

# SPATIAL SENSOR WEB REFERENCE MODEL

S.H.L. Liang, V. Tao

GeolICT Lab, York University, Toronto, Ontario, CANADA M3J 1L4 – (liang, tao)@yorku.ca

Commission I, WG I/3

**KEY WORDS:** Sensor networks, Interoperability, Sensor, Standards, Networks

## ABSTRACT:

In this paper, we introduce a Spatial Sensor Web reference model. Firstly, we present the concept of the Sensor Web and the Spatial Sensor Web. Then we use a layered conceptual model to describe the Sensor Web. Thirdly, we present the Spatial Sensor Web reference model. The reference model is composed by seven logical layers. It provides an architectural framework for constructing a Spatial Sensor Web as well as provides a way of thinking about architectural issues in terms of the applications and constraints of the Spatial Sensor Web. Lastly, we applied the seven layers to ISIES (Intelligent Sensorweb for Integrated Earth Sensing). We use the ISIES as a real-world example to illustrate the seven layers of the reference model.

## 1. THE SENSOR WEB AND THE SPATIAL SENSOR WEB

### 1.1 The Sensor Web

Today, it is feasible and economically viable to deploy enormous amount of low-cost, low-power in-situ sensors to continuously monitor our environment. We also see more and more advanced remote sensing satellites have been or scheduled be launched. The combination of these heterogeneous sensing systems can provide enormous amount of timely, comprehensive, continuous and multi-resolution observations for applications in smart spaces, agriculture, environment monitoring, habitat monitoring, transportation, homeland security, defence to even planet exploration.

However, these ad-hoc networked sensors or sensor systems don't connect to each other. The sensors of a sensor network connect to each other only within their proprietary network. They are deployed for their own purposes, for specific applications, and to make it even worse, they are using proprietary network protocols, information models, and data formats. There is no resource sharing and collaboration between heterogeneous sensor networks. Today's sensor networks' situation is just like the situation of computers without the World Wide Web (WWW).

It is critical to develop a Sensor Web for the sensor networks that is similar to the WWW for the computers (Liang, Croitoru, & Tao, 2005). The Sensor Web is an information infrastructure, a backbone that connects the heterogeneous in-situ and remote sensors over the wired and wireless networks. The vision of the Sensor Web is to allow these real-time sensor resources, such as sensor data and sensors' tasking capabilities, accessible from everywhere at any time.

The concept of the Sensor Web is similar to the concept of the WWW. What Sensor Web is to the sensor networks is what WWW is to the computers. The WWW is an information infrastructure that interconnects heterogeneous computers on the Internet, and provides rich information, including text and multimedia files, and other network services. In a similar spirit, the Sensor Web is an information infrastructure that

interconnects heterogeneous networks of sensors, and provides sensor information, including sensor metadata, sensor observations<sup>1</sup>, sensors' tasking capabilities and other related functions.

### 1.2 The Spatial Sensor Web

All sensing tasks happen, they happen somewhere. All sensor information has a spatial context. The Spatial Sensor Web is a special type of the Sensor Web that concerned with the spatial properties of the Sensor Web, including geographically referenced sensors, their observations, and associated geographical features.

The spatial properties are critical to the Sensor Web. Consider the following hypothetical scenario:

Mike is driving from suburban Toronto to downtown today. Before he arrives downtown, he uses his PDA phone to send out a query to a parking-space finder service. Mike specifies the destination of his desired parking space (e.g. street intersection) in the query, and his PDA phone also adds Mike's current location (from PDA's built-in GPS) in the query message. Through the Spatial Sensor Web, the parking-space finder service connects to a network of video cameras throughout Toronto to track parking space availability. Based on Mike's destination, the parking-space finder service uses image processing algorithms to process the images captured by the cameras, and identifies the nearest available parking space. Then the service sends a map with driving directions to the parking space from Mike's current location.

