Report to the University of Hawaii at Hilo EPSCoR Group

on

Data Collection & Storage Options for the Hawaii Permanent Plot Network

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Submitted: 2 April 2007

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Introduction

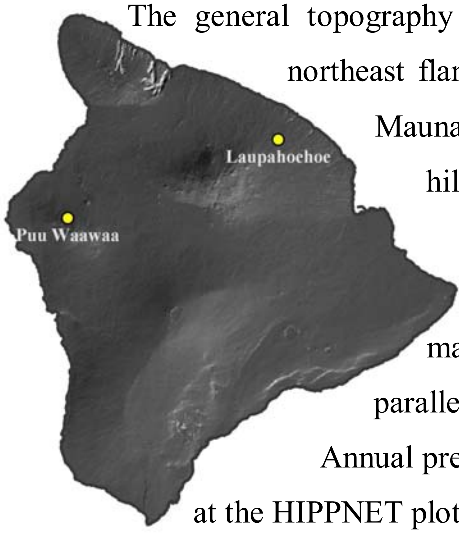
This report was produced at the request of Dr. Jene Michaud of the University of Hawaii at Hilo EPSCoR Group and is being submitted as a project deliverable as specified in the consultant's scope of services. The analysis that led to the production of this report was performed under an informal agreement 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 data collection and storage alternatives for instrument stations 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.

It has not yet been decided if data from the sensor arrays will simply be recorded on-site using data-loggers and periodically collected by technicians or if data will be automatically collected from the sensor arrays through a wireless transmission network and delivered to a base station and internet server. Both options are evaluated here to provide information that may be used to make an informed decision on the appropriate means of data collection and storage for the HIPPNET instrument stations.

HIPPNET Site Descriptions

The two HIPPNET sites that have been identified to date are both located on Hawaii Island. The first site is located in the new USDA Forest Service Hawaii Tropical Experimental Forest (HTEF) at Laupahoehoe, at an elevation of roughly 4,000 feet (MSL) on the windward slopes of Mauna Kea. The vegetation communities at this site are dominated by native forest plants (>80%), with and abundance of large Ohia Lehua and Koa trees. The maximum forest canopy height in this area is estimated to be 60-80 feet. This plot site is considered to be representative of undisturbed wet mid-elevation forest areas in Hawaii. Although the HIPPNET plot size is likely to be limited to 10 acres, the entire Laupahoehoe forest area exceeds 12,000 acres in size.



The general topography of the Laupahoehoe HIPPNET area located on the northeast flank of Mauna Kea includes the remnant portions of the Mauna Kea shield that are characterized by relatively uniform hillslopes declining from the mountain summit to the coastline at average grades of 9-12%. The shield remnants have been deeply incised in this area by many perennial and ephemeral streams that generally run parallel to each other in a southwest to northeast alignment. Annual precipitation varies with elevation and averages 150 inches at the HIPPNET plot. Soil age varies from 4,000 to 65,000 years in this area.

The second site to be identified as a HIPPNET site is located at Puu Waawaa, on the leeward side of Hawaii Island. This area has been designated as the Puu Waawaa Forest Bird Sanctuary, a conservation area managed by the State of Hawaii Department of Land and Natural Resources (DLNR) – Division of Forestry and Wildlife (DOFAW). The bird sanctuary is approximately 4,000 acres in size, and elevation ranges from 4,000 to 6,000 feet (MSL).

Again, much of the area is dominated by native forest plant communities (>60%), with Ohia Lehua and Koa making up the forest canopy in many places. Canopy height in this area varies with elevation and appears to be a maximum of about 70-80 feet at elevation 5000-5500 feet MSL. Not coincidentally, this elevation corresponds to the rainfall maximum in Hawaii. Long-term annual median precipitation in the Puu Waawaa sanctuary area is 40 inches.

The Puu Waawaa area is located on the northwest flank of the dormant Hualalai volcano. Topography in the area can be generally described as relatively uniform hillslopes with grades ranging from 8 to 40%; no perennial streams exist in this area, but ephemeral drainages are common. Soil age ranges from 750 to 5,000 years.

Several additional sites are presently being evaluated for their inclusion in the HIPPNET system, including sites on Oahu and Kauai. However, it has yet to be determined which sites will be included, and it is unclear when these decisions will be made.

Sensor Arrays at HIPPNET Monitoring Stations

It has already been decided that tower mounted sensor arrays will be installed at the Laupahoehoe and Puu Waawaa HIPPNET sites to allow for climate measurements to be made both above and below the forest canopy. Sensors to be installed at ground level at the tower sites include air temperature, relative humidity, and photosynthetically active radiation (PAR) sensors. Several soil heat flux, soil temperature and soil moisture sensors will be installed beneath the soil surface near the base of the towers. Sensors to be installed near the top of the towers include rainfall, air temperature, relative humidity, wind speed and direction, PAR and net radiation sensors. Finally, air temperature, relative humidity, and PAR sensors will be installed at some intermediate point on the towers.

The additional eight HIPPNET sites for which locations have yet to be determined will be instrumented with tripod-mounted sensor arrays instead of towers due to cost limitations. The proposed strategy is to locate these instrument stations in forest clearings that will allow for accurate measurements of rainfall, air temperature, relative humidity, PAR, and incident solar radiation. The clearings may also allow for data transmissions from the field stations to a base stations via one of the telemetry methods described in this report.

On-site Data Recording

The EPSCor Research group has decided to use data loggers manufactured by Campbell Scientific, Inc. for both the tower- and tripod-mounted sensor arrays. Campbell CR1000 loggers will be used for data collection and on-site storage at the two tower sites (Laupahoehoe and Puu Waawaa). A satellite CR3000 micro-logger will be used to collect and record data from the soil sensor arrays (temperature, water content, and heat flux) and will transmit these data to the CR1000 logger at the same site. CR3000 micro-loggers will be used for all on-site data collection, recording, and storage at the eight HIPPNET clearing sites.

The Campbell CR1000 data logger was designed to replace the popular CR10 and CR10x loggers with enhanced capabilities such as more internal memory and more measurement channels. The CR1000 features 16 single-ended or 8 differential analog inputs that can be individually configured along with 2 pulse counters. A mulitplexer unit can also be used with this logger to allow for additional input channels. The CR1000 comes with 2M SRAM standard for program and data storage, and additional data storage capacity can be achieved using Compact Flash memory cards. A detachable keyboard/display that can be easily transported between sites and used to interface with multiple data logger units is also available.

The CR3000 micro-logger is a compact, self-contained datalogger with a built-in alphanumeric keyboard and display. The CR3000 comes with 4M SRAM standard for program and data storage; 28 single-ended or 14 differential analog inputs and 4 pulse counters are available to accommodate various sensors. The advantages to using Campbell Scientific loggers for this application are substantial. Campbell loggers are commonly considered the industry standard for the flexibility they offer and for their proven record of precision, reliability, and durability. No matter how the sensor arrays at the HIPPNET stations are modified in the future, the flexibility and expandability of the Campbell dataloggers should allow for these changes without upgrading logger hardware.

