Design and Implementation of a Wireless Video Camera Network for Coastal Erosion Monitoring*

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Abstract–The short-term rate of coastal erosion and recession has been observed at island shoreline bluffs near waterways among Boston Harbor, Massachusetts, USA. This erosion has been hypothesized partially related to waves from high-speed wakes. Recording the physical erosion events during extreme high waves is significant to evaluate the dynamics of bluff erosion and to document these short-term processes. Still and motion imagery are important media to observe rare and extreme events in ecology, geology, and environmental condition. The study of coastal erosion requires recording devices for these modalities capable of long-term, low-cost, low-power operation with low maintenance, and with the ability to support a large dynamic range in both time and space. We describe recent work in the development of a wireless video camera network for an ecosystem observation platform. These cameras are enclosed in weatherproof housings and supported by solar energy harvesting. The cameras are Internet-enabled and thus live video can be accessed remotely. Video streams are transmitted via wireless network, and delivered to and stored

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at a remote server. This system has been functional as designed since installation in October 2012 on Thompson Island, Massachusetts, and is expected to operate indefinitely. To date, a number of erosion-related events have been successfully captured. This platform has shown the potential to be used in large scale for a variety of environmental monitoring studies.

1 Introduction

Global climate change is predicted to cause a rise of 50 centimeters in sea level in the next century [1], and rising sea level in turn impacts the erosion of coastlines worldwide. In particular, rising sea level in the Northeast of the Unites States has changed sediment supplies and pathways, and altered patterns of erosion and deposition. The Boston Harbor Islands National Recreation Area, Massachusetts, USA shown in Figure 1 is an exceptional geological system of 34 islands resulting primarily from the submergence of drumlins [2]. The short-term rate of erosion and shoreline recession is predominately related to incident waves, high tides, ferry wakes and exposure to storms [3]. Erosion rate varies from island to island. Between 1938 and 1977, Thompson Island (shown in Figure 1) experienced bluff retreat of 18 meters. The highest rates have been observed along a shoreline in coastal waterways, which is subjected to only moderate waves [4]. It has been hypothesized this erosion is partially related to the high-speed wakes generated by passenger ferries and regional vessels. At high tide these waves may reach 0.3 to 0.6 meters, and are able to reach the base of the bluff. Capturing the actual erosion events during extreme high waves is significant to understand the dynamics of slumping on the bluff and to document the short-term process of bluff erosion.

Still and motion imagery include a wealth of visible details for the observation of behavior of organisms, infrequent and extreme events in ecology, geology, environmental condition, and meteorology. They serve as important media to document both short- and long-term changes. For example, cameras have been used for census of bats emerging from shelters [5], observing activities in bee colonies [6], tracking green-up forests [7], monitoring polar environments [8], and nearshore ocean studies [9]. Such uses of cameras enable unobtrusive and unattended observation over long time periods. Archived images and videos can be further analyzed using various advanced image/video processing algorithms [10, 11, 12] for modeling and understanding marine environment, such as summarizing hours of video down to a few short segments containing only targeted salient events [13].

Traditional ecological cameras produce a relatively small number of still images. These images are either stored locally and downloaded manually, or packed and delivered to remote servers. Few of these cameras are deployed without wired power and network infrastructure. The physical environment of most studies in ecology and geology set severe limitations on such cameras as they need to be able to operate long-term, low-cost, low-energy, and low-maintenance, and to support a large dynamic range in both time and space. In addition, these cameras must be enclosed in weatherproof housings, and be able to harvest energy if needed. As videos are increasingly being applied to continuously monitor dynamic processes, there is a desire for remotely accessible live video solutions in ecological studies, which must be supported by wired or wireless telemetry. The rich visual details in video data require significant energy resources to sustain recording,

