National Technology Alliance

Opportunities to Accelerate Temporal Geospatial Capability

30 July 2004

Rosettex Technology & Ventures Group

Swiftsure Spatial Systems Inc

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EXECUTIVE SUMMARY

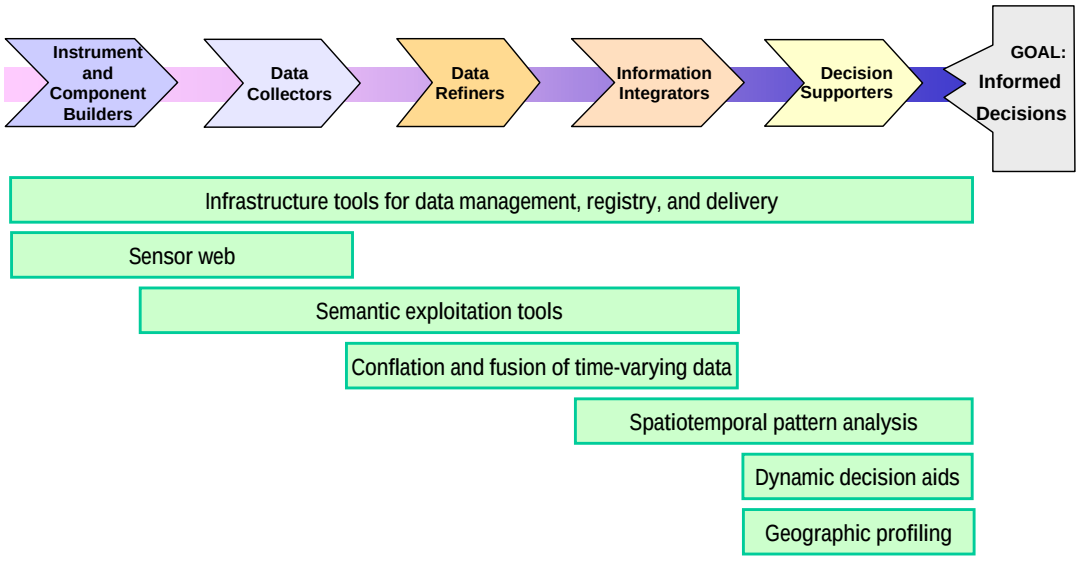
Geospatial change is information in and of itself. Change can have pattern, trend, and cycles, and it can deviate from pattern, trend, and cycles. Decision makers need to understand and assess information about geospatial change with the same care that they would take with spatial location and pattern. To ignore spatial change is to leave an entire dimension of information and its impacts unrevealed.

Proper treatment of time-varying information is a critical need for responding to market fluctuations, security threats, disease vectors and epidemics, environmental change, and natural disasters. Key investments can stimulate commercial opportunity, increase capacity to make better decisions, and provide a better basis for subsequent technology development.

This is the final report of a project called "Temporal Geospatial Data Management and Exploitation Needs and Technology Assessment" which was performed for Rosettex on behalf of the National Technology Alliance. The project's goal was to define how to move toward better treatment of time-varying geospatial information.

Development opportunities have been mapped to a value chain model to illustrate the stakeholders in each potential investment area (see below). The report elaborates on each development opportunity in terms of its contribution, current activities by the NTA, and technologies of interest. A sampling of technologies is described in each category to illustrate the state of the art, which represents the starting point for further improvement.

A final section describes a recommended programmatic approach to advance commercial capability and ensure coordinated development that can be integrated into technology environments of today and tomorrow.



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1. INTRODUCTION

Geospatial change is information in and of itself. Change can have pattern, trend, and cycles, and it can deviate from pattern, trend, and cycles. Particular moments in time acquire meaning, and are considered events—the rough equivalent of geospatial features. Geospatial features move, and their movements are influenced by spatial factors and by spatial changes. Decision-makers need to understand and assess information about geospatial change with the same care that they would take with spatial location and pattern. To ignore spatial change is to leave an entire dimension of information and its impacts unrevealed.

Technological progress in geospatial information systems provides many options for establishing an enterprise system to inform decisions with a geospatial context. But the commercial capability to collect, refine, resample, integrate, and use time-varying geospatial information using COTS tools is almost nil. Doing it across more than one technology environment is nearly impossible.

Deficiencies in treating geospatial change reduce our ability to make good decisions. For businesses, understanding spatial and temporal fluctuation in product demand improves just-in-time delivery of goods. For security, detecting pattern or deviation from pattern could help prevent a crime. For health surveillance and disease control, early warning of related factors (e.g., floods lead to mosquitoes, which are vectors of West Nile virus) makes a difference in stemming an epidemic. For environmental management, understanding normal ranges and balanced states helps in assessing adverse impacts and in disaster remediation.

Individual researchers and vendors working independently will not succeed at removing the obstacles involved in treating time-varying spatial information. A concerted and coordinated effort is needed to identify what technology is needed, what already exists, and what remains to be developed.

This is the final report of a project called "Temporal Geospatial Data Management and Exploitation Needs and Technology Assessment" which was performed for Rosettex on behalf of the National Technology Alliance. The project's goal was to define what needed to be done to move toward better treatment of time-varying geospatial information. It had two major goals.

- Identify and assess the most critical user needs of the US Government in the area of temporal geospatial data management and exploitation. The focus was on improving support to decision makers by improving the information and technology used to make decisions.
- Identify tools, techniques, and products available in the commercial market and under development, and the technology gaps that must be addressed to meet the community's requirements to address dynamic situations using time-varying information.

Technology gaps represent opportunities to invest in development to improve the current ability to work with time-varying geospatial information. Because time-

varying information is integral to every aspect of the operational environment, a programmatic approach is required to ensure that new technology can be introduced into operational use.

1.1. Background

Earlier reports have presented a framework comprised of spatiotemporal concerns and identified key capabilities required;[1] performed SWOT analysis;[2] and defined a vision and roadmap for overall capability improvement via establishment of a standards-based architecture for prototyping and demonstration.[3]

This report places the concerns and capabilities in the context of communities of interest, and assembles information about technologies of interest. It also recommends a programmatic approach for advancing a COTS capability to implement technology environments that treat geospatial change as valid information to be analyzed in and of itself.

1.2. Organization of this report

Section 2 describes the analysis and introduces the development opportunities. A value chain approach was used to show communities of interest relative to user concerns, functional needs, and development opportunities.

Section 3 describes the current state of spatial technology standards related to time-varying information and identifies gaps that need to be addressed.

Sections 4 through 10 describe development opportunities in more detail. The description includes a listing of technology providers of interest, which will serve as a starting point to pursue each opportunity.

Section 11 describes a programmatic approach for development. This approach ensures that the right architectural elements will be available to integrate new application software into operational systems. Architectural requirements include extensions to interfaces, standards for conceptual schemas and database languages, and a web service architecture for extensibility.

[1] "Recommended Spatiotemporal Capability for NIMA." NTA Report delivered to Rosettex by Swiftsure Spatial Systems Inc. 16 September 2003.
[2] Strengths, weaknesses, opportunities, strengths. The analysis used the categories of Enterprise, Engineering, Information, Technology, and Computation, as per the RMODP framework (Reference Model for Open Distributed Processing).
[3] "Vision and Roadmap for Temporal Geospatial Capability." NTA Report delivered to Rosettex by Swiftsure Spatial Systems Inc. 15 December 2003.

2. IDENTIFICATION OF DEVELOPMENT OPPORTUNITIES

2.1. Methodology

The value chain model[4] was chosen as the organizing structure to distill information on needs and gaps. The value chain model defines a series of related activities that successively add value. Value chain analysis ensures that value is added by each activity.

Our value chain model has five activities, which are defined as communities of interest. A given organization normally belongs to more than one community of interest. The communities are as follows.

- **Instrument and component builders**, who produce data collection technology through the design and development of sensors, instruments, platforms, and interfaces.
- **Data collectors**, who convert signals to data via the deployment of sensors and instruments.
- **Data refiners**, who convert raw data to certified data products through quality assurance processes that transform coordinates, impose categorical schemes, remove errors, and format as needed.
- **Information integrators**, who blend data elements from different sources to create specialized or customized information sets for particular audiences or purposes.
- **Decision supporter**s, who analyze the information with particular goals in mind, and provide the results of the analysis to decision-makers to inform their decisions.

2.2. Value chain assessment of needs

The first stage of value chain analysis involved selecting a set of individuals who were "interested parties" and engaging them in conversations on what they would like to be able to accomplish using time-varying information. We then mapped their concerns to the value chain as a way of understanding the communities of interest that share in each concern (Figure 1).

[4] Michael Porter (1985). *Competitive Advantage: Creating and Sustaining Superior Performance.* The Free Press.

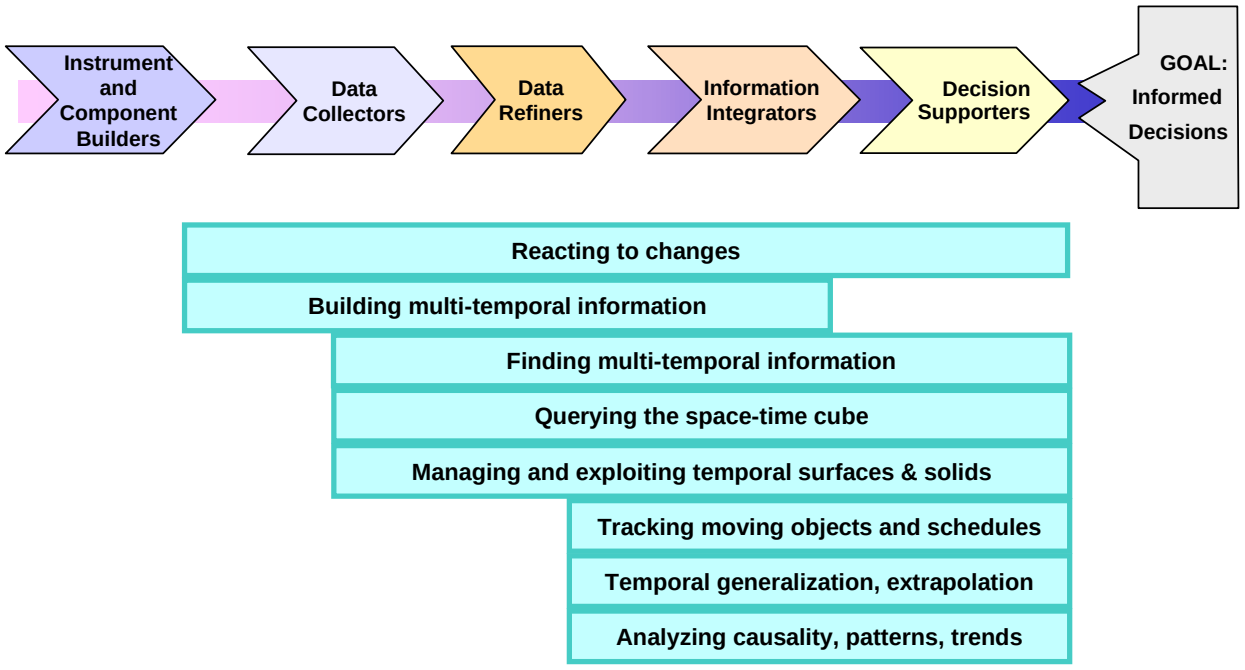


Figure 1. Concerns of users as mapped to the value chain.

The value chain mapping reveals that the concerns expressed by users lean toward the right side of the value chain, where value-add processes have produced an information commodity that helps to achieve the goal of making better decisions. Users express fewer concerns that affect the left side of the value chain. These early stages guarantee a data stream, without which there can be no decision support. But because the deficiencies in producing a data stream are less understood by end users, most express less concern.

The next step was to define a set of functional needs to address the concerns of users, and map them to the same value chain model (Figure 2). Note that the functional needs shift to the left of the value chain, acknowledging the deficiencies in obtaining a reliable data stream to describe time-varying geospatial information. In fact, a key shortcoming today is the lack of data holdings and data exchange capability to permit users to acquire base data describing change over time.

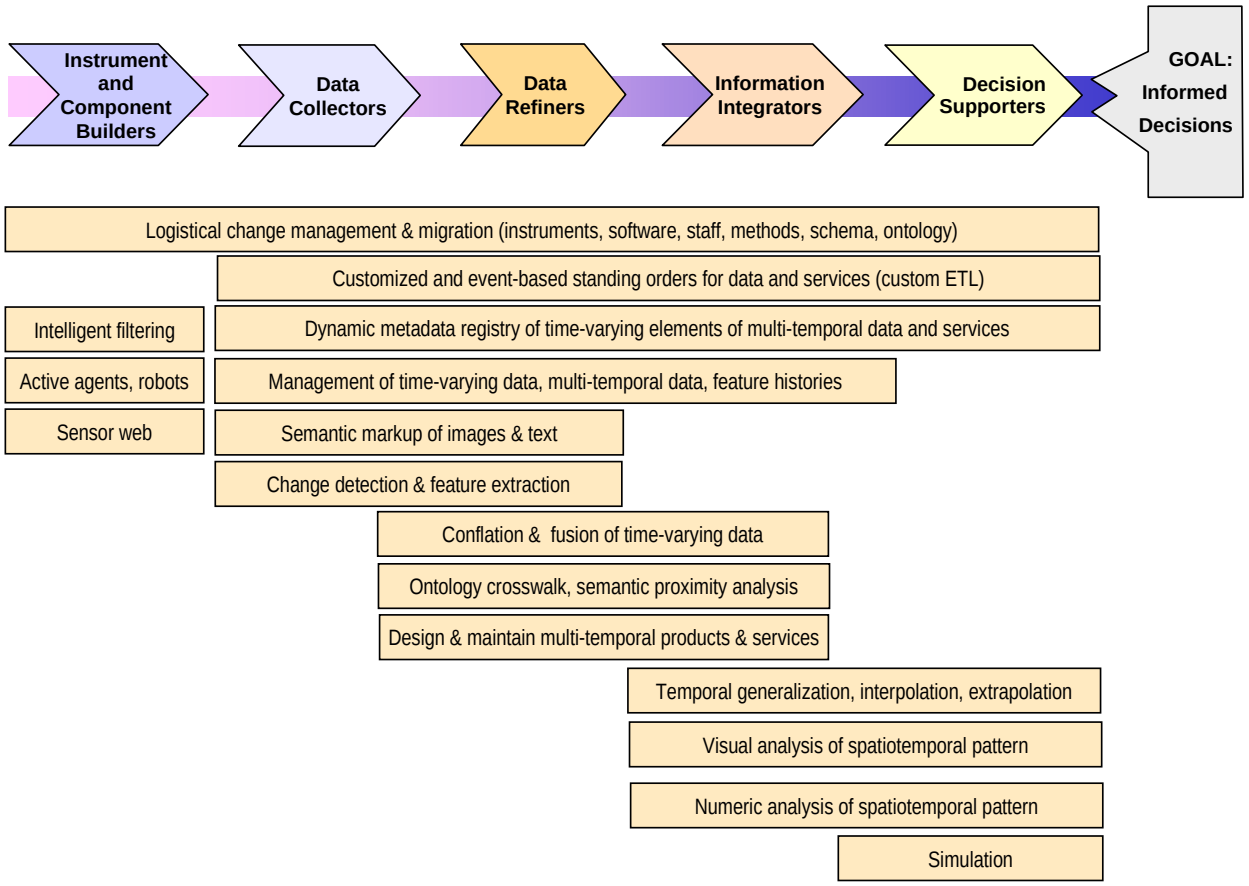


Figure 2. Functional needs as mapped to the value chain.

2.3. Value chain assessment of development opportunities

The functional needs presented above were the basis of a search for technology to close the capability gaps via commercial software and formalized standards. A development opportunity exists if good technology options are unavailable, or if emerging technology looks like a promising solution to a problem. The development opportunities are shown in Figure 3, mapped to the value chain. These are described in greater detail in later sections of this report.

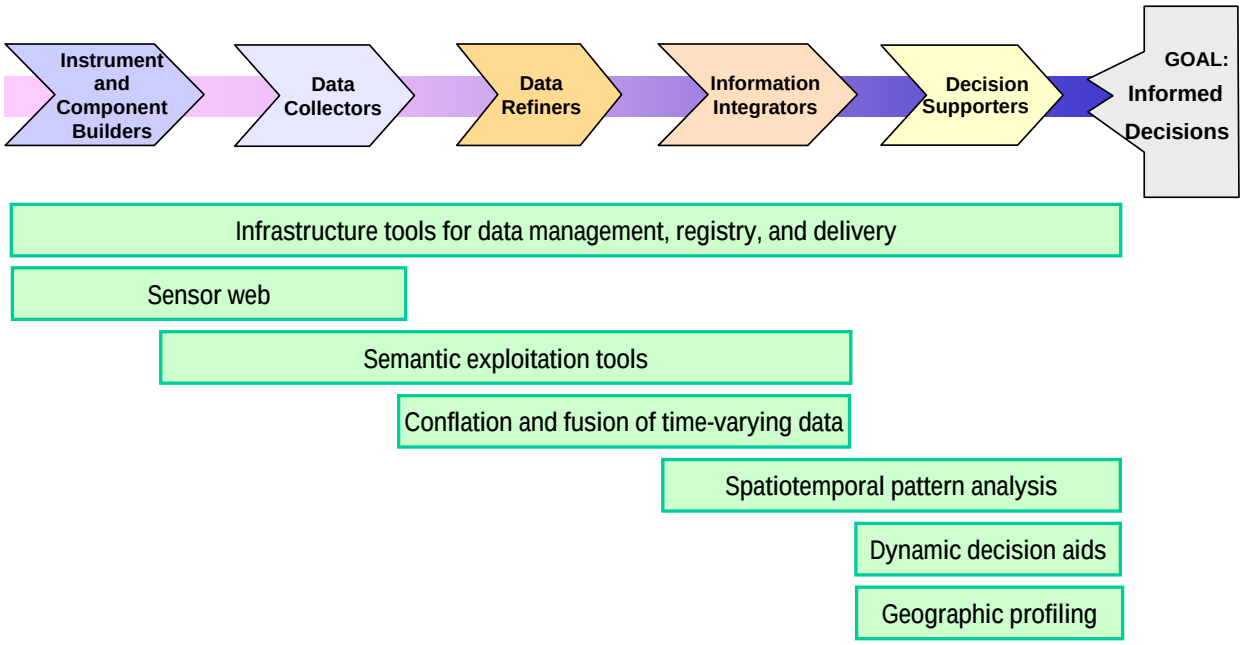


Figure 3. Development opportunities as mapped to the value chain.

The development opportunities shown in Figure 3 do not address all the functional needs shown in Figure 2. This is because some functional needs require standards, policy, organizational restructuring, or configuration specific to a particular installation, and thus are not good candidates for NTA development.

To validate the areas of activity and better understand the development opportunity, we developed scenarios of use for candidate technologies within each activity. Different types of activities would use the technologies (shown as development opportunities) for different purposes. The next two subsections use Data Collectors and Information Integrators as examples of how the technologies might be used in common workflows.

2.3.1. Use of technologies by Data Collectors

Data Collectors can use the candidate technologies in a variety of ways. Figure 4 shows a process flow that takes advantage of the capabilities. Infrastructure tools are used to communicate with and serve data to prospective data users, as well as managing information in-house. Registry interaction that is specific to time-varying information would include maintaining or browsing metacontent on temporal reference, resolution, and timespans of registered datasets. Infrastructure services would include an ability to request data within a given timespan and region, and preview the data's time-varying characteristics via animation and other spatiotemporal graphics.

Data Collectors use the sensor web as a primary data source, and would need mechanisms for monitoring, configuring, extending, evaluating, and formatting the data stream. Sensor webs can sample at regular intervals, providing core data to

be analyzed spatially and temporally. For example, a web could include stream gauges, in-situ sensors to describe local soil temperature and moisture, plus remote sensors to describe flooding and soil factors over a larger area.

