualization module displays the information produced by the decision-aiding module in a format best suited to the current task, and the analyst's decision-making style and training. DACTA will incorporate a simulation environment supporting speculative analysis and exploration of model-generated hypotheses, via realistic simulated terrorist attack events. We intend to rapidly develop a prototype based on our in-house fusion and belief network engines, and demonstrate its validity in the context of a bioterrorism scenario.

Title: Uncertainty-modeling Rules for Situational Awareness (URSA)

Award Start Date: 20JAN09

Abstract: To provide improved Collaborative Situation Awareness (CSA) and, ultimately, improve the Warfighter's operational success, PEO Soldier is developing new equipment, technologies, and tactics, techniques and procedures (TTPs) that leverage the wealth of information available to Net-Centric Soldiers. To support these efforts, RDECOM's Natick Soldier Research, Development and Engineering Center is developing the Infantry Warrior Simulation (IWARS) to provide the ability to model the effects of new technologies and equipment on Ground Soldiers (GS) and Small Combat Units (SCU) in constructive simulations. **IWARS and similar simulation-based analysis tools, however, do not currently provide a means of modeling uncertainty in SA and the effect of uncertainty on the decision making process.** To address this, we propose to design and demonstrate the feasibility of Uncertainty-modeling Rules for Situational Awareness (URSA), a **unified rule-based representation of uncertainty and incomplete information that can be used in constructive simulation** to determine the importance of information to critical GS decisions. URSA provides a transparent, understandable, and validatable model of uncertainty coupled with affordable, easy to use, and freely distributable modeling tools.

See also this paper, "Applications of Bayesian Belief Networks in Social Network Analysis" by authors from Charles River. Abstract (full text here):

> In this paper, we discuss the use of Bayesian belief networks as a tool for enhancing social network analysis. Traditional social network analysis (SNA) primarily uses graph-theoretic algorithms to compute properties of nodes in a network. However, these algorithms assume a degree of completeness and reliability of the social network data, which cannot always be assured. Applying Bayesian belief networks to social network analysis provides additional capabilities for discovering new links and identifying particular nodes in the network that cannot be achieved using more traditional methods of social network analysis. We describe these applications of Bayesian belief networks and their implementation in a SNA tool.

E. Secureboration

Securboration, founded in 2001, is focused on developing technologies to meet the needs for Secure and Collaborative Environments that span areas such **intelligence operations**, mission planning, effects-based assessment, adversarial modeling, and cyber operations, among others.

> Our approach is based on a 'user-centric' perspective that leverages a variety of advanced computational algorithms to get *'the right information, to the right people, in the right format, at the right time'*. We have developed a variety of foundation technologies to support this evolution and enable industry and the Government move towards a net-centric environment, where collaborative solutions draw on a variety of algorithms and heterogeneous data sources across a distributed environment.

The company's research and development organization works with the following representative technologies:

- Bayesian-based probabilistic reasoning
- Ontological modeling (OWL)
- Grid-based net-centric web service development and deployment
- Semantic Markup for web services (OWL-S)
- Natural Language Processing

The R&D division teams with such institutions as Dartmouth College, Virginia Polytechnic Institute and State University (Virginia Tech), and George Mason University to jointly apply research in key areas such as:

- **Uncertainty Prediction**
- Cyber warfare
- Effects-based assessment
- Information Disclosure
- Socio-cultural modeling

Projects:

- The company received a 2003 **SBIR award** (OSD 03-028) for "**Information Uncertainty Portrayal**." In this project, they teamed with Eugene Santos of the University of Connecticut to propose "our innovative approach for visualizing and assessing uncertainty entitled, **Uncertainty Prediction System** (UPSYS)." They planned to demonstrate how the UPSYS technology can be applied to supports visualization and assessment of event uncertainty within the context of Predictive Battlespace Awareness (PBA). UPSYS consist of four main

components: **1) an ontology that specifies PBA classes and relationships 2) an Uncertainty Layer that uses the ontology to automatically generate Bayesian Networks for event uncertainty calculations,** 3) a Casual Analysis Engine that reasons over the ontology to infer cause and effect, 4) visualizations that provide information of all aspects of an event and its uncertainty in relation to other events and PBA workproducts. (Source)

- **Ontology Generation and Evolution Processor (OGEP):** Securboration, working closely with Dartmouth College (Drs. Eugene Santos Jr. and George Cybenko) and George Mason University (Drs. Alex Levis and Abbas K Zaidi) has created a team to develop an innovative approach called Ontology Generation and Evolution Processor (OGEP) that directly attacks the main barrier which prevents the self-learning of ontologies: the ability to understand the meaning of artifacts and the relationships the artifacts have to the domain space. OGEP leverages existing lexical to ontological mappings integrated with Securboration's proven **Semantic Grounding Mechanism (SGM)** and Semantic Processor Engine (SPE) resulting in an innovative approach to user assisted semantic-based ontology generation. Ontologies generated with OGEP will provide capabilities to discover and evolve semantic relationships breaking through the barrier that prevents self-learning ontologies. The team's extensive experience in ontology development will ensure the ontologies generated by OGEP will support automated reasoning within the **fusion/uncertainty domain** as opposed to ending up as a 'paper' document on a shelf.