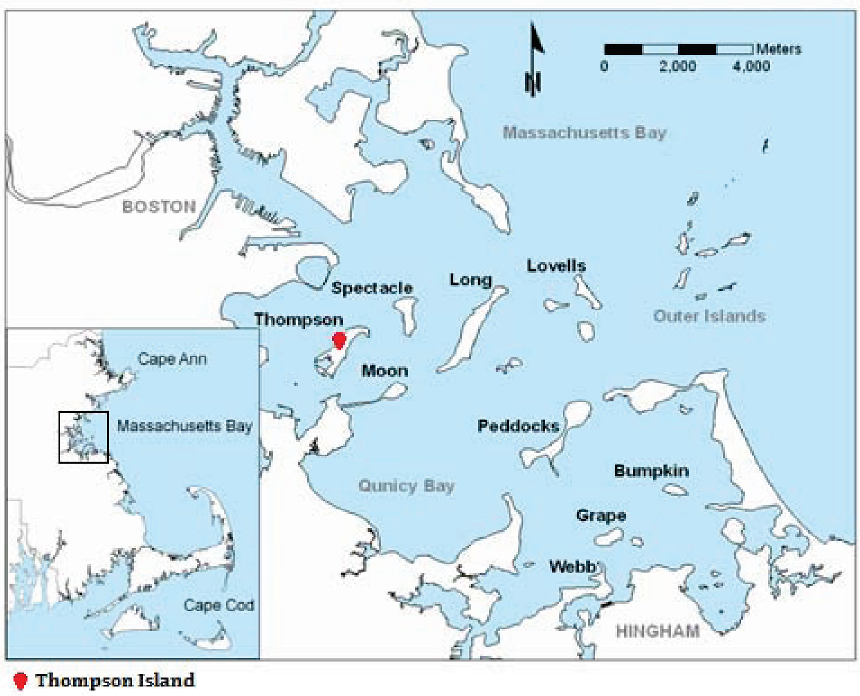

Fig. 1 Boston Harbor Islands

communication, and storage.

Based on our preliminary work of a low-power and low-cost video sensor unit prototype [14], we designed a wireless video camera network to facilitate monitoring and studying coastal retreat. The design demonstrates low-cost, long-term, low-power, energy-harvesting, autonomous operation, wireless network for video delivery, remote access, and live video. A wireless network system with two cameras is implemented to assess the impact of ferry wakes, waves, and high tides on shoreline erosion on Thompson Island, Massachusetts. One camera is studying the 20-foot bluff at the northeast tip that is undergoing rapid erosion. The second camera has been alternately focused on a tidal pond and a low sand and clay beach. These cameras will help to understand the possible driving factors for erosion and will also evaluate the usefulness of video cameras in coastal environmental science. The result from this system can lead to further studies in other parts of Boston Harbor and has already led to reapplication of remote video cameras for other environmental processes.

2 Camera System Design

This section presents major strategies for the camera system design, including the design requirements, network nodes, network setup, power management and energy harvest.

2.1 Design Requirements

The camera system is aimed to operate unattended in the field to support studies of ecology, geology, and environmental sciences. The physical world poses challenging requirements on the system design, ranging from extreme weather to accessibility difficulties and to needs for alternative power. Our approach was to exploit advances in technology to fulfill coastal monitoring requirements as follows.