This scenario demonstrates the importance of the spatial properties of the Sensor Web. Spatial data (e.g. location and orientation of the cameras) and spatial processing (e.g. spatial reasoning, window query support, and nearest neighbour support) of the Sensor Web are the keys to enable the above scenario.

---

<sup>1</sup> In this paper, we define observation as a type of spatial-temporal feature. An observation is an act of observing a phenomenon, with the goal of producing an estimate of the value of the phenomenon.

## 2. THREE CONCEPTUAL LAYERS OF THE SENSOR WEB

This section of the paper introduces a conceptual layered model of the Sensor Web. The conceptual model provides a high level and implementation independent model of the system that describes the structure of the Sensor Web. Sensor Web is described as comprised of three conceptual layers (Liang et al., 2005): 1) sensor layer, 2) communication layer, and 3) information layer. Figure 1 shows a conceptual diagram of the Sensor Web, the Sensor Web's three layers, and the relationships between the three layers.

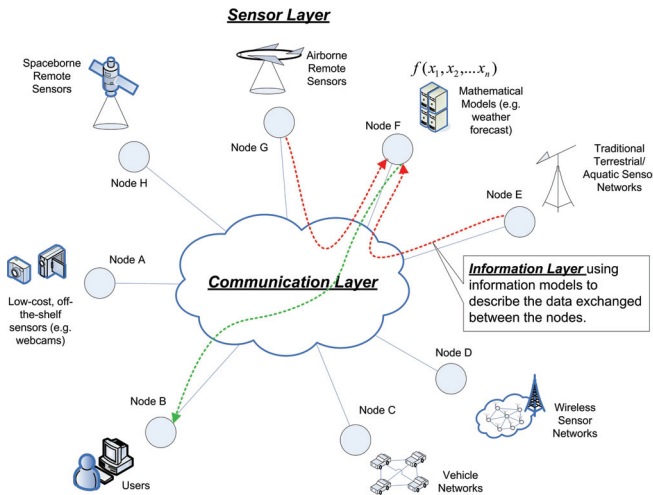


Figure 1 This figure shows a conceptual diagram of the Sensor Web, and the Sensor Web's three layers. Sensor Layers is composed by enormous amount of heterogeneous nodes. Example of the nodes can be node for a real-world sensor (Node E), a node for a mathematical model as a virtual sensor (Node F), or a client node (Node B). Communication layer interconnects the nodes, and routes messages between the nodes. Information layer describes the data exchanged between the nodes (the red lines and the green line) in meaningful and structured ways so that the exchanged data can be used by the nodes. (modified from (Liang & Tao, 2005))

### 2.1 Sensor Layer

The sensor layer is composed by enormous amount of heterogeneous nodes. The node can be a sensor or a virtual sensor (a mathematical model). The nodes are the atomic components of the Sensor Web. At the conceptual level, all nodes have four basic properties: 1) inputs, 2) outputs, 3) parameters and 4) methodologies. A node is an entity that takes one or more inputs, and based on parameters and methodologies, generates one or more outputs.

These atomic nodes are interconnected by a communication fabric (the communication layer) to exchange information (the information layer).

### 2.2 Communication Layer

The communication layer allows the Sensor Web nodes to exchange information. The communication layer is an infrastructure that permits the nodes of the Sensor Web to

transmit and receive data between one another. This layer includes media, topologies, the network communication model and protocols, and routing, etc.

Most of the components of the communication layer will leverage the existing computer networks technologies. However, the design of the Sensor Web's communication layer needs unique considerations comparing to normal computer networks. The Sensor Web is a system deployed in the field. Different environment of the field gives different challenges, including power constraints, extreme weather conditions, etc.

### 2.3 Information Layer

The information layer is composed by information models for the entities involved in the Sensor Web. The purpose of the information layer is to allow the nodes to understand and to use the data exchanged from the other nodes. To fulfil the purpose, it is critical to establish standard information models and encodings to describe the Sensor Web's entities and their relationships.