Programming the CR1000 and CR3000 loggers is performed using the Campbell Scientific LoggerNet software. The same software is also used for communications and data retrieval between Campbell loggers and a PC. LoggerNet is the standard software package recommended for Campbell datalogger networks. It includes the LoggerNet server and integrated client applications that allow for programming dataloggers, collecting data, monitoring and troubleshooting the network, managing dataloggers in the network, creating graphical data displays that update when data is collected, creating automated tasks, and viewing or post-processing the data. It should be noted that while the Campbell Scientific hardware and the LoggerNet software will maximize the user's capabilities and flexibility in data collection and storage, programming tasks are notoriously complicated. For this reason, *it is strongly recommended that the user contract for services to assist with programming and assembly of the Campbell Scientific hardware/software packages.*

The Campbell CR1000 and CR3000 dataloggers selected for use at the HIPPNET instrument stations have sufficient internal memory for data storage over extended periods. Even for the tower sites where many individual sensors will be connected to each of the CR1000 (11 sensors) and CR3000 loggers (12 sensors), the on-site data storage capacity should allow for at least 6 months between data retrieval visits if no other data communications system is used. For the clearing sites, this minimum data collection frequency will be even more than 6 months.

Since many of the sensors to be installed at the instrument stations should be serviced on a 6-month (minimum) frequency, there should never be a time when more than 6 months pass between visits to any one instrument station in the network. For this reason, it is suggested here that unless real-time or near real-time data is needed, on-site dataloggers alone without any data transmission system should be considered as a viable option for data collection and storage for the HIPPNET instrument stations.

That being said, there are limitations to using on-site data storage exclusively, and there are significant advantages to transmitting data from the field stations to a base station/server in real-time or near real-time. These include, but are not limited to, the ability to monitor data continuously for real-time applications such as gathering reconnaissance data for fire-fighting efforts (may be particularly useful at the Puu Waawaa site and future sites located in dry areas) and the ability to quickly determine when there are problems at the network stations with sensor operations, power supplies, and/or data transmission systems. A serious limitation to using on-site data storage exclusively relates to this scenario just described. If there is a sensor or power system failure, and no telemetry system is in place to alert the users of this problem, there is potential for months to pass before the problem is recognized and resolved. Of course this could result in a significant gap in the data record.

Data Transmission Alternatives

Several alternatives were evaluated for real-time or near real-time transmission of data from the HIPPNET monitoring stations to a base station for QA/QC, post-processing, and entry to one or more databases. The data telemetry methods that were identified to be viable alternatives for the HIPPNET data collection initiative include ground-based line-of-sight (LOS) radio frequency (RF) systems, cellular phone modem systems, and a satellite system (GOES). The meteor-burst telemetry technology that is often used for the USDA-NRCS Soil and Climate Analysis Network (SCAN) and Snowpack Telemetry (SNOTEL) networks is not considered to be a feasible alternative due to the substantial capital expenditures required to establish an operational base station for meteor burst transmissions in Hawaii (> $100,000). For this reason, the meteor-burst telemetry alternative was not evaluated for this report.

For each alternative system evaluated, a general description of the data transmission method is first provided. This information is followed by discussions of several system evaluation criteria that should be considered in choosing the most appropriate data telemetry alternative for the HIPPNET instrument stations. These criteria include 1) advantages of each alternative when compared to the other alternatives, 2) disadvantages and/or limitations (both relative and absolute), 3) system costs (both up-front and recurring), 4) perceived reliability and durability, and 5) suitability of each alternative specific to the HIPPNET instrument station sites at Laupahoehoe and Puu Waawaa.

Characteristics of the other HIPPNET sites that could influence the decision on the most appropriate telemetry method were not considered for this analysis since the other HIPPNET sites have not yet been determined. However, the various alternatives were evaluated assuming that future HIPPNET sites will be distributed throughout the Hawaiian Islands as planned, meaning one or more sites will be located on an island other than Hawaii Island.

Alternative # 1: Ground Based LOS-RF System – utilizing SCAN infrastructure

1. General Description

Ground-based LOS-RF systems use UHF or VHF radio transmissions to transmit data from a remote field station a base station receiver. The data transmission can be sent directly from the instrument station to the base station if line of sight is available or it can be routed through other radio receiver/transmitter nodes in a network. These stations that simply receive radio transmissions from the radio at an instrument station and transmit the same transmission on to the next node in the chain are called repeater stations. Line-of-sight is generally required between nodes in a LOS-RF network, although there is some 'wrap' capability to radio transmissions so in some cases transmissions may be possible where perfect line-of-sight does not exist.

Radio waves have very different propagation characteristics depending on their frequency. For this reason, engineers design radio systems to utilize the unique propagation characteristics of a given frequency band. Environmental monitoring data are typically transmitted in packets through radio signals using VHF and UHF frequencies. Several frequencies are used for data transmissions, and the Federal Communications Commission (FCC) requires a license to be obtained to transmit data via radio signals for most of the radio spectrum.

A notable exception to this rule is spread spectrum radio communications that involve the use of 'license-free' frequency bands. Examples of these include 900 MHz and 2.4 GHz, often called the ISM bands (Industrial, Scientific and Medical). FCC licensing is not required to use these frequencies, however only FCC-certified radio devices (with 1 Watt maximum power in the U.S.) are allowed to emit signals on these frequency bands. The FCC-imposed limitation on radio power in the spread spectrum bands limits signal strength and thus limits the range of radio transmissions. Spread spectrum is a coding technique designed to modify the radio signal and 'spread' it out over several frequencies (increases bandwidth). The spread spectrum receiver detects and accepts only these spread-frequency transmissions.

2. Advantages

There are several reasons why LOS-RF telemetry systems are considered superior to the alternative systems. These include the following:

- Stable transmission platform
- Relatively low up-front costs and no recurring costs
- No infrastructure limitations on volume of data transmitted
- Allows for most control over transmission network
- 2-way communications allows real-time data polling
- High reliability
- Proprietary data

Probably the single most significant advantage to using LOS-RF systems versus alternative systems is the opportunity for complete control over the data transmission system. As discussed in later sections of this report, when using other data telemetry technologies, the user is constrained somewhat by the use of a transmission network that they cannot control to a large extent (e.g. cellular tower network, public and private satellite constellations). With a ground-based LOS-RF telemetry system, the end user typically develops the entire transmission network and has ownership and thus control over how it is operated and maintained.

LOS-RF systems can also be the most cost-effective data telemetry solution depending on the transmission network configuration and specifically the need for repeater stations. If many repeaters are needed in order to route data from the instrument stations to the base station, both up-front costs and ongoing maintenance costs will be higher. However if local geography and topography allow for the instrument station network to be established without the need for repeaters, the up-front costs will be relatively low compared to other telemetry options and recurring costs are limited to maintenance.

3. Disadvantages and Limitations

Every telemetry system alternative will have some disadvantages when compared to the other alternatives. For LOS-RF, these disadvantages are very few and in some cases these may not even be applicable.

- May require a propagation study to configure transmission network
- FCC Licensing costs if using UHF or VHF bands, but not spread spectrum
- Capital costs can be relatively high if many repeater stations are required

Range limitations for LOS-RF transmissions are highly dependent on the power of the radio transmitter used and the type of antenna used. In some cases, the terrain and vegetation characteristics between the transmitter and receiver can have significant reducing effects on transmission range. With a powerful radio (e.g. 10 Watt) and good line-of-sight (i.e. no obstructions in signal path), a transmission range of 100 miles over open water can be expected with an omni-directional antenna, although 30-40 miles are more typical range values. For the radios more commonly used for LOS-RF data transmissions (2 or 5 Watt), 20 miles of range can be expected with good line-of-sight. Range can also be extended through the use of a high-gain antenna.