- Low-cost. The camera network for coastal and other ecological monitoring requires supporting a large dynamic spatial range, and thus supporting the potential to be deployed over large scales. The system must be designed for low cost when produced in quantity.
- Long-term. Most coastal erosion is episodic and infrequent. Studies generally last for years to decades. The system must work for long time periods to support the large dynamics in temporal ranges. When a number of relay nodes are implemented, they can form a distributed mesh network.
- Low-maintenance. Typical study areas offer limited access, for example nature reserves and conservation areas. A minimal impact on the studied phenomena is desired, and the system must not cause any significant impact on the environment where it is installed. The mechanical packaging must be robust to survive different, sometimes severe weather conditions in the harsh coastal environment, such as lightning and extreme storms.
- Low-power and energy replenishment. The rich visual details in video data require significant energy resources to sustain recording, communication, and storage. Wired power is usually not available along shorelines. The camera system must be designed to run on batteries with a conservative power budget, and it must be able to harvest energy from the environment such as solar or wind power.
- Remote access and live view. Due to limited access to study area, cameras are required to be accessible remotely to configure imagery and video parameters such as resolution, frame rate, and compression rate. To meet such challenges, the cameras are designed wireless-networked and Internet-enabled. Live views are also required occasionally to monitor the status of the equipment and the site.
- Capable of video delivery and storage. The wireless network must be provisioned to support stable video transmission to the remote server or an arbitrarily-located consumer. Video storage cannot be neglected for further analysis and archive. This challenge implies an integration of network metrics [15], including bandwidth, signal-noise ratio (SNR), and routing.

2.2 Network Nodes

Figure 2 illustrates the general network structure for the camera network including camera nodes, relay nodes, and base stations. Low-cost, off-the-shelf devices are selected, which also ease the installation and operation processes for ecological and geological scientists.

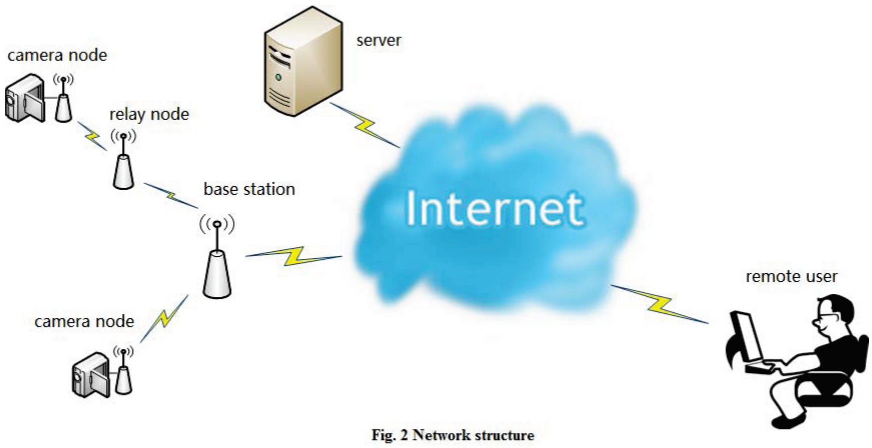

Fig. 2 Network structure

- Camera Node. A camera node is composed of an AXIS M1101 Network Camera (AXIS communications, Inc. Sweden) and a PicoStation2 antenna (Ubiquiti Networks, Inc. San Jose, CA, USA). The AXIS camera provides multiple choices of video compression, resolutions, frame rate, video streaming, and image settings. The PicoStation2 (Pico2) enables omnidirectional wireless connection up to the outdoor range of 150 meters.

- Relay node. A relay node is an optional node intended to extend wireless network coverage, to establish a network route, and/or to support video forwarding. It is composed of PicoStation2 and NanoStation2 antennas (Ubiquiti Networks, Inc. San Jose, CA, USA), depending on the connectivity distances required. A NanoStation2 (Nano2) enables planar directional wireless connection up to 15 kilometers outdoor.

- Base station. A base station aggregates video data from camera nodes and relay nodes, and connects to high-speed Internet and remote servers. The base station is composed of multiple networking devices. We use the PowerStation2 antennas (Ubiquiti Networks, Inc. San Jose, CA, USA) to support large radio coverage (over 50 kilometers) and high-speed communication for video streams.

- Server. The server stores video streams originating from camera nodes. The AXIS Camera Station software (AXIS communications, Inc. Sweden) is installed for video management, and for providing the functions of buffering, recording, organizing and retrieving.