The information layer shall provide at least three basic types of information. 1) It shall identify what are the basic entities involved in the Sensor Web. 2) It shall define the conceptual information models for the entities including their properties, relationships, and the operations that can be performed on them. 3) It shall specify the physical data encodings (e.g. binary format specifications or XML schemas) according to the previously developed information models.

## 3. SPATIAL SENSOR WEB REFERENCE MODEL

This section of the paper presents the Spatial Sensor Web reference model. It is a logical layered model for the Spatial Sensor Web. Although we design this reference model with a focus on the Spatial Sensor Web, we believe this reference model is also of reference value to the general Sensor Web construction.

It serves the following purposes:

- It provides an architectural framework for constructing a Spatial Sensor Web.
- It provides a way of thinking about architectural issues in terms of the applications and constraints of the Spatial Sensor Web.
- It breaks the Spatial Sensor Web into separate abstract layers to reduce the complexity.

Now we describe each layer of the Spatial Sensor Web reference model. In this section, we use a convention of specifying what the layer **contains** (hardware, data processing, functions, etc) and what it **exports** (the data and interface presented to the layer above). In addition to "contains" and "exports", we also list the available **standards** for each layer.

### 3.1 Sensors

**Contains:** Devices (sensors) capable of observing a phenomenon and returning an estimated value of the phenomenon.

In most cases, a sensor is in fact a sensor system that composed by a system of sensor hardware and software. In the context of the Spatial Sensor Web, the sensor system shall at least have

one sensor measuring a physical or logical phenomena contributing to the estimation of the sensor system's location. It can be GPS pseudo-range measurements, blob pixels from a camera, time of flight of an ultrasonic emission, or even a RFID login event.

**Exports:** Raw data values in a variety of formats.

**Standards:** IEEE 1451(IEEE, 2006b)

### 3.2 Local Network

**Contains:** A network that link sensors within a confined geographic area. In most cases, the local network for the sensors uses wireless network because it is low cost and easy to deploy cost in comparison to wired network(Hill et al., 2000). At least one gateway node is needed in the local network layer in order to connect to the Internet. All data values are transmitted via the local network to the gateway node.

The local network is a network deployed in the field. Therefore, the settings and configuration of this network are often depending on the constraints given by the environment. For example, low power and low data rate communication protocols, such as ZigBee(IEEE, 2006a), can be used for geographically dense deployment of tiny and power sensitive sensor nodes (e.g. deploy thousands of nodes in a plant for industrial control). 802.11 family protocols can be used for sensor nodes that have less energy constraints and needs larger range of communication and higher data rates. Long range radio connection protocols can be applied to sparse deployment in rural area.

In a lot of cases, the energy constraint is the greatest challenge when deploying the local network in the field. In-network aggregation is an important technique in order to overcome the energy constraint. The local network aggregates data coming from different sources en route – eliminating redundancy, minimizing the number of transmissions and thus saving energy (Krishnamachari, Estrin, & Wicker, 2002).

**Exports:** It exports data values from the sensors in a variety of formats to the Internet. The data values might be raw or aggregated values.

**Standards:** ZigBee, IEEE 802.11x

### 3.3 Internet

**Contains:** A global communication infrastructure for data transmission and exchange. The Internet is an interconnected system of networks that connect computers around the world via a common set of protocols, such as TCP/IP.

**Exports:** It exports the raw or aggregated data values from local networks to data's destination.

**Standards:** DNS, TELNET, FTP, HTTP, TCP, UDP, IPv4, etc.

### 3.4 Information Models and Encodings

**Contains:** A software module that uses standard information models and encoding methods to transform the received raw/aggregated data values into structured and meaningful information.

Information model is an abstract but formal representation of entities including their properties, relationships, and the operations that can be performed on them. Information encoding is a physical representation of an information model.