4. Costs

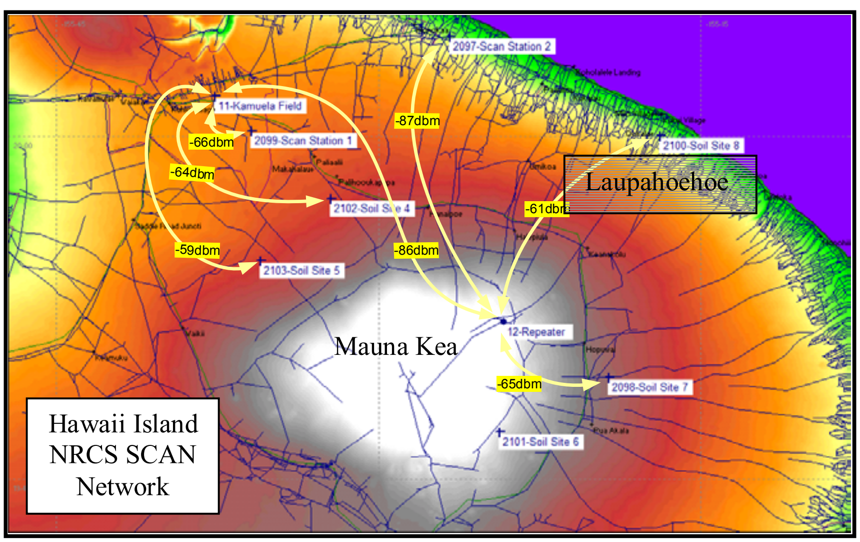
Transceiver units for VHF or UHF radio transmissions can be purchased for approximately $500. The full hardware cost for a single instrument station or repeater station is approximately $1200 including antenna (uni- or omni-directional), power supply, and enclosure. Base station receiver cost is approximately $1000 - $2000. In some cases, FCC licensing costs may also apply. However, there are no real recurring costs for LOS-RF systems other than maintenance costs, which should be nominal unless many repeater stations are needed.

5. Perceived Reliability and Durability

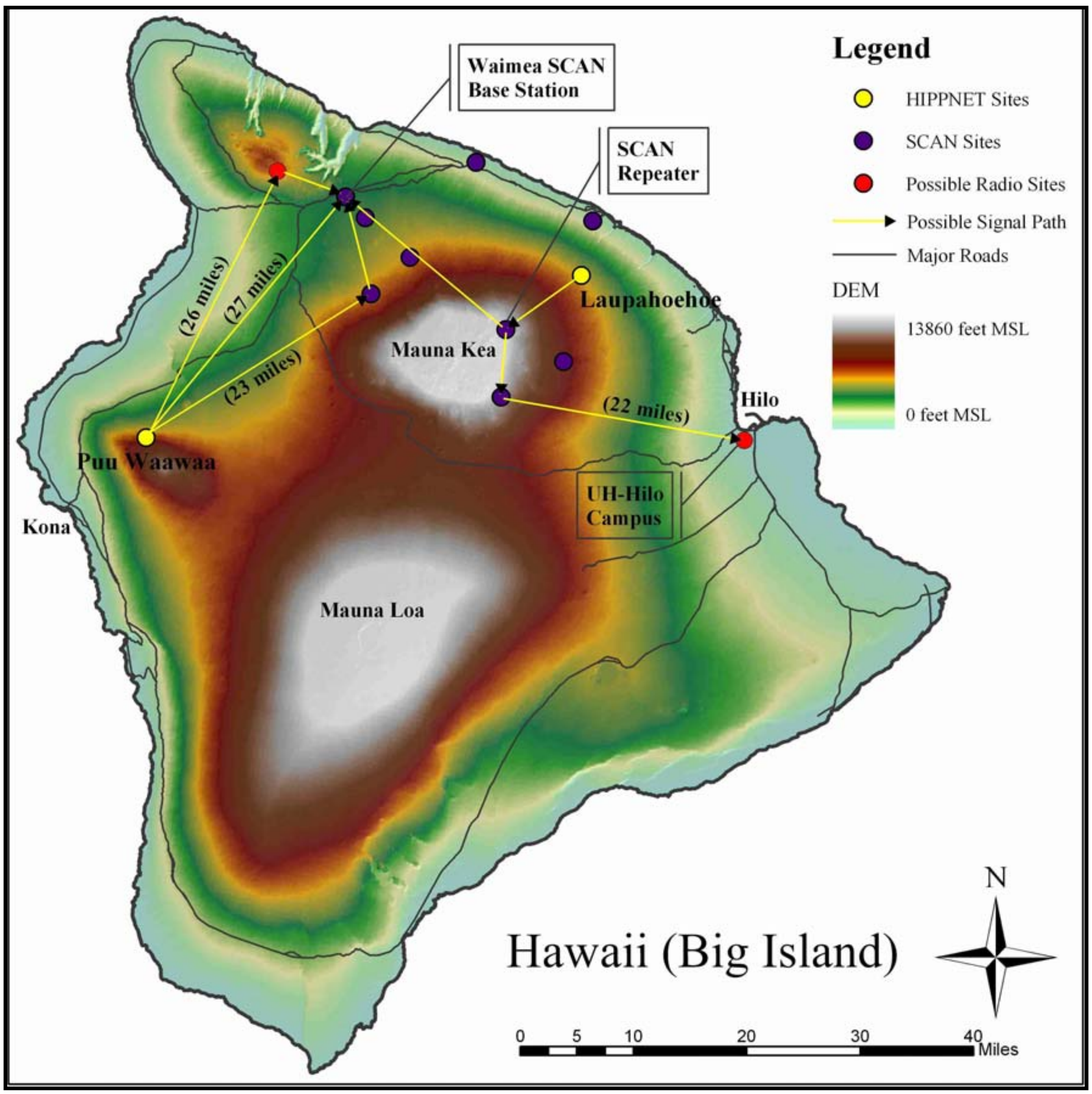
LOS-RF data transmission systems are considered to be extremely reliable in most cases. Of course proper maintenance of the transmission network will enhance both reliability and durability. Overall, this alternative is considered to be the most reliable and durable of all the alternatives evaluated for this report.

6. Suitability to HIPPNET Sites

There is an intriguing opportunity for the new instrument stations at the HIPPNET sites on Hawaii Island to be tied into an existing LOS-RF data telemetry system, that of the SCAN network operated by the USDA Natural Resources Conservation Service (NRCS). The NRCS has already been through the significant effort of performing a propagation study on the island, and they have established a network of soil and climate monitoring stations on the east and north slopes of Mauna Kea. These stations transmit data on an hourly frequency by LOS-RF to a base station located at Waimea (Kamuela), and from there the data is uploaded to an internet server. There are no significant limitations to utilizing this existing infrastructure for near real-time data transmission from the HIPPNET instrument stations to the Waimea base station.



Due to the close proximity of the SCAN repeater station to the proposed HIPPNET Laupahoehoe tower site, it is highly likely that line-of-sight transmissions could be made from a tower-mounted antenna directly into the existing network without the need for additional repeater stations. It is unclear whether additional repeaters would be needed to tie the Puu Waawaa tower-mounted instrument array into the existing network, but at most one or two repeaters would be required. This possibility should be given serious consideration because it is the ideal method of data telemetry from the two HIPPNET tower sites.