- **MPICE Analytical Stability Model (MASM):** MPICE (Monitoring Progress in Conflict Environments) aims to provide a baseline assessment tool for diagnosing stabilization challenges and measuring progress from the point of intervention. The Office of the Secretary of Defense (OSD), the U.S. Agency for International Development (USAID) and the State Department Office of the Coordinator for Stabilization and Reconstruction (S/CRS) sponsored the work. The framework focuses on drivers of violent conflict and instability and the capacity of indigenous institutions to address them in three conflict transformation stages: imposed stability (where active intervention is needed), assisted stability (where local actors and institutions developing sufficient capacity to reduce outside military and civilian intervention), and self sustaining peace (where indigenous institutions cope effectively on their own). (Source) Securboration has teamed with Dr. Eugene Santos from Dartmouth University and Dr. Eunice Santos from Virginia Tech to develop the MPICE Analytical Stability Model (MASM). The pioneering advancements by these professors in computational social sciences, coupled with Securboration's depth of expertise in socio-cultural modeling, effects-based operations, and information fusion enable our team to supplement MPICE with 1) 'social-well being' indicators, 2) a coherent computational model based on quantitative, qualitative, and modeling and simulation information, and long-standing country expertise; and 3) a formalized model of semantic relationships among stability indicators across pillars that supports **understanding uncertainty and related issues within the context of achieving stability goals.**

F. Applied Biomathematics

Applied Biomathematics is a research and software company specializing in ecological and environmental risk analysis. For over two decades, the company has been active in translating theoretical developments in ecology and statistics into practical methods for addressing environmental and ecological problems. Research has focused on developing new methods for addressing problems in wildlife management, conservation, ecotoxicology, cluster analysis and environmental risk analysis.

> Tackle uncertainty with confidence: Turn uncertainty into strength with cutting-edge methods for risk assessment. RAMAS gives you the tools for choosing model inputs, generating bounding estimates of risk, and communicating uncertainty in applications ranging from engineering to human health to ecotoxicology. (See here for the suite of related products.)

RAMAS® Risk Imaging product: Risk Visualization under Uncertainty

> Medical imaging technologies such as MRI, ultrasound, and computed tomography have revolutionized medicine. We believe that risk analysts, regulators, decision makers, and the public would benefit if analogous imaging techniques were available to penetrate the cloud of uncertainty and disagreement surrounding risk data. **RAMAS Risk Imaging** software provides **visualizations of risk in the face of uncertainty** regarding the frequency of adverse events and of uncertainty regarding the severity of adverse events.
>
> Psychometric and socio-cultural theories of risk perception emphasize the disparity between expert risk assessments, which focus on the frequency of adverse events of measured magnitudes, and lay assessments, which are conditioned by additional qualities of the hazard and of the risk perceiver. The RAMAS Risk Imaging approach treats this disparity as a form of **uncertainty** and employs methods to bound variability and incertitude in risk assessments.
>
> Risk is perceived differently by different individuals and interest groups. **RAMAS Risk Imaging visualizes risk by quantifying attitudes regarding the importance of uncertainty, the meaning of disagreements between measurements or opinions, and the meaning of absence of evidence. Visualizations of risk are generated for different risk perceivers. Comparing and contrasting these visualizations facilitates communication and decision making.**
>
> Although the development of this software was guided by theory formulated in risk perception and risk communication research, the method is theoretically eclectic and meant to be adaptable to a wide range of applications and levels of analysis. The commonality expected across applications is the need of risk analysts and decision makers to convert highly **uncertain** measurements of the frequency and adversity of multiple harms associated with a potential hazard into an image of risk as variably perceived by different individuals and interest groups. Risk perception, as conceived in this sense, is unlike an MRI image in that there is no "correct" perception to be recorded. Occupational, environmental, and health risks are experienced and perceived in the context of culturally complex and highly politicized arenas. An analysis informed and colored by these complexities is required. RAMAS Risk Imaging is intended as an aid in the production of uncertainty-informed risk assessment. …
>
> The RAMAS Risk Imaging approach follows four steps in the visualization of risk. The first step is to decompose the risk into its frequency and adversity components. The next step is to i**ncorporate quantitative uncertainty into these components using methods such as interval arithmetic, info-gap, ordination based upon revealed preferences, and dependency bounding.** The third step is to re-compose the risk as a function of uncertain frequency and uncertain adversity. The final step is to focus the risk image on particular risk perceptions by specifying attitudes towards risk and

