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## SEAMONSTER: A demonstration sensor web operating in virtual globes

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## ABSTRACT

A sensor web is a collection of heterogeneous sensors which autonomously reacts to the observed environment. The SouthEast Alaska Monitoring Network for Science, Technology, Education, and Research (SEAMONSTER) project has implemented a sensor web in partially glaciated watersheds near Juneau, Alaska, on the edge of the Juneau Icefield. By coupling the SEAMONSTER sensor web with digital earth technologies the scientific utility, education and public outreach efforts, and sensor web management of the project all greatly benefit. This paper describes the scientific motivation for a sensor web, the technology developed to implement the sensor web, the software developed to couple the sensor web with digital earth technologies, and demonstrates the SEAMONSTER sensor web in a digital earth framework.

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## 1. Introduction

A sensor web is fundamentally a distributed set of sensors coupled with in-web computational power sufficient to autonomously respond to observed changes in the environment. The Juneau area combines the Juneau Icefield, Tongass National Forest, and Inside Passage in close proximity. Diverse sensing needs in the area provide an environment to demonstrate the sensor web concept and to provide a testbed for maturing sensor web component technologies.

The long-term monitoring of changing characteristics of partially glaciated watersheds (driven by glacier recession) requires long duration, low sample rate observations to capture seasonal, annual, decadal or longer trends. Conversely, to study the impact of sudden events in the watersheds (such as catastrophic drainage of supra-glacial lakes or extreme precipitation events) requires much higher sample rate observations. The autonomous reconfiguration between these two sampling regimes illustrates the sensor web concept. To implement this autonomy, field computers must operate year round in harsh environments (e.g. glaciers, the Tongass temperate rainforest or nunataks bordering the glaciers). The power constraints associated with remote computer operation create additional requirements for sensor web autonomy, namely power management. The SEAMONSTER project has implemented a prototype sensor web in partially glaciated watersheds in Juneau, Alaska on the margin of the Juneau Icefield. In order for the diverse

datasets gathered by heterogeneous sensors to be of maximum societal benefit, the dataset must be discoverable and visualizable. The use of public data archives or other alternative ways of hosting the data were not used because of the critical importance of data availability for “in-web” use to trigger autonomous reconfiguration and potential unavailability of internet connectivity. The coordinated management of a diverse set of large numbers of sensors requires considerable infrastructure. Both the needs for data exploration and sensor web management can be combined through the use of virtual globe technologies, as described in this paper.

## 1.1. Sensor webs

An environmental sensor network is a distributed set of sensors, generally operating in a mode of storing the data locally and periodically sending the data via telemetry or manual download. Communication between nodes, coupled with in-web computational power provides the sensor network the capability for autonomous reconfiguration based on the observed environment. The condition which triggers the reconfiguration could be of scientific interest or hazard monitoring and response (such as a glacial lake outburst) or an operational event (such as a temperature sensor which fails or a decrease of available battery power below a critical threshold). The autonomous reconfiguration of the sensor network is the key feature of a sensor web. The Open Geospatial Consortium (OGC) has developed a set of Sensor Web Enablement (SWE) protocols (OGC reference document OGC-07-165). SEAMONSTER is utilizing OGC and OGC SWE protocols and practices. The SEAMONSTER project is primarily supported by

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the NASA Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) project. In the final report from the 2007 NASA Earth Science workshop, the sensor web concept is defined as “a coherent set of heterogeneous, loosely coupled, distributed nodes, interconnected by a communications fabric that can collectively behave as a single dynamically adaptive and reconfigurable observing system. The Nodes in a sensor web interoperate with common standards and services. Sensor webs can be layered or linked together” (AIST Workshop Report, 2007). A software description of the sensor web concept is provided by Gibbons et al. (2003). The sensor web concept incorporates the need for data discovery for unanticipated data use. This aspect of sensor webs is for both the incorporation of unanticipated existing or co-collected datasets as well as the dissemination of sensor web datasets to interested parties (incorporation and publication of data). The SEAMONSTER project has served as a testbed for both incorporation and publication of data. Another aspect of sensor webs that is not discussed in this paper is the integration of model analysis with datasets. The model and data integration within the sensor web can quickly help fine tune analyses and identify anomalous behavior in addition to the reduction and analysis of data gathered. The Earth Information Services prototype demonstrates model integration with the SEAMONSTER sensor web (Hansen et al., 2009).

