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3aAB3. An autonomous, near-real-time buoy system for automatic detection of North Atlantic right whale calls

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A moored buoy system for automatic detection of endangered North Atlantic right whale (NARW) contacts was developed to provide near-real-time information on the presence of vocalizing whales. The marine components include the WHOI buoy platform (mooring, hydrophone, power system, surface expression, antennae) and Cornell buoy electronics (housing, analog interface hardware, GPS, embedded computer, detection engine, and telemetry hardware). Shore-side Cornell components include telemetry equipment, server hardware and processing software, database, and interfaces for data annotation, access, and visualization. The buoy hardware/software system is capable of capturing and ranking NARW contact candidates as 2s, 2000Hz sampled audio clips. Location, timestamp and other metadata associated with each audio clip are assembled and uploaded via satellite for processing. Human analysts regularly annotate incoming data, resulting in a curated database of NARW detections. Periodic 'health and status' data allow for confirmation that buoys are functional. Regular voltage reporting helps predict required maintenance. Following initial implementations of the system in 2005, a series of successes and failures have led to system improvements in the buoy mooring, electronics, and server components. Deployments have progressed from prototype near-shore units to an operational network continuously monitoring the shipping lanes off Boston to meet ship strike mitigation requirements.

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Introduction:

We have developed an acoustic monitoring buoy system for the purposes of providing timely data on presence of North Atlantic Right Whale (*Eubalaena glacialis*) as a near-real-time supplement to existing survey strategies (e.g. visual overflight and long-term acoustic monitoring with submersible ocean bottom recording devices.. These initial proof-of-concept buoys were first deployed in Cape Cod Bay (CCB) Oct 2004, followed by a series of deployments and system improvements in subsequent years. All versions of the buoy electronics implemented some version of Doug Gillespie's NARW Detector[1] (DG). Subsequent deployments occurred in Boston Harbor, the Transportation Separation Scheme (TSS) shipping lanes through Stellwagen Bank National Marine Sanctuary, Cape Cod Bay, and off the coasts of Florida and Georgia. In 2008 we deployed a version of this system in the TSS as a near-real-time monitoring solution to try and protect these endangered animals by alerting ship-captains of NARW detections, who could then reduce their speed to less than 10 knots. Between 04/01/2005 and 05/01/2009 over 271,000 2-second, 2kHz detection events were captured with their audio clips, of which 39,429 were annotated as NRW calls by human experts. This paper provides a brief overview of the equipment deployed, an overview of the evolution of the monitoring system from 2005 – 2009, and compares the false positive rates of the buoy system versions.