This recent paper was co-authored by a researcher at this company:

"A Frequency/Consequence-based Technique for Visualizing and Communicating Uncertainty and Perception of Risk," David Slavin (Imperial College); W. Troy Tucker and Scott Ferson (Applied Biomathmatics); *Annals of the New York Academy of Sciences,* 1128:1: 63-77(15), (2008).

> This chapter presents an approach under development for communicating uncertainty regarding risk. The approach relies on a risk imaging technology that decomposes risk into two basic elements: (i) the frequency of each kind of harm associated with a hazard and (ii) the adversity of each of those harms. Because different kinds of harm are often measured along incompatible dimensions, adversity is quantified on an ordinal scale. Frequency is quantified on a ratio scale. Sampling error, measurement error, and bias all contribute to uncertainty about frequency. Differences in opinion, measurement error, and choice of dimensions lead to uncertainty about adversity. In this chapter, risk is imaged as an area circumscribed by uncertainty bounds around all of the harms. This area is called the risk profile of a hazard. Different individuals and groups respond to uncertainty and risk differently, and the risk profile can be further focused to visualize particular risk perceptions. These alternate risk visualizations may be contrasted and compared across management choices or across different risk perceivers to facilitate communication and decision making. To illustrate the method, we image published clinical trial data.

G. Microsoft Research

MS Research scientists have done some research in uncertainty visualization (one of their papers is discussed in the visualization section), although it does not appear that these efforts have resulted in a commercialized product. See this link for a list.

CandidTree is one visualization approach discussed in a 2007 paper here. Abstract:

> Most visualization systems fail to convey uncertainty within data. To provide a way to show uncertainty in similar hierarchies, we interpreted the differences between two tree structures as uncertainty. We developed a new interactive visualization system called CandidTree that merges two trees into one and visualizes two types of structural uncertainty: location and sub-tree structure uncertainty.

H. Integrated Sciences Group

Integrated Sciences Group claims to have pioneered many of the major advances in **measurement uncertainty analysis**, measurement decision risk analysis, statistical measurement process control and calibration interval analysis. Consequently, "our knowledge in these areas is second to none." Founded in 1987, the company has **incorporated this knowledge in user-friendly software applications** designed to help users make informed measurement analysis decisions, assure measurement quality and deal with the stringent requirements of the international marketplace.

ISG President & Founder: **Dr. Howard Castrup** has been developing advanced measurement science techniques and methods for over thirty years. **He is one of the founders of uncertainty growth modeling** and the originator of statistical measurement process control (SMPC). He is also a major contributor to NASA Reference Publication 1342 and the principal author of the NCSLI Recommended Practice on Calibration Intervals (RP-1).

UncertaintyAnalyzer 3.0

> UncertaintyAnalyzer ($995 USD) is the world's most powerful and versatile measurement uncertainty analysis software product available. With an exhaustive list of features, capabilities

and on-screen information, UncertaintyAnalyzer is a complete, state-of-the-art tool for conducting and reporting uncertainty analyses for direct measurements, multivariate measurements and measurement systems. Our customers consider it to be the Swiss Army Knife of uncertainty analysis software products.

UncertaintyAnalyzer incorporates and extends the concepts and methods found in the ISO Guide to the Expression of Uncertainty in Measurement (the ISO GUM). Consequently, UncertaintyAnalyzer greatly facilitates compliance with ISO 17025 and ANSI/NCSL Z540.3.

UncertaintyAnalyzer's built-in statistical analysis methodologies are combined with user technical expertise through a **user-friendly graphical interface.** All math and statistics are performed in background, requiring little or no statistical training.

Since just about everyone involved in making or interpreting measurements needs to analyze measurement uncertainty, this product is a must for the professional toolbox of test engineers, calibration engineers, research scientists, and the general technical community.

UncertaintyAnalyzer 3.0 runs on Windows 95, 98, 2000, ME, NT and XP (see also SPCView 1.7).