2.3 Network Setup

To monitor erosion at two sites on Thompson Island, the beach/salt pond and the bluff, the network is designed using a star /tree topology with one base station, two camera nodes, and one relay node where necessary. All Ubiquiti devices support IEEE 802.11b/g protocol, commonly known as Wi-Fi. Point-to-point wireless connections are set up between network nodes. For remote access and live view, a fixed static IP address is assigned to each of the AXIS cameras and Ubiquiti devices in the same subnet. The Ubiquiti antennas are configured in the bridge mode for the simplicity and security of this network, and routing schemes are preprogrammed for each network node. We also define users with different authorization and security levels. A remote server is placed close

Table 1: Device Electrical Metrics

Device	Operating voltage (V)	Surge current (A)	Max power consumption (W)
AXIS camera	5	0.5	2.2 (including regulator efficiency)
Pico2	12	1	4
Nano2	12	1	4
PS2	12	1	6.5

$$\begin{cases} \text{Node consumption (Wh/day)} = \sum \text{device consumption (Walt)} \times \text{Node ON time (hours/day)} \\ \text{Solar supply (Wh/day)} = \text{Panel power (Walt)} \times \text{Effective ON time (hours/day)} \\ \text{Battery energy (Wh)} = \text{Battery voltage (volt)} \times \text{Capacity (Ah)} \\ \text{Solar supply IN} \geq \text{Node comsumption OUT} \\ \text{Battery energy(Wh)} \geq \text{Node consumption (Wh/day)} \times \text{Operating time without Sun(day)} \end{cases}$$

Fig. 3 Power Budget Formulation

to the subnet to reduce unnecessary impact of network traffic and firewalls. Management software runs on the server, storing and organizing received real-time video, and providing live view and playback. All devices can be remotely accessed for troubleshooting and configuration. The Live views are also available on the camera's webpage.

Additional network nodes can be connected in the mesh topology, and the Ubiquiti antennas can work under the router mode for large-scale studies with large numbers of interesting targets. Extra routers can be added to enhance advanced routing techniques.

2.4 Power Management and Energy Harvesting

As with many coastal study sites, wired power is not available along Thompson Island‘s coast. All devices need to be powered by a local energy source such as batteries. To sustain the video generation and delivery over the long terms, solar panels are employed for energy harvesting. We plan the power budget of each network node based on the device electrical metrics in Table 1.

The power budget for each node in the field accounted for total device consumption, battery capacity, and solar power supply. The solar panel automatically harvests energy; however, its effective operating time depends on the physical location and time exposure to the sun. For our deployment, we estimated approximately 4 hours of sunlight during mid-winter. The desired working length in days of the camera system without energy source was also considered, resulting in a target of three days of battery capacity. The planning was formulated as Figure 3, and the battery and solar panel were selected to meet these requirements.

We applied a programmable timer to switch each field node ‘on’ in the morning and ‘off’ in the afternoon, instead of running for 24 hours and getting meaningless dark videos every night. The power budget can be further optimized regarding the daily charging surplus, the solar supply minus node consumption. Most erosion is driven by incident waves, high tides, ferry wakes and extreme weather conditions like storms. The ideal coastal erosion video system would turn each node on only during high tides and storms. This will be part of our next generation design.

Table 2: Device Physical and Environmental Characteristics

Device	Weight (Kg)	Operating humidity (%)	Temperature (°C)	Enclosure
AXIS camera	0.94	20 to 80	0 to 50	weatherproof case
Pico2	0.1	5 to 95	-20 to 70	outdoor UV stabilized plastic
Nano2	0.4	5 to 95	-20 to 70	outdoor UV stabilized plastic
PS2	4	5 to 95	-40 to 80	Outdoor UV stabilized plastic and die cast metal

Table 3: Ubiquiti Antenna Performance

Device	Radio Coverage	Radio Angle
Pico2	150m	Omni-directional
Nano2	15km+	elevation 30°C, azimuth 60°C
PS2	50Km+	18°C

3 Camera System Implementation

The AXIS cameras and Ubiquiti antennas can operate over a large temperature range and survive in humid environments with the weatherproof enclosures. The physical and environmental characteristics are listed in Table 2. All devices are small, easy to mount and non-invasive to the surroundings.