Due to the relatively high volume of data that will be recorded and transmitted from these two stations (23 individual sensors planned for each tower station), the other telemetry system alternatives are unattractive for various reasons. For cellular or private satellite systems, data transmissions from the tower sites will be relatively expensive since users are required to pay usage fees according to data volume or transmission time. For GOES satellite telemetry, the bandwidth is simply not available to accommodate high data transmission rates, except for certain applications where damage to life or property is threatened (e.g. flood warning systems).

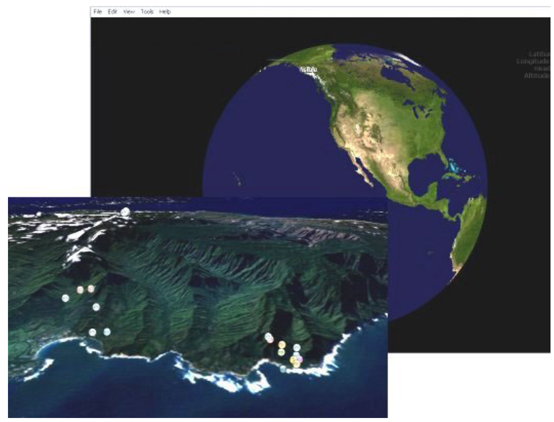
There are other advantages to utilizing the existing SCAN infrastructure on Hawaii Island. First, this system has already been demonstrated to be reliable in this environment, having worked flawlessly for over two years already. Second, as already mentioned, there will be no limitations on the volume of data that can be transmitted through the network. Also, the USDA-NRCS operates and maintains the transmission network and base stations. If the University of Hawaii or the USDA Forest Service was to share this maintenance responsibility, there will be some recurring cost for this, but it seems a small price to pay when compared with the other alternatives presented here.

Alternative # 2: Ground Based LOS-RF System – using InteleCells

1. General Description

A recent entrant into the data telemetry market, InteleSense Technologies has designed their InteleCell to meet many of the requirements of networked sensors. It is a small, ultra-low power, data acquisition platform that collects data from a number of sensors or sensor arrays. It is GPS-enabled and provides unattended monitoring at programmable intervals. It can also be used as a handheld GIS information device or data logger to feed data into the InteleNet in the field. Multiple InteleCells form a self-organizing mesh network, the InteleNet, each collecting and routing data from one or more sensors. The InteleCell was designed to address the challenges of deploying real-world, long-range, unattended networks in areas that are difficult to access. It combines the advantages of self-organizing mesh networks, such as dynamic network configuration and graceful degradation, with long-range wireless transmitters, ultra-low power consumption through several sleep modes, remote programmability, remote firmware upgrade, secure data transmission, and high reliability in tough environments.

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 that, InteleSense developed a visualization tool, 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.



2. Advantages

There are several advantages to using the InteleSense technology for data telemetry when compared to the alternatives. These include the following:

- Very low power draw due to efficient sleep mode programming
- Relatively easy to deploy in the field
- Allows for complete control over transmission network and base station
- 2-way communications
- Can perform data polling, program adjustments, firmware upgrades remotely
- Can be designed to accommodate almost any sensor imaginable
- All-in-one choice includes data telemetry, database entry, and graphic display
- Very low profile

InteleCells are currently being used for wireless data transmissions at several sites on Kauai in another University of Hawaii EPSCoR project. There they have been demonstrated to work well under the extreme environmental conditions that are typical throughout Hawaii. The level of control over the data transmission systems is exceptional when using InteleCells for data transmission. Also, it should be noted that the InteleSense alternative provides more functionality than the others evaluated for this report. This includes not only data telemetry but automated database entry and graphical display of data updated every hour.

3. Disadvantages and Limitations

While there are some great advantages to using the InteleSense technology described above, there are also a few significant disadvantages to using this system when compared to the alternatives. These include the following:

- InteleCells are not yet compatible with Campbell Scientific data loggers
- Several repeater stations would be needed to transmit data to base station

Since it has been decided to use Campbell Scientific data loggers at all the HIPPNET instrument sites, the InteleCell cannot be considered as an immediate option for data telemetry since it is not yet compatible with these loggers. However, InteleSense does have plans to add this functionality to the InteleCell technology within 1-2 years time, so it may be a viable option at some point in the near future.

Another serious consideration is the need to install several repeater stations in order to route data from the Laupahoehoe and Puu Waawaa HIPPNET sites to the base station sites that are likely to be located at the University of Hawaii at Hilo campus or at a facility in Kailua-Kona. In either case, based on the geography and topography of Hawaii Island along the transmission paths, several repeater stations will be needed in areas where access may be extremely difficult. This will of course increase up-front hardware costs and add to the maintenance burden for this alternative. Also, when the future HIPPNET sites are established on Hawaii or other islands, it is highly likely that several new repeater stations and possibly new base stations will be necessary to tie these new sites into the InteleCell networks.

Because the InteleCells use a less powerful radio transmitter (limited to 1 Watt by FCC regulation for the spread spectrum 900 MHz frequency band), slightly less range can be expected for long-distance data transmissions than for the LOS-RF systems described in the preceding section. However, with good line of sight, 7-8 miles of range can be achieved using InteleCells with an omni-directional antenna, and up to 40 miles can be expected using a directional antenna (e.g. YAGI high-gain). In many cases, actual range of data transmissions will be reduced somewhat by terrain and vegetation effects, so 5 miles and 20 miles for omni- and uni-directional antenna, respectively, are probably more appropriate range estimates to use when considering the minimum repeater spacing.

4. Costs

Since the InteleCell technology is relatively new, it is still in it research and development stage, and so it is not yet available to consumers as an off-the-shelf product. However, for the purpose of providing information that can be used to select a suitable data telemetry alternative for the HIPPNET sites, some basic cost information is presented here for an InteleCell network.

The user can expect to pay approximately $2875 for system hardware at each InteleCell station. This includes the cost of the InteleCell itself with an integrated power supply, external enclosure, a solar panel for recharging the battery, a dipole omni-directional antenna (with cable), and mounting hardware. The default dipole antenna can be replaced with a directional Yagi antenna ($220) or a high-gain omni-directional antenna ($270). At the base station end, a single InteleCell is used along with a base station module ($300) and a PC dedicated to operating as the internet server.

Because of the need to perform a radio propagation survey before designing an InteleCell network for Hawaii Island and the expected need to install several repeater stations along the data pathways between the Laupahoehoe and Puu Waawaa HIPPNET sites, the up-front costs for this alternative will be substantial. However, the expected trade-off will be very minimal recurring costs (maintenance only) and complete control over the data transmission network. FCC licensing costs do not apply since the InteleCell's transmitter operates in a ‘license-free’ spectrum.

5. Perceived Reliability and Durability

Because this is new technology, there have been very few test cases on which to base reliability and durability determinations. The system has proved to be very reliable at times at the Kauai testbed sites, but as would be expected for any developing technology there have been bugs that need to be worked out. Often this involves upgrading InteleCell firmware, either by communications with a remote PC or by visiting the instrument station. It is expected that these systems will become more and more reliable in the future as many of the early-model problems have already been resolved, and eventually it will be considered one of more reliable options for data telemetry. There is no way to gauge durability of this technology since it is so new and has not been time-tested yet.