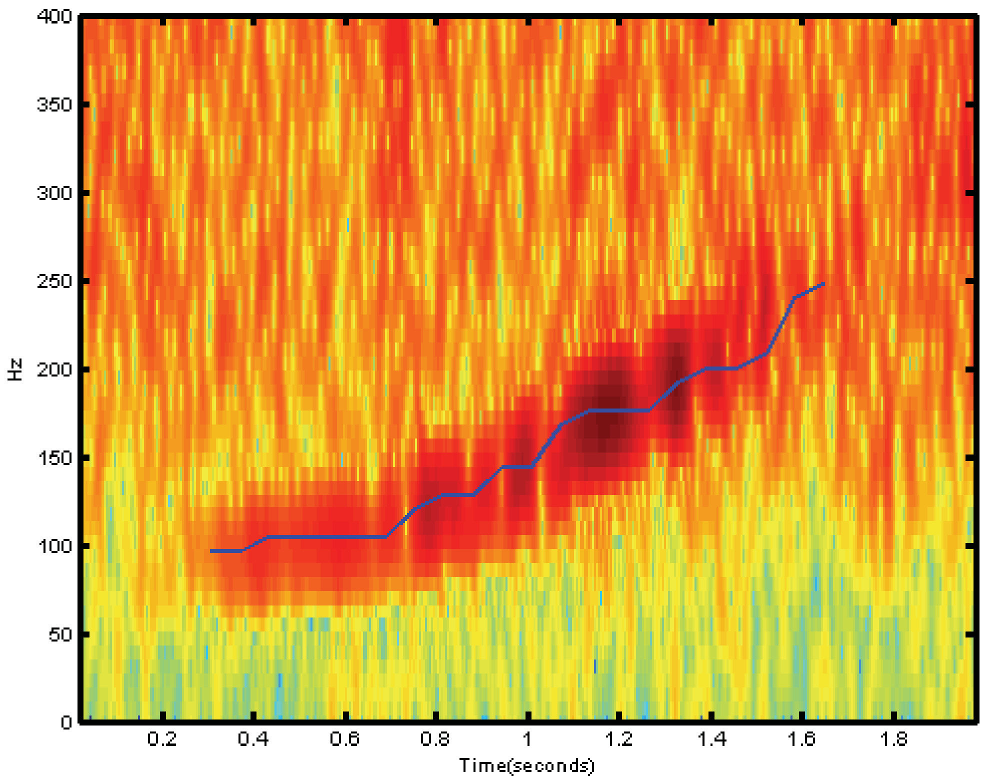


Figure 1: Example upsweep 'contact' call from 28 April 2008 used to detect presence of the North Atlantic Right Whale (Eubalaena glacialis). The blue line is a 'feature vector' created by the onboard detector.

Early Versions (2005-2007):

The first such “auto-detection buoys” were deployed briefly in and around CCB Oct, 2004 (Figure 2), followed by subsequent deployments in March 2005. These monitoring buoys were composed of repurposed marine buoys (Figure 3) from Woods Hole Oceanographic Institute, a hydrophone and a mooring system. Cornell University Bioacoustics Research Program (BRP) provided the buoy electronics in a weather-resistant plastic ‘Pelican’ case, which contained (Figure 4) power and signal conditioning hardware, a Texas Instruments TMS320VC5510 DSK board with custom firmware, and an AirLink Raven CDMA modem for telemetry. An external GPS-18-LVC receiver provided timing information, and an omnidirectional cellular-band antenna provided a data link to shore.

Figure 2: First AB deployment 14 September 2004, with surface buoy, electronics, radar reflector, and cell phone band antenna.