Data Collectors use semantic exploitation technology in two ways. The first use is to ensure that registry entries conform with terminology and language used by the intended audience, and that the registry entries would be properly accessible to users who rely on a wide range of ontologies to search for data. For the time-varying elements of registry information, this means that accepted ontologies of time and change are observed. The second use of semantic exploitation tools by Data Collectors is to harvest information from unstructured sources, as a means of gathering information about spatial change. Unstructured sources may include text fields of databases, documents, and the Web.

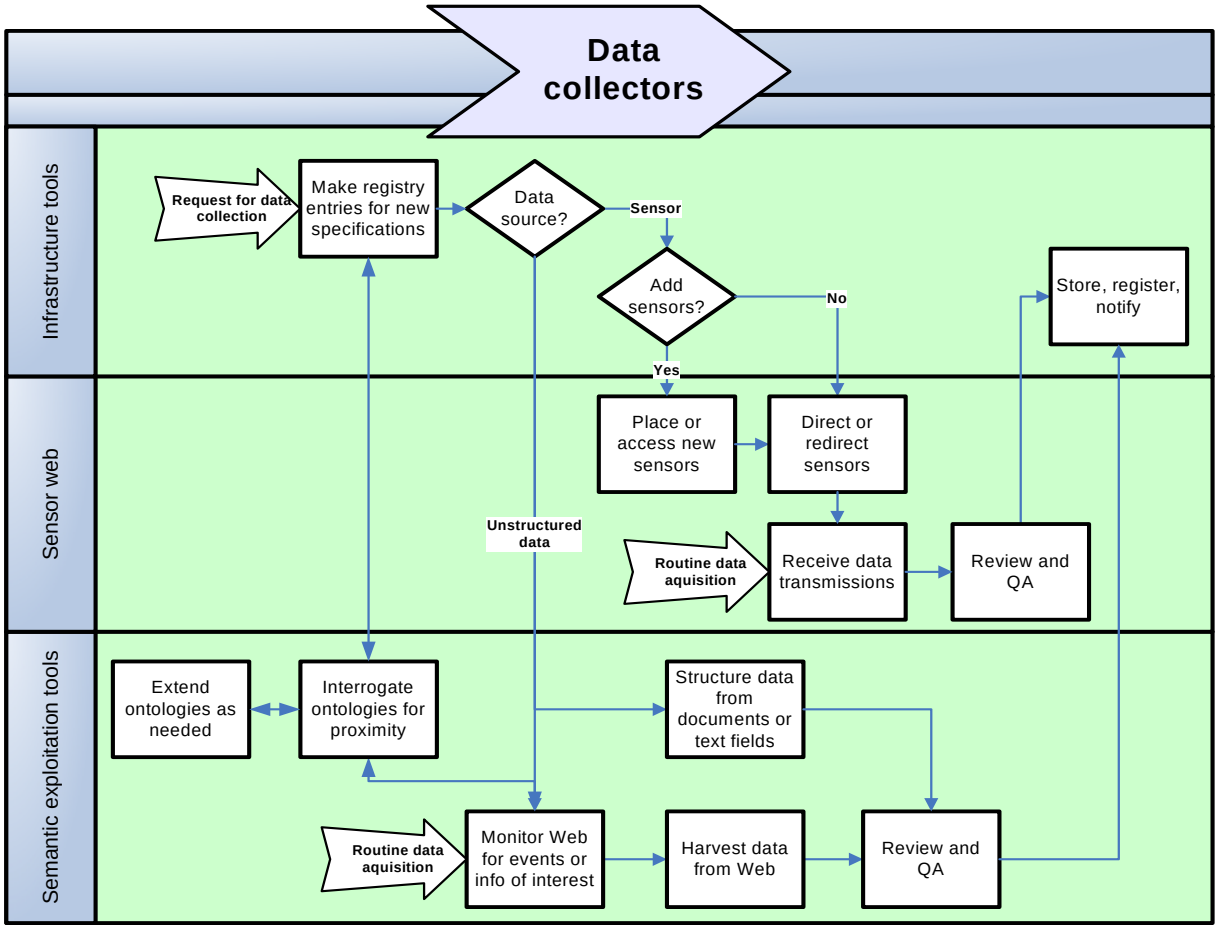


Figure 4. Potential use of recommended tools by Data Collectors.

2.3.2. Use of technologies by Information Integrators

For Information Integrators, the candidate technologies markedly improve the capability to find source data (possibly atemporal) and create customized multi-

temporal datasets. Figure 5 provides a sample process flow that illustrates the use of new technologies. Infrastructure tools are used to communicate with prospective users (as for Data Collectors), and also to search for data that can be used to create datasets to meet a specific need. Information Integrators would use browsing and previewing capabilities offered by Data Collectors to assess data that describe spatial change and look for the best data for the purpose at hand.

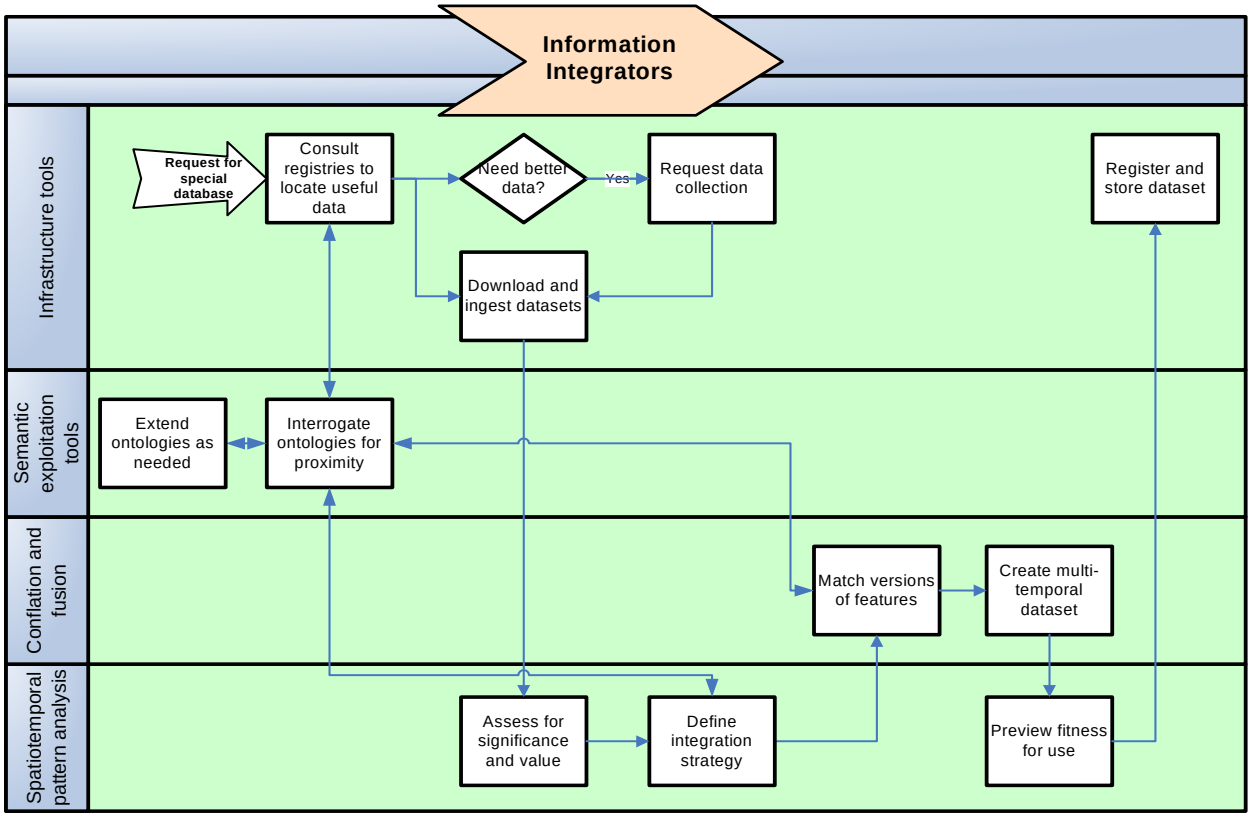


Figure 5. Potential use of recommended tools by Information Integrators.

Information Integrators use Semantic Exploitation Tools to aid in the search for data, and to locate terms to expand the search and improve success. Semantic Exploitation Tools also could be accessed to define an integration strategy prior to conflation, and by conflation software to improve the use of attribution in feature matching, and for creating standard names in conflated dataset schemas.

Information Integrators use conflation and fusion tools to merge source datasets to create a result dataset. Source datasets could be atemporal (i.e., there is no temporal referencing), they could represent a single snapshot or timeslice, or they could be multi-temporal and have multiple versions of features depicting change over time. In any event, the conflation tools would need to be able to match different states of the same feature, then to create a multi-temporal versioned object to represent spatial change.

Information Integrators use spatiotemporal pattern analysis tools to assess whether spatial change occurs in data, and to preview the value of potential source datasets in creating a multi-temporal picture for use by decision-makers. Following conflation of source data, pattern analysis tools can be used to quality-assure the result, since these tools could detect logical inconsistencies that data editing tools do not.

The next sections describe the development opportunities in greater detail by providing:

- a description of the opportunity,
- a definition of the contribution that investment in the opportunity will deliver,
- a summary of current activity within the NTA, and
- a list of the technology providers of interest.

3. INFRASTRUCTURE: TOOLS, INTERFACES, STANDARDS

3.1. Description and background

Infrastructure enables an enterprise.[5] Infrastructure components include the following.

- Security capabilities related to distributed access to multiple information sources over secure encrypted communication.
- Registry management tools for information, services and applications.
- ETL tools to move information across the enterprise in the form most useful for target purposes.
- Tools to monitor networks resources, business requirements, and information sources so that new information can be targeted, validated, and acquired as the situation demands.
- Tools to manage the logistical aspects of change over time to the enterprise, e.g., changes to sensors, analytical capability, detection capacity, storage schemas, roles of participants in the enterprise, scenarios being addressed, communications protocols, languages, and standards.
- Standards for components such as query and programming languages (e.g., SQL, Xquery, C++), interfaces (e.g. Call Level Interface, better known as ODBC) and encodings (e.g., HTML, XML, and GML) and ontology definition and sharing (e.g., OWL and RDF).

Infrastructure components underpin all communication across the network and make it possible for users at the knowledge and decision end of the value chain to communicate their requirements to the data and detection part of the chain. Infrastructure also permits integrators to analyze the value that already exists in base data before adding value in the form of interpreted or locally acquired data.

[5] Enterprise architecture is “the set of descriptive representations (i.e. models) that are relevant for describing an enterprise such that it can be produced to management’s requirements (quality) and maintained over the period of its useful life (change).” From Information Resource Management Glossary, http://www.cio.gov.bc.ca/other/daf/irm_glossary.htm#E

Investments in infrastructure components for time-varying data must be well coordinated with standard practices and application architectures.

3.2. What is the contribution of infrastructure tools?

Infrastructure is critical to the management and analysis of spatial change for the following reasons.

- Quality of information links back to the configuration of infrastructure components. For example, a work-around that compensates for poor infrastructure design can introduce error or increase cost.
- Organizations change continually, an infrastructures must accommodate changes to personnel, roles, data, schemata, technology, etc. Stability is the exception, not the rule, yet many systems are designed only for stable times.
- External factors may require sudden change to data access needs. For example, in an emergency it may be important to grant data access privileges that would not ordinarily be granted.

The focus of this report is on enabling the analysis and understanding of spatial change in the "universe" of interest to an enterprise, which will occur primarily at the application and data levels. However, it would be remiss not to summarize the infrastructure elements that are needed so as not to build a powerful analysis system on inadequate underpinnings. Data are only as good as the infrastructure that supports capture, management, and access.

3.2.1. Network interoperability and registry management tools

Network interoperability and registry management tools expose information so that conflation capability, semantic exploitation tools, and spatiotemporal pattern analysis software can find and exploit data from internal and external sources across the network. They maintain and give access to descriptions of stored information, which can range from free text to structured metacontent to semantic ontologies.

There is a complementary relationship between these infrastructure functions and the semantic exploitation opportunities described in Section 5. Semantic exploitation tools search, harvest, evaluate, and collate geospatial information using networks. The network interfaces and protocols of the infrastructure enable the semantic tools to perform these tasks. Registry, catalog, and feature services of the infrastructure enable the semantic tools to access, parse, and interpret structured and unstructured information across many domains at a much greater depth than simple web pages. Without network interoperability services, interfaces and semantic registries, information remains hidden; intuitive links that convert information to intelligence also cannot be made.

3.2.2. Transaction management tools

A spatiotemporal system must have a robust means of managing updates to data holdings and controlling versions of information. Versions can represent different viewpoints, levels of resolution, time periods, stages of processing, or other. Regardless, it is critical that the same database management safeguards available

to aspatial and atemporal environments be available in a spatiotemporal environment. In addition, it should be possible to preserve previous data states in such a way that feature change over time can be queried and extracted to application schemas. It also should be possible to define rules regarding how many versions of a feature can exist at any given time, and in what situations.

The data model and methods used are important because spatiotemporal databases are large, and even situation-specific datasets for a particular purpose can be multi-gigabyte in size. The option of change-only update (rather than creating complete copies of data states) is essential.

3.2.3. Security and distributed access

Security and distributed access are affected by the inclusion of spatiotemporal information because over time everything about the enterprise will change and this adds complexity to access control. For example, schema change means that different schemata are valid during different periods, and access privileges are also tied to those periods. Staff roles change, too, and it could be important to know who had access to data of what period, and when. For example, if updates create a historic stream of information and it is possible to edit the data retroactively, defining who has had access and who is allowed access become relatively complex. In addition, emergencies or special events could require that access privileges be extended to staff who normally do not have access. In summary, access to data would need to be granted based on data values (e.g., particular periods, regions, and themes), and it would need to be tracked historically.

The security framework should allow local responsibility and control over business processes and geospatial data, because the value chain required to provide information about spatial change to decision-makers requires collaboration and information sharing. This in turn requires a high degree of control over who can access specific information and under what conditions. Any acceptable solution must be simple to configure and administer, adapt to a wide range of environments, remain operational 24/7, and be as invisible as possible to users.

3.2.4. Registry management tools

Registries provide information about information (meta-information) and can describe content, products, network resources, services, and people. They are a crucial means for enterprises to selectively expose data holdings and for users to search for and evaluate data of use to them. Creating spatiotemporal datasets for analysis will involve data integration for the foreseeable future, thus strong registry management tools are a major requirement.

Improvements in registry technology will come from the massive effort being expended on developing the Semantic Web. Meta-information can be captured automatically via network-aware search engines, encoded in an ontology language (e.g., OWL[6] or RDF) and presented to the enterprise via a series of registries. The

[6] OWL stands for "Web Ontology Language", which is being developed by W3C for the application of semantic registries and their automated processing. OWL is a semantic markup language for publishing

registries mediate access to information and comprise the underpinnings of the *"Semantic Web"*. Semantic Web development opportunities for registries are discussed here. Applications that use the Semantic Web are discussed in Section 5.

A semantic registry is a structured resource much like a data dictionary, in which the meaning and syntax of all pieces of information used within a broad enterprise can be stored. Examples of semantic registries that have been established in a global context for specific domains of application are as follows.

- The Basic Semantic Register (BSR) is a work item of ISO TC 154 that includes semantic descriptions of resources commonly used in Electronic Data Interchange (EDI). The goal is to provide a navigation capability for developers and users of software systems to query, adopt, and apply common fields, concepts, and schemas (see www.ubsr.org).
- The Environmental Data Registry (EDR) is operated by the Environmental Protection Agency for the environmental reporting community. EDR is a comprehensive, authoritative reference for information about the definition, source, and uses of environmental data. The EDR promotes the efficient sharing of environmental information among EPA, states, tribes, and other information trading partners by defining the structure and meaning of information elements used in data exchange.

Neither the BSR nor the EDR contain real 'data;' they contain the descriptive information of the concepts and their instantiation that can be navigated in ways that go well beyond traditional metadata.

The syntactic and semantic interoperability of similar data sets will remain a challenge until a common global standard for expressing and encoding geospatial concepts is adopted. A network of operational semantic registries is not possible until that time. A network system would permit individual organizations to publish digital geospatial information, along with a data model or schema to interpret its syntax (structure) and a semantic model to describe its precise content. Wherever possible, the elements of the semantic model would be associated with equivalent semantic elements in national or professional information schemas to help in the automated interpretation or transformation of both the data structure and its semantic content.

3.2.5. Spatial ETL Tools

When an enterprise integrates data from many intelligence sources over time, the problems of data management are exacerbated. ETL tools (Extract, Translate, Load tools) aid in the move towards interoperability because they offer flexibility in how users can access data in a variety of formats and schemas from multiple databases without conversion. Thus, data always remains at its source and in its native format. This can be important for sites with high-frequency updates. Spatial ETL tools can perform these and other functions.

- **Support of legacy enterprise applications.** When an organization moves to new technology or schemata, older legacy applications can continue to be supported. An

and sharing ontologies on the World Wide Web. It builds upon a varian of XML that expressly describes relationships between objects, known as the Resource Description Framework (RDF).

ETL application can move data back and forth between the old and new systems, ensuring that data is structured and presented consistently to all systems.

- **Initial data loading.** When building a new database, source data may be scattered across multiple systems, formats, or schemata. The ETL tool's job to migrate this data into a common ontology or schema in the new system. Time-varying data requires that all data coming into a common system be adequately time stamped so data is not overwritten or otherwise corrupted.
- **Multi-vendor solutions.** Many organizations have solutions that cross vendor boundaries or have requirements for data to be shared between systems.
- **Data sharing.** Data may be shared between organizations. The relationship could be among suppliers, customers, or business partners. ETL tools ensure that the data sharing between these different organizations and their enterprises respects technical integrity and security considerations.
- **Quality assurance.** An ETL tool can run checks on data quality as part of translation and loading. This is especially important with time-varying information, which may have quality problems related to real-time data streams or staleness.
- **Direct read.** Providing a unified interface so that applications can directly access data from other systems may have great impact. Here, the "T" (Transform) in ETL can be immensely valuable as applications typically require the data be presented in a specific schema (or view) before using it.

A small number of companies have made Spatial ETL a core business. As a result, their products have superior overall capability and robustness with respect to handling spatial complexity. Some new products are emerging but they do not always provide full support for full integration of trustable data sources.

3.2.6. Standards for time-varying data

Standards are "…documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines or definitions of characteristics, to ensure that materials, products, processes and services are fit for their purpose."[7] Probably the most important part of this definition is "fit for purpose": it implies, that one must know what practical objective is to be attained before embarking on the use or development of a standard.

Standards are more than an abstract good or a public service. Experience has shown that information technology standards have accelerated commercial development in key areas by creating a stable target for commercial development. Obvious examples are HTML, XML and SQL.

A comprehensive standard that will address all the issues related to time-varying information will take years to develop, discuss, and approve. But certain business cases and the methods needed to treat them are candidates for fast tracking. Consequently, a recommendation has been made to ISO TC211 to undertake the following.

- Initiate a New Work Item to address the time-varying aspects of moving features.

[7] This definition comes form the ISO/IEC Web Site.

- Initiate work to determine the best incremental approach for completing the standardization process for time varying information.

The New Work Item (NWI) to develop a standard schema for moving features was submitted through DGIWG[8]. The vote on the proposal will be in October 2004. The work would be coordinated with groups within ISO that are addressing the needs of location-based services (LBS), tracking and services, and multi-modal LBS.

The NWI will produce a conceptual schema for features that move in three dimensions (x,y,z) without deformation or change in dimension. The work will address the representation of features that move on constrained paths (e.g., orbital objects, on-road vehicles, trains) and on relatively unconstrained paths (e.g., aircraft, animals, foot traffic, off-road vehicles).

The NWI is separated from work on other types of geospatial change, which could be conducted as a parallel project. The rationale for fast-tracking moving features is that their issues and concepts are well understood, and as such will invite constructive discussion, development of terminology, and generation of a conceptual schema that is forward-compatible to other types of geospatial change.

The core conceptual model for moving features must be shared among all interested parties to ensure proper interfaces between market areas. Backward compatibility must be achieved for existing implementations (e.g., that of SC24). Backward compatibility is also needed for spatial geometries defined by ISO 19107 Geographic information – Spatial schema and ISO 19108 Geographic information – Temporal schema. TC211 Standards that may relate to moving features and require backward compatibility are 19107, 19108, 19109, 19132, 19133, 19134, 19136.