6. Suitability to HIPPNET Sites

As already mentioned in the preceding sections, in order to use an InteleCell mesh network to transmit data from the Laupahoehoe and Puu Waawaa HIPPNET sites to base stations located at the UH-Hilo campus and/or a Kaila-Kona facility, several repeaters must be installed along the data pathways. In some cases, these repeater locations may be difficult to access and property ownership is unknown at this point in time, so it is difficult to say whether establishing a cost-effective data relay network will even be possible.

Because the locations of many of the HIPPNET instrument sites have yet to be determined, it is not possible to evaluate the suitability of this data telemetry alternative for all HIPPNET sites at this time. However, since current plans are for some of the new HIPPNET sites to be located on islands other than Hawaii (e.g. Oahu, Kauai), it can be assumed that at least one separate LOS-RF InteleCell network will be required on each island where a HIPPNET plot is located. Each InteleCell network will require its own base station, including a PC server.

Alternative # 3: Ground Based Cellular Modem Systems

1. General Description

Transmissions through the cellular phone infrastructure are also a common means for data telemetry at remote instrument stations. Of course this infrastructure was originally designed for voice communications, but procedures have been developed by the various service providers to use the cellular systems for data transmission.

The various cellular service providers use different cellular protocols including GSM (Cingular, T-Mobile), GPRS (Cingular), and CDMA (Verizon). GSM is the most widely

used cellular standard in the world. GSM modems utilize circuit switched technology, allowing data transfer at speeds of 9.6 kbps (9600 baud). GSM is a form of multiplexing, which divides the available bandwidth among the different channels. The CDMA protocol is also a form of multiplexing that uses spread spectrum transmissions, spreading a data signal over a much greater bandwidth than the original signal. Higher data transmission speeds can be achieved using CDMA modems than GSM modems.

2. Advantages

There are several advantages to using cellular modems for data telemetry versus the alternatives. These include the following:

- Relatively low up-front costs
- Uses existing transmission infrastructure
- No maintenance responsibility for transmission network
- 2-way communications
- Event notification by pager, internet, or cell phone

The most significant advantages in the above list may be the relatively low capital costs and the use of existing transmission infrastructure. This relieves the user of the need to develop their own transmission network as with typical a LOS-RF system. Two-way communications and the ability to poll data stations at any time is also an advantage over one-way alternatives such as GOES satellite telemetry. However, there are some potentially serious disadvantages to the use of cellular systems for data transmissions when compared to the alternatives evaluated here.

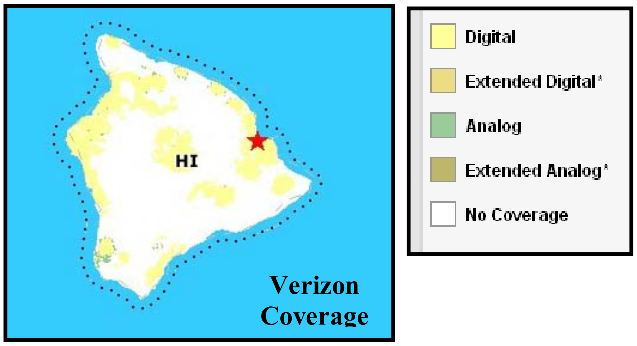
3. Disadvantages and Limitations

Features of cellular data telemetry that may be considerable drawbacks include the following:

- Limited coverage area
- Users have no control over transmission network
- Significant recurring costs
- Relatively low reliability
- Speed & latency of data transfer affected by other cellular users
- Connection may be 'dropped' during transmission activities
- Poor technical support from cellular service providers
- Minimum 1-year or 2-year contracts

An obvious limitation to the use of cellular modems for data telemetry is the limited coverage area of the various cellular service providers. While it is expected that cellular coverage will be available at several of the HIPPNET sites, it is unlikely that coverage will be available at all of the sites. This means that data telemetry through cellular networks will not be the solution for the complete line of instrument stations at the HIPPNET sites,

and one or more other alternatives will have to be used in conjunction with cellular. This



combination approach may allow for real-time or near real-time data transmissions from all the sites, but it could also complicate the set-up and operations of the systems.

The lack of ownership (and thus control) over the transmission system can be viewed as a positive or a negative factor. The positive is that the maintenance burden for the majority of the system infrastructure falls on the cellular service provider and not the customer. However, many users are not comfortable with the relative lack of control over the transmission systems that also results. For instance, if a user invests in cellular modems for data telemetry from their remote instrument stations and the cellular service provider changes the transmission network somehow (e.g. removes a single cellular tower from network), sites that were once covered by the provider may suddenly be outside the coverage area. A more likely scenario is that the cellular provider makes a substantial change in their standards, such as shifting from GSM technology to the 'next-generation' GPRS technology as Cingular is now doing. Cellular communication technology has been shown to advance at a very rapid pace, and the possibility of cellular modems and other hardware becoming outdated in a short amount of time is very real.

Everyone who has used a cellular phone knows that they are not always reliable. Signal quality can quickly deteriorate to nothing when just seconds before it was strong. Voice communications often become scrambled beyond comprehension. Dropped calls can be frequent occurrences. This variability also applies to cellular data networks. Cellular towers attempt share the frequency with all users, so speed and latency in data transmissions are strongly influenced by both location and the amount of traffic in the network at the time of transmission. This may be a factor of particular concern if it is deemed important to have the ability to transmit data during emergency events (e.g. hurricane or large forest fire). At these times, cellular traffic often peaks, resulting in little to no chance of getting transmissions through. To summarize, cellular transmissions are considered the least reliable of the data telemetry alternatives evaluated here.

Finally, there is the recurring cost associated with a cellular service plan. None of the alternative telemetry technologies presented here have significant recurring costs (other than maintenance costs). Using cellular modems, however, there will be the up-front costs of purchasing the modem and antenna and an activation fee. And then there are the monthly subscription (usually a flat monthly fee) and data rate costs (charged by the minute of 'air-time' or volume of data transferred). As the reader can see, there are significant potential disadvantages to using cellular systems for data telemetry from remote sites, and these must be weighed against the advantages this technology provides, along with cost and other considerations.

4. Costs

As previously mentioned there are up-front costs and recurring costs associated with cellular data transmission. Start-up costs include purchasing the modem, antenna, associated hardware/cables, and a one-time activation fee. The hardware costs are not likely to exceed $1200 per station. The activation fee that must be paid for every station in the network (since each requires its own account) can be sizeable (about $1000 in the case of GPRS systems) but is usually nominal (around $50-$100). Recurring costs include a service plan monthly fee ($50-$80, again on a per station basis) and usage or air-time fees, normally charged by the minute or by volume of data transferred over some monthly limit specified in the service plan. Activation of cellular service accounts often requires at least a one-year contract, enforced with a large early termination fee.

5. Perceived Reliability and Durability

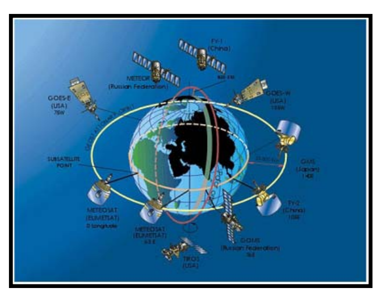
These issues have already been touched on in the preceding sections, but it bears repeating here, cellular transmissions are considered the least reliable of the data telemetry alternatives evaluated in this analysis. This can be explained by the reasons outlined in the Disadvantages and Limitations section above. Durability is also an issue due to the nature of cellular transmission technology. It often seems that the 'cutting edge' technology is outdated too soon after it is purchased because there is always the new technology on the horizon. And unfortunately for users of cellular for data telemetry, the technology is being driven by the public's desire for advances in cellular voice communications, web browsing, email exchange, or image/music downloads.