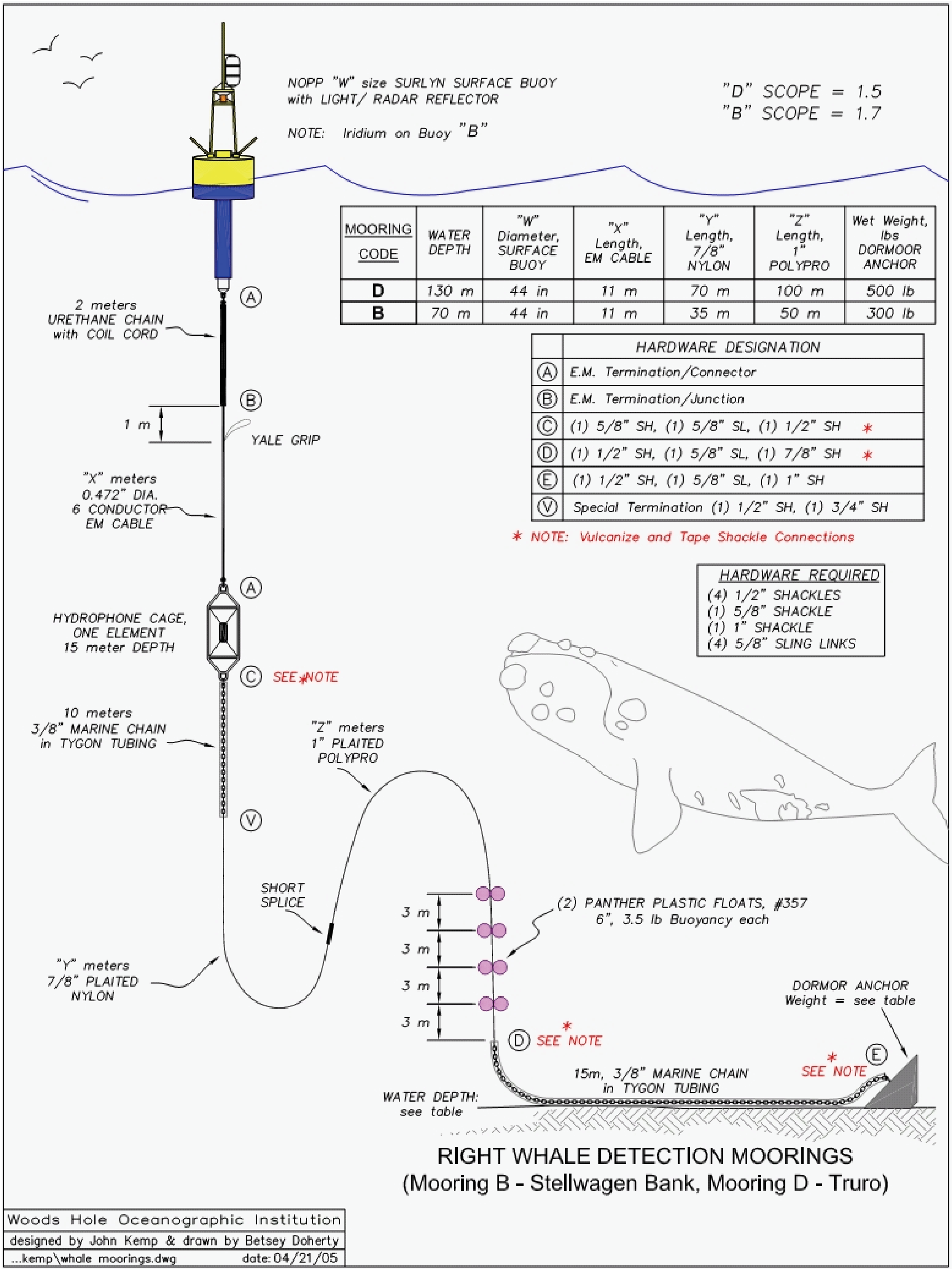


Figure 3: WHOI's mooring system deployed early versions of the system (2004-2006).

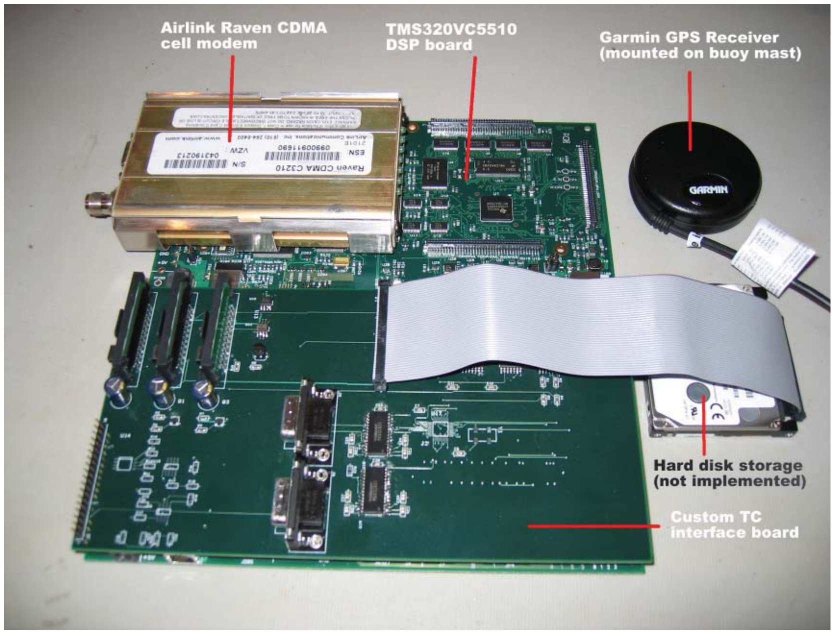


Figure 4: Buoy electronic components used 2004-2008.

Event Detection:
The conditioned hydrophone signal was fed into the DSK's A/D, where it was converted into a time-series of digital values and the magnitude-squared DFT spectrogram was computed. This was then processed by a fixed-point implementation of Doug Gillespie's NARW upsweep detector[1], which checked for time-frequency cells with energy greater than an integer multiple of the background level estimate. Time-frequency cells with energy over this threshold were grouped in time and frequency to form candidate events. Parameters from each event were extracted and tested in a series of stages. A numerical score of 2-10 was then assigned to each event based on which of these tests it was able to satisfy (Figure 5). If an event's score exceeded a 'storage threshold', its metadata (time and score of detection, a feature vector of time-frequency cells used by the detector) were stored. If this score also exceeded the 'clip storage threshold' a 2 second, 2 kHz audio clip was stored in addition. When working properly, the time of detection was measured precisely using the connected GPS (in some cases there were problems reading the GPS receiver which resulted in drastically incorrect timestamps).

