Report to the University of Hawaii at Hilo EPSCoR Group

on

Selected Existing Environmental Data Collection Networks

for use in the planning and design of instrumentation for the

Hawaii Permanent Plot Network

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Introduction

This report was produced at the request of Dr. Jene Michaud of the University of Hawaii at Hilo EPSCoR Group and is being submitted as a project deliverable as specified in the consultant's scope of services. The analysis that led to the production of this report was performed under an informal agreement between the University and the consultant rather than a formal contract due to schedule limitations.

The objective of this phase of the project was to evaluate selected existing data collection networks that might be useful as examples in the planning of new data collection networks to be established within the Hawaii Permanent Plot Network (HIPPNET). HIPPNET is being designed as a network of forest plot sites distributed throughout the Hawaiian Islands across dramatic climate, elevation, and substrate age gradients. These permanent forest plots will primarily be used for long-term ecological research studies, and for this purpose there is a need to install environmental monitoring systems at each of the HIPPNET sites. The planned monitoring systems include tower-mounted sensor arrays at two sites on Hawaii Island (Laupahoehoe and Puu Waawaa) and tripod-mounted sensor arrays located in forest clearings at eight additional sites throughout the state (two on Oahu, two on Kauai, and four more on Hawaii). The target plot size for HIPPNET is about 10 acres.

Many data collection networks exist throughout the world that serve similar functions to those planned for the HIPPNET sites, and obviously not all of them could be evaluated for this report. For this reason, only a few existing networks were selected for this evaluation. Several factors were considered in the selection process to ensure that the examples documented here are appropriate for comparisons with the planned HIPPNET data collection networks. Because site conditions can vary greatly according to geographic location, several examples from Hawaii were selected because these systems have been shown to work in environments very similar to those likely to be encountered at the HIPPNET instrument stations. Other factors considered in the selection process were the types of data collection, transmission, and storage systems used for the various existing networks.

The reader will see that the data networks described here employ a variety of these system components. This leads to the impression that there are not standard systems that are consistently selected when designing these networks, but that there are several good options for all system components including sensors, data loggers, telemetry systems, database and data visualization systems. These different system components are being used in different combinations at all of the data collection networks evaluated here.

A total of five existing data collection networks were selected for documentation in this report. The purpose of the report is not only to describe what is being done by other organizations in other places, but also to provide insights into system performance and overall level of satisfaction with other data collection networks by their operators.

The five existing data networks detailed here include the following:

1. The Soil Climate Analysis Network (SCAN) of the USDA - Natural Resources Conservation Service, with special emphasis on the Hawaii Island SCAN network

2. The NOAA - National Weather Service (NWS) weather/climate monitoring network in Hawaii

3. The UCLA Center for Embedded Networked Sensing (CENS) environmental monitoring networks at James Reserve, California

4. Data collection networks at the HJ Andrews Experimental Forest and Long Term Ecological Research (LTER) site in Western Oregon, operated jointly by the US Forest Service and Oregon State University

5. InteleSense Technologies monitoring networks on Kauai, developed through the University of Hawaii using EPSCoR funding

For each of the data collection networks listed above, detailed information on monitoring strategies, sensors, on-site data recording, data transmission, data review and quality control, data formatting and archiving are presented here.

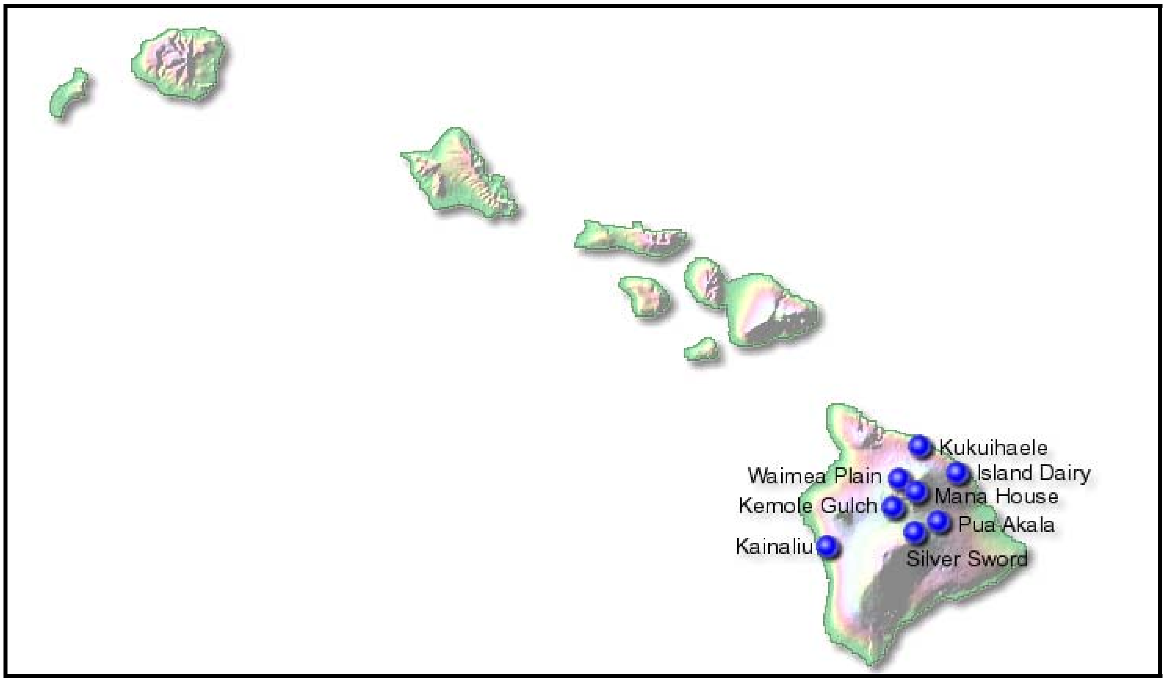
1. Soil Climate Analysis Network in Hawaii

The SCAN network is operated nationwide by the USDA Natural Resources Conservation Service, in partnership with MeteorComm, out of Kent, Washington. This network consists of 123 near real-time stations in 39 states (plus 5 in Puerto Rico and 1 in Antarctica) that primarily provide measurements of standard weather parameters and soil moisture, although some SCAN stations are instrumented to make water quality measurements as well. In much of the eastern and central U.S., MeteorComm collects and stores data from NRCS SCAN stations, and delivers these data to the NRCS on an hourly basis. In Hawaii, MeterorComm does not play a role in data collection or storage as the SCAN network is operated solely by the NRCS.

Much of the SCAN network developed to date has been focused in agricultural areas. This data network is providing many farmers and ranchers with near real time climate and soil data that can be used to support management decisions. However, there are many other potential uses of SCAN data and the NRCS has intentions to expand the network to more than 1,000 remote stations nationwide. Other uses of SCAN data include the following: water supply forecasting, drought monitoring, soil classification, engineering applications, input for global circulation modeling, and ground-truthing satellite measurements or soil moisture model predictions. SCAN data is also used as input data for many models involved in forecasting and prediction of changes in runoff, irrigation water requirements, and crop or range productivity.

Spatial Layout of SCAN Stations in Hawaii

In Hawaii, the SCAN network has so far been limited to areas around Mauna Kea and Mauna Loa on the Big Island. A total of eight (8) stations have been established here as well as a base stations at Kamuela (Waimea) and Kealakekua. A map of the spatial layout of the SCAN network in Hawaii is shown below. The NRCS has been actively pursuing plans to expand the SCAN network in Hawaii with the probable next stations to be established in Hanalei Valley on Kauai, but a lack of funding has prohibited new development.