These next generation technologies are almost guaranteed to require hardware upgrades for the cellular system users to take full advantage of their enhanced capabilities. Even if these new capabilities are not needed, users may be forced to make changes anyway when the service providers change standards or protocols because the hardware must be matched to the technology. For this reason, the cellular telemetry option is also considered to be the least durable of those evaluated here.

6. Suitability to HIPPNet Sites

It has been field-verified that cellular coverage is available with at least two service providers (Cingular, Verizon) in both the Laupahoehoe and Puu Waawaa HIPPNet plot areas, so it seems possible to transmit data from these two sites using cellular modem transmissions. Since the locations of the other eight HIPPNet sites have yet to be determined, there is no way to say with any certainty that cellular coverage will or will not be available. However, due to the spotty nature of cellular coverage in Hawaii, particularly in the remote forested areas where HIPPNet sites are likely to be located, it is easy to assume that there will be no coverage or poor coverage for at least one and probably more of the to-be-determined sites.

Alternative # 4: Satellite Telemetry System – GOES Satellite



Satellite telemetry systems are a popular choice for long-range data transmissions due to the many advantages they offer over ground-based systems. In a satellite data telemetry system, one or more satellites orbiting the earth are essentially used as repeaters to relay radio transmissions from remote field stations to a base station. There are two main types of satellite systems used for data telemetry. The first is geosynchronous or geostationary satellites that are launched into a high orbit (22,240 miles above the earth) that results in the satellite remaining stationary in relation to a point on the earth's surface.

The second type is Low Earth Orbit (LEO) satellite systems in which a constellation of satellites is launched into relatively low orbits (125 – 1,200 miles). These satellites are not geostationary in relationship to the earth so the satellites appear to move across the horizon from earth. Often these systems are designed to be polar-orbiting and several satellites are launched into the same orbit. The theory is that the satellites are spaced just close enough in the same orbit that for any point on the earth's surface, when one satellite disappears from view, the next satellite in the same orbit is just coming into view or is already in view. This way, at least one satellite can always receive the signal from a ground-based transceiver, allowing for true global coverage.

Up until recent years, possession and operation of satellites was the exclusive domain of large government agencies, but now there are many privately launched and owned satellites orbiting the earth. A handful of these companies offer data transmission services using their satellites in pay-by-use arrangement. Certain satellites such as those in the GOES series are open to use by government agencies or entities sponsored by government agencies only, and there is no fee for their use. However, there are many users and a finite amount of bandwidth available so only limited use of the satellite time is allowed for most users.

1. General Description

The Geostationary Operational Environmental Satellites (GOES) are operated by the National Environmental Satellite, Data, and Information Service (NESDIS) under the direction of NOAA. This series of geostationary satellites are used for many purposes, one of which is telemetry for environmental data monitoring stations. The GOES-West satellite (technically GOES-11) is positioned over the equator at 135° west longitude, providing coverage for much of the United States including all of Hawaii. In order to


GOES Satellite

send transmissions from ground-based stations in Hawaii, an unobstructed view of the sky in the southeast direction above a zenith angle of 55° is required. Use of the GOES satellite for data telemetry is limited to federal, state, and local government agencies.

Because there is so much demand for bandwidth and time for the GOES satellites, their use is strictly regulated, normally through the use of a time-slot system. Instead of users being able to poll data from their field stations through the satellite at any time, they are restricted to regularly-scheduled time slots when their data is automatically transmitted from the instrument stations to the satellite and then to the master downlink station at Wallops Island, Virginia that serves as the ground gateway for all incoming data from the GOES satellites. From there the data is passed on to the end-user either by download from FTP servers or by automatic email distribution.

Data transmissions through the GOES satellite are usually restricted to one 10-second time slot per hour for most instrument stations. Random channels are also available for more frequent transmissions, but these are usually reserved for applications involving potential threats to life or property (e.g. flood warning systems). For small sensor arrays at remote sites the GOES telemetry option may be the ideal solution, but it should be noted that due to the bandwidth (and timeslot) limitations already mentioned, this option may not be feasible for large sensor arrays such as those planned for the Laupahoehoe and Puu Waawaa HIPPNET tower sites.

2. Advantages

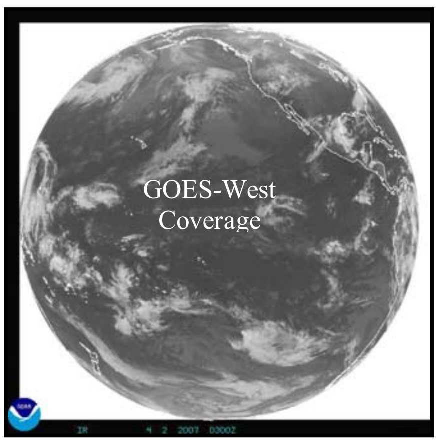
There are many significant advantages to using GOES satellite telemetry when compared to the alternatives. These include the following:

- Proven technology, very reliable data transmissions
- Allows for near real-time data telemetry
- Relatively low up-front costs unless a downlink station is needed
- No recurring cost
- Range includes entire state of Hawaii

- Ideal for remote sites where cellular or LOS-RF won't work well
- No FCC licensing required
- Minimal maintenance required

Probably the greatest advantage to GOES satellite telemetry is the combination of flexibility and reliability it offers to its users. While reliability for data transmissions is not 100%, it is above 95% for most applications. Only the LOS-RF alternative can be considered more reliable.

Because the GOES satellites are geostationary and their coverage areas are very large relative to ground-based repeaters, range limitations are really not a consideration for the use GOES satellites for data telemetry. The GOES-West satellite provides coverage for all areas on all of the Hawaiian Islands with the exception of steep northwest-facing slopes. This factor is significant because several of the HIPPNET plots have yet to be sited, so there is no way to know how well the ground-based data telemetry alternatives will work at these sites. However, it is highly probable that GOES satellite coverage will be available at most, if not all, of the to-be-determined HIPPNET instrument stations. For this reason, GOES would seem like a safe choice for data telemetry from most of the HIPPNET sites.



Recurring costs when using the GOES satellite system for data telemetry are limited to maintenance costs for the instrument stations and a nominal annual fee for satellite use. Maintenance costs may be considered negligible since the GOES transceivers would likely be serviced only during routine maintenance visits for the sensors on a frequency of every 6 months. The transceivers themselves do not require much service, but maintaining the surrounding vegetation, particularly between the directional antenna and the satellite, is very important to ensure radio transmissions from the ground station to the satellite are successful.