## 1.2. SEAMONSTER

SEAMONSTER is the SouthEast Alaska MONitoring Network for Science, Technology, Education, and Research project. The SEAMONSTER sensor web backbone of field-hardened, autonomous power-managing computers has been developed and deployed in the Lemon Creek watershed in Southeast Alaska. Lemon Creek is a small, glacial watershed that hosts a diversity of temperate ecosystems. At the head of the watershed, 1200 m above sea level, lies the Lemon Creek Glacier. The Lemon Creek Glacier covers approximately 20% of the watershed with a layer of ice up to a few hundred meters thick. Following the watershed down from the mountain peaks surrounding the glacier toward the marine environment, the watershed encompasses a range of complex and diverse ecosystems in a fairly small spatial expanse. The ecosystems include sparsely vegetated alpine tundra, lush alpine meadows, new- and old-growth temperate rainforests, cold streams, and, at the lowest reach, tidally influenced wetlands and

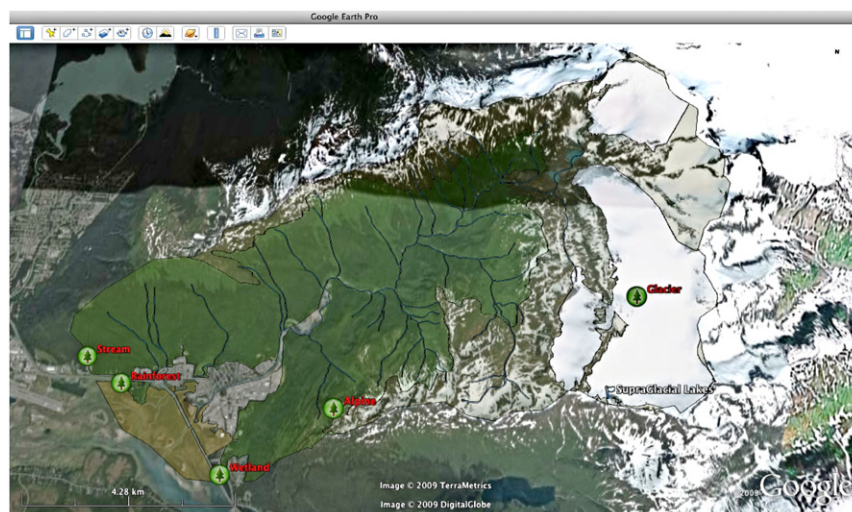
an estuary region. One aspect of note for this study area is that Lemon Creek Glacier is part of the Juneau Icefield Research Program (JIRP) and was monitored during International Geophysical Year (IGY) (1957–1958) (Miller and Pelto, 1999) and continuously on through the International Polar Year (IPY) (2007–2008), providing a relatively long-term record of watershed changes. Some of the information gathered by JIRP is published as kml datasets and can be viewed in parallel with the kml publications from SEAMONSTER, illustrating the power of virtual globes to easily integrate publicly available datasets from disparate sources via kml standards.

The integration of the SEAMONSTER sensor web with virtual globes was originally inspired by the James Reserve network sensor network integration with Google Earth (Askay, 2006). The SEAMONSTER virtual globe effort was focused on outreach (as was the James Reserve network). The SEAMONSTER efforts in virtual globes presented in this paper expand on the James Reserve work by including the integration of the geowiki with the postgres database and the geoserver. The additional integration of tools enhances the virtual globes' contributions to collaboration, development, and technology dissemination efforts.

## 1.3. Science motivation

Glaciers in southeastern Alaska have been retreating and thinning rapidly for the last several decades (Larsen et al., 2007; Arendt et al., 2002). This loss of ice and the associated increase in freshwater discharge has important implications for the hydrology of pro-glacial rivers and the physical properties in downstream receiving marine ecosystems (Hood and Scott, 2008). The proximity to the Juneau Icefield, the fifth largest icefield in North America, allows for the relatively easy deployment of a multi-layered sensor web to address fundamental questions regarding the ice dynamics and hydrology of outlet glaciers draining the icefield. Lemon Creek Glacier ( $\sim 10 \text{ km}^2$ ) has a single supra-glacial lake which fills during the summer and catastrophically drains into Lemon Creek, a relatively well constrained glacial hydrologic system, illustrated in Fig. 1.