SCAN Station Locations in Hawaii

Sensors and Data Collection in the Hawaii SCAN

The standard SCAN station configuration allows for measurement of the following parameters: precipitation, air temperature and relative humidity, wind speed and direction, solar radiation, barometric pressure, soil moisture and temperature (at multiple soil depths). The Hawaii SCAN stations are specifically instrumented as follows:

Precipitation: Texas Electronics 525i Rain Gage (one station only)

Air Temperature & Relative Humidity: Vaisala HMP45C with 6-plate radiation shield

Wind Speed & Direction: RM Young 5103 Wind Monitor – propeller & vane type

Solar Radiation: Li-COR LI200LX Pyranometer

Barometric Pressure: Vaisala PTB101B

Soil Moisture and Temperature: Stevens Hydra Probe

Data Recorder and Telemetry Interface: Campbell Scientific CR10X

Data Transmitter: Meteor Communications Corp. 545B 100-Watt radio

Battery and Voltage Regulator: Hawker Genesis battery, Stevens JL2 charge controller
Enclosures: Stahlin NEMA 4 fiberglass

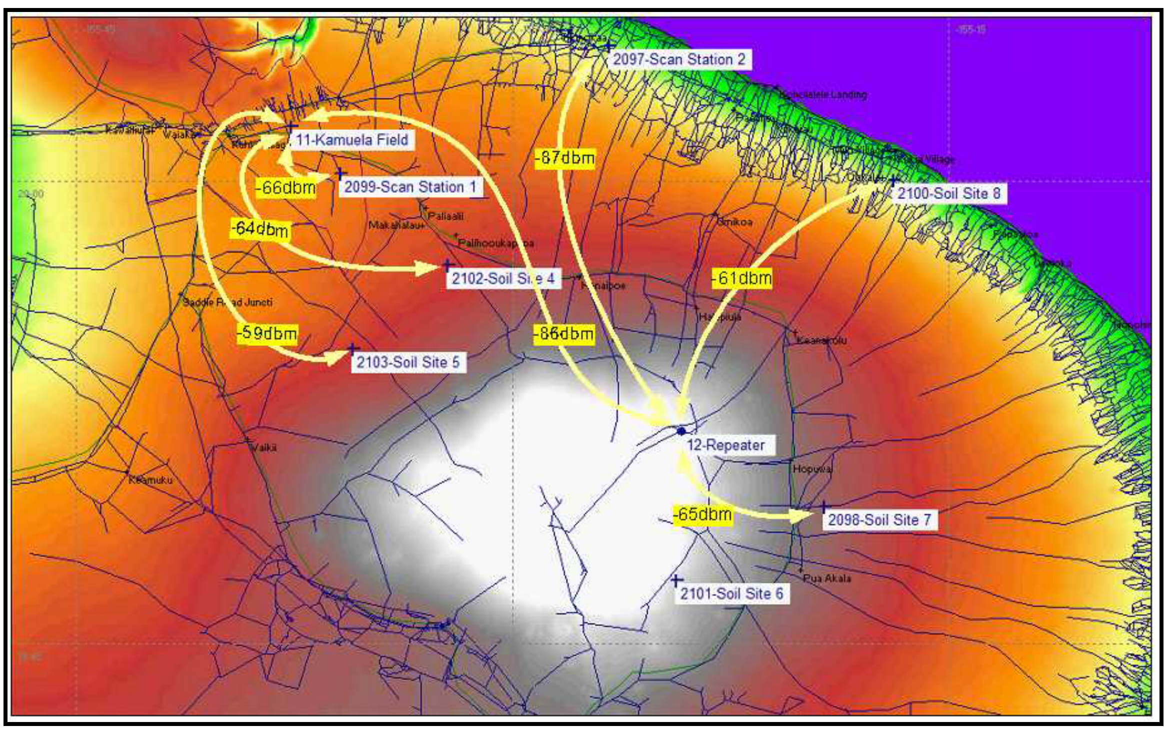
A typical SCAN station is shown below. This particular station is located at Pua Akala, on the northeast flank of Mauna Loa, on Hawaii Island. Most of the SCAN stations in Hawaii are tower-mounted sensor arrays with tower height of twenty feet, plus a ten-foot antenna mast.

The SCAN station at Pua Akala, on the Big Island of Hawaii

Data Transmission in the Hawaii SCAN

Most of the SCAN stations located throughout the country typically transmit their data to a centralized base station receiver and internet server via meteor burst communications. This technology, developed in the 1950s, and used extensively by the NRCS for their SCAN and SNOTEL (SNOpack TELemetry) networks, uses ionized meteor trails as a means of radio signal propagation. Basically, radio frequency (RF) transmissions from the SCAN stations are reflected off of these meteor trails during their atmospheric entry, allowing for very brief communications pathways for stations located up to 1200 miles apart.

However, the NRCS National Water and Climate Center, the agency that administers and operates SCAN networks, decided to utilize a conventional line-of-sight RF telemetry system with ground-based repeaters instead of meteor burst communications for the Hawaii SCAN stations. The decision was largely based on cost considerations as there is no existing base station that could receive meteor burst transmissions from Hawaii, and the cost to develop a new base station in the islands is on the order of $100,000.



SCAN Station Locations on Hawaii Island Showing Signal Strength Between Stations

The data transmission network consists of the eight SCAN field stations, one repeater station located on the eastern slopes of Mauna Kea, and the two base stations at Kamuela and Kealakekua. Line-of-sight is generally satisfied between the network nodes along the transmission pathways shown in the figure above, although perfectly clear line-of-sight is not absolutely necessary for successful transmissions as there is some ‘data wrap’ capability when using the transmitter/antenna/receiver packages employed in this system.

Omni-directional antennas are used along with the MCC 100-watt radios at the SCAN stations to provide a typical transmission range of 30-40 miles with decent line-of-sight. Directional high-gain antennas can also be used to provide extended range (up to 100 miles over water, for example).

With regards to data telemetry alternatives, the system utilized by the SCAN network in Hawaii is very stable, and it provides the operators with maximum control over data routing and complete control over the transmission infrastructure. Since the SCAN network in Hawaii was established in February 2005, the data telemetry systems have performed flawlessly; not a single problem has been reported to date.

Data Processing and Database Management in the Hawaii SCAN

Data is typically converted at the field station from the individual sensors’ raw format (voltage and/or pulse record) to calculated ‘real’ values by applying various mathematical algorithms and calibration information to the raw data. Often data is reduced at the field site before transmission as well.

For the Hawaii SCAN stations, the Campbell Scientific data loggers are programmed to scan the sensors at high frequency (e.g. every 10-15 seconds), but not all of the returned values are stored or transmitted because data is not needed at this high a resolution. Instead, the data logger reduces the 10-15 second data to hourly averages only (e.g. wind direction) or hourly average and peak values (e.g. wind speed). These are the data that are eventually transmitted from the field station to the base station for review, further formatting, and entry to the database. The logger at the SCAN stations are also programmed to generate daily average and maximum values for each sensor and transmit these to the base station once every day, at midnight.

As a backup system of data storage in case the primary data transmission system fails, the Campbell CR10X logger at each SCAN station records the hourly average and maximum value data for each sensor to its internal memory. For the a typical SCAN station configuration, this logger internal memory is sufficient to store hourly data for two years before overwriting old data begins.

Once the data is reduced at the field stations, it is transmitted on an hourly frequency through the radio repeater network to the base station receiver. From the base station the data is uploaded to the NRCS National Water and Climate Center (NWCC) database via an internet server. NWCC-developed software is used to validate the data coming in from the field stations by checking all data values against pre-set limits. Data events that fall outside of these windows are flagged automatically and forwarded to a statistical assistant who determines accuracy and makes corrections, if necessary. Finally, all variables are automatically graphed, and comparisons are made between sensor records to confirm that all data are within the acceptable range.

Once the data review and quality control processing described above are complete, the SCAN data is uploaded to databases that can be easily accessed through the NWCC website. Additional information about each SCAN station, such as a photo of the site, its geographic location (in latitude/longitude coordinates), and local soil characteristics are also included at the NWCC website along with the current and historical SCAN station data.

2. The National Weather Service (NWS) Weather Monitoring Network in Hawaii

The National Weather Service has been operating a Weather Forecast Office (WFO) in Honolulu since 1946, initially at the Honolulu International Airport, and now at the University of Hawaii at Manoa campus. The mission of the WFO Honolulu is to use the best available science and technology to provide accurate and timely watches, warnings, advisories, and forecasts for hazardous weather conditions for the entire state of Hawaii. To support this mission, the WFO Honolulu has established a real-time and near-real time network of weather monitoring stations throughout the state. The quality of data from these stations and the reliability of data transmission systems are both critical to the success of the weather forecasting services provided by the WFO. The WFO Honolulu also provides data to the National Climatic Data Center that acts as a weather and climate data clearinghouse. The Center's mission is to describe the climate of the entire nation and to identify trends and anomalies in weather and climate.

Because of the similarities between the existing NWS weather/climate monitoring network in Hawaii and the proposed HIPPNET (spatially distributed throughout islands at remote sites, high-resolution and high-quality data needs, near-real time data telemetry, etc.), a description of the NWS monitoring networks was included in this report as an example of what is being done by other organizations that has been demonstrated to work well.