In addition to the NWI, follow-on work will be needed to address the following.

- Identify parts of existing schemata that should be incorporated or revised. Candidates for incorporation or revision include dynamic features in GML (19136) and feature succession constructs (19108).
- Identify application schemata that are ripe for spin-off and fast tracking. The basis for choosing schemata to spin-off and fast track includes these factors.
  - Business cases must be generally well understood.
  - There must broad informal agreement as to the appropriate technical approach.
  - The technical approach should not be difficult to implement.
  - There should be widespread need and a large potential market, which creates a strong incentive for investing the necessary effort to address the need.
- Define use cases to document business needs. The lack of use cases is a deterrent to clear communication among discussants. Use cases are critical for defining common technical approaches that can be standardized in application schemata.

[8] DGIWG is a standards group that was originally formed to address NATO interests in data exchange. The acronym stands for "Digital Geographic Information Working Group." Membership extends beyond NATO to include Australia, Belgium, Canada, the Czech Republic, Denmark, France, Germany, Greece, Italy, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Turkey, the United States, and the United Kingdom.

- Analyze and document commonalities in requirements and approaches. The goal is to define a general and common means of treating time-varying information such that all businesses can communicate using the same core constructs, leading to widespread interoperability.

3.3. Current and planned activity by NTA

Solid infrastructure requires care in defining interfaces between components and data stores. For that reason, the proposed program plan includes the development of TOTAL[9], an environment to pilot, test, and evaluate new software applications, infrastructure, and interfaces prior to beta testing. A beta-testing environment, TSUNAMI[10], is also part of the proposed program plan. Section 10 describes TOTAL and TSUNAMI in the context of the proposed program plan.

NTA also is supporting participation in the ISO TC211 work to develop standards for time-varying spatial features.

NTA's Conflation for FLDB project includes development of a "schema remodeler" (part of GeoMedia Fusion), which described in Section 3.4.

3.4. Sampling of technologies of interest

The technologies described in this section are but a sampling of interesting options for enabling an enterprise to handle time-varying spatial information via infrastructure improvements. Table 1 lists the technologies described here, and the interests that they represent.

Table 1. Sampled infrastructure technologies of interest.

Technology of interest	Reason for interest
Compusult Web Enterprise Suite	Web Search, harvest, registry and data management, OGC service provider.
Ionic Red Spider Catalog	Part of an application development environment that provides WMS, WFS, and Catalog and Registry services.
Intelec Geomatics M3Cat and M3Geo	Meta-information and ontology design and management. Includes development and maintenance of linguistic and ontological crosswalk.
PCI Geomatica 9 Exploitation Suite	Application development environment that provides WMS, WFS, and Catalog and Registry services.
Safe Software FME	Spatial and temporal ETL, schema and ontology crosswalks.
Intergraph GeoMedia GDO and schema remodeling	An integrated interface to ETL tools. Development and maintenance of linguistic and ontological crosswalk.
DACS	Distributed security management for the distributed OGC compliant enterprise.
Zope	Portal management tool that supports web registries.
LaserScan	Spatial and temporal database change management at multiple granularities.
GDAL – Geospatial Data Abstraction	Spatial database, vector, and image ETL.

[9] TOTAL stands for Tools and Temporal Analysis Lab.
[10] TSUNAMI stands for Time-Sensitive Unified Networked Analysis and Management of Information.

Library	

3.4.1. Compusult Web Enterprise Suite[11]

Compusult's Web Enterprise Suite (WES) provides capability of use in integrating remote sensing data that describes time-varying geospatial information. WES is an integrated suite of applications for web mapping, cataloging, discovery, retrieval, delivery, and e-commerce services. They include the following.

- Percipio is a commercial data warehouse product for organizations that receive, archive, catalog, maintain, and disseminate data holdings over Intranets and wide area networks such as the Internet.
- PHTML (Parsed HTML) is a development and applications environment that provides Web content managers and developers with the ability to create, integrate, and dynamically update Web pages with content from relational databases, customer back-end systems, and such external applications as e-commerce.
- Relational Gateway is a middle-tier product that permits Web applications to connect to relational databases that are maintained inside firewalls.
- Meta Manager provides linkages that enable data suppliers and custodians to connect relational database catalogs to clearinghouses for searching and data product discovery. Clearinghouses are distributed throughout the world. In North America they are operated by organizations such as the Federal Geographic Data Committee (FGDC) and GeoConnections.
- Meta Miner provides an ability to create a clearinghouse. It includes a Z39.50 client with search specification fields, a clearinghouse server registration and search module, and clearinghouse server searching and result processing. The client look, feel, and operation is customizable and supports XML processing.
- Map Manager is an Internet mapping tool that can present, link, distribute, and publish spatiotemporal data, products and services. Map Manager provides the infrastructure for users to access spatial information from disparate data sources and to display the information in browser client applications. Map Manager is multi-tier with options for deploying clients, servers, administrative, and third-party interfaces. It uses XML technologies for client and server communications. The Map Manager server supports ESRI's ArcXML, which allows map clients to communicate with ESRI's ArcIMS servers and associated services. Map Manager also is OGC Web Mapping compliant. Consequently, map clients can communicate with OGC compliant catalogs and service registries and integrate and display Web mapping layers from distributed Web mapping servers that are also OGC-compliant.
- Service Manager is a catalog toolkit that is OGC compliant and provides discovery, access, harvesting, and maintenance of web-based services metadata. The architecture is designed for deployment in a multi-tier arrangement of clients and servers. Discovery of services is provided through Service Manager Client interfaces. The application also has a metadata harvest process that automatically ingests service metadata from OGC-compliant servers.

Compusult technology is of interest because it provides a consolidated view of heterogeneous data holdings, which is crucial when time-varying information is acquired from data streams that originate from different times, places, and

[11] http://www.webenterprisesuite.com/

organizations. All operations are carried out via the administrative and browser graphical user interfaces. It is highly extensible. It also provides backward compatibility to legacy models and systems. It also takes a standards-based approach, which facilitates access to diverse data sources.

3.4.2. Ionic RedSpider Catalog

RedSpider Catalog is an e-business registry that helps manage a community of OpenGIS services. It provides a standard method for an organization to exchange business messages, conduct trading relationships, communicate data in common terms, and define and register business processes. RedSpider Catalog enables a user to register and find geospatial OGC/ISO Web Services for use in an enterprise application.

RedSpider Catalog is based on the new Web Service profile of the upcoming stateless OGC Catalog 2.0 specifications. The new international standard to exchange secure business information between organizations, ebXML, also forms the foundation of the RedSpider Catalog.

RedSpider Catalog includes a simple interface to directly register such web services as WMS and WFS by providing the service URL. When a user begins to register a resource, the catalog analyzes service capabilities and metadata to perform an activity called harvesting. This enables the Catalog to automatically discover the service interfaces by means of service metadata.

3.4.3. Intelec Geomatics M3GO[12]

M3GO is a multi-use, multi-lingual, multi-standard geospatial ontology server. It allows users to build geospatial ontologies, import existing concepts, and create semantic links between concepts such infrastructure services as cataloging, data discovery, and data integration. It can query a service to obtain synonyms, related terms, broader terms, translations, etc.

The M3GO web-based service manages several geospatial ontology collections of complete, agreed-upon descriptions of concepts in a certain subject area in at least two languages. The service creates semantic linkages of meaning between key words and between words in different languages. It also provides a feature to suggest the most appropriate key words based on those linkages. Using M3GO, data providers can supply users with a wealth of information, including the translation of a given term in a given ontology, synonyms, other related terms and terms that include, or are included by, another term.

M3GO is not a semantic harvesting tool; its primary goal is to provide a more consistent means for *providers* of geospatial information to harmonize data from multiple sources and different languages, and give them a standardized list of terms and translations that are relevant to their subject. It is useful when updating databases to identify correlations between features (i.e., during conflation). For

[12] http://intelecgeomatics.com/ogm3/

users of geospatial data, the M3GO service makes information more accessible by enabling more intelligent search and retrieval.

M3GO was developed by Intelec Geomatics with funding from the Canadian GeoConnections program. M3GO is currently undergoing testing and enhancement with the original project partners (the Quebec Ministry of Natural Resources, Fisheries and Oceans Canada, Natural Resources Canada, Environment Canada and the North American Commission for Environmental Cooperation[13]. Tests are using ontologies appropriate to environmental sciences in Spanish, French and English. There are plans to commercialize the services and technology.

3.4.4. PCI Geomatics – Geomatica 9 Exploitation Suite

Geomatica 9 offers a blend of tools for working with imagery to aid in remote sensing, GIS, photogrammetry, and cartography. It has 250 data transformations in a GUI environment, a scripting language, and a GUI workflow builder. Key features include the following.

- ETL tools for building data transformation workflows.
- Raster and vector processing transformations
  - image mosaicking
  - orthorectification
  - image classification
  - pansharpening
  - atmospheric correction
  - DEM extraction
- Support for OGC interfaces
  - Web map server
  - Web coverage server
  - Web feature server (supporting GML and XML filtering)

PCI offers some of the best capability available for combining image sources with other types of data. It is complementary to the Safe FME, which offers comparable capability for vector ETL. PCI is a member of OGC and is working with Natural Resources Canada on a 5-year program to enhance semantic support for network computing.

3.4.5. SAFE Software – Feature Manipulation Engine

The Feature Manipulation Engine (FME) Suite is an ETL (Extract, Transform, Load) tool for spatial data. It consists of three main components: a translator, a transformation editor and a viewer. FME Suite also includes developer tools and coordinate conversion support.

FME is the primary ETL tool for IBM, Oracle, Autodesk, ESRI, CARIS, MapInfo, and others. Bentley and Intergraph are migrating toward the FME rather than

[13] http://www.cec.org/home/index.cfm?varlan=english

continuing in-house development. Safe Software has an aggressive OEM program that enables third parties to embed FME technology within their own.

FME supports format-to-format and data model translations. There are two classes of translation. The first class is called generic (or thin-pipe) translation, where data is moved automatically from one vendor product to another. This adds little or no value other than providing a simple way to move data between systems. The second class is called semantic (or thick pipe) translation, where users employ the GUI-based FME Workbench translation and transformation environment. FME Workbench users can restructure data, correct, filter, and integrate data from multiple sources and formats, with output to a standard or custom schema and format.

The product has a flexible representation that characterizes all aspects of data being read, and then providing an environment for manipulating it in the schema of the output system. Enabling users to see their data models before and after the transformation, as well as the steps taken during the transformation, is critical. Adding support for time to this product may require the addition of new data types and extension of some product schemas. Enhancements to the user interface may also be required.

3.4.6. Intergraph GeoMedia

Intergraph's GeoMedia is designed to work in a heterogeneous data environment such as would be anticipated when time-varying information is received in multiple data streams. GeoMedia has WFS and WMS components, which permit access to data in other enterprise systems. In addition, GeoMedia's GDO technology has been developed to serve heterogeneous data to GeoMedia without first translating from the original format. Data types that can be ingested by GDO include those produced by most popular GIS and CAD packages. GeoMedia also embeds portions of the Safe FME (incorporated via OEM), to permit ingest of many standard data exchange formats.

GeoMedia also has "schema remodeling" capabilities that allow the user to define and save rules for converting one schema to another, for use in on-the-fly data ingest. Conversions can be to names, attribute types, mapping of feature types, and converting attribute values via functions. This capability gives GeoMedia exceptional capability to ingest alien data sources without changing the data sources themselves. This is of particular use in enterprise systems with multiple database schemas and technology platforms. Intergraph plans to bundle the schema remodeler with data fusion tools (discussed in a later section on Conflation Tools) for commercial release in Q4 2004.

The purpose of GeoMedia ingest functionality is to bring all datasets together into one client for GIS-style analysis. In contrast, the purpose of FME ingest functionality is to output a dataset whose format, schema, complexity, coordinates, etc. can be specified by the user. Both capabilities play a role in a "barrier-free" technology environment.

3.4.7. DACS

The Distributed Access Control System (DACS) facilitates the cooperation of autonomous organizations to control users' access to information services delivered through the World Wide Web. Interacting with existing authentication systems, DACS provides a uniform way for users to identify and authenticate themselves, and for jurisdictions to share their information assets and services with those users in a controlled way. DACS aims to support virtually any authentication method that can be implemented as a web service.

DACS is a framework that manages identities and enforces role-based access control on web services. Rather than dictating policies, its goal is to provide secure, flexible, extensible, and highly available mechanisms. These mechanisms are themselves invoked as web services and allow each jurisdiction in a federation to determine its own authentication and access control policies. Features include:

- Federated identity management - DACS unites independent jurisdictions, forming a federation of web servers with single sign-on. DACS makes it easy to limit the sharing of web content and services to only authorized users.
- Role-based, jurisdictional access control - Each DACS jurisdiction determines the conditions under which access to its resources are permitted.
- Supports many authentication methods - Supported authentication methods include passwords, X.509 certificates, and Pluggable Authentication Modules. Authentication methods can be composed, in which case a user can be required to pass several authentication tests.
- Distributed, scalable, and highly available - The DACS architecture is fully distributed and will typically have no single point of failure.
- Flexible access control rules - Access control rules are powerful and expressive yet typically easy to understand.

Although DACS is a general-purpose and application-independent, it has evolved in conjunction with web-services based systems being developed through OGC[14] and the CGDI[15].

Currently, DACS suffers from the same limitations as other security and access management tools. They do not deal well with organizational and structural change to information and technology assets, which translates into high maintenance overheads. The DACS approach may offer a solution to this because it is designed to offload certain types of operations to other services by creating service chains. Temporal capabilities could be added this way.

3.4.8. Zope

Zope is an Open Source application server and portal toolkit developed by Zope Corporation[16] and a large active community of users. It runs on nearly all UNIX platforms and on Windows NT/2000. It can be used with most popular web servers or its own built in web server. Zope is written (and extensible with) Python, an

[14] http://www.opengis.org
[15] CGDI stands for Canadian Geospatial Data Infrastructure. http://cgdi.gc.ca/CGDI.cfm
[16] http://www.zope.com/

object-oriented programming language, with performance-sensitive components written in C.

Zope is a highly object-oriented Web development platform that covers much more of the problem domain for Web application developers than do the common file-based Web templating systems (e.g., ASP or PHP). It provides clean separation of data, logic, and presentation, along with an extensible set of built-in objects and a powerful integrated security model. The Zope infrastructure relieves the developer of most of the onerous details of Web application development such as data persistence, data integrity and access control, allowing you to focus on the problem at hand.

Zope provides the following tools to integrate data and content from nearly any source into coherent and maintainable Web applications:

- Through-the-Web management
- Integrated access control
- Content management
- Enterprise data access
- Built-in search tools
- Powerful data sharing
- Safe delegation

Zope has a vast array of plug-ins, termed “Products.” Products exist that communicate with relational databases, authenticate via LDAP (Lightweight Directory Access Protocol), and perform custom computations or custom data encapsulation. System administrators may establish roles for users within a Zope application. For example, a system administrator may establish the roles “System Manager”, “Content Manager” and “Author” within a custom Zope application.

3.4.9. LaserScan[17]

LaserScan's recent focus is on delivery of enterprise solutions related to data and workflow management. The cornerstone technology is called Radius. Radius Topology is a software package that adds a dynamic topology management layer to an Oracle9i and 10g spatial database. Radius Topology also provides an advanced spatial processing environment, which extends the Oracle9i database and provides dramatic improvements to the speed and consistency of spatial data handling. Radius Topology integrates with the Oracle database allowing spatial data to be accessed and edited using GIS applications that work directly with the Oracle Spatial Type, e.g. from vendors including Intergraph, Autodesk, and MapInfo. In addition to providing the interface to the data management environment, Radius provides workflow management tools and capabilities to deliver the following.

- Capture and fixing of errors related to topology, logical consistency and geometry.
- Support of topologically intelligent mapping solutions.
- Conflation to create the best, most up-to-date data.

[17] http://www.laser-scan.com/index.php

- Enterprise-wide data sharing free of data errors from transaction collision.
- Generalization to allow the presentation of geospatial information at different scales.

3.4.10. GDAL - Geospatial Data Abstraction Library

Geospatial Data Abstraction Library is a translator library for raster geospatial data formats. It is released under an X/MIT-style Open Source license[18]. As a library, it presents a single abstract data model to the calling application for all supported formats[19]. The related OGR library (which lives within the GDAL source tree) provides a similar capability for simple features vector data. The GDAL supports access and output to over 41 commercial and open source image types, and 16 common vector data formats.

The GDAL could be used to enhance support for time-varying information as follows: it can link to most major commercial platforms, it has a dedicated base of users and developers, it links to commercial ETL tools, and the source can be re-used for development of commercial applications.

4. SENSOR WEB

4.1. Description and background

Sensor webs are distributed sensing systems that are designed to perform science observations, event detection, and phenomenon recognition with autonomous reconfiguration and response. A sensor is a device that measures the physical properties of phenomena and that provides its measurements to a science instrument. Typically, a sensor web is composed of multiple platforms that are interconnected via a communications fabric where at least one platform exists to process the science instrument data.

Kevin A. Delin of NASA's Jet Propulsion Laboratory states that the "Sensor Web concept enables spatiotemporal understanding of an environment through coordinated efforts between multiple numbers and types of sensing platforms, both orbital and terrestrial, both fixed and mobile. Each of these platforms, communicates with its local neighborhood of sensors and thus distributes information to the instrument as a whole. The Sensor Web is to sensors what the Inter-net is to computers, with different platforms and operating systems communicating by way of a set of robust protocols."[20]

Sensor measurements may include the following.

- In-situ measurements (e.g., rainfall, magnetic field strength)
- Remotely sensed data (e.g., infrared photons from a star, acoustic energy, chemistry)

[18] The GDAL "MIT style License" gives users permission to do whatever they want with GDAL source, including building proprietary commercial software, without further permission from the developer, or requirement to distribute source code. A few portions of GDAL fall under slightly different terms.
[19] More information can be found at http://www.remotesensing.org/gdal/
[20] Quote taken from an article by Mark Reichart in GeoSpatial Solutions, April 2003, entitled "The Sensor Web's Point of Beginning". See http://www.geospatial-online.com/geospatialsolutions/article/articleDetail.jsp?id=52681

- 1D/2D/3D/6DOF directional measurements

Sensor registries are required to maximize the potential of sensor webs. For example, The Federal Emergency Management Agency (FEMA) used a sensor registry to discover that NASA had an airborne sensor that could provide thermal imaging through smoke and clouds, which could be used to monitor disasters involving both.

4.2. What is the contribution of sensor web?

Sensor webs offer a data source by which to describe geospatial change via repeated measurements of phenomena. Prospective scenarios include the following.

- To manage a biochemical disaster, biochemical "sniffers" describe actual concentrations in space and time, wind profilers assist in modeling the downwind dispersion of biochemicals, thermal imagery provides information on fires and hotspots. [21]
- To maximize crop health and minimize agricultural costs, in situ sensors provide information on soil moisture, temperature, and chemistry; weather sensors monitor rainfall, air temperature, and humidity; remote sensors monitor crop health and compare it to neighboring farms. In a fully networked system, irrigation could be adjusted remotely as needed.
- To reduce risk of epidemic, in situ sensors could monitor mosquito populations, standing water, and flood gauges; remote sensors could monitor flood boundaries; this information could be integrated with reported cases of mosquito-borne illness, to influence health notifications and ordering of medications.

In all cases, the sensor web provides a data stream that is both spatially and temporally referenced. Thus, it is valuable because it provides up-to-date information and because it creates a "data narrative" of a timespan.

The success of a sensor web is highly dependent on the success of other technologies identified here as development opportunities. For example the sensor web requires infrastructure tools to discover and view data to assess suitability. It requires semantic exploitation tools to define meanings and correlations among data obtained from different sensing systems. And it requires tools to conflate or fuse data either in a time series, or with other complementary or contradictory sources.