For example, a sensor observation information model can be defined using UML diagrams. The UML diagrams define the observation's properties, relationships, and the operations that can be performed on them. The information encoding for the observation model may be a XML schema which follows the information model.

**Exports:** Structured and meaningful information encoded in standard information encodings that follows standard information models.

**Standards:** OGC O&M Model(Cox, 2005), OGC GML(Cox, Daisey, Lake, Portele, & Whiteside, 2003), OGC SensorML(Botts, 2005), netCDF(Unidata, 2006), ESMML(Ramachandran, Graves, Conover, & Moe, 2004), etc.

### 3.5 Spatial Sensor Web Service

**Contains:** A web based system that provides the Sensor Web functions through high level and well-defined service interfaces. Examples Sensor Web functions can be 1) access to sensor's observations, or 2) access to sensor's tasking capabilities, etc. A more advanced Spatial Sensor Web service example can be the parking-space finder service that we presented in section 1.2.

Here we present a general case of the Spatial Sensor Web services. A Spatial Sensor Web service may contain the following functions:

- 1) It reads the stream of measurements. (received from the Internet layer)
- 2) It parses the stream of measurements, and uses embedded rules (e.g. redundancies or contradictions) to clean/validate the data values and reduce uncertainty.
- 3) It assimilates the cleaned data values, calculates the positions of the observations, and uses the information models and encoding layer to transform the data values into time-stamped spatial observation features.
- 4) It stores the observation features in a database.
- 5) It may perform spatial reasoning about the spatial relationship between the observations and observations, and observations and their associate features. The observations' associate features are 1) the sensors perform the observation, 2) the observed phenomenon, and 3) the observations' interested features (e.g. the targets of an observation).
- 6) It may use an interpolation method to determine the values at the spatial-temporal positions without observations.
- 7) It may also use a computing model to fuse the heterogeneous observations from different sensors and generate higher-level outputs. For example, a predictive model assimilates and fuses observations and auxiliary data, and then produce higher-level knowledge. (e.g. event prediction)

**Exports:** Web service interfaces that allow applications to request the sensor-related functionalities (i.e. access to sensor observations or tasking capabilities).

**Standards:** OGC Sensor Observation Service(Na & Priest, 2005), OGC Sensor Planning Service(Simonis, 2005), OpenDAP(Cornillon, Gallagher, & Sgouros, 2003), etc.

### 3.6 Service Discovery

**Contains:** A system that allow applications to search relevant descriptive information of the resources available on the Sensor Web and to locate the services that provide the resources. These Sensor Web resources include sensors, their observations, their tasking capabilities, and associated features. The system shall also provide a means for the services to publish their presences.

When an application firstly joins the Sensor Web, the application doesn't have a priori knowledge of the available services of the Sensor Web. Before accessing to any services, application needs to know where the services are and what capabilities the services can provide. The service discovery layer is like a "*Sensor Web Google*" that allows applications to locate, access, and use arbitrary sensing resources.

**Exports:** A query interface providing, at minimum, a list of available sensor services. In a Spatial Sensor Web context, spatial query functions shall be provided, such as spatial window search, nearest neighbour search, etc.

**Standards:** OGC Sensor Catalog(Nebert & Whiteside, 2004), UDDI(Curbera et al., 2002), etc.

### 3.7 Applications

**Contains:** A system provides access to the Spatial Sensor Web services. It can be a webGIS client, a spatial decision support system, a geospatial exploration system, or even a web service. It connects to the Sensor Web services through the service discovery layer. It serves the end users by providing the Sensor Web resources relevant to the users' needs.

**Exports:** A user interface that allows end users to access the services offered by the Sensor Web.

## 4. APPLYING THE SPATIAL SENSOR WEB REFERENCE MODEL

In this section we use the ISIES (Intelligent Sensorweb for Integrated Earth Sensing) project as a real-world example to illustrate the Spatial Sensor Web reference model.