NWS Monitoring Networks in Hawaii

The NWS currently operates 90 near real-time weather monitoring stations throughout the main Hawaiian Islands. Of these stations, 72 are Hydronet sites that can be interrogated for current rainfall data in real-time by NWS forecasters, 9 are Automated Remote Collector (ARC) stations measuring wind, temperature, pressure, and rainfall parameters only, and 9 are part of the more robust Automated Surface Observing System (ASOS). In addition, the NWS receives data from 34 Fire Weather Stations (RAWS), although these are all owned, operated, and maintained by other agencies and organizations. At the RAWS stations, regular observations of fuel moisture are made, and a different wind mast standard is used. Data from these stations can also be collected by weather forecasters and other users in real time for fire monitoring and fire-fighting efforts.

The NWS-owned and operated monitoring network is supplemented by the Cooperative Observer stations, a network of weather stations that are primarily operated and maintained by NWS cooperators (other agencies, organizations, or individuals). There are approximately 200 of these Cooperative Observer stations located throughout Hawaii, and of these 35 presently participate in the ROSA program where cooperators call an automated NWS phone system on a daily basis to enter weather data such as maximum and minimum air temperature and 24-hour rainfall.

The NWS also operates and maintains the Automated Surface Observing System (ASOS), a joint effort of the NWS along with the Federal Aviation Administration (FAA) and the Department of Defense (DOD). FAA-owned ASOS stations are located at airports throughout the country, and together they form the nation's primary surface weather observing network. While these stations are extensively used for weather forecasting and aviation operations, they were also designed to support the needs of the meteorological, hydrological, and climatological research communities. All ASOS stations are running continuously, and observations are updated every minute, 24 hours a day, 365 days a year. In Hawaii, ASOS stations are located at all major airports throughout the state.

Sensors and Data Collection in the NWS Monitoring Networks in Hawaii


Automated Remote Collector Station at Puu Waawaa

The standard sensor array for NWS meteorological stations in Hawaii includes a windset for wind speed and direction measurements, a tipping-bucket rain gage, air temperature and relative humidity sensors, and a barometric pressure sensor. Some additional weather parameters are measured at ASOS sites, including cloud height and visibility. Also, fuel moisture sensors are typically included in the sensor arrays at the Fire Weather Stations. For the Hydronet stations, the full suite of weather sensors are generally not present; some of these stations have only a tipping-bucket rain gage and some have instruments for measuring rain and wind, but nothing else.

Historically the NWS has used sensors and data collection platforms (DCPs) at all of their instrument stations in Hawaii made by Handar, Inc., but this company was bought out by Vaisala, out of Finland in 1999. The Handar DCPs used at the NWS monitoring stations in Hawaii include models 540, 550, and 555, with the latter being the most commonly used DCP. The Handar 555 DCP is an automated observing platform (used at most of the ASOS stations and many other NWS-operated weather stations in Hawaii) that can be configured to use a great variety of sensors to suit the needs of almost any user. Unfortunately, Vaisala recently announced that they will not be accepting any new orders for the Handar 555 series DCPs, but technical support, replacement parts, and repair services for this hardware will be available until March 2011. While Vaisala is phasing out the old Handar hardware, they also offer a new line of high-quality sensors and data collection platforms that have a good reputation in the weather/climate monitoring field.

At most of the NWS meteorological stations in Hawaii the sensors are mounted on a tower in an open area, with a mast extending to 10 meters above ground level. The wind sensors are located at the top of the mast to satisfy the NWS standard for wind measurement (10 meters above ground). The exception to this is the smaller network of Fire Weather Stations where the mast height is limited to 6 meters, resulting in more useful wind data for fire tracking and fire-fighting efforts.

The NWS also follows their own standards for measurement of other weather variables such as air temperature and precipitation. For temperature, sensors should be mounted 5 feet (+/- 1 foot) above the ground surface. A level, open clearing is desirable so the sensor is freely ventilated by air flow, and all temperature sensors should be located at least 1,000 feet from any paved surface. Siting of rain gages is very important because exposure to wind will affect the accuracy of rainfall catch in any rain gage. The NWS standards for proper siting of precipitation gages state that gages should not be located in wide-open spaces or on elevated sites to avoid wind and resulting turbulence effects. The best site is one that is protected in all directions such as an opening in a grove of trees; the height of the protection should not exceed twice its distance from the gage location (http://www.weather.gov/om/coop/standard.htm). It is generally accepted by hydrologists and meteorologists that all rain gages will undercatch at times due to wind effects, and the general rule is that errors will be greater for windier gage sites.

Maintenance of the Hydronet, ARC, and ASOS stations is performed by NWS technicians, typically on a 3-6 month frequency. Because these are all real-time sites with data transmission systems in place, the technicians do not collect or download any data at these sites. However, maintenance visits are still critical to the operation of remote data collection networks to perform the recommended service on the sensors and DCPs (e.g. cleaning out rain gage funnels, change batteries, etc.) and generally ensure that the stations are functioning properly.

Data Transmission in the NWS Monitoring Networks in Hawaii

Of all the NWS weather stations and Cooperative Observer stations in Hawaii, approximately 125 are configured for real-time or near real-time data telemetry (90 Hydronet/ARC/ASOS and 35 ROSA). Many other stations (approximately 135) have no data transmission capabilities; these are generally the cooperative stations where non-NWS observers record data on a daily basis (ideally) or at least several times each month. The stations that are equipped for data telemetry are either transmitting data through the landline telephone network or through the GOES satellite system. The NWS has tried using cellular phone modems for at least one of their Hydronet stations, but this system was abandoned due to poor performance. Overall, system performance for landline data transmissions has been pretty reliable, but there have been some issues with phone lines used to transmit data from some Hydronet sites.

GOES uplinks are utilized at some NWS meteorological stations in Hawaii, especially at the RAWS Fire Weather Stations. Some cooperative stations are also using this technology for near real-time data transmissions (e.g. the USGS at precipitation and streamflow measurement stations). The NWS reports no significant problems using the GOES system for data telemetry in Hawaii, but this alternative does have some significant limitations (e.g. bandwidth). More detailed descriptions of the GOES satellite system and its use for data transmissions from remote sites were provided in a related report titled "Data Collection & Storage Options for the Hawaii Permanent Plot Network."

Data Processing and Database Management by the NWS in Hawaii

After data is transferred from the NWS weather stations to the base station at the Weather Forecasting Office in Honolulu either by wired or wireless telemetry systems, it is then entered to a PostgreSQL database. This free object-relational database management system was built from programs developed at UC-Berkeley; today it is not controlled by a single company (as MySQL is), but instead relies on a global community of companies and individuals to develop it.

Quality control of data coming into the NWS databases is typically a two-tier process, with the first step being automated, rudimentary checks on the data. An example of this type of quality control is programming for bounds checks using MySQL where incoming data values are automatically checked against bounding values set by the NWS forecasting team. If any values fall outside of the specified acceptable range, alerts are automatically generated. The second round of quality control involves a NWS forecaster reviewing all incoming data and attempting to identify any data that may be inaccurate or problematic. Data from the weather station network is typically uploaded to the NWS web server immediately following the first round of quality control (automated), and if data problems are identified during the second round (manual review), 'Missing Data' will be reported on the web server until the problems can be resolved.

Before data is archived in the NWS databases it is converted to the Standard Hydrological Exchange Format (SHEF) using software that was developed internally at the NWS. This is the standard format used by the NWS for encoding hydrologic data. Its flexibility allows for the inclusion of most hydro-meteorological data in the databases, and for this reason it is used for many NWS programs and by many other government agencies and private entities. SHEF was designed to allow for the automation of many data handling tasks yet still present data in a visually readable format.

3. The Center for Embedded Networked Sensing – UCLA

The Center for Embedded Networked Sensing (CENS), one of six National Science Foundation Science and Technology Centers established in 2002, is presently at the forefront in the development and applications of new Embedded Networked Sensing Systems. The Center is headquartered at the University of California at Los Angeles (UCLA), but faculty and students from several other universities in the state of California are involved in the Center's research initiatives.

Embedded Networked Sensing (ENS) systems are defined as "massively distributed collections of smart sensors and actuators embedded in the physical world" that enable spatially and temporally dense environmental monitoring. This allows for "up-close" investigations of various at phenomena that were previously very difficult, if not impossible, to observe and study. This ability to make new observations should lead to a better understanding of our complex, physical environments, and hopefully encourage better management of them.

To maximize efficiency, the ENS systems must employ long-lived power systems and wireless communications capabilities that allow for unattended environmental monitoring. These systems are designed to utilize computational data reduction and filtering at the field stations, minimizing the volume of data transferred though the network and thus conserving power. Another important design criteria of ENS systems is the ability of networks to self-configure, adapting to the unpredictable and frequently changing environments where ENS systems are deployed.