4.3. Current and planned activity by NTA

The proposed program plan (see Section 10) includes a recommendation to examine and develop opportunities in the area of Sensor Web.

[21] This example was taken from an OGC pilot that implemented Sensor Web interfaces and capability. See GEO World - Jun 2004 - OGC Looks to Enable the Sensor Web, www.geoplace.com/gw/2004/0406/0406ogc.asp

4.4. Sampling of technologies of interest

Sensor Web is an area of extreme activity and interest for researchers, developers, and standardization. A quick survey cannot do justice to the many interested parties that are now active in this field. For that reason, this section references the larger interests and projects rather than the individual companies. A study that focuses on Sensor Web and what it can offer to spatiotemporal data collection is highly recommended.

4.4.1. OGC Sensor Web initiative[22]

OGC members are specifying interoperability interfaces and metadata encodings that enable real-time integration of heterogeneous sensor webs into the information infrastructure. Developers will use these specifications in creating applications, platforms, and products involving Web-connected devices such as flood gauges, air pollution monitors, stress gauges on bridges, mobile heart monitors, Webcams, and robots as well as space and airborne earth imaging devices.

OGC members have developed and tested the following candidate specifications. Others are planned.

- SensorML - Information model and XML encodings for discovering, querying and controlling Web-resident sensors.
- Observations & Measurements - Information model and encodings for observations and measurements.
- Sensor Collection Service - Service to fetch observations from a sensor or group of sensors.
- Sensor Planning Service - Service to assist in 'collection feasibility plans' and to process collection requests for a sensor or group of sensors.
- Web Notification Service - Service to manage dialogue between a client and Web service(s) for long duration asynchronous processes.

4.4.2. GeoSwift[23]

GeoSwift is an ongoing project whose goal is to build a geospatial infrastructure to connect distributed sensor networks for the sharing, access, exploitation, and analysis of sensing information. The development of GeoSwift involves both software engineering and communication development work. Various intelligent sensors will be deployed to the field. Effectiveness of the deployment will be demonstrated via several different real–world applications, including snow depth monitoring, crop yield prediction, nuclear safety, meteorological services, and real-time tracking.

GeoSwift is a partnership among GEOIDE, PRECARN, CRESTech, MacDonald Dettwiler Inc., Canadian Centre of Remote Sensing (CCRS), and Canadian Nuclear Safety Commission (CNSC). It uses a service-based architecture that

[22] http://www.opengis.org/functional/?page=swe
[23] http://sensorweb.geoict.net/Assets/publications/GSN%20Workshop%20paper%20Tao.pdf

complies with W3C and OGC specifications. GeoSwift is built upon GeoServNet, a GIServices system developed at GeoICT lab at York University.[24] GIService allows users to access, assemble, or even "rent" geoprocessing components that are distributed across a network via standard web browsers.

4.4.3. SensorML - Sensor Modeling Language[25]

SensorML provides the models and XML schema encoding for defining the geometric, dynamic, and observational characteristics of a sensor. The purpose of SensorML is as follows.

- Provide general sensor information in support of data discovery.
- Support the processing and analysis of the sensor measurements.
- Support the geolocation of the measured data.
- Provide performance characteristics (e.g. accuracy, threshold, etc.).
- Archive fundamental properties and assumptions regarding sensor.

SensorML can apply to virtually any sensor, whether in-situ or remote sensors, and whether it is mounted on a stationary or dynamic platform. Geolocation of observed data will be supported through "plug-n-play" models for sensor grids, frame cameras, scanners, and replacement sensor (RPC - Rapid Positioning Coordinates/Rational Polynomial Coefficients). Other geolocation models and response models can be developed by independent communities and incorporated into SensorML.

Development and testing of SensorML has progressed primarily under the auspices of the OpenGIS Consortium, through funding from the NASA AIST program, EPA, NIMA, and JITC. SensorML is also under review as part of the ISO TC211 Projects 19115 (Part 2), 19129, and 19130.

4.4.4. WebSim[26]

WebSim is a partnership whose goal is to encourage the development and application of open standards and conceptual guidelines that will enable the M&S (Modeling and Simulation) community to leverage this new style of architecture and to integrate their products into systems with a broader scope.

The WebSim vision is of M&S components participating as part of a horizontally integrated systems architecture using web technologies and aligned business practices. Under this style of architecture, M&S components should be autonomous systems capable of interfacing with other operational systems, data feeds, and data consumers in real-time. Decision-makers should be able to task M&S systems as part of their set of normal operational tools. M&S systems, in turn,

[24] Technology transfer and utilization is a top mission of GeoICT Lab. A primary goal is to develop beneficial partnerships with the private sector, investors, governments, or individuals who want to use, license, or commercialize technology developed at GeoICT Lab. This link lists software, algorithms, and prototypes that are available for commercialization or licensing:
http://www.geoict.yorku.ca/TechnologyTransfer/TechnologyTransfer.htm
[25] http://stromboli.nsstc.uah.edu/SensorML/
[26] http://www.websim.net/

turn, should be able to integrate components of the operational system with simulated components and data to perform rapid and relevant what-if analysis for decision makers. Migration of legacy components must be supported as well.

WebSim partners include Object Management Group[27], OGC[28], W3D[29], and Simulation Interoperability Standards Organization[30].

5. SEMANTIC EXPLOITATION TOOLS

5.1. Description and background

The Semantic Web is arguably the most active area of research in information technology today. It has evolved far beyond its original goal to bring structure to the content of Web pages, where software agents roam from page to page and perform sophisticated tasks for users.[31] Today the Semantic Web aims to make all types of web content decipherable to computers, so as to automate discovery, automation, integration, and reuse across various applications[32]. Growth of the Semantic Web will lead to more precise search engines, while avoiding information overload and allowing faster access to many types of knowledge sources. Information may come from web pages, web services, and repositories of documents that can be accessed via the Internet.

Implementation of the Semantic Web is based on the use of ontology languages. An ontology is a conceptual information model that describes “the things that exist” in a given domain. A given ontology can be complex and cryptic so the evolution of rules for presenting concepts in consistent way has been arduous.

If information is spatially located, there are additional challenges relating to concepts such as accuracy, precision, and spatial reference. If information is temporally located, challenges relate to distinguishing between concepts of collection time, system time, storage time, and temporal averaging and smoothing related to measurement.

Current research efforts in the area of Semantic Web technologies aim at topics like ontology engineering using semantic patterns, merging of ontologies, eLearning based on the Semantic Web, clustering of ontology-based metadata, ontology learning, evolution of metadata in ontology-based knowledge management systems. Other research and test-bed implementation activities aim at migrating data-intensive Web sites into the Semantic Web, thus achieving the so-called semantic portals. Tools for the development and use of ontologies already exist, but most of them are still developmental.

[27] http://www.omg.org/
[28] http://www.opengis.org/
[29] http://www.web3d.org/
[30] http://www.sisostds.org/
[31] "The Semantic Web" by Tim Berners-Lee, James Hendler and Ora Lassila. *Scientific American* May 17, 2001
[32] Nykänen, O.: Semantic Web: Definition; 2003; http://www.w3c.tut.fi/talks/2003/0331umedia-on/

5.2. What is the contribution of semantic exploitation tools?

Semantic exploitation tools offer a means of acquiring and exploiting data that describe spatial change. Using semantics encoded via OWL[33], it is possible to formulate intelligent searches whereby the computer recognizes context and relationships in both structured and unstructured information, irrespective of differences in terminology (Figure 6).

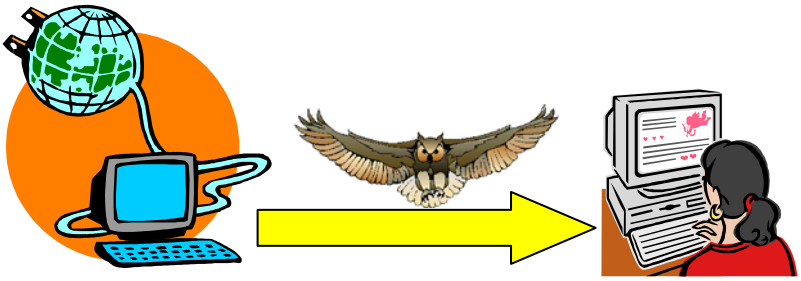


Figure 6. Structured and unstructured sources can be searched using semantics.

Unstructured data (e.g., documents, text fields in databases, web sites) represent an enormous untapped source of information about spatial change. Semantic data harvesting tools armed with enriched ontologies that include spatial and temporal concepts could comb through structured and unstructured data for information of interest, then structure it to suit the needs of analysis tools.

The next subsections describe functions that are needed to acquire data that describes spatial change.

5.2.1. Search for relevant data

Context-aware semantics would assist in the intelligent search of distributed data resources on published websites, metadata registries, public databases, etc. The search would need to take into account semantics, availability, fitness for use, data structure, and all the normal issues involved in using data produced outside one's own organization.

5.2.2. Define semantics and proximity

Ontologies must be created, maintained, and cross-referenced. Each enterprise must define the ontology that describes itself, then define crosswalks (correlations) between the enterprise ontology and other useful ontologies that are registered by others. This function can be regarded as part of the enterprise's infrastructure, and is also discussed in Section 3 of this report.

[33] Web Ontology Language (OWL) is the successor to DARPA Agent Markup Language (DAML).

Spatial and temporal ontologies have been developed,[34] and many scientific fields have developed ontologies to define important concepts.

5.2.3. Gather data of interest from structured and unstructured sources

Data harvesting can involve screen scraping, peer-to-peer database access, parsing of unstructured text, and many other technical functions. A service architecture is the most likely to deliver the incremental improvements that will be needed in the fast-moving field of semantic exploitation.

Unstructured data sources are of particular interest. It has been estimated that over 70% of the world's data is buried in unstructured sources. A capability to find and format data from database text fields, reports, and web pages will lead to an invaluable reconstruction of historic data states.

5.2.4. Create integrated multi-temporal dataset

Harvested data are likely to be snapshots of something that existed in a place at a moment. To create a dataset to describe spatial change requires integrating such samples into a multi-temporal dataset based on a specification created for the purpose of analysis. The integration function is a specialized type of conflation (which is described in Section 6). The integration rules could consider logical consistency given time considerations and measurement limitations (e.g., could one person be observed in three locations given travel times required).

The integration function requires metacontent that describes all aspects of the data processing involved: when and how was information gathered, transmitted, what rules were used for integration, possible error, etc.

5.2.5. "Listen" or "Search" for new information

In addition to gathering information to create a dataset, it is possible to establish functions to monitor changes to information, including new posting of information of interest. This is useful to maintaining enterprise data, and also useful for monitoring situations that could affect the operations of an enterprise.

5.3. Current and planned activity by NTA

NTA funded Semandex[35] to develop a semantic routing capability for use by the Marine Corps (Figure 7). Semantic routing uses semantic metadata to deliver a user's request for information to the right information providers, who then respond to the user.

The proposed program plan for continued development includes an IA&E project to investigate gaps in commercial capability for Semantic Web that present development opportunities.

[34] There is an OWL-S Time Ontology (see http://www.cs.rochester.edu/~ferguson/daml/) and a sub-ontology of OWL-S that is simpler to use (see http://www.isi.edu/~pan/damltime/AAAIsymp2004.pdf). A key researcher in this area is Jerry Hobbs of SRI.
[35] http://www.semandex.com/

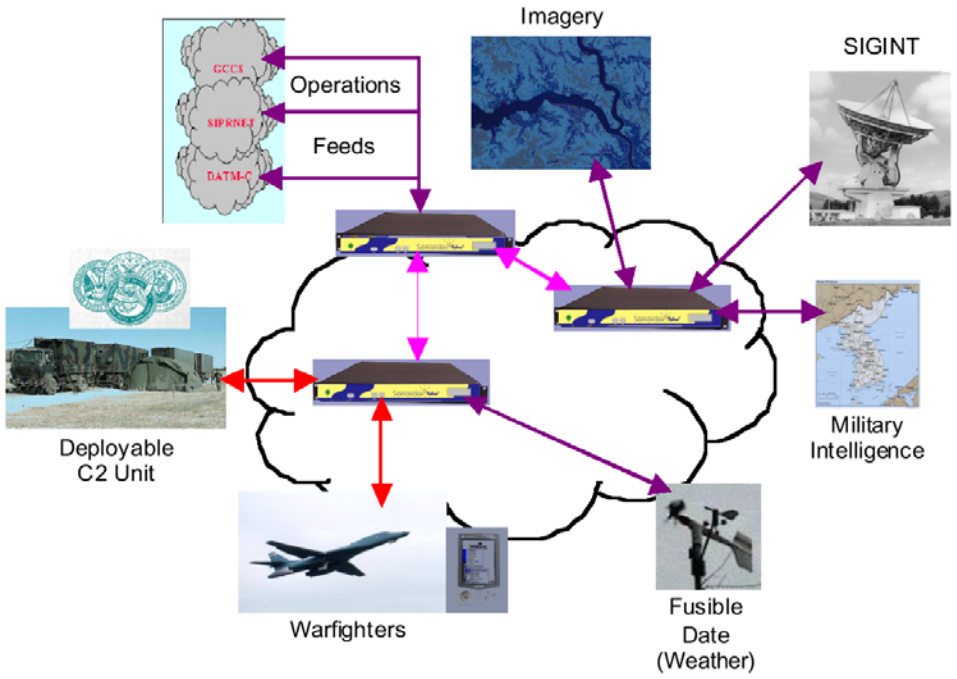


Figure 7. Semantic routing capability developed for NTA by Semandex.

5.4. Sampling of technologies of interest

Time did not permit a thorough review of capability in this broad and active field of development. This section describes a very small sampling of technology. A focused examination of capability in this area is strongly advised as part of the proposed program for developing a capability to analyze spatial change.

5.4.1. DARPA semantic object web developments

DARPA has a project to examine the Semantic Web for Intelink, which would enable automated integration of pieces of information available from that source. A technology architecture was developed that could access information from disparate sources and assemble them into a single Semantic Knowledge Object, with pointers back to the original sources. Semantic markup tools were used to created marked-up documents (via OWL) from simple unstructured document sources. The user could access an ontology server to build queries, which would be executed by mediators for each search engine or query system.

HORUS is useful in part because it identified the key components required to support this type of functionality. The architecture itself was too costly for most organizations, but the cost of similar components is decreasing as competition increases.

5.4.2. Metacarta[36]

Metacarta produces applications to turn text documents into geographic data layers. It is able to parse documents and files to extract any mention of a place and display the results on a map background for exploration by the users. Location can be described as a coordinate, a placename, a landmark, or in other ways.

The Metacarta approach is two-phased: a database of documents and web pages is identified and pre-processed to facilitate the parsing; then the database can be queried to extract information of interest.

The Metacarta approach uses natural language rather than semantic tools, but its capability to recognize and extract geospatial content places it in the same category as semantic tools for purposes of this paper.

5.4.3. Attensity[37]

Attensity is currently being used for assisting with automated information analysis for a variety of organizations, including Department of Homeland Security. The tools are targeted for identification of non-obvious relationships that are obscured due to the sheer volume of data and the lack of analytical capability that could be effectively applied. Attensity tools give intelligence personnel the ability to uncover relationships or activities that may constitute threats.

The Attensity Relational Extraction Server provides the capability to automate the extraction of "relational events" from free-form text – including who or what, why, when, where, and how. The product also provides analytical processing for the automated transformation of written language into structured, relational data. Once extracted into this structured form, the information can be pushed downstream to feed virtually any system that processes relational tables. Such tabular data can be integrated with other structured data and stored in a shared data warehouse repository for data mining or link analysis purposes.

Attensity tools enable the following.

- Quickly translates free-form text data into structured relational database tables.
- Analyzes data with high precision and accuracy
- Extracts data from multiple sources (database, email, web) and file types
- Integrates with any analytic or business intelligence system

5.4.4. Fetch Technologies[38]

Fetch Technologies has developed advanced algorithms for extracting information from documents and Web pages. The current capability has focused on processing "semistructured" documents that have no explicit structure or schema, but that do

[36] http://www.metacarta.com/
[37] http://www.attensity.com

[38] http://www.fetch.com/index.asp

have an implicit underlying structure. Many HTML documents, such as online catalogs, have a very regular structure that can be exploited to extract data. The Fetch algorithms are not limited to structured HTML—they can be applied to a wide variety of semi-structured information sources. Text sources, such as email messages, often have some underlying structure that can be exploited to extract fields such as the date, sender, addressee, subject, and body of the message.

Underlying Fetch's information extraction framework is an ability to automatically induce rules that precisely locate the desired information on a page. The extraction rules are based on "landmarks" that enable software agents to locate the start and end of fields within a page. Fetch has developed a hierarchical induction algorithm that learns these landmarks based on examples labeled by the user. The hierarchical approach is not only computationally efficient, it also has the advantage of being able to extract data from pages that contain complicated formatting layouts (e.g., lists embedded in other lists) that previous approaches could not handle.

Building on this capability, Fetch Technologies has developed information-gathering and integration solutions for a variety of government users in the areas of intelligence, law enforcement, and defense. One development was an interactive Information Assistant that accesses a wide variety of sources, including sources for geo-spatial data, text, images, maps, and video. The user is able to reduce the time required to collect and compile the regional information. Each time the data is viewed, it is refreshed by referencing the original sources.

5.4.5. BioGeoMancer [39]

BioGeoMancer provides a georeferencing service for collectors, curators, and users of natural history specimens. In its current state, Biogeomancer can parse English language place name descriptions and provide a set of latitude/longitude coordinates associated with that description, including offsets from locations.

There are two major steps in the georeferencing process. First, geoparsing evaluates the locality string for possible place names, and determines spatial relationships (at this stage very simple relationships) between any identified places. Second, place names are checked against gazetteer data, and coordinates returned. There are a number of gazetteer services extant, and BioGeoMancer will likely be a client of gazetteer services like the Alexandria Digital Library Gazetteer (ADL). What sets BioGeoMancer apart is that it performs geoparsing. Biogeomancer does not use ontologies to perform geoparsing, but its capability to recognize and extract geospatial content places it in the same category as semantic tools for purposes of this report.

A SOAP/XML version of Biogeomancer is currently in development, and is meant to provide an interoperable solution for multiple geoparsing/georeferencing requirements.

[39] http://www.biogeomancer.org

5.4.6. SIMILE[40] and DSPACE[41]

The SIMILE[42] project seeks to enhance interoperability among digital assets, schemas, metadata, and services that are distributed across individual, community, and institutional stores. It is a collaboration involving W3C, Hewlett Packard, MIT Libraries and MIT's Lab for Computer Science. SIMILE began in February 2003 and will conclude in February 2006.

SIMILE is undertaking key upgrades to DSPACE, which is a digital library system to capture, store, index, preserve, and redistribute the intellectual output of a university's research faculty in digital formats. DSpace is organized to accommodate the multidisciplinary and organizational needs of a large institution. It provides access to the digital work of the whole institution through one interface. The following digital content types are supported.

- Text
- Images
- Audio
- Video
- Documents such as articles, preprints, working papers, technical reports, conference papers, books, theses
- Data sets
- Computer programs
- Visual simulations and models

One of the primary goals of DSpace is to preserve digital information. It provides long-term physical storage and management of digital items in a secure, professionally managed repository including standard operating procedures such as backup, mirroring, refreshing media, and disaster recovery. DSpace assigns a persistent identifier to each contributed item to ensure its retrievability far into the future. It provides a mechanism for advising content contributors of the preservation support levels they can expect for the files they submit.

5.4.7. Jena[43]

Jena is a Java framework for writing Semantic Web applications. It was developed by Hewlett Packard Laboratories. It features an RDF API, an RDF/XML parser, a persistence subsystem that provides persistence for models through use of a back-end database engine, a reasoning subsystem, an ontology subsystem, and an RDQL query language.

Jena is distributed under a BSD-style open source license. It includes software developed by the Apache Software Foundation,[44] both in the form of jar files and source code.