The geographic and topographic features of the study site define practical limitations on the site selection. Table 3 provides the antenna performance information from the Ubiquiti device datasheets. All Ubiquiti devices in the field require line-of-sight connections. After we tested several implementation layouts on Thompson Island, the camera system was deployed as shown in Figure 4a in response to the topography of the island. The base station (Figure4 b) is located near the salt tidal pond, where the PS2 achieves high-speed connectivity to the receiver located at the UMass Boston facility. The Nano2 is used to connect the base station to the relay node. Due to the hills and trees on the island and the height of the bluff, the relay node of a Nano2 and a Pico2 (Figure4d) is sited above the bluff, connecting the base station and the camera node at the bluff in Figure 4c. Installation was simplified by using the Power-Over-Ethernet (PoE) technology of the networking devices which allows power to be distributed using a single networking cable. Other circuit components are added to protect nodes' operation, including charge controllers between solar panel and battery, voltage regulators, fuses and lightning arrestors. Table 4 lists devices installed at each network node and the estimation about their costs. Camera B for beach/salt pond is connected directly to the base station to reduce the implementation cost for a second camera node, but it can also be wirelessly networked similar to Camera A. The power budgets for this configuration are identified as shown in Table 5.

Functional tools on each Ubiquiti device configuration page are used to analyze and optimize network performances, including site survey of interfering Wi-Fi channel usage and antenna align-