CENS is a major research enterprise with an incredibly ambitious vision: to develop large-scale, distributed systems, composed of smart sensors and actuators embedded in the physical world, to eventually connect the entire physical world to the virtual world, expanding on the concept of the Internet. CENS researchers see potential to apply their "revolutionary" wireless sensor network technology "to radically transform critical scientific and societal applications."

At CENS, research activities can be generally categorized as Technology Research and Applications Research. Within the Technology category, research themes include Systems, Multi-scaled Actuated Sensing, Sensors, and Statistics and Data Practice. Within the Applications category, research themes include Terrestrial Ecology Observing Systems, Contaminant Transport Observation and Management, Aquatic Microbial Observing Systems, Seismic Sensing, and Urban Sensing.

The full research agenda being pursued at CENS is very broad, ranging from the development of cutting-edge sensors, to designing sensor network architecture, to the use of robotics in data collection systems, to novel data transmission and database management systems, plus applications of all of the above. A complete description of the work being done at CENS is beyond the scope of this report and not necessary since only certain areas of research at CENS are directly applicable to the proposed instrumentation of the HIPPNET sites. The Terrestrial Ecology Observing Systems (TEOS) is the research area most applicable to the task at hand, and for this reason it will be highlighted in the rest of this section of the report. Information on the other research focus areas at CENS can be found online at: http://research.cens.ucla.edu/research/.

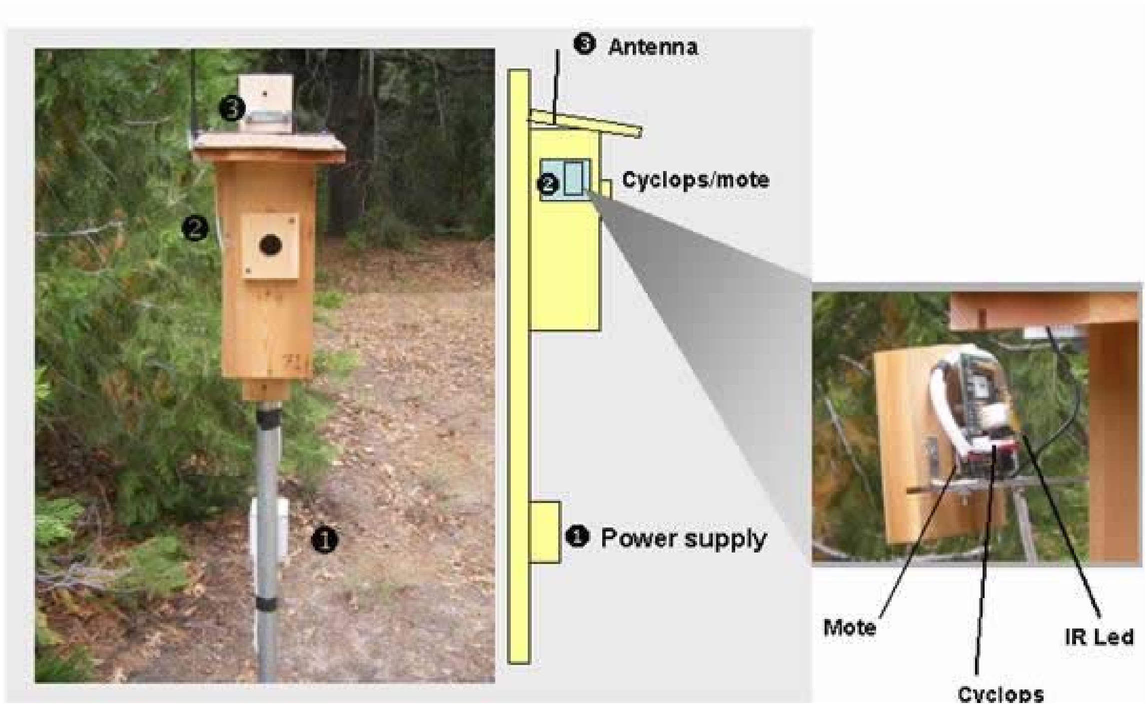
The mission of the TEOS group at CENS is to "design, develop, deploy, evaluate, and support embedded networked sensing systems for *in-situ* continuous measurement of environmental, physiological and ecological variables within diverse terrestrial ecosystems." To this end, a variety of sensing systems have been deployed, ranging from newly-developed technologies for performance testing to application-driven, mature technologies for generating data sets used in scientific research. The majority of these deployments have been in the James Reserve field site.

Environmental Monitoring at the James Reserve

CENS has deployed and is presently operating ENS systems at several test-bed sites. One of the primary field sites is the James San Jacinto Mountains Reserve, commonly called the James Reserve, located in Southern California about 50 miles east of the UC-Riverside campus. This 29-acre reserve, donated to the University of California system in 1966, is in a remote, wilderness setting, surrounded by the San Bernardino National Forest. The entire watershed that bounds the James Reserve is protected for research and study by the US Forest Service. Elevation within the reserve boundary ranges from 5,318 to 7,772 feet (above mean sea level). The habitats present in the James Reserve can be described as mixed conifer and hardwood forest, montane chaparral, montane riparian forest, and perennial mountain streams.

For the TEOS research program, five main project areas have been identified. These include 1. imagers for animal observing systems; 2. imagers for plant observing systems; 3. automated minirhizotron and arrayed rhizosphere sensing systems (AMARSS+NIMS); 4. system infrastructure for environmental sensing and image acquisition; and, 5. EcoPDA for data collection. Sensor systems have been deployed at the James Reserve for all of these project areas.

For the animal observing imager project, wired micro-climate sensor systems and video cameras have been installed at 13 nestboxes to support biological studies of avian nesting behavior. Hobo Microstation dataloggers are collecting data on temperature and humidity inside the boxes, along with temperature and humidity, PAR, and soil moisture outside the boxes. Data from the dataloggers and images from the camera are transferred to the CENS databases and website via hardwire connections. Recently, with the development of a wireless camera system called Cyclops, 12 additional nestboxes have been set-up with wireless cameras to expand the avian study sample size and field test the Cyclops system. Another 13 new nestboxes with Cyclops cameras are planned for 2007, and all 25 Cyclops nestboxes will be outfitted with sensors. For the plant observing imager project, the same technology of time series sensor data plus images collection is being used to study photosynthetic responses of the star moss and bracken ferns.



Wireless Cyclops Camera System at James Reserve Nestboxes

The Networks and Infrastructure for Environmental Sensing and Image Acquisition project within the TEOS research thrust is the most applicable to the planned instrument deployments in the HIPPNET plots. An integral hardware component to this program is the Microclimate Sensor Array that includes environmental sensors, bird nesting sensors, and plant eco-physiological sensors, along with the electronics, communications hardware and system software to control and record the operation of the sensors in the field.

Sensors and Data Collection at the James Reserve

There are currently only six sites within the James Reserve where the Microclimate Sensor Arrays have been deployed. The environmental sensors that make up these arrays typically measure the basics of microclimate, including air temperature, relative humidity, barometric pressure, photosynthetically active radiation, wind speed and direction, and precipitation. Leaf wetness is also being measured at some of the stations.

For onsite data recording, both Campbell Scientific and Onset HOBO loggers are being used in many instances, depending on the application.

In addition to the six Microclimate Sensor Array stations, there are 25 nestbox sites, 27 Cold Air Drainage (CAD) monitoring sites, 1 dedicated soil temperature/soil moisture monitoring site, and several relay stations located within the James Reserve.

Data Transmission at the James Reserve

Although there is a strong emphasis on wireless sensor networks at CENS, there are several monitoring stations in the James Reserve that are hard-wired into the phone network for data transmissions. Significant infrastructure does exist at the James Reserve, at least relative to the HIPPNET sites, including tele-communications and power transmission networks. CENS has made efforts to use these systems when possible, but for remote station deployments they have developed custom power supply and data transfer systems to allow for continuous measurement of environmental variables at unattended, wireless sites.

A key component to this capability are the battery-operated, wireless 'motes' that are essentially small computers that coordinate data collection routines and form adhoc networks that relay sensor data via radio frequency propagation to a specified destination for processing. The motes being used by CENS use commercially-available hardware, the MICA 2 manufactured by Crossbow Technology, and run CENS-developed software and a sensor board that was designed in-house. Crossbow is now selling the complete package that CENS helped develop (www.xbow.com).