### 4.1 Introduction to the ISIES project

ISIES (Teillet et al., 2005) is an integrated Earth sensing sensor web system for improved crop and rangeland yield predictions. ISIES was deployed at two test sites, annual cropping and rangeland, in southern Alberta. The ISIES system was developed to integrate data from heterogeneous sensors automatically to provide maps of leaf area index, soil moisture and biomass, as well as improved predictions of crop and rangeland yield. Figure 2 shows an architectural diagram of the ISIES system.

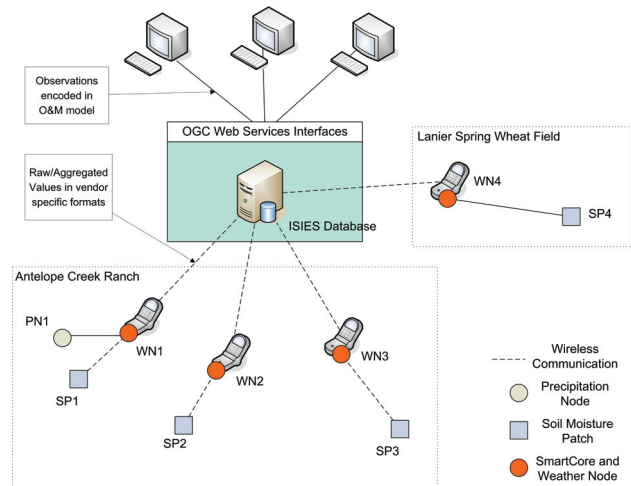


Figure 2 An architectural diagram of the ISIES system. (modified from (Teillet et al., 2005))

### 4.2 Applying the reference model to ISIES

**4.2.1 Sensors:** ISIES deployed three types of sensor nodes (sensor system) at the two sites. The first type of the sensor nodes has a mix of mostly surface soil moisture probes (Decagon Echo probes) and a few Decagon soil temperature probes and Decagon precipitation gauges. The second node type has one or more sets of sensors deployed vertically in the ground to capture a depth profile of soil moisture. The third type of the nodes has weather sensors and precipitation sensors. These sensors export their own vendor specific data formats.

**4.2.2 Local Network:** ISIES uses short-range RF for their local network. The sensors are hard-wired to a radio transceiver, which communicates with a gateway node via short-range RF.

ISIES uses SmartCore devices as its gateway node to the Internet. The SmartCore is designed and built by the Canada Centre for Remote Sensing. Like most of the sensor systems in the field, the ISIES system also suffers from severe energy constraints. The SmartCore is designed to conserve energy by controlling data traffic and performing local data aggregation. It can control sensor data traffic autonomously via short-range RF. The SmartCores daily connect to the Internet wirelessly using digital cellular modems, and send stored data values to a central server.

**4.2.3 Internet:** The SmartCore device connects to the Internet wirelessly using digital cellular modems. It daily sends the raw and aggregated data values from the sensors to a central database in Vancouver.

**4.2.4 Information Models and Encodings:** ISIES uses O&M as its information model and encoding. O&M is OGC's conceptual model and encoding for observations and measurements. ISIES' information model module takes the raw/aggregated data values as inputs, combines them with associated metadata, and transforms them into structured and meaningful O&M models. Figure 3 shows an example of an observation of the ISIES.

```

- <om:Observation>
- <om:eventTime>
- <gml:TimeInstant>
  <gml:timePosition>2005-10-09T10:32:00Z</gml:timePosition>
</gml:TimeInstant>
</om:eventTime>
<om:eventLocation xlink:href="#location1457656"/>
<om:procedure xlink:href="urn:isies:sensor:ANT1HB05.xml"/>
<om:observedProperty xlink:href="urn:isies:phenomenon:airtemperature"/>
- <om:featureOfInterest>
- <om:Station>
- <om:position>
- <gml:Point gml:id="location1457656">
  <gml:pos gml:srsName="EPSG:4326">50.5971 -112.1794</gml:pos>
</gml:Point>
</om:position>
</om:Station>
</om:featureOfInterest>
<om:result uom="urn:isies:unit:temperature:celcius">9.25</om:result>
</om:Observation>

```

Figure 3 An example of an ISIES observation encoded following the OGC O&M model. Every O&M observation must have six basic properties: 1) Time, 2) Location, 3) Feature of interest, 4) Phenomenon, 5) Procedure, and 6) Results.