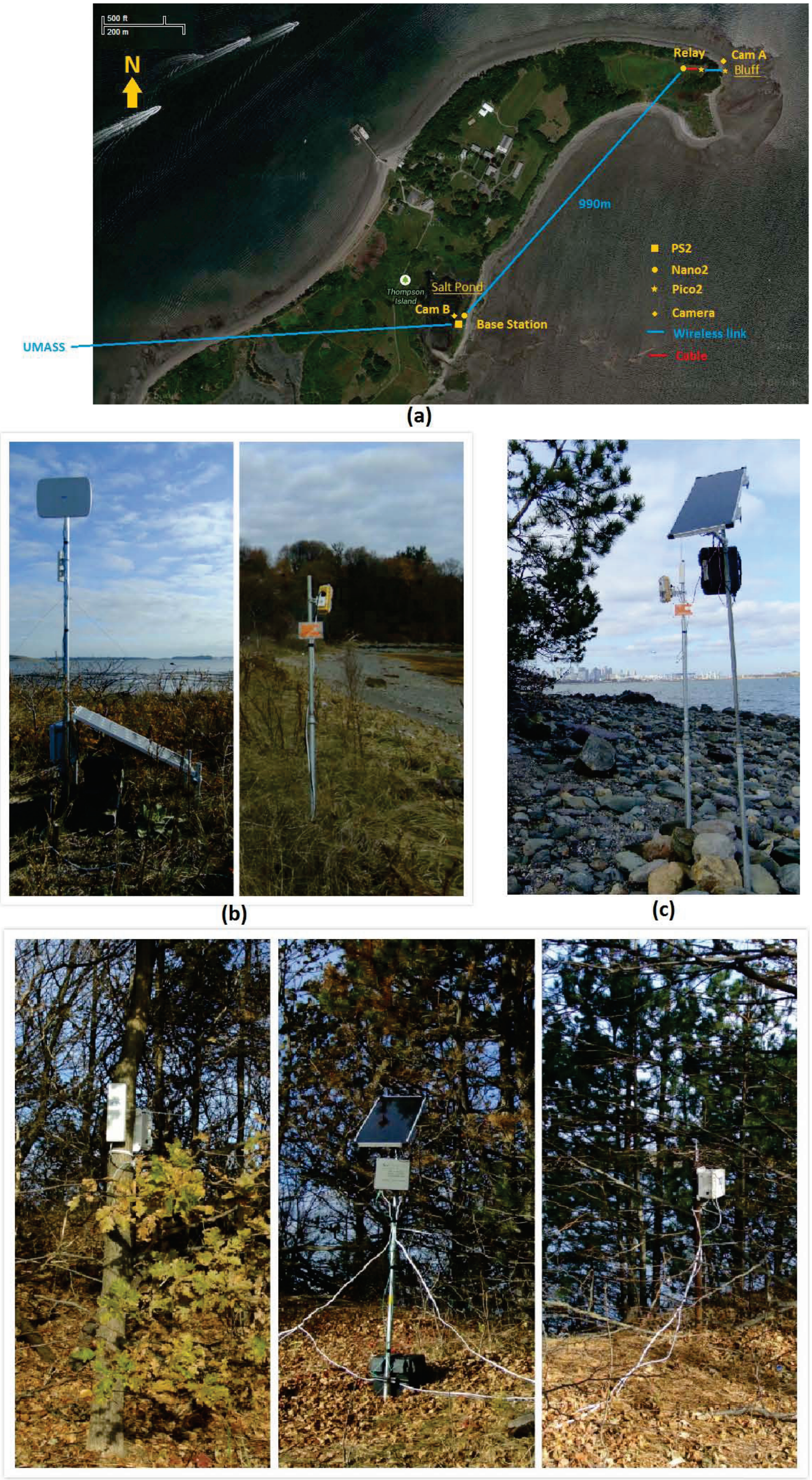

Fig.4 **Camera Network Implementation:**
(a) map of implementation;
(b) base station; (c) bluff camera node;
(d) relay node on the bluff.

Table 4: Network Node Deployment and Cost

Network Node	Devices	Power Components	Circuit control	Cost ($)
Base Station	PS2, Nano2, AXIS camera	Solar panel, Marine battery	solar charge controller, voltage regulator, timer switch, fuse	795
Relay Node	Nano2, Pico2	Solar panel, Marine battery	solar charge controller, timer switch, fuse	290
Bluff Camera Node2	Pico2, AXIS camera	Solar panel, Lead-acid battery	solar charge controller, voltage regulator, timer switch, fuse	440

Table 5: Network Node Power Budget

Node	Consumption			Solar Supply					
	Device (watt)	ON time (hr/day)	Daily (watt-hr/day)	Power (watt)	Effective ON time (hr/day)	Daily (watt-hr/day)	Voltage (volt)	Capacity (Ah)	Total (watt-hr)
Base Station	13.1	6	78.6	85	3	255	12	80	960
Relay Node	9	5	45	27	3	81	12	80	960
Bluff Camera Node	6.6	5	33	27	3	81	12	12	144

ments. Our two wireless links (Link A and Link B in Figure 4a) are tuned to different channels to eliminate interference or congestion between adjacent links inside our network and that from outside networks. Antennas are aligned to achieve the highest wireless signal strength. The improved wireless link characteristics are shown in Table 6, including channel, signal strength, speed rate, throughput etc.

The implementation process consists of assembling the camera and network components and their site deployment in the field. Hardware assembly is the construction of the node support structures and pre-testing of all connectivity. Once all hardware is procured, this can be completed off-site in one to two days by two people. With a good knowledge of topography, the site deployment requires as similar level of effort. Node deployment involves initial testing of locations for wireless connectivity, installation of structures, and final tuning of wireless settings. Total effort for construction and deployment should range from 32 to 64 person-hours, assuming all supplies and site surveying are prepared ahead of time.