MICA 2

These motes serve as a wireless platform for the low-power sensor networks. They transmit data via a multi-channel radio transceiver (868/916 MHz) and provide for a maximum data transfer rate of 38.4 kbps. They have a multi-year battery life, and at the James Reserve field stations, their batteries are typically charged by a photo-voltaic panel. When using these motes for data transmission, every node in the network has router capabilities, providing for self-configuring networks and variability in data pathways. This is important since it allows for maintained functionality in the network even if individual nodes become inactive.

At the James Reserve, the motes are programmed to transmit data from the field stations on the 433 MHZ frequency to a base station that is connected to the internet. CENS researchers and technicians have observed satisfactory network performance (i.e. much better range and connectivity) using this frequency, but it is important to note that they have experienced significant trouble transmitting on other frequencies. RF propagation in some higher frequencies (e.g. 916 MHz) in particular appear to be more sensitive to interception and attenuation by branches and foliage, according to CENS staff.

Data Processing and Database Management at the James Reserve

Not much pre-processing of the raw sensor data occurs at the Microclimate Sensor Array stations; instead the ADC (analog-to-digital converter) values are transmitted to the base station, and eventually these are converted to millivolts and then calibrations are applied in the database. Once data has been transferred from the field stations to a microserver at the end of the wireless network, it is automatically placed in a James Reserve MySQL database using software that was built in-house at CENS. Data management is typically handled by automated scripts (e.g. applying calibrations) and by hand (e.g. adding or removing sensors in the database list).

Quality Assurance / Quality Control (QA/QC) has received less attention at CENS than other aspects of data management until recently. In the past, some very limited filters have been applied to the data to make sure everything is in line. Graphs of the incoming (real-time) data are automatically generated using ‘home-built’ programs. These programs also monitor battery levels at the instrument stations and alert staff when levels are low to avoid gaps in the data set. It is expected that in the future, further QA/QC measures will be developed at CENS based on data correlations to alert users when there are problems at the sensor sites (e.g. when the rain gage is registering precipitation but the humidity sensor reading is low or the leaf wetness sensor reading is dry). Also, systems have been developed to automatically send alert emails to researchers and/or technicians when the camera systems go down.

With so many data streams constantly coming into the CENS databases, and occasional human and systems errors (lightning strikes, inclement weather, hardware malfunctions) causing data loss, the need for QA/QC has become evident. CENS staff has created a number of automated scripts that traverse each data stream in the Data Management System to look for gaps. This allows for early detection of any problems at the instrument sites so that the problems can be rectified as soon as possible, minimizing data gaps.

Finally, students involved at CENS are also developing another database called SensorBase. Using this database option allows users to publish, share, and manage sensor data much in the same way that you can publish, share, and manage journal entries in a blog. SensorBase also allows for data from many different sensor networks to be centralized and no longer in the form of scattered text files (www.sensorbase.org).

4. HJ Andrews Experimental Forest, Oregon

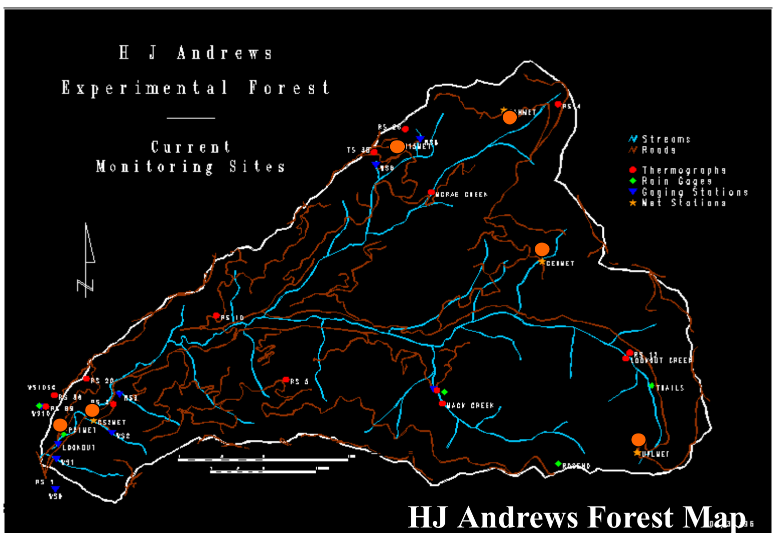
The HJ Andrews forest is located on the west side of the Cascade Mountain Range in western Oregon. The HJ Andrews Experimental Forest was first established by the US Forest Service (USFS) in 1948, and for many years it was primarily used by Forest Service researchers to investigate interactions of climate, vegetation, and soils to develop forest and watershed management strategies. Scientists from several universities became involved in research activities at the Andrews Forest during a 10-year period beginning in 1969 when the International Biological Programme-Coniferous Forest Biome (IBP-CFB) was running. After the conclusion of this program, the HJ Andrews Forest became part of the Long Term Ecological Research Network (LTER). This program, established by the National Science Foundation (NSF) in 1980, was intended to support research of long-term ecological phenomena in the various regions of the United States.

Today more than 1,800 scientists and students are involved in collaborative efforts to study ecological processes over long temporal and broad spatial scales at LTER sites. The HJ Andrews Experimental Forest was one of the six original sites designated for LTER status at the program's inception. Currently there are a total of 26 LTER sites located mainly within the United States, with the exceptions being two sites in Antarctica, one site in Puerto Rico, and one site in French Polynesia (Moorea). Each LTER site involves unique ecosystems, research strategies, investigators, and management systems, and the LTER Network promotes synthesis and comparative research across sites and ecosystems. The HJ Andrews LTER site was included for evaluation in this report because of its rich and diverse research history, and its demonstrated success in environmental data collection efforts for more than 50 years.

Monitoring Stations at the HJ Andrews

Within the 6,000 acre HJ Andrews Experimental Forest, there are presently four benchmark meteorological stations and many secondary meteorological stations. The first of these stations was established in the Andrews as early as 1956 for the Small Watersheds Experiment and now it has a continuous record in excess of 50 years. Many other stations were added to the Forest's monitoring network in the 1960s and 1970s generating valuable long-term data sets.

In 1994, a three-level network for hydro-climatological data collection was established. The first tier in the network includes the Benchmark Meteorological Stations (BMS) and Benchmark Stream Stations (BSS). The BMS provide for complete, long-term, meso-scale hydro-meteorological data at high resolution, and they were designed to represent the hydro-climatological environment across the entire HJ Andrews Forest. Meteorological parameters and the methods and instruments to measure them are generally standardized between all the BMS. Measured parameters at all BMS include air and soil temperature, relative humidity, calculated dew point temperature and vapor pressure deficit, wind speed and direction measurement, incoming solar radiation, photosynthetically active radiation (PAR), soil moisture, snow melt, and snow moisture and depth. Sites for the BMS were selected based on elevation, aspect, vegetation gradients, and access. Investigators at the Andrews hope to link the BMS with regional weather stations to expand the scope of future studies.



HJ Andrews Forest Map

The next tier in the HJ Andrews monitoring network includes the Secondary Meteorological Stations. While these stations follow standardized methods and serve similar purposes to the Benchmark Stations, they are more limited in the meteorological parameters that are measured. The locations of the Benchmark Monitoring Stations and Secondary Monitoring Stations in the Andrews Experimental Forest are shown above (as bright orange dots).

The general approach to hydro-climatological monitoring on the HJ Andrews Forest has been to use forest clearings to gather unbiased weather/climate data rather than using towers in forested areas to monitor weather and climate variables above and below the forest canopy. In fact, no towers are being used in the data collection networks at the HJ Andrews. The BMS sites in the HJ Andrews are all located in forest clearings, either natural clearings or clear-cut areas. These sites are cleared and the openings are maintained according to standards of the National Weather Service, the LTER network, and the National Atmospheric Deposition Program (NADP), where appropriate. The Secondary Meteorological Stations are also located in forest clearings, some of these in former clear-cuts where natural forest regeneration is causing problems for data collection. Most of the forest reference sites are not located in clearings but are instead located under forest canopy. These sites are not presently telemetered. Telemetry systems for the all BMS were completed in 1996. These systems will be described in a later section.

Sensors and Data Collection at the HJ Andrews

Environmental variables measured at all Benchmark Meteorological Stations within the HJ Andrews include the following: air and soil temperature, relative humidity, calculated dew point temperature and vapor pressure deficit, wind speed and direction measurement, incoming solar radiation, photosynthetically active radiation (PAR), soil moisture, snow melt, and snow moisture and depth. Information about the specific instrumentation used to collect data at these stations is provided below.