[40] http://web.mit.edu/simile/
[41] http://www.dspace.org/
[42] SIMILE stands for Semantic Interoperability of Metadata and Information in unLike Environments.
[43] http://www.hpl.hp.com/semweb/jena.htm
[44] http://www.apache.org/

5.4.8. Pervasive's Data Junction and Extract Schema Designer[45]

Data Junction uses text pattern recognition to automatically extract structured data from unstructured text sources. The enabling technology is the CXL[46] Engine, which is a line-oriented text manipulation and pattern recognition engine invented in, and built with, specific wiring to Pervasive Data Junction back-end high-speed Integration Engines. In just a few lines of code, one can extract perfect row and column "views" from streams of otherwise unreachable dirty text and simple HTML sources.

Pervasive Data Junction has a graphical user interface that enables non-programmers to mark up an unstructured text file quickly and to build an entire extract schema. The Extract Schema Designer generates CLX code to feed into the Pervasive Data Junction unstructured text parsing engine. The Extract Schema Designer also includes visual debugging, source data viewers, add-on modules for .pdf and other document formats, and the ability to handle non-text binary and print characters.

Pervasive Internet Rapid Integration Services SDK (djIRIS) supports harvesting data from the Web via screen-scraping technology. It works at the browser interface level to navigate HTML content.

5.4.9. ImageMatters[47]

ImageMatters has developed software called UserSmarts, which is middleware technology for implementing Context-Sensitive Service®, a.k.a. smart (Web) service. It is an essential set of building blocks for constructing service nodes for the Semantic Web. UserSmarts is based upon evolving research in semantics, context and Web technologies. UserSmarts provides an engineered interface for weaving semantic and context technologies into the fabric of service platforms, whereupon these technologies can then be exploited by other applications and services that can interact with the interface. ImageMatters is active in the OGC working group described next.

5.4.10. OGC Information Communities and Semantics Working Group

The OGC recognizes that true interoperability will not be achieved without an increased capacity to communicate and understand ontologies. The Information Communities and Semantics Working Group (ICSWG) represents a potential source of input to use cases as well as source potential solutions from both government funded laboratories and commercial software providers. NASA, the UK Ordnance Survey, and Natural Resources Canada are active in ICSWG and have projects underway to move forward and address the challenges of semantics for geospatial information. Oracle, BAE, PCI Geomatics, Galdos, Image Matters, and other commercial interests are continuing to build toward critical mass.

[45] http://www.umsl.edu/~sauter/DSS/Harvesting-UnstructuredData.pdf, http://www.pervasive.com/
[46] CXL means Content Extraction Language
[47] http://www.imagem.cc/

ICSWG may represent a nucleus for the development of user requirements and use cases that will contribute to a coherent technology development roadmap.

6. CONFLATION AND FUSION OF TIME-VARYING DATA

6.1. Description and background

Conflation and fusion share a purpose: to merge datasets to create a result dataset that is takes the best of both worlds. Both are data integration processes. Typically, "conflation" refers to vector-to-vector operations, and "fusion" refers to operations that include image source, although this distinction is only loosely observed. Because the data compilation and update processes involve data integration, aspects of conflation and fusion are present throughout all data production environments. The focus here, however, is on software that automates aspects of feature matching or "deconfliction", where the matched and unmatched components are merged via defined rules.

6.2. What is the contribution of conflation and fusion?

Conflation of time-varying information aids in the recognition of changes and also in the integration of multiple versions of information into multi-temporal representations that show change over time. The data source can be from an update stream, in which case the feature is matched and the new version is sorted and added to the chain of representations. Or the data source can be from a traditional atemporal dataset, perhaps a snapshot of what existed at a point in time. In that case, the snapshot is compared to the multi-temporal information already available to glean any new information that it offers.

6.3. Current and planned activity by NTA

NTA has funded three conflation projects to date. The first is a conflation IA&E project that will conclude in Winter 2004. Its current activity is to oversee the evaluation of six vendors who provide conflation capability using evaluators from multiple government organizations. The result of the evaluation will be feedback to the vendors from evaluators, and exposure of evaluators to the present state of the art. This information will be used to refine the statement of gaps in commercial capability, and select areas that are ripe for investment by the government.

The second NTA conflation project is entitled "Conflation for FLDB." This project has extended an existing GeoMedia conflation capability to address needs of NGA's Feature Level Database. The result will be the commercial capability described below in Subsection 6.4.3.

The third NTA conflation project is complete, and was entitled "Conflation Research Hub," which funded OSSI to stand up a suite of software, data, and algorithms at the University of Southern Mississippi. The intention was to encourage researchers to address conflation problems of interest to the government.

A program plan for continued development of conflation capability has been proposed, and includes improvement of feature matching and deconfliction, development of schema correlation capabilities, and investigation of vector-to-image needs and capabilities.

6.4. Sampling of technologies of interest

6.4.1. Digital Engineering Corporation/Citygate ConfleX[48]

ConfleX matches lines and polygons from multiple vector sources with a goal of transferring attributes from one set of geometry to another. The focus is on matching features, as opposed to deconfliction to harmonize differences and produce an integrated result. ConfleX aims for a one-step batch process rather than iterative interaction. It makes its matches between line features using line characteristics, node topology, and connecting segments. Handles "lumpy" error, distortion, and rotation. Interactive editing tools are provided to correct error and match unmatched features.

ConfleX is a standalone application and does not require any base GIS Software. It is based on ESRI Map Objects and has an ArcGIS look and feel with a small footprint. It supports multiple data sources including ESRI Shape, Intergraph DGN, and AutoCAD DWG and DXF formats.

ConfleX is being evaluated for performance and results as part of the ongoing NTA Conflation IA&E project.

6.4.2. ESEA MapMerger[49]

MapMerger matches lines from multiple vector sources and can support several types of result datasets. The focus is on matching features, as opposed to deconfliction to harmonize differences and produce an integrated result. MapMerger takes an iterative approach, whereby the user defines match points and the software aligns the areas and matches linework. Node matches are based on a maximum search distance, an attribute (if one exists), and the number and angle of adjacent line features. Line matches are based on a maximum search distance, an attribute (if one exists). Some attribute inconsistency can be tolerated. Interactive editing tools are provided to correct error and match unmatched features.

MapMerger is an extension to ArcMap and requires ArcInfo 8, ArcEditor 8, or ArcView 8. ESEA is an ESRI partner.

MapMerger is being evaluated for performance and results as part of the ongoing NTA Conflation IA&E project.

[48] http://www.digitalcorp.com/conflex.htm
[49] http://www.esea.com/products/

6.4.3. GeoMedia Fusion

GeoMedia Fusion includes feature matching and deconfliction capabilities. It matches points, lines, and areas from multiple vector sources and can support many types of result datasets. It can also perform cross-geometry matching (i.e., points to lines, points to areas, and lines to areas). Matches are based on distance, topology, geometry, and attributes. GeoMedia Fusion has a component to facilitate attribute correlation so attribute values can assist in matching features; this component is called Schema Remodeler, and is described in the section on infrastructure tools.

GeoMedia Fusion will be released in Summer 2004 as an extension to GeoMedia Professional. It was designed specifically for high-volume data production organizations.

GeoMedia Fusion is being evaluated for performance and results as part of the ongoing NTA Conflation IA&E project.

6.4.4. Northrop Grumman SIP-ET

Northrop Grumman SIP-ET includes feature matching and deconfliction capabilities. Its original platform was Unix-based ArcGIS. It is being ported to a Windows-based ArcGIS environment and some of its capabilities may change. On the Unix platform, SIP-ET matches points, lines, and areas from multiple vector sources, and performs cross-geometry matching (i.e., points to lines, points to areas, and lines to areas). Matches are based on distance, topology, geometry, and attributes.

SIP-ET uses ArcGIS capabilities and requires that ArcGIS tools be installed on the same workstation. The Unix version required ESRI SDE, but the Windows version may not.

SIP-ET is being evaluated for performance and results as part of the ongoing NTA Conflation IA&E project.

6.4.5. Open Source Java Conflation Suite[50]

The JCS Conflation Suite is open source software that includes an API and a set of interactive tools to perform conflation on spatial datasets. It matches points to points and lines to lines. It can edge-match neighboring datasets in addition to conflating coincident datasets. It was developed to conflate particular types of data, and thus may require some adjustment before it can be used as a general-purpose tool.

JCS uses the JUMP Workbench and the JTS Topology Suite (both open source) to provide visualization, support for interactive workflow, spatial data processing, and basic geometric functionality. No commercial software applications are required.

JCS is being evaluated for performance and results as part of the ongoing NTA Conflation IA&E project.

[50] http://www.vividsolutions.com/%5Cprojects%5Cjcs.html

6.4.6. LaserScan Radius Topology[51]

LaserScan Radius Topology (RT) can assist in the deconfliction side of conflation. The input is a link file that matches features in two source datasets (produced by any desired feature-matching method). The process uses rules to integrate the lower-confidence dataset with higher-confidence base data. The link file is used to shift the features in the lower-confidence dataset to integrate with the higher-confidence dataset. And features that differ from the base data are updated to match the base data. The software works with Oracle 9i and with LaserScan's Gothic architecture.

6.4.7. USC/ISI Geospatial Integration[52]

The Information Sciences Institute of University of Southern California is developing capability to automatically georeference imagery to vector datasets by identifying matching control points in the two sources. If a sufficient number of nodes are matched, the line features that are terminated by the nodes can also be matched. The software also seeks corresponding attribute information from on-line databases to round out the information resource.

The Geospatial Integration capability uses Windows and Java. No commercial software applications are required.

The ongoing NTA study had a focus of vector-to-vector conflation. It has been proposed that the study expand to address vector-to-raster conflation such as this capability provides.

7. SPATIOTEMPORAL PATTERN ANALYSIS

7.1. Description and background

Spatiotemporal pattern analysis attempts to detect pattern, trend, or clustering in space and time, and to understand their underlying causes. Visual and numerical analysis methods used together provide a means of understanding factors at work in an area. Visual methods include graphics and maps (static and animated). Numerical methods include statistics, graph analysis, trend surfaces, kriging, filtering, generalization, interpolation, and extrapolation. Spatiotemporal pattern analysis is a key component of dynamic decision aids.

7.2. What is the contribution of spatiotemporal pattern analysis?

Pattern can indicate underlying causes of activities and events. Understanding past patterns can assist in predicting future activities or events.

[51] http://www.lsl.co.uk/papers/PAI_white_paper.pdf
[52] http://www.isi.edu/info-agents/TerraWorld/

7.3. Current and planned activity by NTA

A proposed program plan has been submitted to the NTA program office that includes tasks to investigate needs and capabilities for spatiotemporal pattern analysis (see Section 10).

7.4. Sampling of technologies of interest

The sampling of technologies described here includes those that support primarily visual analysis, and others whose focus is on numerical analysis. Table 2 summarizes the focus of the technologies described below.

Table 2. Focus of analytical methods for sampled technologies.

Technology	Analytical focus
TimeMap	Visual
Tracking Analyst	Visual
GoldSim	Numeric
Apoala	Visual, Numeric
Precision Computing Intelligence	Visual
Tom Sawyer	Numeric
Terraseer	Visual, Numeric
Space-Time Toolkit	Visual, Numeric

7.4.1. TimeMap[53]

TimeMap™ is a low-cost and general-purpose product for visual analysis of spatial change, including time filtering and onscreen animation. Using the Web or Windows-based software, distributed users can register and share time-varying data through a central clearinghouse and combine dispersed datasets to generate interactive maps and online publications. The Windows version also generates SWF files for web delivery and can create low bandwidth animations by users with no special skills.

TimeMap includes a mapping applet[54] that can search for and load thousands of local maps dynamically as the user zooms and pans. The applet also time-filters and animates maps on the fly (from seconds to millions of years). The applet can filter huge datasets server-side and download only the data needed. It adapts legends dynamically as scale changes but tells users how to find hidden layers. TimeMap can be customized using XML.

7.4.2. Tracking Analyst (TASC/ESRI)[55]

ArcGIS Tracking Analyst provides tools for playback and analysis of time series data. Tracking Analyst helps a user visualize complex time series and spatial patterns and interactions while integrating with other ArcGIS data within the ArcGIS system. Tracking Analyst supports the following functions.

[53] http://www.timemap.net/ , http://www.timemap.net/showcase/tmjava/introduction.htm
[54] The applet size is less than 300K and can be embedded in a web page.
[55] http://www.esri.com/software/arcgis/extensions/trackinganalyst/

- Play back historical data.
- Use rule-based drawing.
- See temporal patterns in data.
- Integrate temporal data within a GIS.
- Leverage existing GIS data to create time series visualizations.
- Build charts for analyzing change in historical or real-time data.

7.4.3. GoldSim[56]

GoldSim is simulation software that is designed to model complex systems that include time-varying elements. The goal is to gain a diagnostic understanding of the system, ask "what if" questions about it, and evaluate alternative designs, policies, and plans. GoldSim includes the following capabilities.

- Quantitatively address the inherent variability and uncertainty that is present in real-world systems using Monte Carlo simulation.
- Superimpose the occurrence and consequences of discrete events onto continuously varying systems.
- Build top-down models using hierarchical containers that facilitate the simulation of large, complex systems while keeping them easy to understand and navigate.
- Dynamically link external programs or spreadsheets directly into the GoldSim model.
- Directly exchange data between any ODBC-compliant database and the GoldSim model.
- Insert graphics, notes and hyperlinks (to documents, websites, and presentations) in order clearly explain your model to diverse audiences.
- Create custom designed graphical interfaces to explain and demonstrate models using the GoldSim Dashboard Authoring Module.

The various objects with which a GoldSim model is constructed are referred to as elements. Each element represents a building block of the model. GoldSim provides a wide variety of built-in elements. Some of these elements, called Input Elements, provide a mechanism for the user to enter inputs into the model. There are three types of Input Elements: Data, Time Series and Stochastics.

Data elements allow the specification of a single scalar value (e.g., the discount rate) or an array of related values (e.g., the salaries of each individual in a group). Time Series elements allow the specification of a time series of a value (e.g., monthly rainfall rates, quarterly cashflows). Stochastic elements allow the specification of uncertainty in a particular input by defining it as a probability distribution.

Spreadsheets can be directly linked to a GoldSim model. Throughout a simulation, a user can dynamically send data from GoldSim to a spreadsheet, force a recalculation, and then retrieve the updated information from the spreadsheet back into GoldSim. In simulations that require a great deal of input, the simulation model can access the various data sources directly to facilitate and ensure the quality of the data transfer.

[56] http://www.goldsim.com/Home.asp

To achieve this, GoldSim allows input elements to be linked directly to an ODBC-compliant database. With a defined linkage, a user can instruct GoldSim to download the data at any time. When it does this, GoldSim internally records the time and date at which the download occurred, and this information is stored with the model results. This mechanism provides very strong and defensible quality control over your model input data. A user can also export a portion (or all) of your simulation output to any ODBC-compliant database, from where it can be readily imported into any number of programs (for example, a statistical analysis package or a GIS program).

7.4.4. Apoala project at Penn State[57]

Researchers in the Penn State geography department have been engaged in developing capability to analyze spatial change for over 10 years. The Apoala project builds on earlier efforts. The system architecture consists of the following three interrelated modules: a temporal GIS data management system known as Tempest, a data mining software package known as AutoClass, and a set of Geographic Visualization tools developed in IBM Data Explorer and Tcl/TK.

Apoala's data management system is based on the triad database model developed and implemented in previous research as a Temporal GIS system called Tempest. Tempest provides extremely fast access to data using a number of tools including linear and cyclical queries. It also provides a number of simple summary statistics for spatial and/or temporal subsets of the data.

Apoala's data mining attempts to find patterns that would not otherwise be discernable.

Apoala's geographic visualization techniques display data in a way that allows a domain expert to take advantage of the nature of human visual processes to find patterns. Visualization of a time-space cube in IBM Data Explorer allows a user to visually search for periodicity or other pattern in both time and space.

7.4.5. Precision Computing Intelligence CrimeLink and Time Event Chart[58]

Precision Computing Intelligence (PCI) provides visual analysis tools for investigating fraud, gangs and drugs, organized crime, and other investigations that require compilation of large amounts of data. PCI produces the CrimeLink software.

CrimeLink compiles large amounts of seemingly independent and unrelated data into orderly, understandable, and comprehensible graphical formats. Support includes displaying photos, manual annotation of all charts, and attaching documents, audio and video files to people and entities.

It includes a Time Event Chart (TEC), which maintains a chronological record of an individual or group's activities. It plots events along a timeline to assist in the examination of temporal pattern.

[57] http://www.geovista.psu.edu/grants/apoala/index.htm
[58] http://www.pciusa.us/tmevtct.htm

7.4.6. Tom Sawyer software[59]

The Tom Sawyer Analysis product family helps a user to develop graph analysis applications quickly and efficiently. With these products, users can enhance applications with clustering, graph traversal, path analysis, dependency analysis, impact analysis, network analysis and other high-value functions that improve analytic decision-making. The products have full XML integration.

The Tom Sawyer Visualization product family helps a user to develop graph visualization applications quickly and efficiently. With these products, users can enhance applications with graph display, viewing, and editing technologies presented in an eye-catching, intuitive graphical user interface. Users can customize both the display and the interactive behaviors of applications using such industry-standard components as toolbars, menus, and mouse-event handling.

7.4.7. TerraSeer[60]

Terraseer designs software to assist in detecting underlying patterns in time-varying geospatial data. Products include TerraSeer STIS™ (Space-Time Intelligence System), ClusterSeer™ (Space-Time cluster identification), and BoundarySeer™ (geographic boundary analysis). All product operate in a Windows environment and can stand alone or work alongside a GIS.

TerraSeer STIS implements a proprietary space-time data structure where time is an integral part of the data and the software interface. Thus, all views of the data can be animated, from maps to histograms to tables, giving the user a natural, intuitive understanding of data changes through space and time. TerraSeer STIS links data views together, and helps make statistical inference about patterns in the data.

ClusterSeer was designed to evaluate disease clusters to investigate whether they are chance or causal.

7.4.8. Space Time Toolkit[61]

The Space Time Toolkit (STT) is a Java-based toolkit developed by the VAST team at the University of Alabama at Huntsville. STT integrates spatially and temporally disparate data within an interactive 3D display environment. Unlike most tools that require that data be converted to a common spatial and temporal grid before integration, the STT allows one to ingest swath, map-projected, station, event, or path data in whatever spatial and temporal domain in which it exists. The STT then allows the end-user to select the 2D or 3D display domain and then on-the-fly maps all data into that domain as needed. In addition to the user-selection of the spatial domain, the end-user has equal control over the aggregation and resolution of the temporal domain.

[59] http://www.tomsawyer.com/home/index.php
[60] http://www.terraseer.com/about/about_us.html
[61] http://vast.uah.edu/SpaceTimeToolkit, http://stromboli.nsstc.uah.edu/SpaceTimeToolkit/

STT deals well with distributed data sources. Data are accessed through URLs that either point directly to data files or point to more intelligent data services in the form of Java Servlets or CGI scripts. The current trend with STT is to move away from URLs that point directly to files, and toward intelligent servers. The advantages are as follows.

- The STT client becomes and can remain a lighter-weight application since it doesn't have to deal directly with various data formats and data structures
- There is less need for support of client-side native code (C/C++/FORTRAN) libraries for data readers, etc.
- More intelligent servers can greatly reduce the amount of data distributed over the web and can return the data in the most appropriate form to match the need
- This allows data providers to add new data sets to STT, without intervention or hindrance of the UAH VAST team
- This reduces the need for the UAH VAST team to become familiar with every data format or structure, and puts support for data readers back in the hands of those who understand the most about the data.

The current preferred modes of providing data to the STT is through Web Mapping Testbed (WMT) compliant servers or through a simple Java Serialized Object (JSO) being developed by the VAST team (and hopefully considered as a WMT standard in the future). The current WMT capabilities are very limiting with regard to highly dynamic or 3D data sets. The VAST-JSO is, in contrast, a highly flexible yet simple protocol for representing georeferenced points, lines, grids, surfaces, images, and volumes.