SEAMONSTER has begun expanding into the Mendenhall Glacier watershed. Approximately a dozen ice-marginal lakes form on the Mendenhall Glacier. Mendenhall Glacier terminates in Mendenhall Lake. These two features make the glacial hydrology of Mendenhall more complicated than the Lemon Creek system. The critical questions the deployed sensor web will



**Fig. 1.** Lemon Creek watershed. The figure illustrates .shp files exported from ESRI's Arc suite of software, served by the PostGIS powered GeoServer, used to designate the different ecosystem portions of the Lemon Creek Watershed. The supra-glacial lake forms on the south end of the Lemon Creek Glacier (the glacier flows towards the North, which is up in this view).

address are: Do accelerated rates of glacial melt and the associated increased runoff beneath the glacier create a positive feedback effect by increasing the rate of basal ice motion which, in turn, increases the rate at which ice is being delivered to low elevation ablation zones? What in turn, is the impact of changing glacial control of the watersheds on the ecosystem? Understanding the relationship between glacial hydrology and glacier mass balance is critical for predicting environmental responses to climate change.

## 2. Methods

The primary technological goal of the SEAMONSTER project is to instantiate a testbed sensor web in a harsh environment with multiple relevant science use cases. Hardware efforts were driven by requirements for power, communications, and in situ processing required for autonomy. Software requirements included autonomous reconfiguration, data management, data discoverability, data browsing, and integration of additional, unanticipated data streams. Design goals for both hardware and software included the integration of existing technology with clear documentation of any modifications made for the SEAMONSTER project.

### 2.1. Hardware

The backbone of the SEAMONSTER sensor web is a small headless field computer or Microserver developed by Vexcel Corporation in Boulder, Colorado. Vexcel Microservers were developed from 2003 to 2008 with NASA support. These were conceived as general purpose sensor platforms spanning signal frequencies from one sample per day up to kilohertz sampling frequency, with applicability across a broad variety of field science disciplines and applications (seismology, meteorology, visual monitoring, GPS surveys of glacier motion, robotic surveys of stream and lake chemistry and more). Microservers are field-hardened for survivability in harsh environments. They include a standard COTS WiFi router or an equivalent high bandwidth communication device to enable creation of ad hoc field networks used for sharing data and in the future enabling sophisticated software to direct limited field resources towards interesting events. Microservers are also able to act as base stations for localized lightweight sensor networks built on mote technology such as TelosB motes available from Crossbow Technologies. Microservers address the power-cost-data challenge in environmental monitoring by providing a battery recharging system and a power conditioning subsystem that permits the unit to hibernate when the primary external energy source (typically a lead-acid battery) is depleted. Hibernation continues (drawing microwatts of power) until the system determines that the primary battery is sufficiently recharged, typically by solar panels. The computing environment is an ARM-based Single Board Computer and the device also incorporates a GPS board. Supported communication protocols in addition to WiFi include a PC/104 bus, Ethernet, USB, and RS-232 serial ports as well as several analog-to-digital (ADC) channels. Data storage capacity of many Gigabytes is provided by a solid state USB flash drive.

As noted Microservers can act as base stations for second-tier lightweight mote-based sensor networks. SEAMONSTER follows the technology lead of the Johns Hopkins University “Life Under Your Feet” soil ecology program employing the Koala/FCP protocols to deploy physical heartbeat sensors: total solar radiation, photosynthetically active radiation, temperature, soil moisture, relative humidity, and electrical conductivity. The motes use the 802.15.4 Zigby protocol to periodically recover data to the base station (Microserver file system) and from there a series of daemons move raw data to the SEAMONSTER online GeoServer data catalog.

### 2.2. Sensors

Weather stations, based on Campbell Scientific data loggers, have been deployed at the top of Lemon Creek Glacier (near the lake) and near the terminus of the glacier to measure parameters such as air temperature, precipitation, solar radiation, wind speed and direction, and snow depth. The station overlooking the lake includes a high-resolution digital pan/tilt/zoom web camera. A pressure transducer to measure lake level is installed in the supra-glacial lake. Mounted downstream in Lemon Creek is an YSI probe that measures water-quality characteristics such as water temperature, pH, dissolved oxygen, and turbidity.