Air Temperature: Campbell Scientific model 107 temperature probe, Vaisala HMP35C or HMP45C relative humidity/temperature probe, or type T thermocouple wire – samples every 15 seconds, mean hourly or 15-minute air temperature values are recorded (depending on station)

Relative Humidity: Vaisala HMP35C or HMP45C relative humidity/temperature probe with locally-designed PVC radiation shield – mean hourly relative humidity values are recorded

Dew Point Temperature: Dew point values are calculated from air temperature and relative humidity values every sampling interval (15 seconds) using Teten's Equation for the relation between temperature and the partial pressure of water vapor – hourly mean dew point temperature values are recorded

Vapor Pressure Deficit: Water vapor pressure deficit values are computed from relative humidity and air temperature values every sampling interval (15 seconds) - mean hourly vapor pressure deficit values are recorded

Wind Speed & Direction: RM Young Model 05103 Wind Monitor – samples every 15 seconds, hourly mean wind speed, daily mean and max wind speed, resultant mean wind vector magnitude, resultant mean hourly wind vector direction, daily wind direction vector components (wind rose), and/or standard deviation are recorded

Incoming Solar Radiation: Kipp & Zonen solar radiation pyranometer with thermopile type sensor, model CM-6B located on top of shelters - total incoming solar radiation values in langleys per 15 minutes are recorded

Solar PAR: Li-COR PAR quantum sensor (LI190SB) - daily average, daily maximum and 15-minute PAR value averages in micromoles/sec/m^2

Soil Temperature: Type T thermocouple wire or Campbell Scientific model 107 temperature probe – samples every 15 seconds, mean hourly soil temperature values recorded

Soil Moisture: Campbell Scientific CS615 Water Content Reflectometers at depths of 10, 20, 50 and 100 cm - daily mean, maximum, and minimum soil moisture values are recorded

Soil Moisture Potential:	Campbell Scientific model 223 gypsum soil moisture blocks at depths of 10, 20, 50 and 100 cm - daily mean, maximum, and minimum soil moisture potential values are recorded

Rate of snow melt, snow moisture content and snow depth are also measured and recorded at several of the HJ Andrews monitoring stations, but information about the specific instrumentation used to measure these variables is not included here since it is likely not applicable to data collection at any of the HIPPNET sites in Hawaii.

A strict program of sensor maintenance and calibration is followed at the HJ Andrews for quality control purposes. To avoid data gaps, spare sensors with current calibrations are always kept on hand for swapping out sensors that are scheduled for lab calibrations (many sensors are sent to their manufacturers or special testing facilities for calibrations). The HJ Andrews does not have a program in place for replacing sensors or data loggers after a specified time period; hardware is typically changed out on an as-needed basis.

Campbell Scientific data loggers are used at all of the Benchmark Monitoring Stations and Secondary Monitoring Stations. These loggers are typically models CR10, CR21X, CR500, or CR23X, most of which have been retired and replaced in the CSI data logger line. Some of the monitoring stations are now being upgraded from the old CR10X to the newer CR1000 data logger or CR3000 micrologger. The Climate Data Manager at the HJ Andrews claims that they have had good experiences with all the Campbell Scientific data loggers and that they intend to continue using these in the future.

HOBO sensors and data loggers, made by the Onset Computer Corporation, are being used for many temporary instrument stations in the HJ Andrews. Investigators tend to use this less expensive and less complicated hardware for instrument deployments that are expected to last from several months to a few years. For long-term environmental monitoring at the HJ Andrews Experimental Forest, investigators have made and continue to make the use of high-quality, durable sensors and data loggers a high priority.

Data Transmission at the HJ Andrews

Several different methods of data transfer from the field instrument stations to the database are employed at the HJ Andrews. For many of the forest reference sites where sensor arrays are deployed below dense forest canopies, wireless data transmission is not a viable option. At most of these stations, on-site data loggers (either HOBO or Campbell Scientific) are simply recording data from the sensor arrays to their internal memory, and a technician visits the site every three weeks to collect data from the loggers and clear their memory. This is considered the 'old-fashioned' way of data transmission, but it is effective and justified for a monitoring program like the HJ Andrews' where technical staff is in residence for much of the year.

Automated, wired data transmission is used for the instrument station close to the main HJ Andrews Field Station. Of course this method is not an option for the more remote instrument arrays such as the Benchmark Meteorological Stations, so a wireless data transmission network has been established. As of 1996 when this transmission network was completed, all four of the Benchmark Meteorological Stations and eight stream gaging stations are using a line-of-sight (LOS) UHF radio frequency (RF) network to transmit data from the field sites to the base station located at the main HJ Andrews Field Station building.

While the existing system has worked well and been reliable for the past 10 years, it has become somewhat outdated during its period of use. Most of the new LOS-RF systems being used today are VHF systems rather than UHF, and the UHF radio hardware used at the HJ Andrews cannot even be purchased from vendors today. For this reason, data managers at the Andrews are now considering upgrading to a new VHF radio or a satellite-based data telemetry system. At this moment in time they are leaning towards using spread-spectrum (900 MHz, 2.4 GHz) VHF LOS radio technology because of its relatively low costs, the lack of FCC licensing requirements, and its supposed ability to better handle the interference effects of forest canopy. There is no definite plan or timeline for upgrading wireless data telemetry systems at the HJ Andrews at this time.

Data Processing and Database Management at the HJ Andrews

Much of the data processing, data review, quality control, and data formatting are performed at the HJ Andrews before the data ever leaves the Experimental Forest boundaries. Even though the data loggers at the field instrument stations are typically scanning the sensors on the order of seconds, the loggers are programmed to quickly reduce this high-resolution data to mean, minimum, and maximum values. So much of the data processing actually happens at the instrument stations before it is ever transferred to the base station.

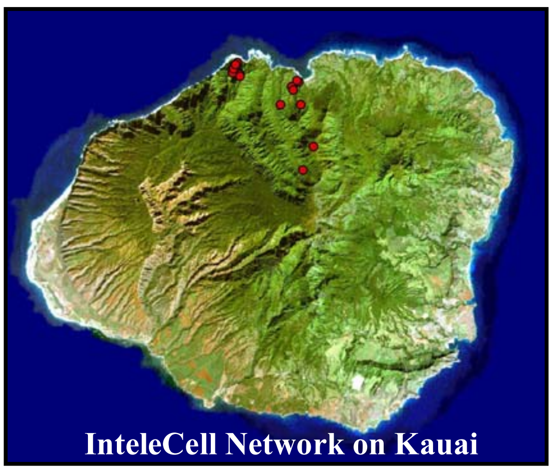
Once data from the instrument sites is moved to the base station at the HJ Andrews Field Station building, all incoming data is graphed through automated scripts and the data plots are reviewed by the Climate Data Manager who attempts to locate any data anomalies. Next, the data are re-formatted (e.g. conversion of date and time from Julian format to calendar format), again using automated scripts, to prepare them for entry to the master database. All of the above work is done using Microsoft FoxPro database software. Once the re-formatting has been completed, the datasets are sent to a MySQL database at Oregon State University in Corvallis via a dedicated T1 line between the University campus and the HJ Andrews Field Station.

5. InteleSense Monitoring Networks on Kauai

With funding from the NSF - EPSCoR program, the Center for Conservation Research and Training (CCRT) at the University of Hawaii at Manoa has been developing wireless environmental monitoring networks on Kauai in close collaboration with InteleSense Technologies. Three types of monitoring stations have been established in three north shore valleys on Kauai: weather stations, stream gaging stations, and water quality stations. Data is generated at these stations and transmitted automatically through the network of neighboring stations and repeaters to a base station where it is uploaded to an internet server. InteleSense has developed automated scripts to produce graphs of incoming data, and the InteleView data viewing platform allows users to visualize environmental data on a background of high-resolution, global-scale satellite imagery, in 3D, and in real time.

Monitoring Stations in the Kauai EPSCoR Network

Deployments of environmental monitoring stations in the EPSCoR networks on Kauai have so far been focused in three north shore valleys: Limahuli, Lumahai, and Waipa. Almost the entire Limahuli Valley is included in the Limahuli National Tropical Botanical Garden (NTBG), and in this valley instrument stations have been deployed to measure and collect weather/climate, streamflow, and water quality data. In Lumahai Valley, located a few miles east of Limahuli (with the large Wainiha Valley in between), EPSCoR deployments have been concentrated in the back of the valley where The Nature Conservancy (TNC) manages areas of near-pristine native forest for Kamehameha Schools, the landowners. Data being collected in Lumahai Valley includes weather/climate data at the valley's high point (Namolokama) and streamflow data at a remote gaging station on the upper Lumahai Stream. These data will be useful later for comparisons after TNC implements conservation treatments here that could result in changes in hydrology and water quality (proposed treatments include feral animal eradication and aggressive control of invasive vegetation).