Uncertainty Sidekick Pro 1.0

Uncertainty Sidekick Pro ($195 USD) is a complete measurement uncertainty analysis tool that does not "dumb down" uncertainty analysis, does not require a knowledge of statistics to use, and does not require a spreadsheet application to operate.

Uncertainty Sidekick Pro incorporates methods found in the ISO Guide to the Expression of Uncertainty in Measurement (the ISO GUM), handles direct and multivariate measurements, and utilizes interactive uncertainty analysis procedure checklists that access drill-down screens and worksheets that facilitate your uncertainty analysis. Analyses developed with our Uncertainty Sidekick freeware are upwardly compatible with the Pro version.

Uncertainty Sidekick Pro is by far the most cost-effective, comprehensive measurement uncertainty analysis tool for achieving compliance with ISO 17025 and ANSI/NCSL Z540.3. This product is an ideal uncertainty analysis solution for calibration laboratories that support a wide variety of test and measurement equipment.

Uncertainty Sidekick Pro 1.0 runs on Windows 95, 98, 2000, ME, NT and XP.

I. Systems Technology, Inc.

Systems Technology Inc. (Hawthorne, CA) received a 2007 SBIR award for developing an "**Aeroelastic Uncertainty Analysis Toolbox."**

TECHNICAL ABSTRACT: Flutter is a potentially explosive phenomenon that is the result of the simultaneous interaction of aerodynamic, structural, and inertial forces. The analytical prediction of flutter in the transonic regime requires high fidelity simulation models that are computationally expensive. Due to the computational demands, traditional uncertainty analysis is not often applied to flutter prediction, resulting in reduced confidence in the results. This Phase I research is aimed at exploring methods to reduce the previous computational time limitations of traditional uncertainty analysis. To dramatically reduce the computational burden of uncertainty analysis, Systems Technology, Inc. proposes to investigate both the coupling of Design of Experiment (DOE) and Response Surface Methods (RSM), and the application of robust stability techniques, namely Âƒà -analysis. Using Reduced Order Models (ROM), the DOE/RSM and Âƒà -analysis approaches will be compared to traditional Monte Carlo based stochastic simulation. The result of the Phase I program will be to demonstrate the utility of the core elements of the Aeroelastic Uncertainty Analysis Toolbox (AUAT). AUAT will contain multiple methods for addressing flutter uncertainty analysis, coupled with a state-of-the-art nonlinear aeroelastic code.

POTENTIAL NON-NASA COMMERCIAL APPLICATIONS: Applying the uncertainty analysis early in the design process will enable manufacturers to design high performance aircraft with expanded flight envelopes that are robust to uncertainties pertaining to aeroelastic phenomena such as flutter. Rapid uncertainty analysis capability will enable designers to evaluate a larger design space in less time, decreasing the amount of incremental flight testing, thereby reducing the cost of development.

J. Others

The Association for Uncertainty in Artificial Intelligence lists some companies that either provide software or services related to uncertainty. Their list includes the following companies of interest, with short descriptions:

- Hugin Expert A/S is the world's leading expert system software house in construction and execution of Belief Networks (also known as Bayesian Networks, or Causal Probabilistic Networks)
- Knowledge Industries (KI) is the market leader in the development of probabilistic diagnostic systems.
- Lumina Decision Systems, Inc. is a computer software and services company that develops and markets state-of-the-art software for modeling and decision support.
- Norsys is making advanced belief network and influence diagram technology practical and affordable with their Netica product.

VI. Appendix

A. Other Resources

Other resources that may be of interest to the team:

- **Wikis:** Uncertainty Visualization Wiki ; Wikipedia Uncertainty page; and Wikipedia Bayesian network page… Generalizations of Bayesian networks that can represent and solve decision problems under uncertainty in influence diagrams.
- **Professor McGill's blog** on "Thoughts on Risk, Uncertainty, and Everything Else" (William McGill, Penn State, works with security risk analysis).
- "Words of Estimative Probability," Sherman Kent (1962), available full text at the CIA website.