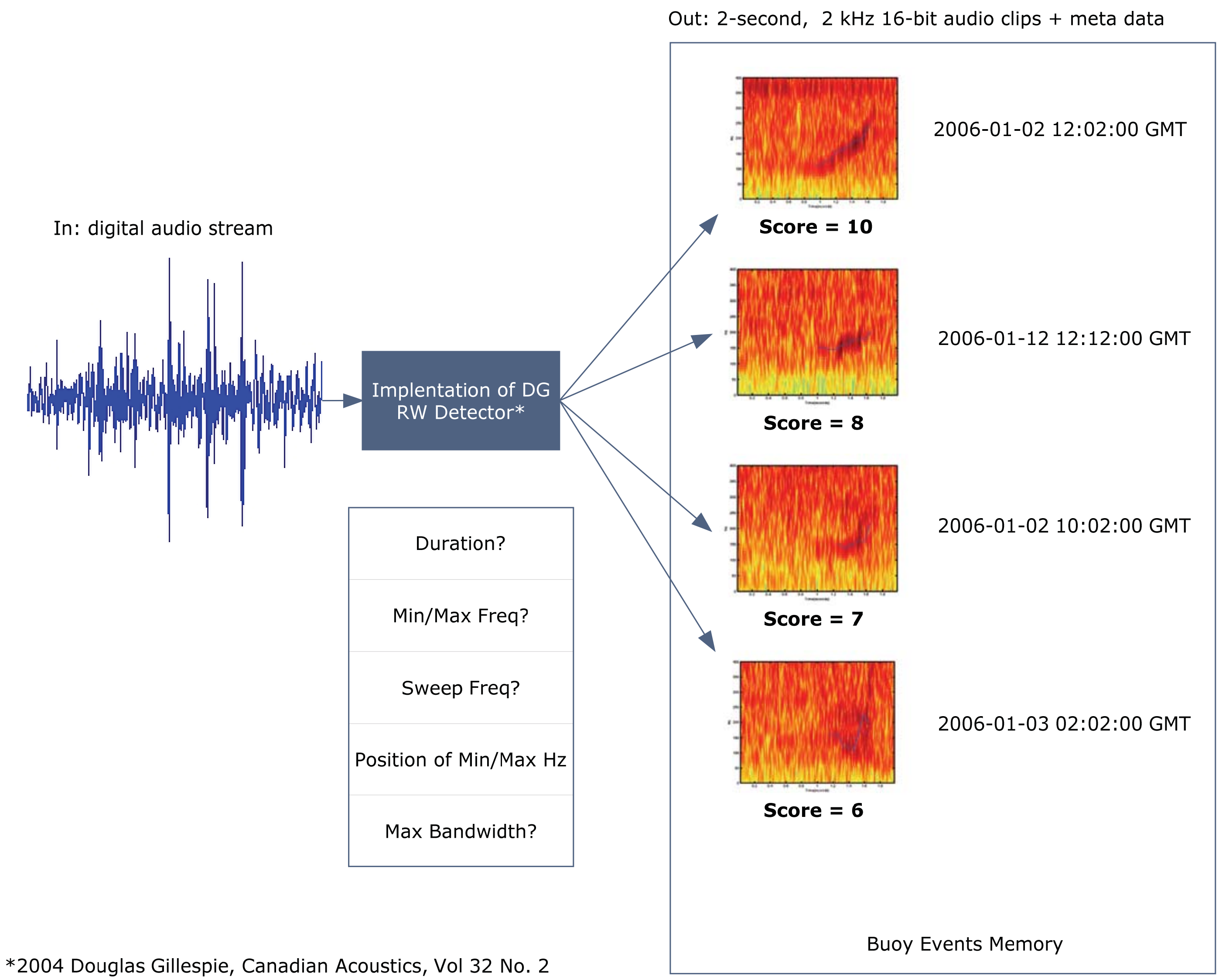


Figure 5: Event Detection

These events were stored in the limited volatile memory of the C5510, and lower-scoring events were continuously displaced by newer, higher-scoring ones. Only the 10 'best' detection audio clips (based on score) were stored in the buoy memory. When a report was triggered, the detection event memory would be converted into a transfer format and a series of upload attempts would be tried via the cellular link. While in this reporting mode, the buoy was unable to detect new NARW calls. If no successful upload occurred after 10 attempts, the transmit buffer was purged and monitoring would continue. As a result, an NARW contact call which was successfully detected by the buoy was at risk of being replaced by subsequent detection events or purged if a successful cell connection could not be established when in the transmission buffer.