Table 6: Wireless Link Characteristics

Characteristics		Link A	Link B
Channel (1-11)		9	5
Frequency (Hz)		2452	2432
Signal Strenth (dBm)		-55	-50
Noise Floor (dBm)		-96	-94
Transmit CCQ [1] (%)		88	95
ACK Timeout (ms)		40	32
Speed Rate	Tx (Mbps)	9.24	18.71
	Rx (Mbps)	9.24	18.71
Throughput	Tx (kbps)	437	771
	Rx (kbps)	580	454

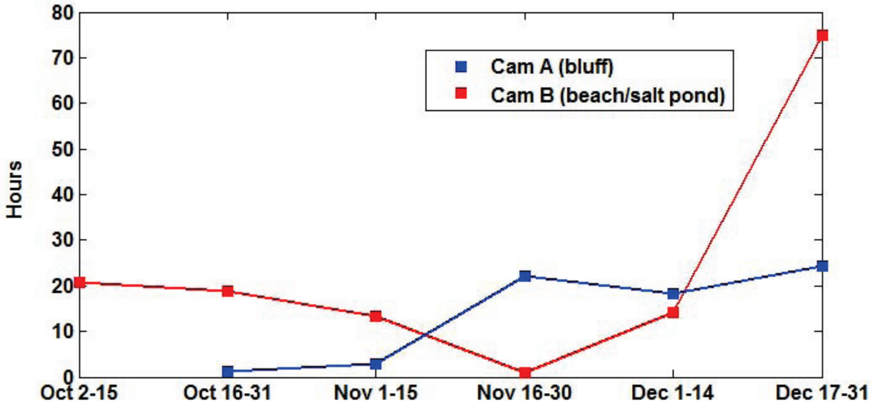

Fig.5 Video Stored on the Server

[1] Transmit CCQ is an index of the connection quality by integrating transmit errors, latency, throughput, etc. The percentage level is based on a perfect link state as 100%.

4 Results and Discussion

We first established the ability to deliver video of the salt pond from camera B through the network in the beginning of October 2012. After the relay node was added in the middle of October, video of the bluff from Camera A arrived at the server, but the capability was sporadic. Through improving efforts on power budgeting and antenna channel tuning in November 2012, the video streams became much more stable. A significant improvement was made to the bluff camera A in early November when we added power-cycling timers. Late in November we discovered that camera B was defective, which led to poor results at that time. Camera B was replaced in early December; and there have been no subsequent maintenance issues since this time. The power-cycling timers have demonstrated effective scheduling to reduce individual device power consumption by shutting-off devices when no recordings are active. In total, 211 hours of video (over 112GB) have been transmitted from these cameras and have been stored on the remote server. Figure 5 shows how the volume of stored video has steadily increased from October to December due to the improvements described above. The system has been designed to accommodate the worst-case sunlight harvesting period (winter) and thus we are confident it will continue working in spring and summer when more solar energy is available. In the future we anticipate additional energy savings by combining the schedule of tide with the diurnal cycle to only enable cameras at peaks during daylight. This will be achieved with a customized microcontroller power cycling system programmed with tide tables. We will be sure to capture the high-tide waves and the systems will be safely within the power budget of the solar panels.

Since initial operation, several significant erosion related events have been successfully captured. Figure 6 presents snapshots from the bluff video of these event periods. A major event on the bluff was identified by the images before (Fig.6a) and after (Figure 6b) Hurricane Sandy on Oct 29, 2012. The network was not robust enough at that time to obtain live video when the erosion was happening during the hurricane, but video of falling debris was captured on Nov 1, 2012 (Figure 6c and d). Video of boat wakes hitting the bluff during an extreme high tide was captured on Dec 18, 2012 (Figure 6e). No noticeable change in the bluff was observed after being battered by waves 2 feet above the beach edge, suggesting that boat wakes are not prolonged enough to erode the hard clay of the bluff. During the period from Dec 22, 2012 to Jan 6, 2013, a combination of factors produced erosion. On Dec 27, high tide and high winds with gusts up to

45 mph caused a major bluff change. The bluff camera did not record during the event, but camera images from Dec 28 (Figure 6g) showed significant erosion. During this period the temperature was also steadily below freezing. Snow covered the bluff for periods, and frozen soil was visible in the images (Figure 6f). On Jan 6, 2013, minor slumping was visible in the camera images (Figure 6h). Video shows that tides were not high enough to reach the base of the bluff; but this slumping appears to be caused as a result of the frost. Even though the cameras have been in the field only a short time, the bluff camera has already captured valuable images that may refute boat wakes as a cause of erosion and raise the possibility that frost could play a major role in winter.