B. Selected SBIR Award Abstracts

1. OSD 2003

Phase I Selections from the OSD 03.2 Solicitation (selected awards – see also discussion of 21st Century Systems, Aptima, and Securboration in the chapter on Commercial Activities):

ALPHATECH, INC.
6 New England Executive Park
Burlington, MA 01803

Phone: (703) 284-8444
PI: Dr. William H. Bennett
Topic#: OSD 03-027 **Awarded:** 21JAN04

Title: Confident Declaration Fusion Methods for Intelligence Processing of Relational Evidence

Abstract: Developing confident fused estimates derived by combining multi-source data (e.g. sensor data, human intelligence reports and open-source data) is a challenge for intelligence analysts. Data that can provide evidence about terrorist network operations are sparse, uncertain, disparate, and can include both misinformation and disinformation. In particular, open source data is often uncorroborated and has incomplete or unknown pedigree. Intelligence analysts need improved information fusion capabilities that can 1) detect/recognize patterns that indicate operations of terrorist networks while 2) characterizing the uncertainty of pattern recognition consistent with the uncertainty of the evidence. This effort will develop a consistent confidence assessment capability based on analytical methods that are independent of the cognitive assessments of human intelligence analysts. Our Phase I effort will lead to improved models of terrorist networks that characterize uncertainty, enabling improved fusion of uncertain information for counter-terrorist operations. ALPHATECH proposes an innovative approach in developing a confidence assessment capability for information fusion of evidence on terrorist operations by applying the theory of complex networks to model the uncertainty in information sources and pedigree. To facilitate this effort, we will leverage an existing ALPHATECH prototype system for fusing relational evidence to establish link detection for counter-terrorist operations.

SCIENTIFIC SYSTEMS CO., INC.
500 West Cummings Park - Ste 3000
Woburn, MA 01801

Phone: (781) 933-5355
PI: Dr. Adel El-Fallah
Topic#: OSD 03-027 **Awarded:** 08JAN04

Title: Unified Robust-Bayes Multisource Counter-Terrorism Fusion

Abstract: If the states and information sources for counter-terrorism problems were like those associated with conventional sensor/target problems, then they could be solved using a systematic and proven mathematical methodology---the Bayes filter. This filter provides an explicit methodology for modeling

uncertainties, propagating these uncertainties through time, and extracting estimates of desired quantities (as well as measures of reliability of those estimates) that correctly reflect the influence of system uncertainties. The ambiguousness of human intelligence information sources and of A PRIORI human cultural context would seem to automatically preclude the feasibility of the Bayes filter in counter-terrorism applications. Scientific Systems Company, Inc. (SSCI) and its subcontractor Lockheed Martin Tactical Systems (LMTS) believe that this may not be the case. Certain more conventional DoD problems---force structure analysis and single-target filtering using unconventional information (natural language, inference rules)---can be addressed using Bayes filter methods, and these problems bear a family resemblance to counter-terrorism applications. Consequently, we propose the investigation of a novel Bayes-filter information-fusion approach to counter-terrorism applications that both hedges against, and accounts for, inherent uncertainties. Specific Phase I tasks are: (1) develop a theoretical/mathematical/algorithmic foundation; (2) design high-level techniques for modeling states and measurements; (3) develop high-level designs for mathematical algorithms, including uncertainty assessment; (4) design potential test simulations; (5) develop implementation, simulation, and test plan; (6) develop a detailed plan for further analysis and implementation in a Phase II effort. The project team includes Dr. Ronald Mahler of Lockheed Martin. Lockheed Martin will provide both technical and commercialization support in the application of counter-terrorism technologies.

STOTTLER HENKE ASSOC., INC.
951 Mariner's Island Blvd., STE 360
San Mateo, CA 94404

Phone: (206) 545-3533
PI: Mr. Matt Broadhead
Topic#: OSD 03-027 **Awarded:** 30DEC03

Title: Improving Information Fusion Capabilities through the Explicit and Pervasive Consideration of Uncertainty

Abstract: A variety of forces have led to decreases in the average experience of intelligence analysts. This shift is an incredibly important development since a lack of experience has been strongly linked to: failures in locating key information sources; the incorporation of faulty information in reports; and the premature closing of investigations. To help mitigate these impacts and generally improve intelligence analysis capabilities we propose an approach to information fusion that employs an integrated probabilistic framework in order to explicitly account for disparate indicators of uncertainty and thereby improve human decision making. The use of this integrated framework, in which information extraction and fusion decisions are made with a common pool of evidence and inference procedures, will also allow much richer forms of inference than possible with the current state of the art technologies. To further extend the reach of the proposed system, Assure, to higher level fusion tasks, we will employ a mixed-initiative interaction paradigm that will enable a form of cooperative information fusion and uncertainty analysis. Phase I research and development of a limited prototype will provide a solid foundation for the complete implementation of Assure in Phase II and its eventual commercialization.