**4.2.5 Spatial Sensor Web Services:** The ISIES Sensor Service consists of two major modules. 1) ISIES database server 2) ISIES OGC SOS server.

The ISIES database server provides the following functions: 1) Communicate with the SmartCore devices and retrieve the sensor data values from the field sensors on a daily basis. 2) Parse, validate, and store the received raw/aggregated data values in a relational database. 3) Automatically run two simulation models to assimilate and fuse heterogeneous sensor data values, and produce biomass and yield prediction map

The ISIES OGC SOS server provides the access of ISIES products and metadata of the ISIES sensor systems via WWW. The ISIES products include the sensor observations, and the simulated biomass and crop yield prediction map. The ISIES OGC SOS server provides two major functions: 1) fetch ISIES products according to spatial-temporal queries (e.g. Figure 3 is an example response to a spatial-temporal query), and 2) describe ISIES sensors.

**4.2.6 Service Discovery:** Current ISIES system uses a XML catalog file which has a list of all the available Spatial Sensor Web services and sensing resources in the ISIES project. Since the ISIES server is following OGC SOS specification, it can also publish its presence to the existing OGC Sensor Catalogs. Applications can link to the ISIES service through the OGC Sensor Catalogs.

**4.2.7 Applications:** ISIES uses ISIES viewer, a 2D/3D geographic exploration system<sup>2</sup>, for its users to access ISIES products. The ISIES viewer supports OGC WMS, WFS, WCS, Sensor Catalog, SOS, SPS, SensorML, and O&M specifications. The ISIES viewer provides for a unified global context within which users can access, visualize and analyze the ISIES products through standard OGC web services. Starting from a 'zoomed out' view of the globe, users can select the interested ISIES sensor site, navigate to it, search and discover sensors, and query the measurement results. Figure 4 shows a screen capture of the ISIES viewer.



Figure 4. It shows a screen capture of the ISIES viewer. The main window of the viewer showed a yield prediction map of the sensor site. The ISIES Spatial Sensor Web service periodically runs two simulation models to assimilate and fuse observations and generate biomass and yield prediction map. The icon (ANT1) shows the location of a sensor. User can mouse click the icon, and query: 1) historical observations measured by the sensor, and 2) the metadata of the sensor.

## 5. CONCLUSION

The vision of the Sensor Web is to allow the real-time sensor resources, such as sensor observations and sensors' tasking capabilities, accessible from everywhere at any time. To enable the vision of such a pervasive information infrastructure for the heterogeneous sensors, interoperability is the key. Implementation of interoperability needs well-defined and well-accepted standards.

However, most of the existing sensor networks or Sensor Webs are not designed with interoperability in mind. They are using proprietary communication protocols and customized information models (if there is any) in their own ad-hoc "web" for their own ad-hoc application.

A Layered reference model approach has been proven useful to build a global scale interoperable system. Two most well-known examples are the WWW and the Internet. The interoperability of the WWW and the Internet are achieved through layers of standards.

<sup>2</sup> The 2D/3D visualization engine of the ISIES viewer is GSN GlobeView technology. It is developed by GeoTango Inc. The Sensor Web module of the ISIES viewer is developed by YorkU GeoICT Lab.