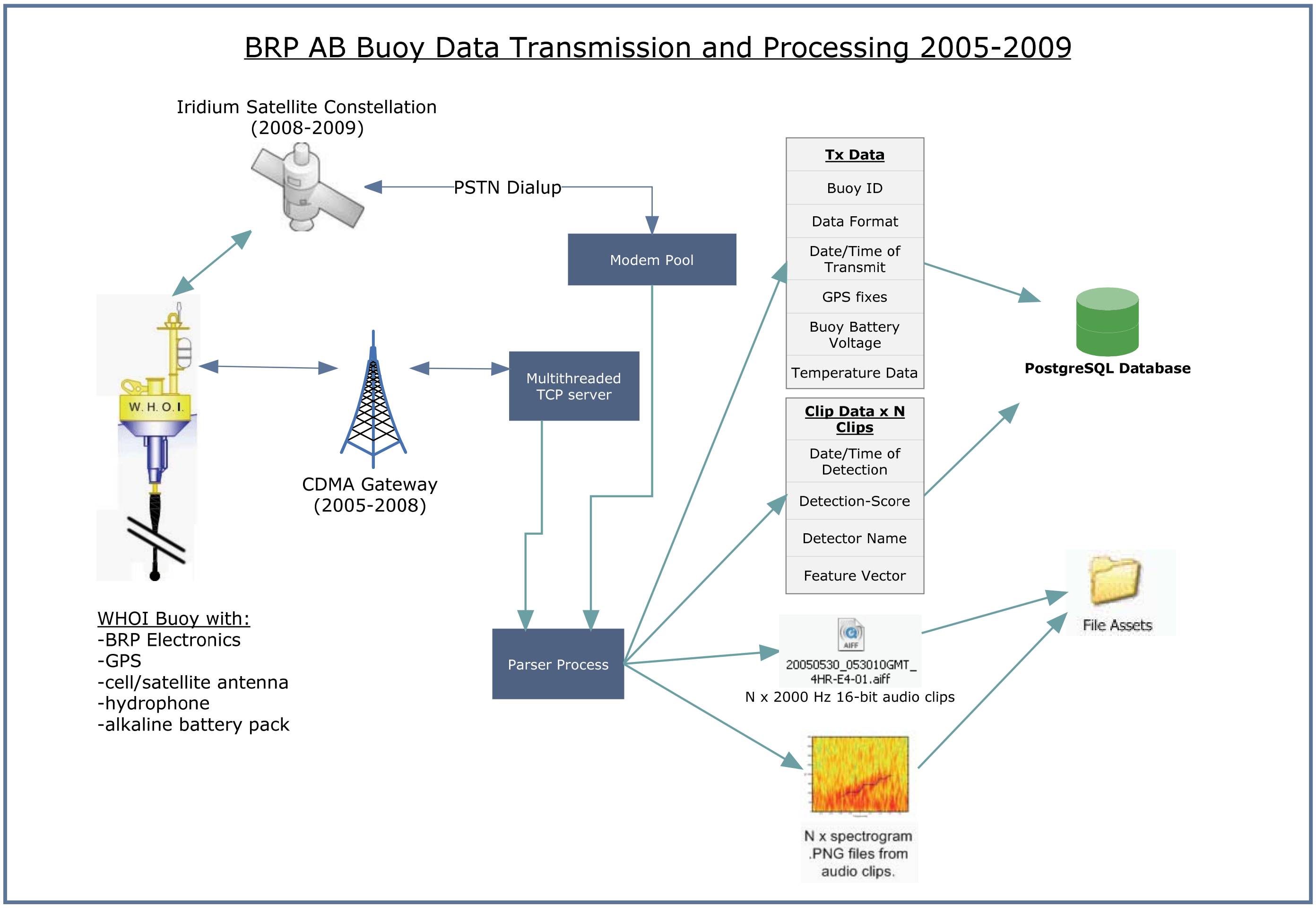


Figure 6: Data Telemetry, Processing, Annotation and Output.