ALPHATECH, INC.
6 New England Executive Park
Burlington, MA 01803

Phone: (781) 273-3388
PI: Dr. Gregory S. Lauer
Topic#: OSD 03-028 **Awarded:** 05DEC03

Title: Information Uncertainty Portrayal

Abstract: The information age has produced a flood of information to system operators and decision-makers in a multitude of application domains. Each piece of data that feeds a system can produce complex interactions with other data in the scenario. This project will examine the uncertainty associated with data that describes a battlefield awareness scenario and will determine techniques for visualizing these uncertainties with the goal of aiding in the decisions that a commander must make. This work will draw upon previous ALPHATECH work, including the outputs of tracking, automatic target recognition, and information fusion software algorithms, for the generation of data and uncertainty information. A scientific experimental procedure will be used to guide a group of mock decision-makers through a series of experiments. Results of the experiments will be analyzed, with the goal of extracting those visualization techniques that work across the information domains tested. We will also extrapolate of the results of the experiments to non-military domains. Universal concepts for visualizing uncertainty will complete domain specific concepts, resulting in a demonstration of the most promising visualization techniques identified.

ATC - NY
33 Thornwood Drive, Suite 500
Ithaca, NY 14850

Phone: (607) 257-1975
PI: Dr. Robert Joyce
Topic#: OSD 03-028 **Awarded:** 05DEC03

Title: Interactive Display of Probabilistic Geo-Spatial Information

Abstract: Systems that integrate and present data from multiple sources often ignore the probabilistic uncertain nature of the information they are handling. Such systems are often designed with pre-determined thresholds or other algorithms to make binary go/no-go decisions, rather than presenting the entire picture and all data sources. Indeed, simply displaying all information sources and uncertainties used in making a calculation can be unwieldy and confusing to decision makers. ATC-NY, in collaboration with Architecture Technology Corporation, will design and build uVIZ, an intuitive, interactive visualization system to display uncertain information associated with both raw data sources and derived information. uVIZ will provide a layered view, where users can select the level of detail displayed about any particular piece of information: single values that are the result of estimation algorithms, modeling error distributions, and so forth, all the way down to raw sensor error information and human observations. As information uncertainty generally increases as observations age, existing probabilistic models that incorporate time can also be employed, allowing visualization of past or future scenarios as well as time-lapse animations.

BMA ENGINEERING, INC.
11429 Palatine Drive
Potomac, MD 20854

Phone: (301) 299-9375
PI: Dr. Bilal M. Ayyub
Topic#: OSD 03-028 **Awarded:** 05DEC03

Title: Information Uncertainty Portrayal

Abstract: The objective of Phase I: identify and develop innovative methods for portraying information for decision makers so that data uncertainty and content are readily understood. The specific objectives of the proposed effort are: 1. Review the present practice of visualizing uncertainty in battlefield data; 2. Examine the use of various visualization methods, as discussed in Section 1, for various uncertainty and ignorance types as defined in Figure 2; 3. Develop methods for visualizing uncertainty based on our ignorance hierarchy; 4. Incorporate our risk management process in the development of these methods; 5. Define, format, and collect the data needed to support these methods; 6. Demonstrate the effectiveness of the methods, especially concerning improvement in the ability to make more appropriate (right or correct) decisions; 7. Develop a plan for Phase II of the SBIR effort in the form of prototype products with a high potential for successful commercialization. We will develop innovative methods for portraying information for decision makers, so that data uncertainty and content are readily understood, based on our unique hierarchy of ignorance. The visualization developed visualization methods will satisfy the following principles: (1) apprehension, (2) clarity, (3) consistency, (4) efficiency, (5) necessity, and (6) truthfulness. The following icon attributes can be used to communicate information about uncertainty and ignorance: (1) form, (2) orientation, (3) color, (4) texture, (5) value, (6) size, (7) position, (8) motion, (9) intensity, (10) shading, and (11) special effects, such blinking, animation, etc. We will further develop our unique Ignoriconsc, and perform the following tasks: (1) Define the types of ignorance and uncertainty; (2) Identify visualization requirements for battlefields; (3) Develop visualization methods; (4) Incorporate our risk mitigation tools in developing the methods; (5) Development a variety of Ignoriconsc; (6) Define data needed to select and format Ignoricons; (7) Demonstrate models; and (8) Develop a plan for Phase II of the SBIR.

2. Other Selected SBIR/STTR Awards

DOD has funded studies related to uncertainty by small companies in a variety of SBIR programs. We list some of them below as indicative of the breadth of interest in the area, as well as for further research on commercial activities. A number of projects are related to mission and battlespace planning.