In this paper, we introduced a seven layer reference model to construct a Spatial Sensor Web. It breaks the Spatial Sensor Web into separate logical layers to reduce the complexity. It also allows us to partition the work and research problem appropriately. We also listed the available standards of each layer. We showed that the Spatial Sensor Web can be constructed using layers of standards. We also showed the ISIES system as a real-world example to illustrate the layered reference model. Future work will analyze more implementations of all layers of the reference model in the context of additional applications.

#### ACKNOWLEDGMENTS

The authors would like to acknowledge and express the appreciation of funds received from GEOIDE, CRESTech, PRECARN, and OGC. Additional acknowledgement is extended to Dr. Phil Teillet at CCRS and Mr. Ali Shankaie at MDA for the precious discussions on the ISIES project.

#### REFERENCES

- Botts, M. (2005). OpenGIS Sensor Model Language (SensorML) Implementation Specification (No. OGC 05-086).
- Cornillon, P., Gallagher, J., & Sgouros, T. (2003). OpenDAP: Accessing Data in a Distributed, Heterogeneous Environment. *Data Science Journal*, 2, 164-174.
- Cox, S. (2005). *Observations and Measurements* (No. OGC 05-087).
- Cox, S., Daisey, P., Lake, R., Portele, C., & Whiteside, A. (2003). *OpenGIS Geography Markup Language (GML) Implementation Specification v.3.0* (No. OGC 02-023r4).
- Curbera, F., Duftler, M., Khalaf, R., Nagy, W., Mukhi, N., & Weerawarana, S. (2002). Unraveling the Web services web: an introduction to SOAP, WSDL, and UDDI. *Internet Computing, IEEE*, 6(2), 86-93.
- Hill, J., Szewczyk, R., Woo, A., Hollar, S., Culler, D., & Pister, K. (2000). System Architecture Directions for Networked Sensors. *ACM SIGPLAN Notices*, 35(11), 93-104.
- IEEE. (2006a). *IEEE 802.15.4 Wireless Personal Area Task Group 4 Standards*. Retrieved May 20, 2006, from <http://www.zigbee.org/en/index.asp>
- IEEE. (2006b). *IEEE 1451: Smart Transducer Interface Standards*. Retrieved May 22nd, 2006, from <http://ieee1451.nist.gov/>
- Krishnamachari, L., Estrin, D., & Wicker, S. (2002). *The Impact of Data Aggregation in Wireless Sensor Networks*. Paper presented at the Distributed Computing Systems Workshops, 2002. Proceedings. 22nd International Conference on.
- Liang, S. H. L., Croitoru, A., & Tao, V. (2005). A Distributed Geospatial Infrastructure for Sensor Web. *Computers and Geosciences*, 31(2), 221-231.
- Liang, S. H. L., & Tao, V. (2005, August 17-19). *Design of an Integrated OGC Spatial Sensor Web Client*. Paper presented at the Geoinformatics 2005, Toronto, Canada.
- Na, A., & Priest, M. (2005). OpenGIS Sensor Observation Service Implementation Specification (No. OGC 05-088).
- Nebert, D., & Whiteside, A. (2004). *OpenGIS Catalogue Services Specification* (No. OGC 04-021r2).
- Ramachandran, R., Graves, S. J., Conover, H., & Moe, K. (2004). Science Markup Language (ESML): a Solution for Scientific Data-Application Interoperability Problem. *Computers & Geosciences*, 30, 117-124.
- Simonis, I. (2005). OpenGIS Sensor Planning Service Implementation Specification (No. OGC 05-089).
- Teillet, P. M., Chichagov, A., Fedosejevs, G., Gauthier, R. P., Ainsley, G., Maloley, M., et al. (2005, June 14-16). *Overview of an Intelligent Sensorweb for Integrated Earth Sensing Project*. Paper presented at the 26th Canadian Symposium on Remote Sensing, Wolfville, Nova Scotia, Canada.
- Unidata. (2006). *netCDF (network Common Data Form)*. Retrieved May 20, 2006, from <http://www.unidata.ucar.edu/software/netcdf/>