3. Disadvantages and Limitations

The GOES satellite data telemetry option would seem an obvious choice if were not for some substantial limitations that are inherent to the system. These include the following:

- 1-way communications, not a real point-to-point connection
- Bandwidth limitations restrict most users to 10-second transmissions
- Need south-east exposure with clear view of sky above 55° zenith angle
- Master downlink at Wallops Island, VA means one more link in data chain
- Solar activity can prevent successful satellite data transmissions
- Up-front costs for transceiver/antenna relatively high compared to alternatives
- Primarily available to government agencies
- Data is public domain (non-proprietary)
- Minimal trouble-shooting capabilities

Of the drawbacks to GOES telemetry listed above, the bandwidth limitation may be the most significant in regards to the HIPPNET applications. For the clearing instrument stations where only 3-4 sensors are planned, data transmissions through the GOES satellite will not be a problem. However, for the tower stations with 25 or more individual sensors recording, data transmissions within the allotted 10-second time slot on an hourly transmission frequency may not be possible. Of course there is potential for programming the data loggers at the tower stations to minimize the volume of data to be transmitted by reducing recorded data on-site to the minimum resolution allowable.

As an example, the loggers could be programmed to perform 15-second scans for a sensor in the array, but instead of recording at a 15-second resolution, they would reduce the 15-second data to 15-minute summaries (average and maximum values) and record these. While data resolution is lost in this scenario, the resolution achieved may still be considered acceptable depending on the potential applications of the data. Minimum data resolution is a decision that should be made by the potential users of the data, or the users should at least be allowed to provide input into the decision.

Another potential drawback to using GOES satellite telemetry systems is that it does not allow for 2-way connectivity. In other words, this alternative does not provide a real point-to-point connection that allows the user to control the field station online. Data polling is not possible using GOES, as all transmissions are made according to a set schedule.

Also, GOES data telemetry cannot be considered real-time since data updates can be no more frequent than hourly. Many users transmit every four hours or even daily, depending on the data application. It is unclear whether there will be significant advantages to real-time data collection for the HIPPNET instrument stations. Real time wind and rainfall data could be useful for fire-fighting efforts at some of the drier HIPPNET sites. Other than this, potential real-time applications are unknown to the consultant.

Normally, data transmissions from ground stations to the GOES satellite are routed to the master downlink station located at Wallops Island, Virginia, and then passed along to the end users by automatic email or download from an FTP server. The exception is if the user installs a Local Readout Ground Station (LRGS) which is essentially a downlink that can receive data transmissions directly from the GOES satellite. Since most users do not have access to a LRGS, primarily due to cost, the Wallops Island base station represents an extra link in the GOES data chain.

Since most GOES-transmitted data is routed through this single station, there is always a chance that transmissions will fail if disaster strikes the base station area. This has happened several times in the past following lightning strikes at Wallops Island, usually resulting in outages of only a few hours. NESDIS is aware of the potential problems that could occur if a hurricane made landfall near Wallops Island, and for this reason there are plans to develop a back-up central downlink in South Dakota in the near future. Other problems with the GOES data chain result during extreme solar flare activity that can prevent transmissions to or from the GOES satellite, or any high orbit satellite for that matter.

Finally, in order to transmit data to the GOES-West satellite from ground stations in Hawaii, an unobstructed view of the sky in a southeast direction above a zenith angle of 55° is generally required. While this should not be a problem for most sites in Hawaii, it could potentially be prohibitive for sites with large topographic obstructions along a southeast bearing from the station. For the Laupahoehoe and Puu Waawaa tower sites, this should not be an issue if the satellite antenna can be located above the forest canopy, as planned. It may be an issue at future HIPPNET sites, but it is not likely if the instrument stations are located in clearings, as planned.

4. Costs

The up-front costs associated with using the GOES telemetry alternative are primarily for the purchase of hardware for the field stations. This includes a GOES radio transceiver, a directional satellite antenna, a GPS antenna, and a power supply system (battery and solar charger). For a package consisting of the above hardware components, the user can expect to pay $2500 - $3500. Since the rest of the transmission network consists of the GOES satellite, the central downlink at Wallops Island, and the internet, there are no other up-front costs to the user unless a LRGS is needed. The approximate cost to establish a LRGS in Hawaii is $50,000. It should be noted that the NOAA National Weather Service in Honolulu operates a LRGS that could possibly be used to receive transmissions from the HIPPNET instrument stations.

As previously mentioned, there are no significant recurring costs when using GOES for satellite data transmissions. NESDIS does charge an annual fee for satellite usage, but this fee is nominal, about $20 per station per year.

5. Perceived Reliability and Durability

With the exception of the LOS-RF alternative presented earlier, the GOES alternative is considered the most reliable alternative evaluated in this analysis. While satellite data transmissions are susceptible to disruption by infrequent solar flares, as stated earlier they are reliable more than 95% of the time. To account for infrequent failed transmissions, redundancy is normally designed into the data collection/transmission scheme. For example, if transmission frequency is one hour, the data logger could be programmed to send not only the previous hour's data but also for the hour prior to that. This way, if a single transmission fails for any reason, the missing data will be transmitted the following hour, avoiding gaps in the dataset.

The GOES satellite option is also considered to be durable when compared to the alternatives. The overall system is likely to remain durable for as long as the GOES satellite series is maintained. With so many users dependent on the GOES satellites for various applications, it seems highly unlikely that the GOES satellite program will ever be dropped.

6. Suitability to HIPPNet Sites

Because of the GOES satellites' bandwidth limitations, and because so many sensors are planned for the Laupahoehoe and Puu Waawaa tower instrument stations, this may not be a suitable option for these two sites. Further information, particularly on required data resolution and the minimum acceptable transmission frequency, is needed to make this determination.

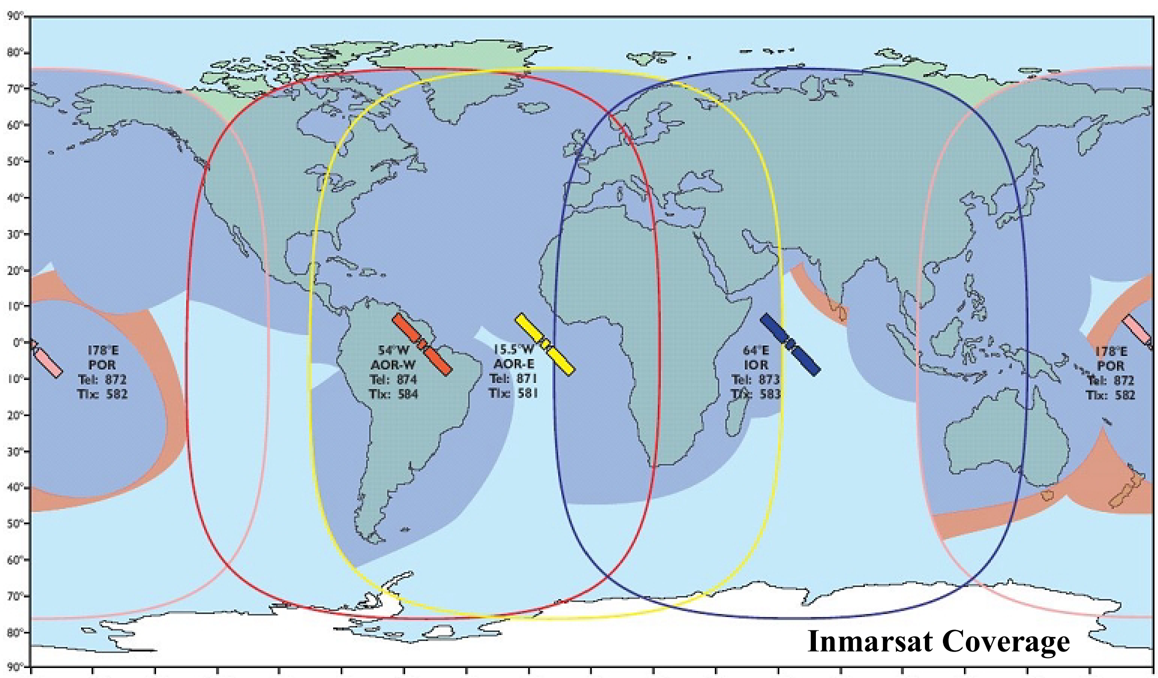
For the clearing sensor arrays at the HIPPNET sites yet to be determined, GOES satellite telemetry is likely to be a suitable option unless topography or other obstructions will prohibit transmissions to GOES-West. Also, if the sensor arrays at these sites are likely to be expanded in the future, adding several sensors to the few currently planned for these stations, the GOES option may not be suitable at that time. Again, the determination depends on the volume of data to be routed through the satellite, which is largely dependent upon the number of individual sensors in the array, the resolution of recorded data, and the desired transmission frequency.