At Waipa, the next valley east from Lumahai, a similar data collection network has been developed that includes weather, streamflow, and water quality monitoring stations. Like TNC in Lumahai, the Waipa Foundation has plans to implement conservation practices at Waipa that should result in changes in water quantity and quality, so the data being collected through the EPSCoR network now will be useful as a baseline for trend monitoring later. Also, the network of real-time streamflow gaging stations at Waipa will be useful for irrigation management in the future since there is a high water demand from the Waipa Stream for the many taro farms in the area.

Because the three valleys where the monitoring stations have been deployed are so close to each other, the station layout was designed as a mesh network where each station in the field is within line-of-sight of at least one more station that serves as a relay point for routing data from the field to the base station. The distance that data is transmitted from node to node in the network is typically five miles or less. A single base station was established at the Limahuli Gardens hale, and when data is received here from the field stations it is automatically uploaded to the InteleSense internet server via DSL connection.

Sensors and Data Collection in the Kauai EPSCoR Network

On Kauai, InteleCells are being used to collect and transmit data from several different sensors that can be categorized as weather sensors, water level (stage) sensors, and water quality sensors. For weather sensors, both Campbell Scientific and Onset HOBO systems are being used, but there generally has been a transition from Campbell hardware to HOBO hardware due to logistical and cost factors. Difficulties encountered in programming the Campbell Scientific data loggers, interfacing them with the InteleCells, and the much higher cost of the Campbell equipment compared to the HOBO equipment prompted the switch. For all new weather station deployments, HOBO sensors and data loggers are being used at the Kauai testbed sites. A typical weather station array includes the following:

Precipitation: HOBO RG-2 tipping-bucket rain gage smart sensor

Air Temperature & Relative Humidity: HOBO 12-bit Temperature/RH smart sensor with radiation shield

Wind Speed & Direction: HOBO Wind Speed / Direction Smart Sensor

Solar Radiation: HOBO Silicon Pyranometer smart sensor

Data Recorder and Telemetry Interface: HOBO Micro Station Data Logger

Data Transmitter: InteleCell

Battery and Voltage Regulator: Included in InteleCell, solar panel used to charge battery

Enclosures: Waterproof Pelican Case used as housing for InteleCell and data logger

WL400

There are presently three stream gaging stations (two at Waipa, one at Lumahai) in the InteleCell network on Kauai, and there are plans to add several more in the near future. The existing gaging stations are not yet producing streamflow data because the gage ratings (relating water stage to discharge) have yet to be developed. The stations are really very simple with a single sensor deployed in the stream channel at an appropriate location for streamflow measurements and the InteleCell and its associated components (antenna and solar panel). The sensors being used to measure water stage are conventional pressure transducers manufactured by Global Water Instrumentation, Inc., out of Gold River, California (model WL400). These sensors were selected for their accuracy, reliability, and rugged design that is essential for prolonged use in Hawaii's fast and debris-loaded streams. Measurements of streamflow at various stream stage conditions are being made now to develop the ratings for the Waipa and Lumahai stream gages. Once this is complete, these stations will provide real-time streamflow data for Lumahai Stream, Waipa Stream, and the Waipa irrigation diversion.

Gaging Station in Waipa Auwai

InteleCell for Waipa Auwai Station

In addition to the weather and streamflow data being collected in Kauai's North Shore Valleys, the InteleCell network also includes two automated water quality monitoring stations. These stations utilize a YSI multi-probe made for extended deployments in harsh environments (model 6600EDS V2). These probes collect data on various water quality parameters for a tributary of Waipa Stream and the mainstem Limahuli Stream, including water temperature, dissolved oxygen levels, pH, salinity, conductivity, and stream turbidity. InteleCells at these stations transmit water quality data to the base station on an hourly basis.


YSI 6600

Data Transmission in the Kauai EPSCoR Network

The InteleCell unit is the heart of the InteleSense technology. It is a wireless datalogger and data transmitter that uses VHF radio propagation to transmit data over distances up to 40 miles (more typical range for practical applications is 7-8 miles). These units tend to be very conservative in their power consumption allowing for a very low profile in their design; each unit measures roughly 8 inches x 4 inches x 2 inches. Under most conditions, the InteleCell does not require an external battery, but instead charges an internal battery using a single 10 inch x 10 inch solar panel. This low profile design is possible because the InteleCells utilize low-power radios (1 Watt) to transmit and receive data in a spread spectrum radio frequency (900 MHz). Because this is spread spectrum technology, FCC regulation does not apply, saving users the time, effort, and money required to obtain licenses to use more powerful radios or different radio bands.

Multiple InteleCells form a self-organizing mesh network, each collecting and routing data from one or more sensors to a base station where data is uplinked to an internet server. Each InteleCell can act as a repeater station in the mesh network, so as long as every InteleCell in the network can transmit a signal to at least one other network node, data will be routed from all field InteleCells to the base station on a user-determined frequency. Also, the InteleCells can be used to determine if line-of-sight and sufficient signal quality can be achieved between network nodes in the field without commissioning an expensive radio propagation study.

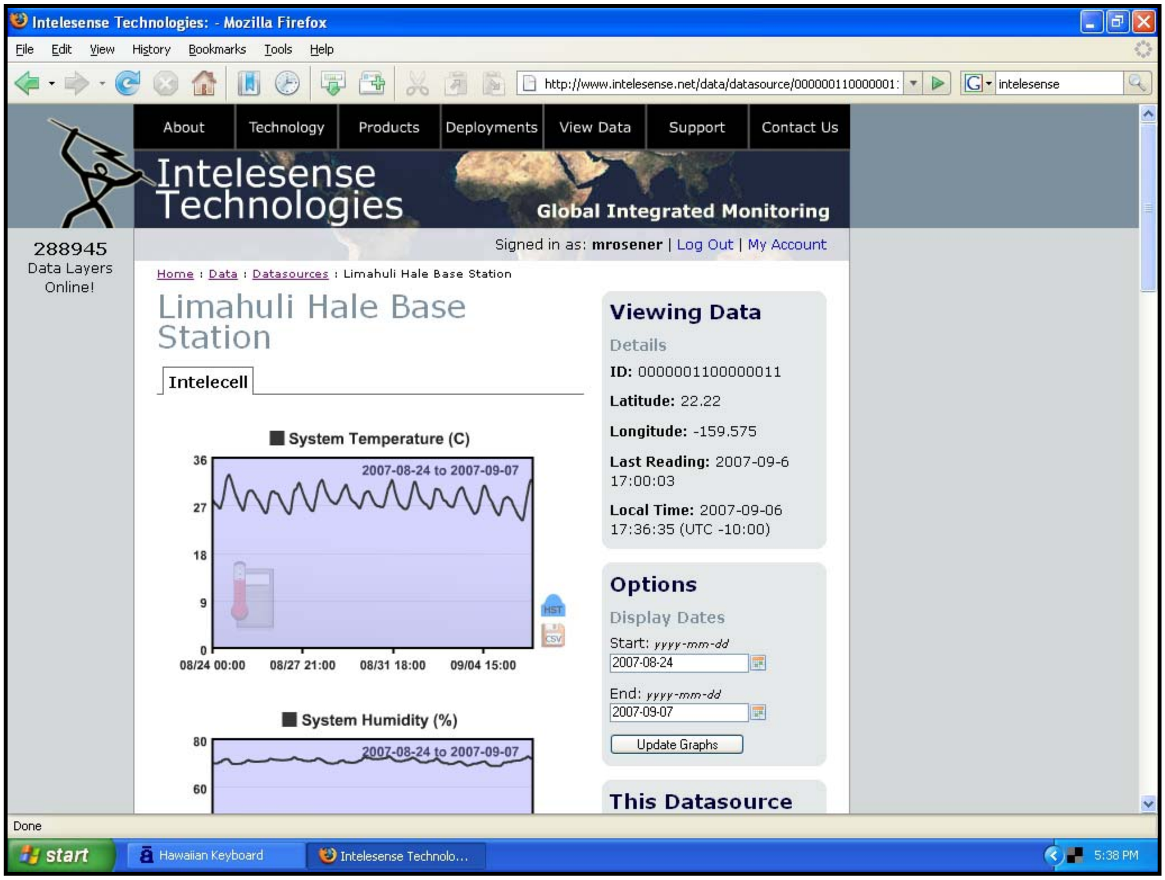
On Kauai, the InteleCell network starts at the base station housed at the Limahuli Gardens (NTBG). The base station is simply a receiving antenna, a small base station module, and a DSL internet connection. A repeater station InteleCell was installed high on Limahuli Ridge that provides the gateway for the rest of the network to the base station. There are a total of 10 stations that are part of this network, located throughout the Limahuli, Lumahai, and Waipa Valleys. The general strategy for data routing is to locate repeater stations on high ridges with good line-of-sight in every direction. This allows data to be transmitted from stations located in the valley bottoms all the way to the base station as long as they have line-of-sight to a ridge repeater.