### 2.3. Software

The SEAMONSTER project generates heterogeneous datasets at irregular time intervals. Managing the data to allow ease of access, public outreach, and easy of comparison between the different instruments by researchers motivated our use of a single SQL database for final storage of all data. (In situ data are typically stored as ASCII files within the Microserver filesystem.) As illustrated in Fig. 2, all the data streams through sensors to the Microservers and into a PostgreSQL database with GIS extensions enabled, called PostGIS (Hsu and Obe, 2007). The GIS extensions require that every table entry be associated with a location and time entry. Coupling the PostGIS database with the Open Geospatial Consortium (OGC) GeoServer automatically provides the ability to disseminate the data streams through a web portal (<http://seamonster.jun.alaska.edu/browser/>), kml for 4-D Geobrowsers (such as Google Earth or Microsoft Virtual Earth), services to more traditional GIS systems (such as the ESRI suite of Arc software), and through the geowiki. The PostGIS database stores both raster and vector (e.g. ESRI .shp files). The geowiki is a project wiki using mediawiki, which requires a SQL database for page storage. By using the same PostGIS database as SEAMONSTER data, a spatio-temporal location is required for each wiki page. Fig. 2 illustrates the SEAMONSTER architecture with output to end-users. For readability, the data feedback loops enabling the sensor web aspects of SEAMONSTER are not shown, but the feedback loops are an integral aspect of the SEAMONSTER sensor web.

To enable autonomous reactivity, SEAMONSTER has implemented several strategies. The Vexcel Microservers continuously run on-board code used to react to the local power conditions. Vexcel Microservers have scheduled scripts running to analyze data from other platforms and react. For example, when the pressure transducer data indicate the supra-glacial lakes begin to drain, the scripts on the Vexcel Microserver force the pan/tilt/zoom camera to image the draining lake. SEAMONSTER also serves as a testbed platform for more sophisticated sensor web management solutions such as the MACRO (multi-agent architecture for coordinated, responsive observations) project implementing a CORBA-based solution (Kinnebrew et al., 2007). For resource management, SEAMONSTER makes use of the munin/rrdtool package and integrates the scheduled collection and plotting of resource information in the kml generation.

## 3. Results

The coupling of the PostGIS database and GeoServer allows multiple dynamically generated access methods, as illustrated on the right side of Fig. 2. This section describes three different examples of the access methods to the SEAMONSTER sensor web with virtual globes. The first example describes the geowiki, primarily illustrating the education and public outreach benefits of coupling sensor webs and virtual globes through Google Earth



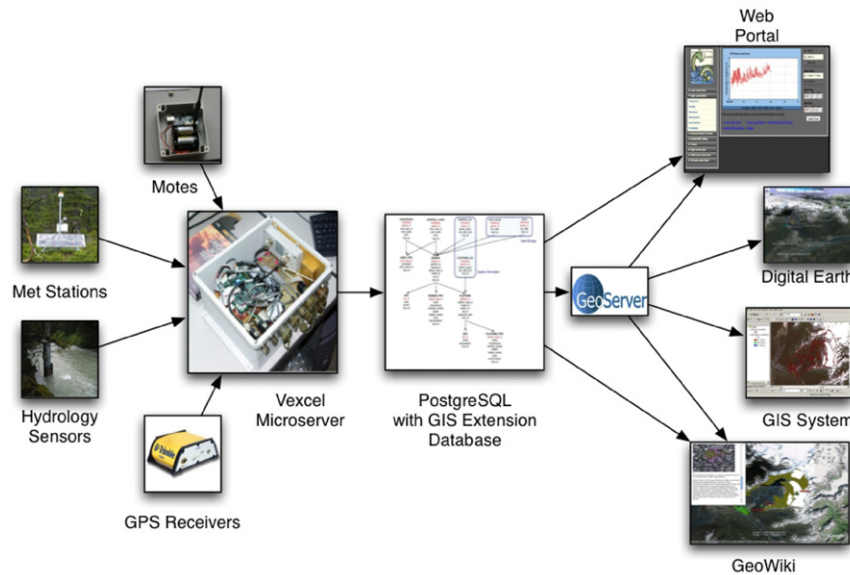


Fig. 2. Conceptual diagram showing sensor flow to Vexcel Microserver, aggregation in the PostGIS database, and multiple output streams.

network links and dynamically generated kml. The data browsing and access potential of coupling SEAMONSTER and virtual globes are illustrated in the second subsection describing the integration of the SEAMONSTER data browser and Microsoft's Virtual Earth via openlayers technology. Finally, the benefits of using virtual globe technology for sensor web management are described.