8. DYNAMIC DECISION AIDS

8.1. Description and background

Dynamic decision aids (DDAs) are the payoff to users for the effort expended in acquiring and supporting time-varying geospatial information resources. DDAs provide an interactive gaming-style environment that supports "what-if" explorations. They must account for data that varies spatially over time (e.g., weather) to ensure realism. Examples of dynamic decision aids include dynamic mobility models, dynamic line of sight models, real video applications, numerical modeling applications, and interactive simulations. DDAs can incorporate spatiotemporal pattern analysis tools that have been tailored to suit particular purposes.

8.2. What is the contribution of DDAs?

DDAs help users to review past events and develop what-if scenarios. DDAs help users visualize spatial change, which places events in context and informs the planning process. Realistic graphics can reveal logical inconsistencies in the information, which may stem from error in the data or from a significant event in the true situation. In either case, detection is helpful.

8.3. Current and planned activity by NTA

A proposed program plan has been submitted to the NTA program office that includes tasks to investigate needs and capabilities for Dynamic Decision Aids (see Section 10).

8.4. Sampling of technologies of interest

Most DDAs include "fly-throughs" and other three-dimensional visualizations. The dataset of a fly-through is usually static--only the viewpoint changes while one data state is viewed from different locations. In contrast, this study is seeking ways to work with data that are NOT static—the data state changes regardless of any changes in the viewpoint. For all DDAs, there is a need to enhance the capability to bring in real-time information from sensors and other intelligence sources to describe spatial change.

The technologies of interest discussed in this section are those that might be moved in the multi-state direction, or which have updating or other multi-temporal capability. The companies listed do not represent an exhaustive list and should be considered a representative sampling of a large and growing community of technology providers that compete and collaborate.

8.4.1. MultiGen-Paradigm[62]

MultiGen-Paradigm is a supplier of real-time 3D solutions for visualization, simulation, and training applications. Applications include sensor solutions, urban simulations, and 3D GIS. Clients include military and intelligence organizations in the US, UK, and Canada.

MultiGen-Paradigm products deal with the problem of integrating 3D attributes commonly found in GIS databases with other forms of 3D data, then processing the combined dataset into meaningful 3D content for mission planning. Two components provide real-time update and synchronous multiple viewpoints, and are described below.

- SiteBuilder 3D uses 2D data to create the terrain model geometry of a site. All of the source data is embedded in ArcView GIS data and pulled from such common elevation sources as contour maps and digital elevation models. In the beta site case[63], the research team draped aerial photographs over a digital elevation model. The tool automatically extrudes the site features and places them into the 3D scene. To simulate temporal variation, users can choose environmental settings to view the model under changing conditions of fog, clouds, and time of day, adding to the realism of the scene.
- MultiGen CreatorPro™ can add detail and update the basic model as more data becomes available. For example, users can add rooflines, eaves, balconies, and street scene elements after the fact. In addition, textures of unique building facades

[62] http://www.multigen-paradigm.com/
[63] DREV-Defense Research Establishment Valcartier, Canadian Department of National Defense, Contact: Francois Letourneau 418-844-4000 francois.letourneau@drev.dnd.ca.

can be added to the models using site photographs. The products communicate through the OpenFlight specification (described next).

8.4.2. OpenFlight specification

OpenFlight is an industry-standard real-time 3D scene description format. It was originally developed by MultiGen-Paradigm in response to a need for database transportability within the visual simulation community. OpenFlight is the most widely used file format for visual simulation databases and is supported by dozens of vendors of real-time 3D tools.

Because of its prevalence in the industry, any capability to incorporate spatial change into DDAs would require an evaluation of OpenFlight to see how it might need to be enhanced to deal with time-varying information. MultiGen-Paradigm owns and maintains the OpenFlight specification. Modification requests can be submitted to MultiGen-Paradigm, who determines whether to modify the specification.

8.4.3. 3ds max 6 by Discreet[64]

Discreet (a division of Autodesk) provides software for digital media creation, management, and delivery across all disciplines from film and television visual effects, color grading and editing to animation, game development, Web and design visualization. A key Discreet product is 3ds max, which is a highly customizable and scalable 3D animation, modeling, and rendering solution for creative professionals and large-scale pipelines. 3ds max is used in workflows and software by Bluerock Technologies and TERREX (discussed below).

8.4.4. Flight Studio by Bluerock Technologies[65]

Flight Studio is a tool suite for import, edit, and export of OpenFlight scene graphs and databases. Edits can be made while retaining scene graph structure and attributes. Flight Studio is a certified plug-in for Discreet's 3ds max (see previous subsection). The data to be edited could be exported from Terravista software (see next subsection). This provides OpenFlight artists with access to the scene graph, which gives a great deal of control over the visual presentation.

8.4.5. Terravista by TERREX[66]

TERREX (also called Terrain Experts, Inc.) develops software tools for terrain database generation and visualization. The Terra Vista terrain generation products support real-time 3D image generation, battlefield visualization, mission rehearsal, mission planning, and other applications that demand the highest possible realism and 3D rendering performance.

The components in the products support the creation of correlated datasets within a consistent framework based on a common set of source data. Features such as

[64] http://www4.discreet.com/company/
[65] http://www.bluerock.com/products.html
[66] http://www.terrex.com/www/index.htm

tunnels, overpasses, and multiple elevation structures are fully supported in both visual and SAF[67] domains. SAF simulations are supported in the ModSAF, OneSAF OTF, Janus, JCATS, ITEMS™ and STRIVE™ formats.

8.4.6. Carbon Graphics[68]

Carbon Graphics specializes in software products & services for the visual simulation market. Their main product is Geo - a 3D modeling and animation tool used for building, editing, and animating dynamic real-time models and scenes.

Carbon Graphics has just released a new product called GeoRoad 3D, which allows users to build complex, textured highway networks using profile definitions and parametric 2D/3D construction tools. The resultant database includes road intersections, multiple levels of detail, and road-side information. This builds on the Geo PRO capabilities for object modeling, and animation for creation and editing of real-time content. The user can create 3D cultural objects such as buildings, vegetation, and vehicles, then import these objects into GeoRoad for automatic placement or bring a highway database into Geo for additional large-scale editing, texturing, and optimization.

This product supports OpenFlight as well as other exchange formats. It has been evaluated for military and intelligence use by larger integrators such as Northrop Grumman (Airborne Ground Surveillance and Battle Management Systems).

8.4.7. Other military and civilian research

The bulk of DDA research and development in the US government is concerned with the diverse aspects of Command and Control (C^2) and Intelligence, Surveillance and Reconnaissance (ISR). Systems such as All Source Analysis System (ASAS) and Force XXI Battle Command, Brigade-and-Below (FBCB2) are examples of early adoption of technologies targeted at presenting a complete up-to-date picture for strategic and tactical deployment.

The same type of capacity is also critical for evaluation of intelligence for the detection and analysis of threats from foreign or domestic sources. The US National Security Agency (NSA) has established an Advanced Research and Development Activity[69] (ARDA) Intelligence Community (IC) center for conducting advanced research into information exploitation. One track in information exploitation is Geospatial Intelligence Information Visualization (GI2Vis)[70]. This track has 4 sub-components related to different aspects of information gathering, synthesis, fusion, presentation, and understanding. Many of the research projects focused on change detection, pattern recognition, real-time update, and event management. One project of note has resulted in prototype software called GeoTime[71], which provides analysis, visualization, and decision support utilizing

[67] SAF is a data format for simulation.
[68] http://www.carbongraphics.com
[69] http://www.ic-arda.org/index.html
[70] http://www.ic-arda.org/InfoExploit/aquaint/gi2vis/index.html
[71] http://www.dodccrp.org/events/2004/CCRTS_San_Diego/CD/papers/137.pdf

inputs on location, events, and entities (e.g., people, assets, etc.). GeoTime is tailored to the C^2 deployment but its underlying architecture can be applied to other applications.

8.4.8. FloodTrack – Flood Surveillance Service[72]

FloodTrack Online is aimed at organizations and individuals who need fast and accurate information on flooding in floodplains. It is use for both emergencies and post-flood analysis.

- FloodTrack provides timely, synoptic flood extent information derived from synthetic aperture radar image data quickly, cost-effectively, and conveniently. FloodTrack Online is a worldwide service available to anyone with access to an internet connection
- FloodTrack starts with synthetic aperture radar (SAR) imagery, which high sensitivity to open water and flooded vegetation in floodplains and operates day or night in all weather. The service includes planning of radar data acquisition using the RADARSAT satellite or other synthetic aperture radar (SAR), analysis of the imagery to determine flood extent, and generation of electronic and optional hardcopy flood extent maps.
- Products include fast delivery compressed Geotiff flood masks and ArcView Shape files are standard and are delivered via FloodTrack Online. Options include large format hardcopy, web page content or integrated GIS databases for mapping, post-flood analysis or engineering studies.

FloodTrack is not real-time. Data can be ready for analysis within 48 hours after it is requested. Data are delivered to the client within an average of 52 hours after request. Turnaround could be shortened by adding automated (potentially agent-based) services to the data delivery environment.

9. GEOGRAPHIC PROFILING

9.1. Description and background

If you are searching for a needle in a haystack, it is helpful to reduce the size of the haystack. Geographic Profiling is a technique used by police investigators to search for serial criminals. It is useful when the goal is to track down those who are trying to hide their home location, but who can't hide their actions. Geographic Profiling helps to define where a criminal might live, work, or play, based on the locations of the crimes committed. Using such information as where victims were picked up or dropped off, where phone calls were made, and where supplies were purchased, it is possible to formulate a "hunting ground" and the most likely locations of the criminal within that hunting ground. Geographic Profiling uses the criminal's spatial behavior to facilitate identification and capture of the criminal.

The successes of Geographic Profiling in solving civilian crimes are dramatic. It has been used to solve over 700 violent crimes worldwide over the past five years. In the vast majority of cases, the criminal lived or worked in an area calculated to

[72] http://www.floodtrack.ca/ftonline/ftonline.asp

be his *most likely* location. Imagine a lawn sprinkler—even if it is removed, the droplets of water leave a trail that show where it was.

Lives are saved when crimes are solved, since 10% of criminals commit 50% of crimes. Commercial software exists and is used by police departments worldwide. Current users include Bureau of Alcohol, Tobacco, and Firearms; FBI; National Institute of Justice; RCMP (Canada), Ontario Provincial Police (Canada); Centrex (National Crime and Operations Faculty, UK); South Wales Police (UK); Bundeskriminalamt (Germany); Limburg Police (Netherlands).

Geographic profiling relies on basic element of human behavior that apply equally well to many policing and military applications.

- Criminal or military events occur at specific known locations
- In many cases those locations were chosen by human perpetrators according to understandable criteria and in accordance with their own mental map of the area
- Perpetrators will tend to follow the same repeated patterns of behavior even in apparently random choices.
- Those who wish to conceal their home location tend to follow predictable geographic patterns in their attempt to choose unpredictable locations
- Those geographic patterns can by analyzed to determine the most likely locations of the perpetrator's home base by the principle of global optimization of journey cost
- The more locations available for the analysis, the more statistically reliable the results

9.2. What is the contribution of geoprofiling?

The roles of the military and the police increasingly overlap as military forces are called upon to deal with terrorism and provide local policing in counties where law enforcement has broken down. Military forces have excellent surveillance and information analysis systems, but lack specific tools for dealing with such policing situations as counter-terrorism, war crimes investigation, and prevention of smuggling.

Geoprofiling is particularly useful in situations where human intelligence is limited by fear of reprisals, since it relies on geographic information that may be more readily available. It integrates well with existing military information systems that provide geocoded event information. Geoprofiling can deal with real-time situations where information is arriving rapidly from a variety of sources, and with historical investigations where crimes have occurred in the past.

These situations are particularly suited to the models used within geoprofiling software, and are being examined by the ongoing NTA evaluation.

- **Tracking down terrorists and groups responsible for covert attacks.** In the hands of trained analysts, geoprofiling can help prioritize likely locations for the base of operations of serial criminals and terrorists. Research in geographic profiling also suggests that this technique may be useful for prioritizing locations where they are most likely to strike next.
- **Locating radio-silent headquarters.** Radio silence (near-zero electronic emissions) is one way of hiding the locations of valued resources. Communications occur in short-burst transmissions followed by movement to a new location, or via frequent emissions

from locations that are chosen to be pseudo-randomly distributed at some distance from the protected location. Geoprofiling has proven to be effective in locating people who are attempting to hide their home base through attempts at random behavior. Integration of geographic profiling with existing electronic signal analysis systems would create an effective new method of exploiting electronic signals intelligence.

- **Locating mobile missile launcher bases.** The behavior of the operators of mobile missile launcher platforms in selecting a launch location involves the same types of attempted randomness that are analyzed through geoprofiling.
  - They operate from a home maintenance base of unknown location, which we want to find.
  - The locations from which they fire a missile are pinpointed immediately after firing, so they attempt to randomize these locations with respect to the home base.
  - They try not to go any further from the maintenance base than necessary, as they need to return there after firing.
  - They prefer not to fire in a "buffer zone" around their home base (an area where there is a reduced probability of an event occurring due to reluctance to operate in close proximity to the base for fear of revealing it).
  - In other words, each missile-firing site is the equivalent of a "crime site", the maintenance base is the "anchor point" of the offender, and the system is performing its analysis on the basis of the mobile platform's journey to the crime site. Multiple platforms operating out of the same maintenance base are statistically equivalent.

9.3. Current and planned activity by NTA

An NTA project is underway to evaluate the use of Geographic Profiling procedures and software to locate the sources of attacks on US forces in Iraq and Afghanistan. Evaluators are drawn from intelligence analysts, prior to expanding to the broader intelligence community. Evaluators will test the commercial software using real data that describe past and current military problems, and recommend ways to extend the software and investigative techniques to improve its results for use in support of the global War on Terrorism. The NTA initiative will substantiate the effectiveness of the Geographic Profiling and develop a technology roadmap for integration of a robust capability into national security infrastructure. This work will benefit a number of DoD, IC and Federal law enforcement organizations. Local law enforcement will benefit from new capabilities that will become available to them as a result of the NTA effort.

9.4. Sampling of technologies of interest

9.4.1. ECRI Rigel[73]

Only one company—ECRI—provides a commercial geoprofiling capability that includes training and support. ECRI is a Vancouver-based company founded in 1994 to develop geographic profiling systems, primarily for criminal investigation. The company's main customers are local, regional, and national police agencies.

[73] http://www.geographicprofiling.com/rigel/index.html

ECRI's Rigel system is used by professional geographic profilers and leading police agencies throughout the world, and has been used in hundreds of cases. Rigel™ is based on the Criminal Geographic Targeting (CGT) algorithm developed by the inventor of geoprofiling,[74] which has been patented by ECRI.

Rigel is Java-based; it supports a variety of GIS and text data sources and can be customized according to customer requirements. Rigel can effectively manage the integration of address and location information, as well as incorporating additional geographic layers (i.e. schools, shops, playgrounds etc.) that are of interest.

It can extract information from a case linkage system such as ViCLAS. Information can include crime locations, suspect information, case details and investigator details. Rigel presents the results in the form of a two or three-dimensional surface maps called "jeopardies" showing the most probable locations of an offender's residence.

9.4.2. CrimeStat[75]

CrimeStat® is a spatial statistics program for the analysis of crime incident locations. It was developed by Ned Levine & Associates under grants from the National Institute of Justice (grants 1997-IJ-CX-0040 and 1999-IJ-CX-0044).[76] CrimeStat is copyrighted by and the property of Ned Levine and Associates and is intended for the use of law enforcement agencies, criminal justice researchers, and educators. It can be distributed freely for educational or research purposes, but cannot be re-sold.

The purpose of CrimeStat is to provide supplemental statistical tools to aid law enforcement agencies and criminal justice researchers in their crime mapping efforts. CrimeStat is being used by many police departments around the country as well as by criminal justice and other researchers.

The in-house program is Windows-based and interfaces with most desktop GIS programs. The program inputs incident locations (e.g., robbery locations) in 'dbf', 'shp' or ASCII formats using either spherical or projected coordinates. It calculates various spatial statistics and writes graphical objects to ArcView®, MapInfo®, Atlas*GISTM, Surfer® for Windows, and ArcView Spatial Analyst©.

9.4.3. Dragnet[77] and Predator[78]

Geoprofiling is of great interest to academic criminologists. Two academic software packages exist, and their developers work collaboratively to consider the uses and limitations of these techniques.

[74] Rossmo, Kim (1999). *Geographic Profiling.* CRC Press.
[75] http://www.icpsr.umich.edu/NACJD/crimestat.html
[76] Ned Levine. CrimeStat: A Spatial Statistics Program for the Analysis of Crime Incident Locations (v 2.0). Ned Levine & Associates, Houston, TX, and the National Institute of Justice, Washington, DC. May 2002.
[77] http://www.i-psy.com/publications/publications_dragnet.php, canter@liv.ac.uk
[78] http://www.crimelibrary.com/criminal_mind/profiling/geographic/5.html?sect=20, www.drmauricegodwin.com

Dragnet is open source software that is available to qualified personnel from its author, Dr. David Canter, director of the Center for Investigative Psychology at the University of Liverpool, England. Dragnet is a geographical prioritization package. Using the locations of a series of crimes Dragnet prioritizes the surrounding areas in relation to the likely location of the offender's base.

Predator is a software application developed by G.M. Godwin, who collaborated with Dr. Canter while attending the University of Liverpool. The Predator software has the same goals as Rigel—to narrow the search for a criminal's home base—but it uses slightly different algorithms and is not available commercially.

10. PROPOSED PROGRAMMATIC APPROACH

There is a need to treat change over time as information in and of itself. The value chain analysis of Section 2 shows that all aspects of data collection, refinement, information integration, and decision support are affected when time-varying information is part of the value being added. A programmatic approach is required to ensure a comprehensive treatment of time-varying aspects of information within the geospatial community. The goals of a program to advance the treatment of geospatial change are as follows.

- **Accelerate development of key applications.** Key applications are described as development opportunities in this report.
- **Ensure interoperability and scalability.** Interoperability and scalability are achieved by pursuing standards and infrastructure, as described in Section 3 and Appendix A. Establishment of a test and evaluation facility, TOTAL, also is critical to meet these goals. TOTAL is described later in this section.
- **Accelerate migration of capabilities to production.** Speedy migration to production is accomplished by establishing a beta facility, TSUNAMI, as described later in this section.
- **Enlarge user base.** The user base is enlarged via continued IA&E[79] to identify communities of shared interest who can benefit from similar development. Outreach, workshops, and software evaluations are assisted by TOTAL, which serves as a standing test facility (described later in this section).

Major proposed activities are described next.

10.1. Design and implement TOTAL

TOTAL[80] is a development lab that supports experimentation and discussion of interfaces, settings, standards, and tools (Figure 8). It provides a bridge by which capabilities of interest can move through phases of specification, development, evaluation, and integration prior to beta-testing for specific production environments. The establishment of a standards-based facility separate from a particular production environment will ensure that software is broadly usable, and not tied to one particular agency's needs. This is critical to ensure commercial success and sustainable commercial support.

[79] IA&E means Independent Assessment & Evaluation.
[80] TOTAL stands for Tools and Temporal Assessment Lab.

One of the critical functions of TOTAL is to spearhead standards for metacontent, products, services, and interfaces required to manage multi-temporal information. It will be possible to use the standards-based architecture to formulate extensions that can be proposed to OGC and TC211, who in turn offer considerable expertise and interest for the best possible outcome.