Other Alternatives

Private (subscription) satellite services were initially considered as an option for data telemetry from the HIPPNET sensor stations. These services advertise excellent reliability 2-way connectivity, real-time data capability, and additional features such as voice communications. However, they were not considered viable options for this application for a variety of reasons.

Globarstar, a private Low Earth Orbit (LEO) satellite system, does not currently offer coverage in Hawaii and has no plans to add this soon. Iridium, another private LEO system that uses 66 polar-orbiting satellites to offer true global coverage, is only compatible for use with SEBA data loggers at the present time, and there is no indication that Iridium radio transceivers are being developed for use with Campbell Scientific loggers. Iridium also requires unobstructed east-west views above a 15° zenith for Hawaii's latitude range, which may be prohibitive for some HIPPNET sites.

Inmarsat-C is the one subscription service that has potential for use in this application. The Inmarsat satellite constellation consists of four geostationary satellites that provide coverage for most of the world's landmass and many of its ocean areas. However, this system was considered to be cost prohibitive for use in the HIPPNet monitoring scheme because of the substantial up-front costs and relatively high recurring costs.



Of course, the durability of the private satellite alternative has not been well-demonstrated since subscription services have not been around for long. But it can be assumed that if the company went under at some point in the future, the investment in this technology could very well be a complete loss.

Summary and Recommendations

Due to the nature of the Hawaii Permanent Plot Network (remote, widely-distributed plot sites featuring high forest canopies), the choice of data telemetry systems is a challenge. An alternative that may be an obvious choice for one site may not even be a possibility at another site. Of course a combination of telemetry methods could be the best approach in this case, but it is still not ideal.

As outlined in this report, every alternative has advantages and also limitations and drawbacks. These must all be considered along with the costs, convenience, and reliability of each option before the decisions can be made. The analysis for this report was solicited as an attempt to provide the information needed to make the best choice(s) for the Hawaii Permanent Plot Network. As its name implies, HIPPNET is designed to be a long-term program, and since a significant investment will be made into data telemetry systems for the HIPPNET sites, the selection of alternatives should not be taken lightly.

To summarize the information presented for each alternative evaluated for this report, a table is provided here that shows what are considered to be the most significant advantages and disadvantages of each option as well as rough cost estimates for both up-front and recurring costs. Perceived reliability of each alternative relative to the other alternatives is also shown in the table.

Alternative	Advantages	Disadvantages	Costs	Reliability
1. Ground Based LOS-RF System – utilizing SCAN infrastructure	Very reliable, 2-way communications, low cost	Can be difficult to configure, may require propagation study, can be costly, FCC licensing may apply	Up-front: $1200/station, base station $1000 - $2000, Recurring: None	Highest
2. Ground Based LOS-RF System – InteleSense InteleCell	Complete control over network, 2-way communications, data archive and display features	Not compatible with Campbell loggers, several repeaters necessary	Up-front: $3000/station, $3000/repeater, base station $4000, Recurring: None	Potential to be very high
3. Ground Based Cellular Modem Systems	Uses existing transmission network, low up-front cost, 2-way communications	Limited coverage area, no control over network, low reliability, contract	Up-front: $1200/station for hardware, $100/station for account start-up, Recurring: $50/month/station	Lowest
4. Satellite Telemetry System – GOES Satellite	Reliable, no range limitations, low cost, good for remote sites	No 2-way communications, bandwidth limitations, time delay in data transmission	Up-front: $3000/station, Recurring: None	High

For data telemetry from the HIPPNET tower sites at Laupahoehoe and Puu Waawaa, it seems reasonable to consider all of the alternatives presented here, perhaps with the exception being the GOES satellite alternative that may not be possible due to bandwidth limitations of the satellite. Line-of-sight radio telemetry utilizing the existing SCAN infrastructure seems like the alternative with the most potential for these two sites, but if a single alternative is desired for use throughout the HIPPNET system, this option cannot be considered because of its distance from potential plot sites on other islands.

Because cellular coverage is known to be available at the Laupahoehoe and Puu Waawaa instrument sites, cellular modem systems may also be a good choice for data collection from these two sites, but there are serious questions about the reliability and durability of these systems. Also, this option minimizes up-front costs, but significant recurring costs (on a contract basis) must be expected.

Because the final plot locations have yet to be determined, it is impossible to assess the suitability of the evaluated alternatives for these sites. If a decision on data telemetry must be made before the final plot sites are selected, it is recommended that the alternative(s) allowing the most flexibility (i.e. least limitations) be pursued. For the clearing sites at the unknown plot locations, the alternatives providing the most flexibility are GOES satellite systems and cellular modem systems. Since it is unlikely that cellular coverage will be available at all of the future HIPPNET sites, and the GOES option has the important advantage of no recurring costs, the recommendation would be to use a

GOES data telemetry system. However, if it seems likely that the sensor arrays at these sites will be significantly expanded in the future (i.e. several new sensors added), then the bandwidth issue of the GOES satellite may become limiting. NESDIS does intend to expand GOES bandwidth in the future to accommodate the increasing demand for the satellites' time from its many users, but this is not expected to happen for several years.

In the end, a combination of the alternatives presented here may be the logical approach. Of course a consistent method of remote data collection is most desirable for this application, but it may not be feasible given the limitations of each alternative presented here. Obviously, before any decisions regarding appropriate data telemetry systems are made, it should first be collectively decided by the users that data telemetry systems are actually warranted. If there is no special need for frequent updates of the databases for the various sensor stations associated with the HIPPNET programs, then the on-site data logging option should be strongly considered.

If the decision is made to pursue a data telemetry alternative for one or more of the HIPPNET sites, it is recommended that the question of minimum data resolution be answered before attempting to choose an approach. If this is done, the resolution information could be used with specifications for the individual sensors that will be installed in the HIPPNET tower arrays to predict the volume of data to be recorded and transmitted from these sites. This will allow for final determinations of whether or not GOES telemetry can be considered an option for these sites and will provide the information needed to predict the recurring cost for the cellular modem option.

If the GOES alternative is found to be a viable option for the tower sites, the recommendation would be to use GOES satellite telemetry for all HIPPNet instrument stations. This would provide the consistency in data collection for the entire plot network that probably cannot be achieved using any other alternative. If it is determined that GOES telemetry is not an option for the tower sites, another alternative must be selected for these two sites, but GOES should still be considered for the future HIPPNET sites.