Data from the sensor stations are typically collected and recorded onto the InteleCell's internal flash memory at intervals from 1 minute to 60 minutes. Recorded data is transmitted through the InteleCell network once every hour. If the regularly-scheduled transmission fails for whatever reason, data is not lost but remains on the InteleCell's flash memory and will be re-sent during the next regularly-scheduled transmission (every hour). The internal memory of the InteleCell is sufficient to store at least one year of data for the current applications on Kauai, so even in the event of a large network failure, a back-up data storage system is in place. When the internal memory of the InteleCell is filled, it simply begins to overwrite old data when recording new data.

Once data is received at the base station at Limahuli Gardens, it is uplinked via a DSL connection to an internet server located near the InteleSense headquarters in Silicon Valley, California. The facility that houses the server is ideal for data storage because of its redundant back-up power systems, tight security protocols, and large bandwidth capacity for data users.

Data Processing and Database Management for the Kauai EPSCoR Network

In a typical InteleCell network, raw data is collected and transmitted from the field stations to the base station and uploaded to the internet server without any data manipulation or reduction. Once received at the server site, incoming data is automatically entered to a MySQL database and graphical displays of current data are updated every hour.



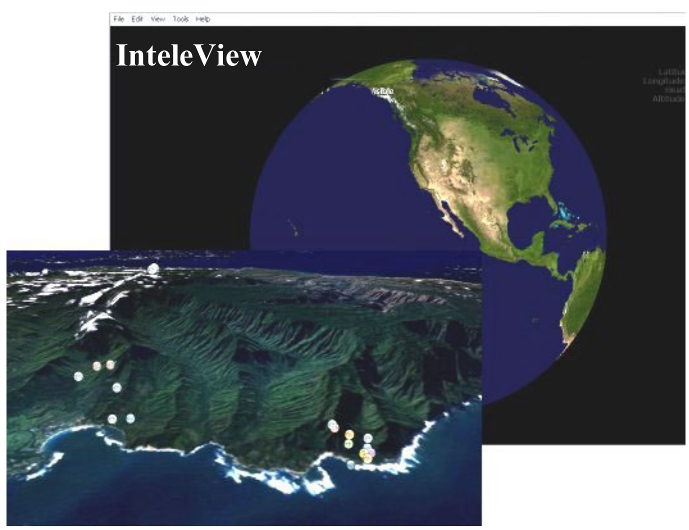
Graphical Display of InteleCell Station Data on InteleSense Website

Quality assurance and quality control are performed by the network operators and data users. InteleSense does not usually review data coming in from the various InteleCell networks as it is the responsibility of the owners/operators of the individual InteleCell networks to ensure the quality of the incoming data. Of course, an important element of quality control for environmental data collection is proper operation and maintenance of the sensor networks once they are field-deployed. Again, this is the responsibility of the network owner/operator, and thus it is done in different ways in different places.

Operators can simplify quality control by using the alarm capabilities of the InteleSense database program. To do this, users access their data and specify out-of-range conditions for various incoming data streams through the InteleSense website. Email alarms will then be generated automatically when incoming data values fall outside the specified range. This may prompt a visit to the instrument station to determine the cause and solution to the problem in a timely manner, reducing lost or faulty data.

Data Visualization for the Kauai EPSCoR Network

Visualizing and analyzing large amounts of data from a number of different data sources effectively, on large scales, and in real-time requires a powerful GIS tool. To accomplish this, InteleSense developed a visualization tool called InteleView that displays data with widely varying spatial and temporal attributes on high-resolution satellite maps, on a global scale, in 3D, and in real-time. InteleView is a plug-in to the open source software package NASA WorldWind.



InteleView allows the user to "zoom in" to anywhere on the planet and pull down many different types of satellite imagery from servers located anywhere over the Internet. Users may tilt down and "fly" around the terrain, investigate line-of-sight issues, examine topological changes and their potential impact, and integrate many data sources into the same, interactive 3D world. Icons displayed on the map of the InteleCell deployment zone depict real locations of water and weather sensors, tracked animal collars, wireless video cameras, as well as repeater nodes and the base station. The user can click on any icon to bring up an interactive web page showing the sensor information (photo, sensor type/info, calibration information, etc), as well as the live data (sensor values) and plots for trend analysis. Besides displaying and analyzing sensor data, InteleView can be used for network planning, sensor network architecture development, network maintenance and characterization, and resource allocation. InteleView also adds several layers of security features to WorldWind, including the ability to expose public data to everyone while selectively protecting proprietary data sets.

It is important to point out that this new visualization tool works, literally, for anywhere on the planet and pulls the highest resolution satellite or aerial imagery available for that particular region. In this way, sensors may be deployed anywhere on the planet and immediately have real-time visualization of their location and full interactivity with the sensors automatically, within minutes. This is an extremely powerful visualization tool which allows users to bring up any location on the planet and overlay their own sensor data, as well as data from other sources. This integrated *georepository* is a powerful and effective research and educational tool, useful in understanding environmental trends, impacts of human development, and their interaction.

Summary

The evaluation of existing environmental monitoring networks presented here is in no way exhaustive in its scope. For every example selected for this analysis, another ten could have easily been selected in its place. The networks detailed here were chosen because they are all proven to work and work well in challenging environments similar to those that are likely to be encountered in the Hawaii Permanent Plot Network. It should be obvious by now that there are significant differences between all of these networks, from general monitoring strategies down to specific hardware being used. However, the research for this report did not inspire a sense that any one system is inherently better for the HIPPNET application than the others. As is usually the case, there are advantages and disadvantages to every alternative that should be considered for long-term monitoring at the HIPPNET plots. Many of these were presented in greater detail in the related report submitted earlier, "Data Collection & Storage Options for the Hawaii Permanent Plot Network."

The reader should also sense that although there are major differences between the many existing networks, there are also some significant similarities that should be considered, if only because it implies that something must be working well if it is being used repeatedly for varying applications. One example would be the commitment to the very highest-grade hardware in data acquisition (sensors, dataloggers, and accessories) for programs that are intended to be long-term monitoring programs at their inception (e.g. LTER, NWS, SCAN networks). HIPPNET's name implies that it is meant to be such a program.

Another example is the tendency towards ground-based, real-time data telemetry systems, and particularly LOS-RF systems, where they are a viable option in comparison to cellular, microwave, meteor-burst, or satellite telemetry systems. A LOS-RF data telemetry system can provide the user with the highest level of reliability and control over the transmission infrastructure, and also allow for true real-time data capability through unrestricted two-way communications at all times. The only significant limitations of these systems are topography (where line-of-sight between stations cannot be achieved) and range (50 miles or less). Satellite telemetry systems, using the GOES satellite service in particular, may be a good alternative if these limitations are considered too large an obstacle to overcome when designing the spatial layout of the HIPPNET plots.

For database management, the use of MySQL database programs or programs stemming from this code seems as close to being a standard as anything in this field where options can seem frustratingly manifold. And the emphasis that network operators put on data quality control, specifically on regular system maintenance, should come through in this report loud and clear.

Many of the questions relating to overall monitoring strategy (e.g. single large plot vs. many small plots, plot size, number of monitoring stations per plot, etc) have seemingly been resolved already by the HIPPNET investigators. However, some very important decisions have yet to be made, such as the plot locations, the selection of data collection, storage, and telemetry systems, and the choice between using tower-mounted sensor arrays in forest canopy or tripod-mounted sensors in natural forest clearings. It is hoped that by providing the HIPPNET developers with the detailed information presented in this and the accompanying reports, these decisions will be rendered less cumbersome, and that they will be made with greater confidence in the ability of the HIPPNET data networks to produce accurate data using reliable, durable, and user-friendly data collection platforms.