### 3.1. Geowiki

The SEAMONSTER sensor web is testing new technology development for NASA, documenting impacts of climate change and glacier control of watersheds, and providing views and information about a popular tourist destination (approximately one million tourists visit Juneau every year). Education and public outreach are a major component of the SEAMONSTER project (Bernier et al., 2007). As part of the efforts for education and public outreach as well as facilitating data discovery and sharing by other scientists, a public wiki was conceived of as a two-way conduit for general information about the sensor web. The wiki is intended to have a larger scope: a hypothetical example is a biologist interested in wind and temperature data in the Juneau area for a migratory bird study. The SEAMONSTER meteorologic data could be discovered and the migratory bird information could be easily added by the biologist to the public wiki. The mediawiki engine is used to implement the public wiki, requiring a SQL database backend. Typically, mediawiki is configured to use MySQL. However, the SEAMONSTER mediawiki installation makes use of the PostGIS database already containing the SEAMONSTER data. The benefit of using the PostGIS database in conjunction with the public wiki is the PostGIS requirement that every database entry have geospatial information, so every wiki page is georeferenced. Fig. 3 illustrates the geowiki, with a screen capture from Google Earth showing the output from a network link, dynamically generated by the GeoServer requests into the PostGIS database. The network link provides both the kml features and the geowiki page content. The geowiki network links provide the wiki pages within Google Earth (the Glacial Outburst Flood wiki page is shown, along with the dataset showing the lake drainage at the bottom of the wiki page view). Another geowiki network link provides ecosystem polygons generated by ArcView (as .shp files) which delineate glacier,

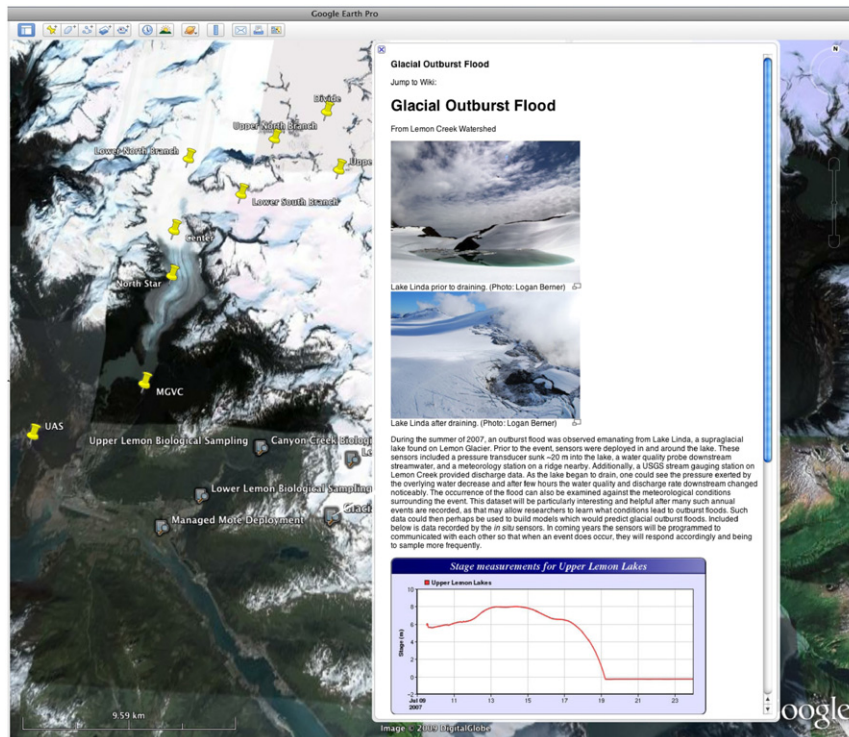
wetland, stream, alpine, and rainforest areas of the Lemon Creek watershed. Over 50 photographs related to the watershed are included as a layer served by the GeoServer/PostGIS geowiki. The integration of the virtual globe, sensor web, and wiki technologies through the PostGIS database, GeoServer, network links, and kml provides the SEAMONSTER education and public outreach portal.