Topic No	Title	Firm	Agency	Phase
N06-T025	C-RAM: Cognitively-Based Rapid Assessment Methodology	21st Century Systems, Inc.	NAVY	1
N04-231	Ants on the AEDGE	21st Century Systems, Inc.	NAVY	1
N01-137	EXLOG21: An Innovative DSS-based Expeditionary Logistics Tool	21st Century Systems, Inc.	NAVY	2
AF06-T031	Holistic Analysis, Visualization, & Characterization Assessment Tool (HAVCAT)	21st Century Systems, Inc.	AF	1
SB022-034	INSIGHT: Interpreting Network Structures To Obtain Intelligence On Groups Of Hidden Terrorists	Alphatech, Inc		
N03-196	Self Assessment Tool for Intelligent Prognosis (SATIP)	Alphatech, Inc	NAVY	1
N02-097	Control Architecures for Autonomous Teams (CAAT)	Alphatech, Inc.	NAVY	1
AF02-103	Machine Reasoning for Effects-Based Operations: A Generic Architecture for Multi-Domain Workarounds Reasoning	Alphatech, Inc.	AF	2
OSD03-029	Portraying **Uncertainty** in Battlefield Weather Situational Awareness	Aptima, Inc.	OSD	1
N08-166	LUCID: Limiting **Uncertainty** in Command Information Displays	Aptima, Inc.	NAVY	1
N07-089	CoVE: Collaborative Visualization Environment	Aptima, Inc.	NAVY	1
N07-087	Cultural Agent Model to Predict in Habitant Opinion Reactions (CAMPHOR)	Aptima, Inc.	NAVY	1
AF06-T031	Intelligent Icons for Meta-information Adaptive Presentation (12MAP)	Aptima, Inc.	AF	1
AF06-055	**Uncertainty** Visualization for Modeling and Simulation of Complex Systems	Aptima, Inc.	AF	1
SB901-060	Development of Planning Systems for Problems Subject to **Uncertainty** And Resource Scarcity	Artificial Intelligence Atlanta	DARPA	1
AF98-124	ILIA: Intelligent and Learning Interface Agent	Charles River Analytics Inc.	AF	1
AF083-024	Advanced Visualization and Support Environment (ADVISE)	Charles River Analytics Inc.	AF	1
AF06-055	Meta-Information Representations In Advanced Modeling and Simulation (MIRIAM)	Charles River Analytics Inc.	AF	1
AF06-054	Facilitated Argumentation through Automatic Acquisition and Synthesis of Time-critical information (FAAAST)	Charles River Analytics Inc.	AF	1
A08-186	**Uncertainty**-modeling Rules for Situational Awareness (URSA)	Charles River Analytics Inc.	Army	1
ST081-004	Probabilistic and Relational Inferences in Dynamic Environments (PRIDE)	Charles River Analytics, Inc.	DARPA	1
SB043-041	Rapid Evidence Aggregation Supporting Optimal Negotiation (REASON)	Charles River Analytics, Inc.	DARPA	1
OSD03-029	Weather Prediction **Uncertainty** Management And Representation (PUMAR)	Charles River Analytics, Inc.	OSD	1
OSD03-028	Acquiring representations of Meta-information to Enhance Battlespace Awareness (AMEBA)	Charles River Analytics, Inc.	OSD	2
OSD02-CR12	Organizational and Cultural Criteria for Adversary Modeling (OCCAM)	Charles River Analytics, Inc.	OSD	2
N05-T019	Combining Model-based Reasoning with Knowledge Discovery Techniques for Level 2 and 3 Fusion	Charles River Analytics, Inc.	NAVY	1
MDA07-045	Optimized Planning for Threat Interception using Markets for **Uncertainty** Management (OPTIMUM)	Charles River Analytics, Inc.	MDA	1
MDA05-058	Meta-Information Visualization and Processing for C2	Charles River Analytics, Inc.	MDA	2
A99-107	MARAD: Multi-agent Architecture for Robust Adaptive Decision-aiding	Charles River Analytics, Inc.	ARMY	1
A97-120	AVID: Agent for Visualization and Intelligent Decision-Aiding	Charles River Analytics, Inc.	ARMY	2
A04-T002	Meta-Information Visualization to Enhance the Common Operational Picture (MIVEC)	Charles River Analytics, Inc.	ARMY	1
A04-108	Building Interfaces for Operator-in-the-Loop Data Fusion (BIFOLD)	Charles River Analytics, Inc.	ARMY	2