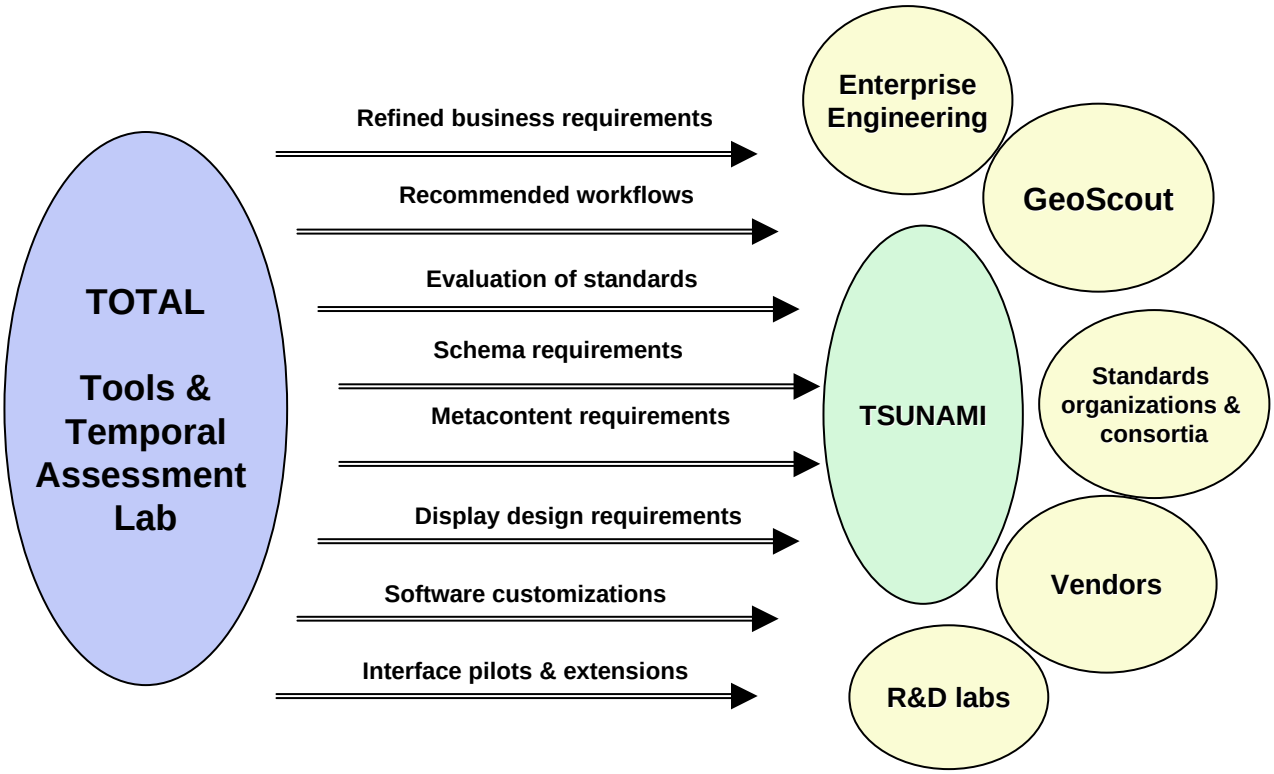


Figure 8. Contributions of TOTAL.

10.2. Design and implement TSUNAMI[81]

TSUNAMI is a beta testing and integration environment and procedures (Figure 9). Each organization that wishes to integrate capability into its environment might have slightly different TSUNAMI specifications, since the goal is to replicate key components of a particular organization's data and system to ensure proper integration of new technology and workflows.

[81] TSUNAMI stands for Time-Sensitive Unified Networked Analysis and Management of Information.

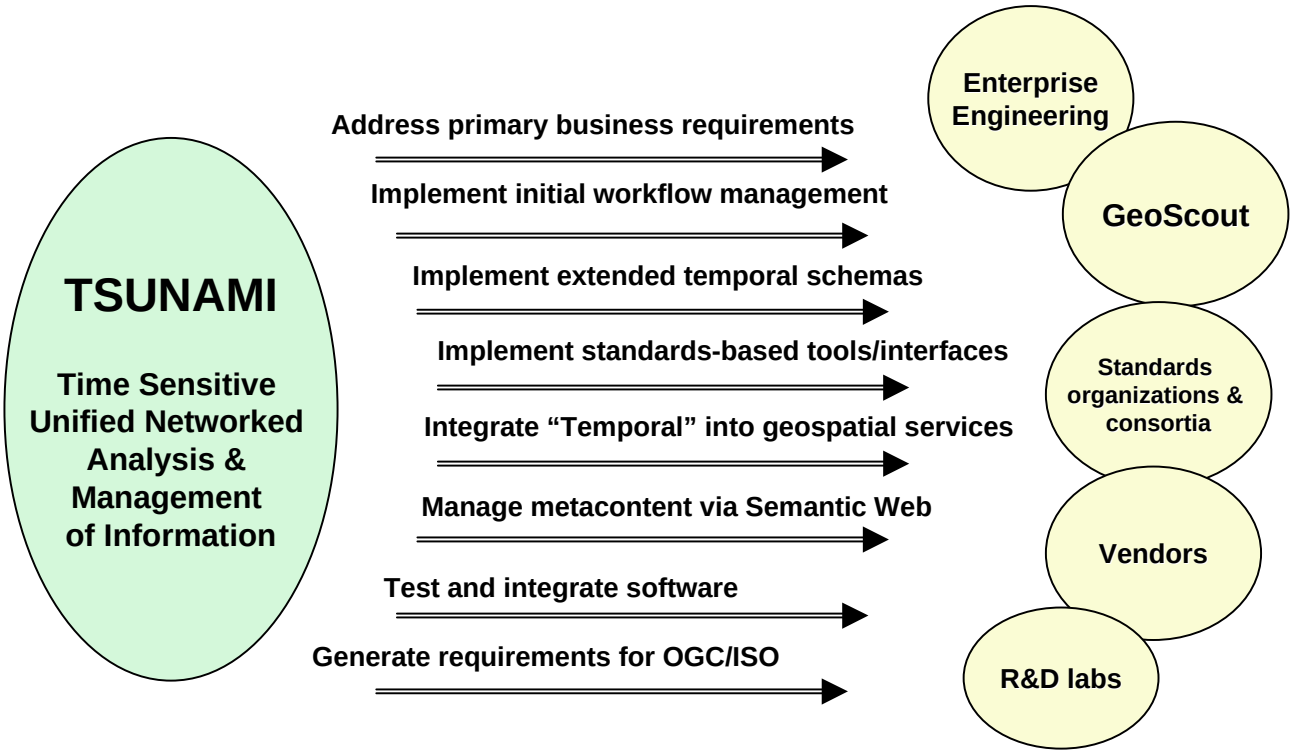


Figure 9. Contributions of TSUNAMI.

10.3. Comparison of TOTAL and TSUNAMI

TOTAL provides a simple standards-based "proving ground" for assessing, customizing, and configuring technology. TSUNAMI provides an integration environment to ensure that the technology can be introduced into production environments without disruption. TOTAL and TSUNAMI used in tandem provide a bridge from development labs to the production environment (Figure 10). Together they achieve the following.

- Deliver a sustainable piece of infrastructure that will provide the basis for ongoing service delivery and development.
- Be implemented in conjunction with GeoScout and Enterprise Engineering.
- Take advantage of existing information systems to deliver enhanced access.
- Build on internationally recognized standards (ISO, DGWIG) and specifications (OGC). The infrastructure will be compatible with OGC developments in OWS-2.

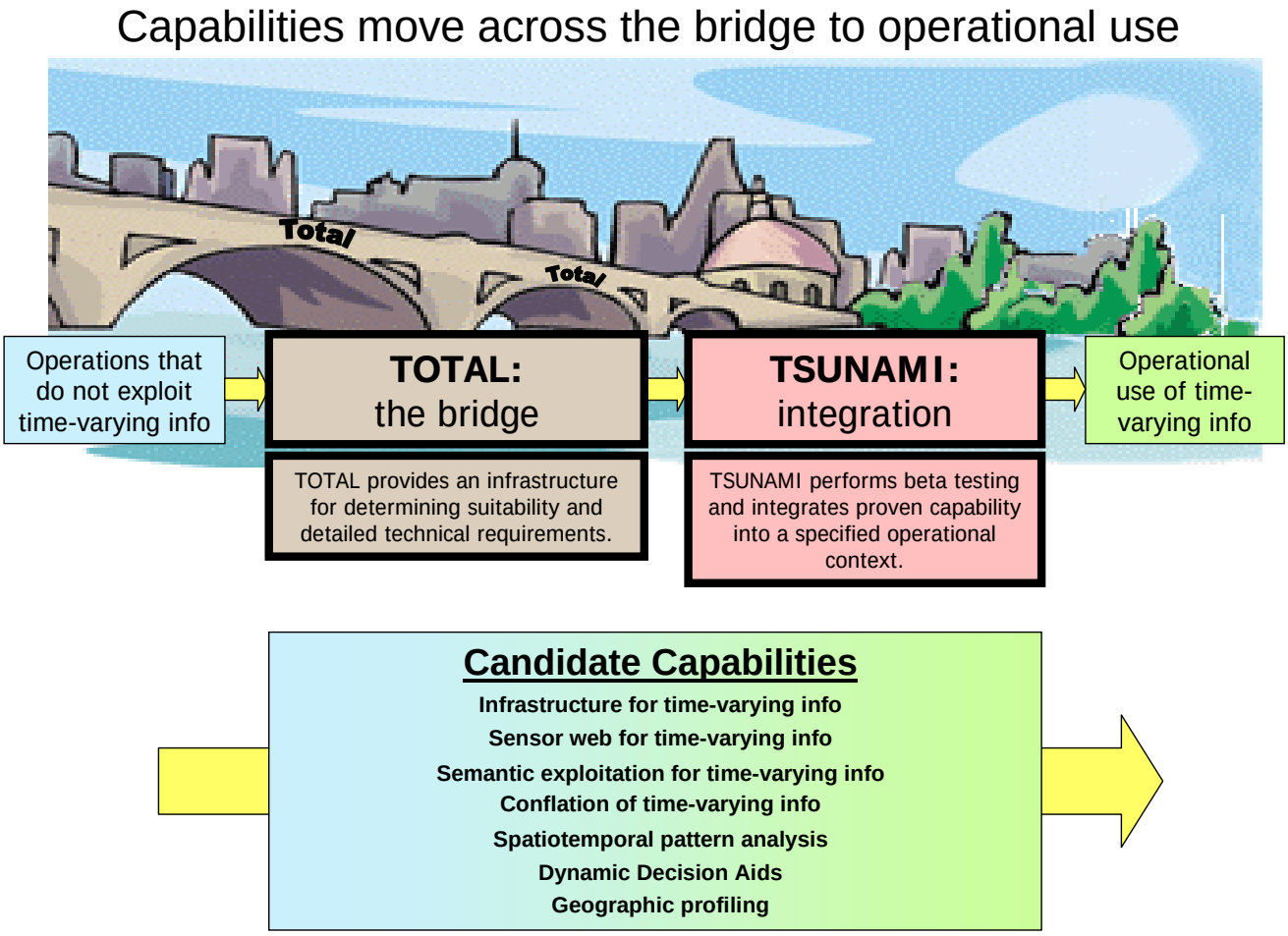


Figure 10. TOTAL and TSUNAMI provide a bridge between development labs and operational use.

TOTAL and TSUNAMI will support ongoing incremental improvement in capability by simplifying the process of assessing new technology and by reducing the disruption of introducing new technology. Figure 11 shows a prospective process flow.

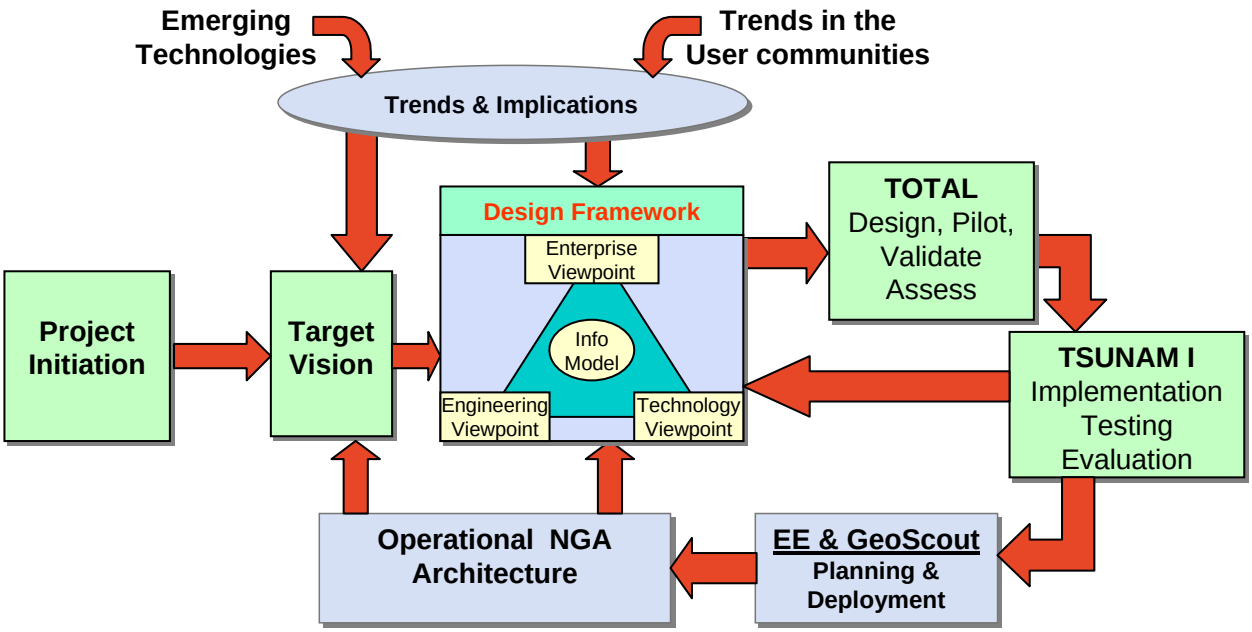


Figure 11. Prospective use of TOTAL and TSUNAMI.

A critical aspect of TOTAL's mission is to collaborate with ISO, OGC, and W3C to achieve the following.

- **Reduce technology risk** – Technology providers are encouraged to innovate when broad communities of interest signal their stability by defining and validating open interfaces that express their needs. Working with consortia like OGC and W3C can encourage the technology providers to demonstrate their integration with other standards-based products as part of doing business.
- **Improve choice and competition in the marketplace** – Since no single application meets the needs of all users, an open environment permits different applications to be used for what they do best.
- **Reduce technology life cycle costs** – By using standards-based COTS in the technology architecture, less custom code needs to be maintained.
- **Rapidly insert new technology** –By working with industry and academia to implement ISO Standards and OpenGIS® specifications, new technologies are easier to insert into an existing architecture.

10.4. Develop applications to meet key requirements

Sections 3 through 9 of this report identify technology areas that have numerous development opportunities. Applications need to be prioritized, specified, developed, tested, evaluated, and integrated. As shown previously in Figure 8, TOTAL provides a means to evaluate the interfaces, define configurations, solicit feedback from users, and generally "kick the tires" of newly developed software. TSUNAMI provides the environment by which the applications can be beta tested in a realistic production environment.

10.5. Enlarge user base

Commercial success of software developed via NTA funding has intangible payoffs to the government. It means that the software will be well supported, upgraded regularly, and available indefinitely. It also means that economies of scale push prices lower, and that spin-offs, value-adds, and copycats increase the available functionality.

A large user base is helpful to ensure commercial success. Development opportunities might begin with a limited number of stakeholders, then additional IA&E can increase awareness and usage via workshops, demonstrations, discussion groups, and pilots. By engaging additional prospective users, it may be possible to broaden the appeal of software via modest extensions. IA&E also can find good fits between new stakeholders and software underwritten by the government. Continued IA&E will also seek development opportunities in such areas as feature extraction from hi-res video (UAV), expanded numerical analysis, navigation and tracking, and multi-resolution pluralistic data fusion.

APPENDIX A: STANDARDS EXISTING AND REQUIRED

International standards exist to describe standard schemata for spatial and temporal information (ISO TC211 19107 and 19108, respectively). The schemata address the requirement to describe dimensional features via geometric objects, and to reference dimensional features to locations in time and space. The schemata in their current form do not specifically address requirements to describe change over time to dimensional features. This section briefly describes requirements that are addressed by the existing standards, and those that are not adequately addressed by the existing spatial and temporal standards.

A.1 Requirements that *are* addressed by existing standards

The existing standards (19107 and 19108) are sufficient to describe some types of change over time. 19108 discusses "feature association" and "feature succession," which provide sufficient capability to meet the following requirements.

A.1.1 Schema change over time

The present standards are adequate to describe changes to a schema over time. The necessary schema elements exist to describe the following.

- A Feature Type is added or removed.
- A Feature Type's properties change, resulting in the removal of some Attribute Types and the addition of others.

A.1.2 Sequent measurements at a point

The present standards are adequate to describe a series of measurements taken at a single location. Examples of this case include in situ sensors such as stream gauges or data buoys, and also plots that are sampled over time to measure change (e.g., for vegetation surveys). Section 8.3.2 of ISO/FDIS 19109:2003(E) includes an application schema for measurement activity in a single location at a defined frequency.

A.1.3 Changes that do not track feature ancestries

The present standards are adequate to describe changes that are represented by the birth (insertion) of new instances of features without reference to their ancestors, and the death (retirement) of existing instances of features without reference to their descendents. For example, a new data source could spur the update of a broad area of vegetation, soils, land use or land cover, demographic information, shoreline, etc. The feature succession construct from 19108 would be used to retire existing features by adding a timestamp to close their periods of validity. Then new features would be inserted with a period of validity open at one end. This approach is common in legacy systems. It is also useful for representing base data. The approach supports the query: "Show me the state at a given moment in time," but not "Show me how this feature changed over a specified period of time."

A.2 Requirements that ***are*** ***not*** adequately addressed by existing standards

The existing standards (19107 and 19108) are not sufficient to address a number of business needs that concern time-varying features. The inadequacy is not necessarily due to a lack of standard schema elements. The problem relates more to how open-ended the implementation options are, which makes interoperability among different developments extremely unlikely. For that reason, a set of standardized application schemata for specific usages is highly desirable. This section is a starting point for determining which application schemata could be standardized. A corresponding approach may be to provide an unambiguous set of rules for the definition of application schemata for time-varying information.

A.2.1 Moving features

The existing standards are not adequate to describe features that move in three dimensions (x,y,z). The simplest case is non-dimensional features (points) that move, or dimensional features that move without deformation, rotation, or change in dimension or thematic property. The more complex case is dimensional features that divide, fuse, rotate, and change in shape, dimension, and thematic property. In both cases, motion could be described via a function (e.g., velocity and direction, orbital ephemerides, behavioral model).

Features can move on constrained paths (e.g., on-road vehicles, trains, orbital objects) and on relatively unconstrained paths (e.g., aircraft, animals, foot traffic, off-road vehicles, named storms).

Manipulating moving points, lines, and areas requires operations to answer queries like "When does this moving point enter that (moving) area?", "What is the trajectory of the moving point inside the (moving) area?", or "What is the speed of this moving point?". Operations defined for fixed spatial types have to be extended to the moving spatial types in a standard way or systems will not be able to interoperate.

Moving features are a key business element of many markets. Location-based services are provided relative to a traceable moving feature, Intelligent Transportation Systems assume a set of traceable moving features, and modeling and simulation can operate on moving features. Thus, moving features are of interest to these groups: ISO TC211 WG8, ISO TC204, ISO JTC1 SC24 and ISO JTC1 SC32.

It is imperative that the core conceptual model for moving features be shared among all interested parties to ensure proper interfaces between market areas. It is also imperative that backward compatibility is achieved for existing implementations (e.g., that of SC24). Backward compatibility is also needed for spatial geometries defined by 19107 and temporal referencing defined by 19108.

This discussion paper recommends that an application schema for moving features be fast-tracked via a New Work Item (see Section 4). The rationale for fast-tracking moving features is that their issues and concepts are well understood, and as such will invite constructive discussion, development of terminology, and

generation of a conceptual schema that is forward-compatible to other types of time-varying features.

A.2.2 Incremental change to the thematic properties of a feature instance

The present standards are inadequate for tracking a series of changes to a feature instance's thematic properties, e.g., a building whose horizontal accuracy, color, or usage changes; or a navigation aid whose light or sound change. The key issue concerns "versioning", which involves creating multiple representations via additional database records to describe versions of a feature instance. If a single property of a feature instance changes, the following options exist.

- Create a new version of the entire feature instance (geometry and thematic attributes).
- Create a new version of the thematic attributes only (which are referenced to the feature instance).
- Create a new version of only the attribute value that changed.