### 3.2. Data access

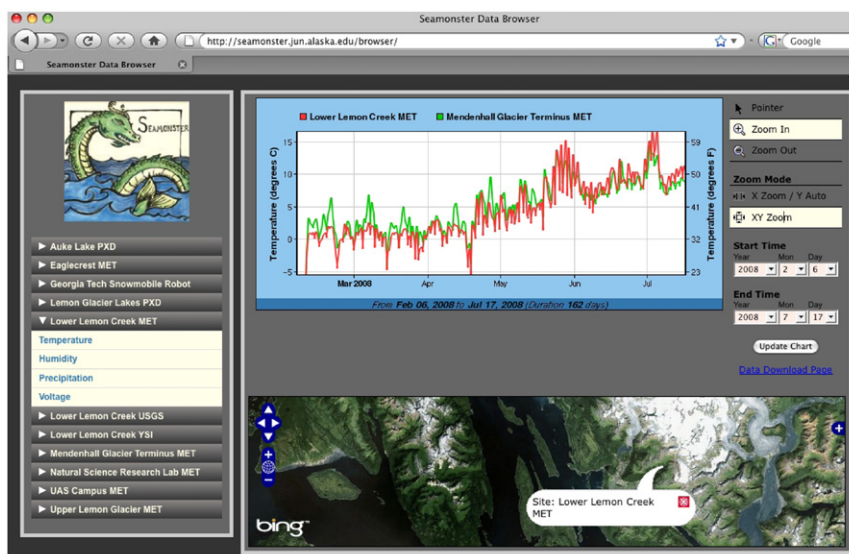
The diverse datasets and non-continuous sampling from various sites created data cataloging and browsing issues. A web portal is used to avoid creating "one-off" in-house solutions which may not be available for interested public or scientists. Fig. 4 illustrates two temperature records from different sites in the SEAMONSTER study area. The left panel shows a list of all the stations in gray. Selecting a station triggers (via openlayers) the map at the lower portion of Fig. 4 to identify the location of the sensor. The measurements available at the station are shown as a drop down menu (temperature, humidity, precipitation, and voltage are shown). After selection of a measurement, the graph updates to show the most recent year of measurements. The user can zoom in and out of the plot graphically or select a date range. One more dataset of a similar measurement from a different location can be overplotted on the plot, as is shown in Fig. 4. The raw data can be downloaded in various formats (text, netcdf, xls) via this web interface. The SEAMONSTER data browser shown in Fig. 4 is a second example of the benefits of the integration of the Sensor Web and Virtual Globe concepts. The data browser code is available through the project SVN (see Section 6) and has been tested for use by at least two other projects.

### 3.3. Sensor web management

The third benefit resulting in the integration of the sensor web and virtual globe technologies is in the operation and management of the diverse resources of the sensor web. Visualizing power, communication, and other state of health information is critical, especially in the distributed, relatively harsh environment in which SEAMONSTER is operating. Fig. 5 illustrates a large number of placemarks designating sensors (e.g. Lake Pressure Transducer),



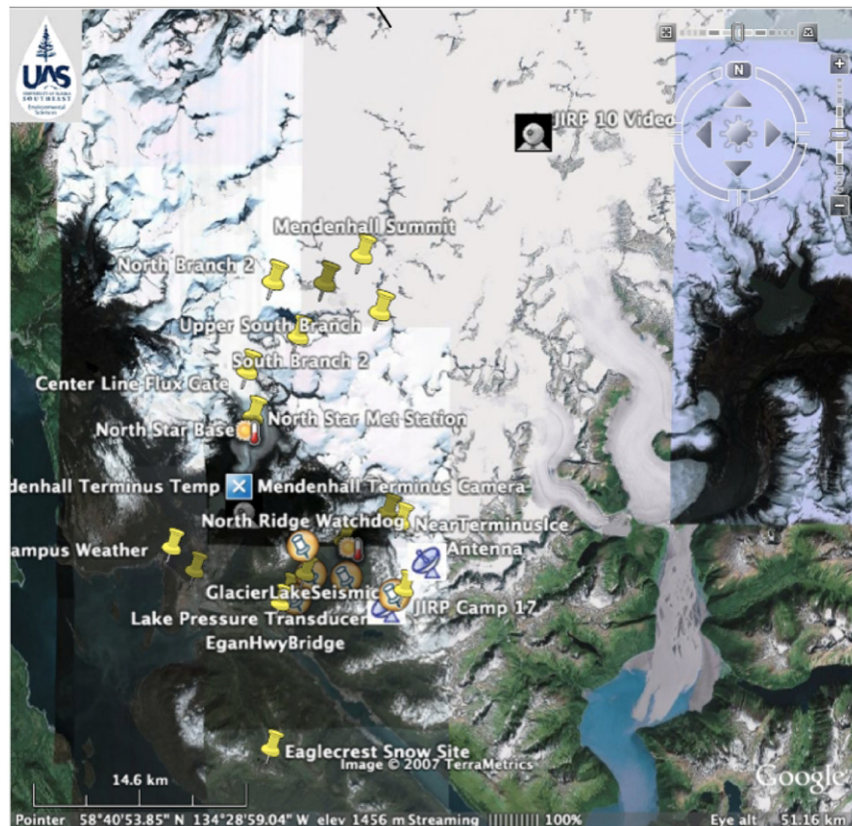
**Fig. 3.** A screen capture of the dynamically generated SEAMONSTER geowiki content, primarily used for education and public outreach. The Mendenhall Glacier and Lemon Creek measurements sites are shown as push-pins, geowiki content pages describing various features of the Lemon Creek Watershed are shown, with the Glacial Outburst Flood page opened, showing data observed during the 2007 lake drainage.