Communications and reporting:

Buoy firmware determined when it was time to transmit data on a fixed, pre-determined schedule, it would then bundle the data into a transfer format and initiate the upload procedure (typically every 10 minutes for the first hour on power-up, and 4 hours for the remainder of the deployment). Serial data were transmitted from the DSP-board through the modem, which encapsulated the data into a TCP stream which was then sent to the buoy server process at Cornell (Figure 6). This process was initially implemented as a single-threaded application (requiring each buoy to target a specific TCP/IP port number) and later as a multithreaded application, allowing the use of a single port and simplifying the scaling of the number of simultaneous TCP/IP connections (and therefore deployed buoys).

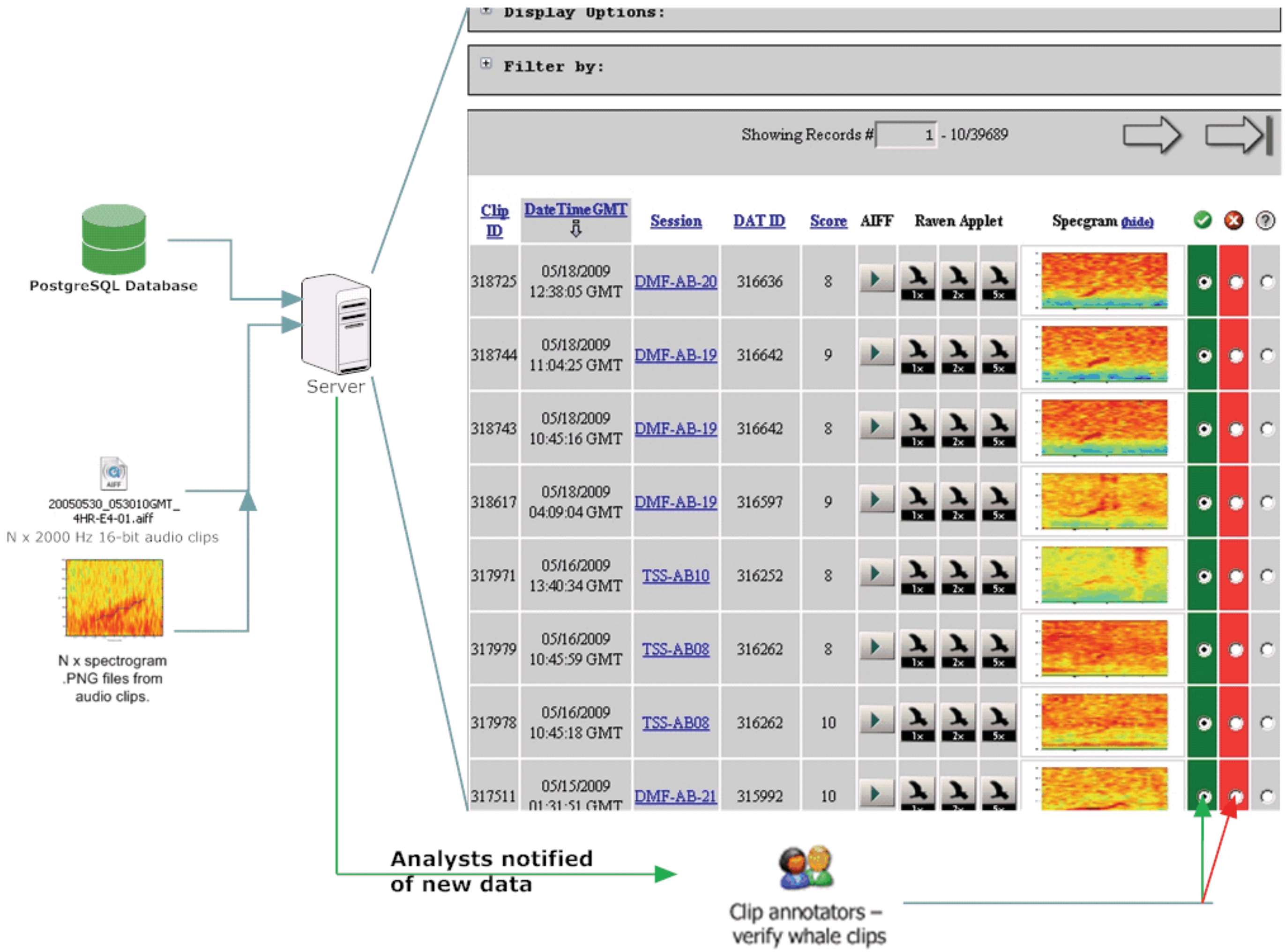


Figure 7: Clip annotation interface which human analysts used to accept or reject received detection candidates.