Arguments for and against each of these practices exist. A designer's choice is based on the capability of software used and the expectation of how feature types could change. The standard should provide an application schema that offers a choice to designers, while still ensuring clear communication and interoperability. The existing constructs of feature association and feature succession (19108) can be extended to offer a basis for addressing these requirements.

A.2.3 Incremental change to the geometric properties of a feature instance

The present standards are inadequate for tracking changes to a line or area feature's geometric properties, e.g., a road that over time is partially paved, one section is straightened, and a third section is closed (see example in Section 3). How to create versions is one issue (see the discussion in the previous section on versioning for thematic properties). This includes the case where the dimensionality of geometry changes, e.g., from line to area. A second issue is how to derive and reference fragments of geometry to represent the geometric change. Options include the following.

- The geometry for one version of a feature has topological intersections within that moment in time alone.
- The geometry for one version of a feature is intersected across an interval in time for that feature instance alone.
- The geometry of one version of a feature is intersected across an interval in time for all feature instances.
- Each vertex of the geometric representation is described via (x, y, z, t).

As with other considerations involving versioning, a designer's choice is based on the capability of software used and the expectation of how feature types could change. The standard should provide an application schema that offers a choice to designers, while still ensuring clear communication and interoperability.

A.2.4 Time-varying aspects of networks and categorical coverages

Time-varying aspects of networks and categorical coverages pose special challenges. Examples of these types of features include census tracts, administrative boundaries, road networks, hydrological networks, cadastres, managed vegetation (crops or plantation forests), open-cut mine shells, land cover classifications. There is enormous incentive and interest in reaching consensus on how to represent time-varying aspects such that proper analysis is possible.

The challenge lies in the fact that when one component of the network or coverage undergoes geometric change, the geometric description of other components may be affected. In addition, analysis may summarize differences between complete states, or it may analyze the history of one feature type or one feature instance. .

A.2.5 Complexity in timeline topology

It is possible to have a timeline topology that is a network, as described below.

- If a feature instance divides and fuses, the versions form a networked timeline topology. Examples include animal herds, refugee groups, segments of a highway, and parcels that are subdivided or amalgamated.
- If multiple sources of a feature instance are used to create multiple representations that co-exist in time, the concurrent versions form a networked timeline topology. Examples include forest stands delineated via multiple interpretations, shorelines delineated using different tides and datums, and administrative boundaries that are disputed or whose legal descriptions do not provide clear ground locations.

This issue is discussed briefly in 19108, but its treatment needs expansion and clarification in the spatiotemporal context.

A.2.6 Explicit tracking of the history of spatial topology

Spatial topology sometimes is described explicitly in stored data. Thus, in addition to describing thematic and geometric properties, there are explicit references to the graph that provides underlying structure to the data (i.e., begin node, end node, left face, right face). If geospatial change is tracked, the question remains whether it is required to track changes to the explicit topological references (i.e., previous begin node, next begin node, etc.) There is no obvious requirement to track changes to spatial topology, but this must be confirmed through consultation.

A.2.7 Temporality of surfaces and solids

Surfaces and solids change over time, and standards are needed to describe these changes. Key business drivers will come from mining, petroleum, water resources, oceanography, and geophysical sciences. An example scenario would be the tracking of meso-scale and micro-scale current eddies in the Gulf of Alaska, as part of a global ocean circulation and climate model. Eddies can be modeled on the sea surface, with the added complexity that every point on the surface has a velocity and direction (i.e., is a 3D point vector). As time advances, the centroid of an eddy moves on a trajectory and the current moves around it, causing fluctuations in sea surface height. Eddies also can be modeled as 3D solids rather

than as surfaces, which introduces new challenges. Similar requirements can be drawn from the field of petroleum reservoir engineering, where knowledge of the interface between gas, petroleum fluids, and ground water is paramount for the design of effective recovery mechanisms. It will be important to define key requirements and their appropriate spatiotemporal treatments to be backward-compatible with the 0D, 1D, and 2D treatments.

A.2.8 Explicit causal links

Businesses need to be able to express whether a feature type is a state, event, or evidence. These distinctions support the representation of causal relationships between time-varying features. States and events are defined in 19108, Section 5.5.2, as follows.

- An event is an action that occurs at an instant. In fact, almost every event occupies a short interval of time, but when that interval is short relative to the resolution of the scale of measurement, it is specified as an instant. The GF_AttributeType.valueType of an event shall be either a TM_Instant, a TM_Node, or a TM_TemporalPosition.
- A state is a condition – a characteristic of a feature or data set that persists for a period. That characteristic may be represented by a feature attribute or metadata element. A GF_TemporalAttributeType that describes a state may be instantiated in two ways. In the simple case, the GF_AttributeType shall be instantiated as an attribute of a class that represents a feature type. Its GF_AttributeType.valueType shall be either a TM_Period or a TM_Edge. When more information is needed, a GF_TemporalAttributeType that represents a state shall be instantiated as a UML class. That class shall be a subtype of TM_Period that inherits the associations Beginning and Ending, or a subtype of TM_Edge that inherits the associations Initiation and Termination. The characteristics of the state shall be described by one or more attributes of the class. Its recurrence shall be indicated by the multiplicity at the attribute end of its association with the feature type class. Often, a change in state is associated with an event that initiates or terminates the state. That event shall be identified by an attribute of the class that represents the state.

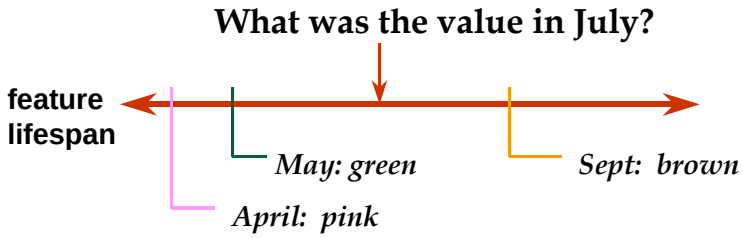
These definitions relate primarily to timeline geometry. The following working definitions are proposed for the business constructs. New terminology may be needed to separate the business and schematic concepts.

- Business description of a state: same as in 19108. A state has spatial and temporal extent, and associated thematic properties.
- Business description of an event: An occurrence of importance to the business, and which is capable of inducing state change. Examples include storm, insect infestation, wildfire, flood, battle. Business events are represented just as any other feature type, since they have spatial and temporal extent, and associated thematic properties. Business events can have sub-events that (e.g., stages of flooding, spot fires, specific campaigns within a battle).
- Business description of causal links: States and events are assumed to be independent, unless a causal link is detected. The possibility of causal linkages among states and events must be defined by the business, as in the examples below.
    - Event contributes to state change: windstorm causes blowdown of trees; flooding causes road washout.

  - State contributes to event properties: heavy brush contributes to spread of wildfire, single-species forests contribute to spread of insect infestation.
  - State contributes to state change: trees beside a clearcut are blown down while those in the forest are intact.
  - Event triggers subsequent event: electrical storm causes wildfire.
- Business description of evidence: the sources by which states, events, state change, and causal links are detected. Evidence has spatial and temporal extent, and associated thematic properties. For example, an air photo covers an area on the ground and was taken at a particular time. A ground survey may have plots (points), transects (lines), and have occurred over a particular period.

A.3 Framework for addressing the issues

This section describes a framework for spatiotemporality that revolves around the concept of tracing and analyzing the history of change over time to features, or "time-varying features."[82] The term "spatiotemporal" has broad and ambiguous meanings. Business requirements are considerably more specific, and revolve around a set of features defined by the business to be of key importance. Features may be of 0, 1, 2, or 3 spatial dimensions. Multiple states of a feature can appear along the timeline (see figure below), changing in constrained or unconstrained ways.



The next subsections discuss concepts of that will be of use to the work that will follow.

A.3.1 Case study of time-varying information management

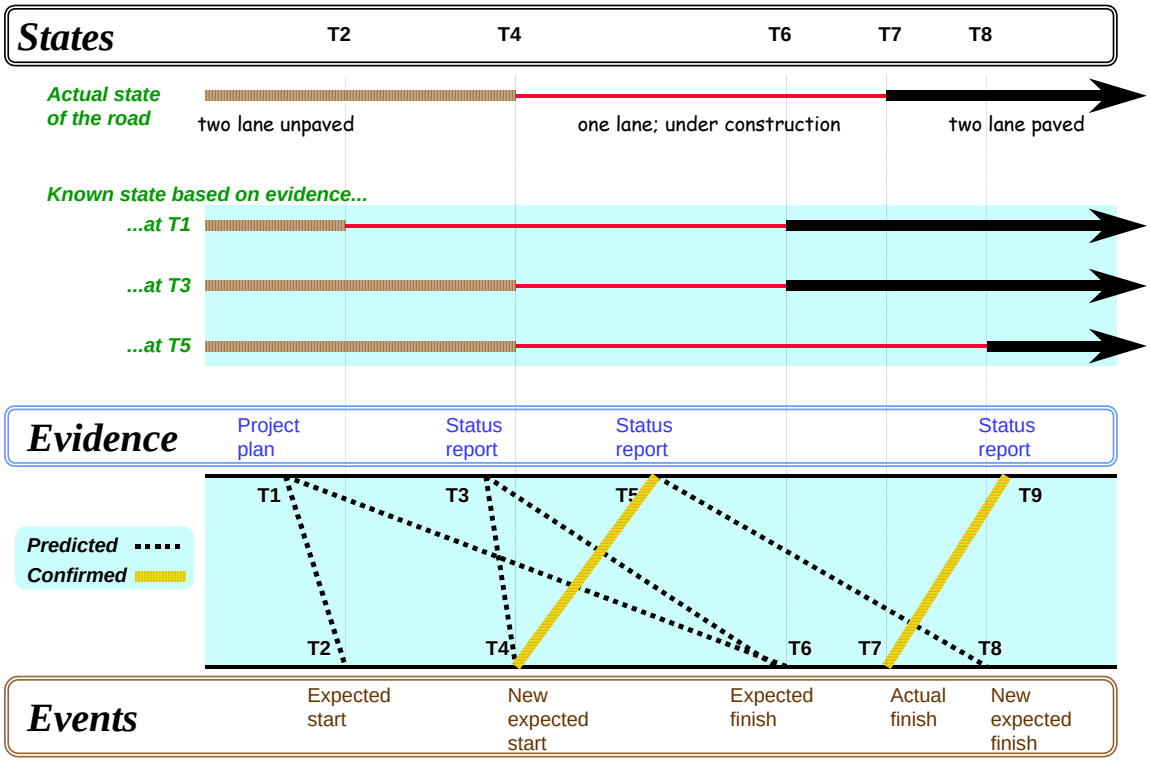
Real-world business systems have data with quality problems. Changes to the data come about through processes that may be poorly understood, subject to change, or otherwise unpredictable. Information about the changes can be out of sequence or in error. A business may need to know more than what changed; it may also need to know what was planned, intermediate steps, and what was represented by the system (and thus known to the enterprise) at each point in between. The example below shows how a highway department might track a road-paving project that proceeded as follows.

- Plans are made to pave a stretch of highway.
- The schedule changes several times.
- Parts of the road are closed, and detours are added.

[82] The same methods pertain to tracing a forecasted future of features.

- Finally construction is completed.

In this simple example, the highway department needs to track information about the road (states), the actions taken to maintain the road (events), and the documents used to gain knowledge about the states and events (evidence). Note that the knowledge of a past moment at that same past moment can differ from what is known at a later date, when additional information about the past becomes available. Similar examples can be drawn from business systems that manage cadastres and land interests, facilities, utilities, forestry, agriculture, navigational charting, monetary transactions, and others.



A.3.2 Histories of feature instances whose identities persist despite changes

There is a business need to know specifics of feature changes. This makes it possible to analyze patterns and particulars of change over time. If a business views an element of business information as essentially the same thing despite its changes, then its feature type must support multiple representations (or versions) of a feature instance. The goal is to support such queries as follows.

- How has this building changed over time? When did its color change, and when was the last time it was purple? What is the average number of years between color changes, and is the most recent color change an unexpected deviation from pattern?
- When and how has erosion or accretion changed a parcel's boundary and size? Is there a trend in where the spatial change is occurring?

- When and where was the road re-routed? What were the effects of road re-routing on business that once were, or that now are, alongside the highway?
- How have changes to the bus schedule affected the use of the bus stop nearest the mall?

As illustrated above, businesses may need to analyze information concerning what specific aspects of a feature instance's thematic or spatial properties changed.

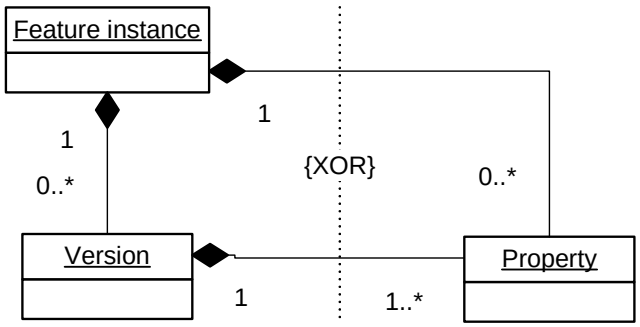
The concepts of association and succession as described in 19108 provide a basis for these constructs. Business rules are required to define whether only one representation can be valid for a given moment in time (as for a temporal feature that does not divide or fuse), or whether multiple representations are permitted (as in multi-source, multi-resolution, unconflated, or uncertain systems). It cannot be assumed that a query for successive versions will produce correct results without explicit linkages and rules (e.g., using TM_Order.relativePosition together with one or more of the Spatial operators defined in 19107).

The conceptual model below illustrates the situation. A feature instance has one or more versions. Each version has properties associated with it (which may change independently). The feature instance itself may have properties that are defined by the business as integral to the feature type, such that the value is constant for each version of a feature instance. If the value of an integral attribute changed, business rules cause that feature instance to "die" and be reborn as something different. For example:

- A public green space can be enlarged, replanted, and its hours of use can be changed, while still remaining a public green space. However, if it is paved or sold into private hands, it is considered to have died and become a new feature.
- A lighthouse can be painted, rebuilt in place, and its light characteristics can be altered slightly while still remaining the same lighthouse. However, if it is moved more than a certain distance or if its light is removed, it is considered to have died and become a new feature (i.e., a new lighthouse or not a lighthouse, respectively).

The concepts of "substitution" and "instantiated associations," as described in 19108, 5.5.4.2.2, are useful.[83] However, the methods and terminology need to be extended somewhat, and their usage needs to be standardized.

[83] Temporal feature associations of the feature succession type may also be instantiated in an application schema as UML associations between feature type classes, or as self-referent associations of a generic feature class. The names, roles, and multiplicities shall be different for each type of succession. The role names shall indicate the order in which one feature succeeded another. To include the time at which succession occurred, an application schema shall represent the succession association as a UML association class with an attribute that identifies the time of occurrence.



A.3.3 Multiple representations of feature instances

Pluralistic representation of features (i.e., multiple representations of feature instances) can result from storing multiple geometries of different scale or detail, from storing information from multiple unconflated data sources, and from multi-temporal representation. The methods used to model all these variants of multiple representation should be the same.

A.3.4 Orthogonality in the information model

If “when/where” semantics are expressed as orthogonal to “what”, there is economy of expression. This is also a more natural representation of time-varying information, which leads to quicker comprehension and adoption. The illustration below is based on work by the Advanced Database Research Group[84].

What?	**Temporal** (e.g., valid, transaction, temporal granularity and indeterminacy)	**Spatial** (e.g., shape, dimension, spatial granularity and indeterminacy)	**Time-varying spatial** (e.g., change in position and/or shape)
Entity Class • Simple • Subclass • Composite • Grouping • Weak			
Relationship			
Attribute • Simple • Composite • Multi-valued			

When/ Where?

By extension, if "where" semantics are expressed as orthogonal to "when", greater clarity and flexibility ensue. Orthogonality and thereby independence ensure that information is not locked into a structure that is too restrictive to permit it to grow and change with the application's requirements. For example, a system which today deals with moving features as dimensionless points may change to include

[84] University of Arizona (Sudha Ram, Richard T. Snodgrass, Vijay Khatri and Yousub Hwang)

the higher level geometry in 2 or 3 dimensions at a later time (e.g., the vehicle is represented with roll, pitch, yaw). If the temporal and geometric properties are orthogonal, it is easier to deal with the issue of multiple representation of geometry. A discussion from the MurMur project follows.

> Not every temporal model supports the association of time with objects, relationships, and attributes. In their support of temporal and spatial features most models supporting inheritance ignore the facilities offered by refinement and redefinition, thus illustrating another way of not achieving orthogonality. They also often include unnecessary constraints on temporal specifications, like the validity period of an attribute…must be within the lifecycle of the objects it belongs to…This prohibits any reference from an object to another older object/value…For instance in a genealogy database, a Person object should be allowed to refer to its Person ancestors even if they did not live at the same time…These temporal constraints should be optional, depending upon the application.[85]

A.3.5 Maintaining forward and backward compatibility

Backward compatibility requires that the syntax and semantics of existing conceptual models remain unaltered. The objective of backward compatibility is to be able to develop schemata for time-varying information without invalidating extant legacy schemata for spatial and temporal, thus protecting the investments in existing standards and products. It also implies that both the legacy schemata and the new time varying information schemata can co-exist. If the extensions for advanced support for time-varying information is a strict superset provided by adding non-mandatory semantics, it would ensure that the extension is backward compatible with existing conceptual models.

Forward compatibility means that any approach to be considered must be extensible to address future requirements. While all future requirements cannot be foreseen, it still is possible to err on the side of flexibility when choosing a conceptual model. This means that new business cases should be able to be addressed using existing constructs in new application schemas. It also means that it is possible to introduce innovative technical approaches that still conform to the standards.

Since one of the main goals for standards development is the benchmarking of requirements so that the risks for commercial applications builders can be minimized, it is important to understand and take into account both orthogonality and compatibility.

A.4 Standards potentially impacted

Many completed and ongoing efforts share common ground with the work described in this documented, as discussed below.

[85] From MurMur Project – Multi-Representations, Multi-Resolutions, Workpackage 2 – The MurMur data modelling approach, Deliverable 4 – State of the Art review. Ref. project: UNIL/CP/MM-WP2-DLA-004/V4.0/ dated September 18-2000, page 21.

- **ISO TC 211** - The following ISO TC211 standards have spatiotemporal components, and thus are potentially impacted.
  - 19107- Spatial Schema
  - 19108 – Temporal Schema
  - 19123 – Schema for Coverage Geometry and Functions
  - 19125 - Simple Feature Access
  - 19130 - Sensor and data model for imagery and gridded data
  - 19132 - Location based services - Framework
  - 19133 - Location based services tracking and navigation
  - 19134 - Location based services for multimodal routing and navigation
  - 19136 – GML
  - 19137 - Core profile of the spatial schema – Image and gridded
- **ISO TC 204 GDF** - ISO TC 204 includes capability to describe transit schedules and periods of validity, which are important to proprietary databases for traffic and routing applications. GDF includes a construct entitled "Restrictive Sub Attributes", which are (essentially) attributes that describe other attributes. The sub attribute called "validity period" can be used to describe the following situations.
  - The gate is closed at certain periods of time except for emergency vehicles.
  - The direction of traffic flow for the centre lane is east/west on Mon-Fri between 7-9AM and 4-6PM, west/east for all other hours, and restricted for use to only cars and emergency vehicles on Saturdays & Sundays between October 15-April 15.
- **JTC1 SC24 WG 8 SEDRIS** - Modeling and simulation are nearly synonymous with time-varying information analysis. The methods used by SEDRIS for representing time-varying geospatial information must be evaluated and harmonization approaches defined.
- **JTC1 SC32 WG 4 SQL/MM Part 3 and OGC SFSQL -** Significant work has been done in the area of adding standard temporal operators and datatypes to databases. The original SQL/MM Part 3 Spatial working draft included temporal elements. Migration of this work in JTC1 SC32 WG 3 resulted in a Part 7 Temporal. Due to a lack of interest from vendors and the inability to reach agreement on early progression, this work was deprecated. With an increase in technical capability the past interest has been renewed and it will be important to establish a liaison to ensure harmonization of effort.
- **OGC Semantic Web and Sensor Web initiatives**