Topic No	Title	Firm	Agency	Phase
A00-041	Information Operations Decision-Aid (IODA) for Data-sparse Environments	Charles River Analytics, Inc.	ARMY	2
N00-074	Modeling and Simulation of Decision-making Under **Uncertainty**	Cognitive Technologies, Inc.	NAVY	1
A96-030	A RSTA Algorithmic Framework with **Uncertainty** Management	Cyber Solutions, Inc.	ARMY	1
AF84-239	Experimental Development Of Information Portrayal Principles For Decision Aids - Phase II	Decision Science Consortium, Inc.	AF	2
A85-108	Cognitive Processes In Decision Making Under **Uncertainty** And Time Stress	Decision Science Consortium, Inc.	ARMY	2
ST081-004	Probabilistic Logic for Knowledge Representation and Automated Reasoning	Decisive Analytics Corp.	DARPA	1
MDA03-009	Distributed Battle Management Techniques	Decisive Analytics Corp.	MDA	1
A08-186	Army Probabilistic Inference and Decision Engine (PRIDE)	Decisive Analytics Corp.	Army	1
MDA03-008	Decision Making under Probability Intervals	Gcas, Inc.	MDA	2
OSD99-006	Prognostic Enhancements to Diagnostic Systems	Global Techn. Connection	OSD	2
AF05-189	A **Bayesian-Based Graphical Modeling Tool** for Probabilistic Reliability Analysis	Impact Technologies, Llc	AF	1
AF01-111	Mixed Resolution Modeling Issues for the Battlespace InfoSphere	Information Extraction & Transport	AF	1
A04-096	DEC-POMDP Stochastic Game Approach for **Uncertain** MultiAgent Systems	Intelligent Automation, Inc.	ARMY	2
AF05-084	Fusion of Entity Information from Textual Data Sources	**Janya Inc.**	AF	2
AF98-063	Graphical Visualization Framework for Representing **Uncertainty** in Dynamic 3-Dimensional Data	**Kitware, Inc.**	AF	1
N95-048	Fighting in the Fog: Preparing Battle Commanders to Manage **Uncertainty**	Klein Assoc., Inc.	NAVY	2
N04-116	**Uncertainty** Management for Teams	Klein Assoc., Inc.	NAVY	1
MDA04-158	Categorical Logic as a Foundation for Reasoning Under **Uncertainty**	Metron, Inc.	MDA	2
N04-137	Probabilistic Error Estimation In Model-Based Predictions	Michigan Engineering Serv.	NAVY	1
N00-074	Modeling and Simulation of Decision-making Under **Uncertainty**	Micro Analysis & Design, Inc.	NAVY	1
N00-074	**Uncertainty**, Stress and Decision Simulation	Micro Analysis & Design, Inc.	NAVY	2
OSD03-029	Portraying **Uncertainty** in Battlefield Weather Situational Awareness	Next Century Corp.	OSD	2
OSD05-NC8	Network Situational Awareness	N-Space Analysis	OSD	1
BMDO02-010	A Bayesian Network Model for Tracking in Support of Discrimination	Numerica Corp.	MDA	2
N03-112	Modeling and Simulation of Cultural Differences in Human Decision-Making	Pacific Science & Engineering	NAVY	1
AF081-024	Predictive Clustering for IED Defeat	Parietal Systems, Inc.	AF	1
N07-091	Risk and **Uncertainty** Management for Multidisciplinary System Design and Optimization	Phoenix Integration	NAVY	2
N94-076	Demonstration Of **Fuzzy Factors** And Relationships For Strategic Availability Analysis	Risk Management Systems	NAVY	1
N08-081	Multi-scale Dynamic Network Graph (MUSING) for Network-based Information Exploitation	Scientific Systems Co., Inc.	NAVY	1
MDA04-158	Seamlessly Unified Reasoning Under **Uncertainty** for Missile Defense Architectures	Scientific Systems Co., Inc.	MDA	1
AF071-082	Advanced Self-Learning Ontologies	Securboration, Inc.	AF	1
AF87-066	Hazard Response Modeling **Uncertainty**	Sigma Research Corp.	AF	1
OSD03-029	Portraying **Uncertainty** in Battlefield Weather Situational Awareness	Sonalysts, Inc.	OSD	1
N08-166	Tools to Support Understanding of Information **Uncertainty** in Combat Operations	Sonalysts, Inc.	NAVY	1
N08-101	Semantics and Tools for Active Modeling and Processing in the Enterprise Data Environment (STAMPEDE)	Stottler Henke Assoc., Inc.	NAVY	1
N07-091	A Software Tool for **Uncertainty** Management in Multidisciplinary System Design and Optimization	Vanderplaats Research & Development, Inc	NAVY	1
OSD03-028	**Uncertainty** Awareness for Battle Space Visualization Systems	Visintuit	OSD	1
OSD03-028	A Framework for Understanding **Uncertainties** in Battle Space Visualization Systems	Visintuit	OSD	2