Camera B is an experimental and opportunistic camera. Figure 7 shows several images from this camera. It was first aimed on the salt pond behind a sand berm, where it captured interesting videos of tidal encroachment on Oct 19, 2012 (Figure 7a and b) and Hurricane Sandy on Oct 29, 2012 (Figure 7c). Later it was aimed on the beach and used to create time-series images of the beach shoreline. On Dec 27, 2012 it captured video of 30 mph winds combined with an extreme high tide (Figure 7f). Video showed waves breaking over the grasses of the sand berm.

5 Conclusions

Ecological and environmental study using video in the physical world implies technical requirements with video cameras and computer networking. To be a viable modality in most ecological observation scenarios, cameras must be low-cost, long-term, low-maintenance, low-power, capable of autonomous energy harvesting, and networked to enable remote access, live view, video delivery and storage. We designed wireless-networked video cameras to meet such challenges, and implemented the system on Thompson Island for coastal erosion monitoring. In the brief period of initial deployment in the fall of 2012, the system has recorded and delivered more than 112 GB of video to the remote server. Valuable erosion related events have already been captured, including impacts from Hurricane Sandy, high winds, extreme tides, boat wakes and frost. It appears that short-term erosion mainly occurs at the highest high tides (with storm surge on top of astronomical high tides) and during winter freeze-thaw cycling, and erosion is not significant at other times of year or due to boat wakes. This information will help to further focus the observation on related factors.

Since January 2013, additional improvements to the system have been achieved. These include optimization of the image and video recording characteristics (resolution and rate), and the introduction of a customized microcontroller-based power cycling system. The use of this device to match the high tide schedule allows a 50% reduction in power consumption. The video cameras have been programmed to more sophisticated settings, such as scheduling to take images at specified time intervals, and opportunistically delivering via multiple network protocols such as FTP. This system has now been functional for more than seven months, and is expected to operate indefinitely with little maintenance (approximately 4 site visits per year to inspect the equipment and facilitate maintenance).

In summary, the camera network installed on Thompson Island has exceeded our expectations for capturing events that would otherwise go undetected by humans. As a direct result of the success of this system, we have been approached to by a team of investigators to assist in installing a comparable system to investigate coastal erosion at the Jones River Watershed near Plymouth, MA. As the cost and availability of this technology continues to improve, we anticipate increasing benefits in its use in ecological study.

(a) (b) (c) (d) (e) (f) (g) (h)

Fig.6 Bluff Erosion Monitoring
(a) Oct 27, 2012 pre-Hurricane Sandy; (b) Oct 30, 2012 post-Hurricane Sandy;
(c) Nov 1, 2012 debris falling; (d) Nov 1, 2012 post-debris falling;
(e) Dec 18, 2012 extreme high waves; (f) Dec 25, 2012 snow and frost;
(g) Dec 28, 2012 erosion post 45 mph winds; (h) Jan 6, 2013 minor slumping.

Fig.7 Salt Pond / Beach Study
(a) Oct 19, 2012 Salt pond tidal encroachment started; (b) Oct 19, 2012 Salt pond high tide; (c) Oct 29, 2012 Salt pond during Hurricane Sandy; (d) Dec 11, 2012 Beach extreme low tide; (e) Dec 18, 2012 Beach boat wakes; (f) Dec 27, 2012 Beach extreme high waves when wind is 30 mph; (g) Dec 28, 2012 Beach possible frost line; (h) Dec 29, 2012 Beach during snow storm; (i) Dec 31, 2012 Beach post snow storm.

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