**Fig. 4.** A screenshot from the dynamically generated SEAMONSTER Data Browser (<http://seamonster.jun.alaska.edu/browser/>). This provides data browsing capability, including the ability to compare similar measurements from diverse locations, in the example shown the temperature at the Mendenhall Glacier terminus (green) is compared with the temperature at the Lower Lemon Creek stations (red). The station location is shown in the Microsoft Bing geobrowser using openlayers. The SEAMONSTER data portal is dynamically generated from the same PostGIS database as seen in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

locations (e.g. Eaglecrest Snow Site), future instrument placement (e.g. JIRP 10 Video), and other components of the sensor network (e.g. Antenna, North Ridge Watchdog). Even in this relatively busy view, it is reasonably easy to identify the Mendenhall Terminus Camera as the large blue X placemark. This is used to indicate that data from the camera have not been received in the time period it

was expected. Fig. 5 illustrates the SEAMONSTER sensor web management kml file which is regularly generated and embeds system information collected via munin and is useful in diagnosing system problems (for example, munin collects and plots battery voltage information, which is attached to the placemarks illustrated in the plot).



**Fig. 5.** A screenshot from the dynamically generated SEAMONSTER kml file. This file is generated based on the status of various sensor web platforms. For example, the data from Mendenhall Glacier Terminus site have not been recently updated, so it is flagged with a large blue X icon, clearly visible among the diverse icons representing sensors, cameras, antennae, etc. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

#### 4. Future work

This paper describes the technology developed for integration of the SEAMONSTER sensor web and virtual globes. The SEAMONSTER project has developed and documented hardware and software. Rigorous evaluation of the success of the virtual globe technology and end user testing has not been undertaken. Feedback from technologists, scientists, and collaborators has been positive, but has only been collected and acted upon at the anecdotal level. A full evaluation of the SEAMONSTER virtual globe interface for usability is beyond the scope of the project. However, the technology developed for SEAMONSTER integration with virtual globes has been utilized as a prototype by other data dissemination groups and has been enhanced and subjected to user testing.

#### 5. Conclusions

The integration of sensor web and virtual globe technology provides dramatic benefits to the goals of sensor web (more efficient observations) and virtual globe (visualization and understanding) visions. The three examples provided illustrate the education/public outreach, data discovery and exploration, and sensor web management benefits realized by the coupling of sensor web and virtual globe technologies. The hardware and software used by SEAMONSTER to instantiate a sensor web coupled with virtual globes are described in hopes that the benefits realized by the SEAMONSTER effort may be duplicated (and improved upon). A final section provides pointers to the specific resources described.

#### 6. Resources

The integration between sensor web and digital earth has been done in an open environment, coordinated through a project wiki, with all code stored in a publicly accessible subversion code repository.

The SEAMONSTER public geowiki is available<sup>2</sup> and is intended to be primarily useful for the description of the SEAMONSTER study area. The SEAMONSTER project wiki<sup>3</sup> is used to document the development efforts and technologies used with sufficient detail to replicate the sensor web and virtual globe efforts. All of the code developed by SEAMONSTER (from assembly code used for power control boards to SQL database design and php code for the data browser) is available through the SEAMONSTER SVN repository.<sup>4</sup> The SEAMONSTER databrowser is also publicly available.<sup>5</sup>

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<sup>2</sup> <http://seamonsterak.com/>

<sup>3</sup> <http://robfatland.net/seamonster>

<sup>4</sup> <http://seamonster.jun.alaska.edu/websvn/>

<sup>5</sup> <http://seamonster.jun.alaska.edu/browser/>



Shannon Siefert, and Nathan Rogers have been integral to the SEAMONSTER project.

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