Data Parsing, Annotation, and Display:

These incoming data were then processed with a Matlab parser, which extracted metadata about the transmission, buoy voltage, GPS timing, and then generated a series of file assets: 10, 2-second 16-bit AIFF audio clips (the 'greatest hits'), spectrogram PNG images of these clips, and Matlab figures of the summed spectra. Database records containing transmission and file assets information were then inserted into a PostgreSQL database (Figure 6), and analysts were notified by email or SMS text message that data required review. The 2-second detection candidates were then annotated by human experts via a database-driven PHP web interface (Figure 7). The web interface included the Raven applet tool as an aid in clip review (Figure 8), which provided adjustable playback rate, zoom, FFT size, and brightness and contrast settings. These tools allowed analysts to curate incoming detection events from anywhere in the world, as long as they had a web browser and internet connection. This database was then queried to generate various visual displays to inform researchers through a web interface (Figure 9), and to generate automated email-reports.

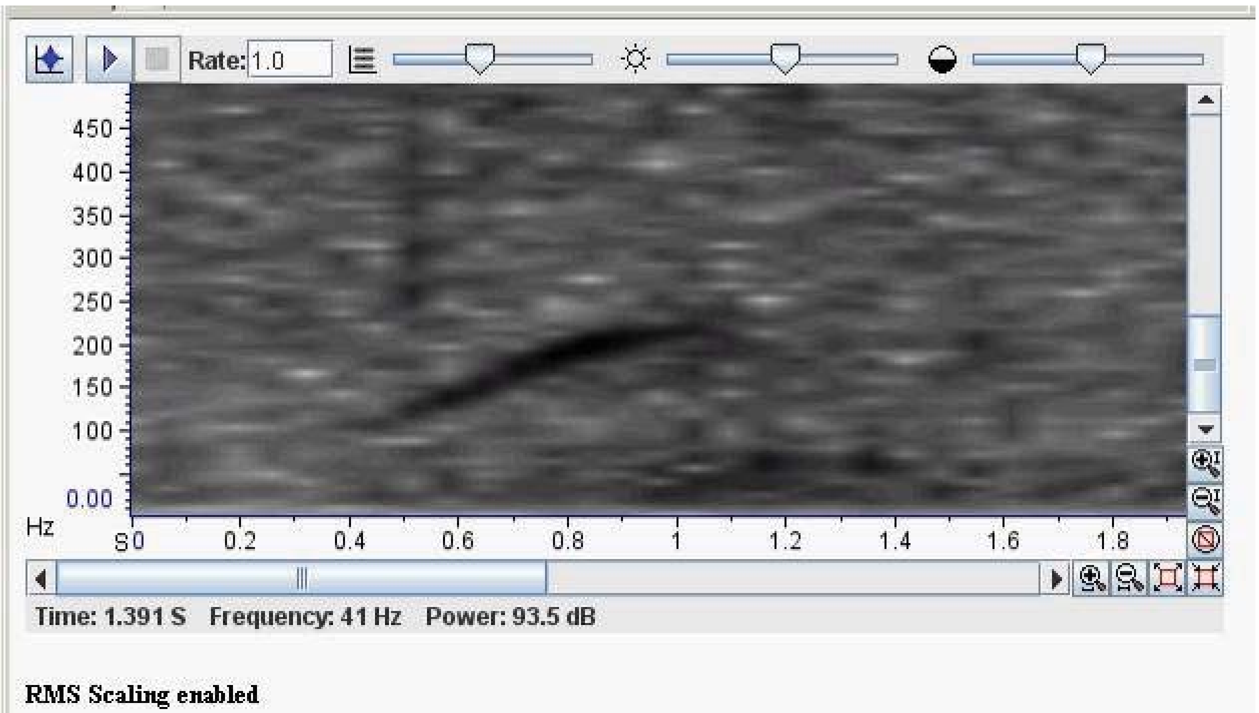


Figure 8: The Raven applet provided interactive visualization and playback of audio clips from a standard web-browser during clip annotation or review.

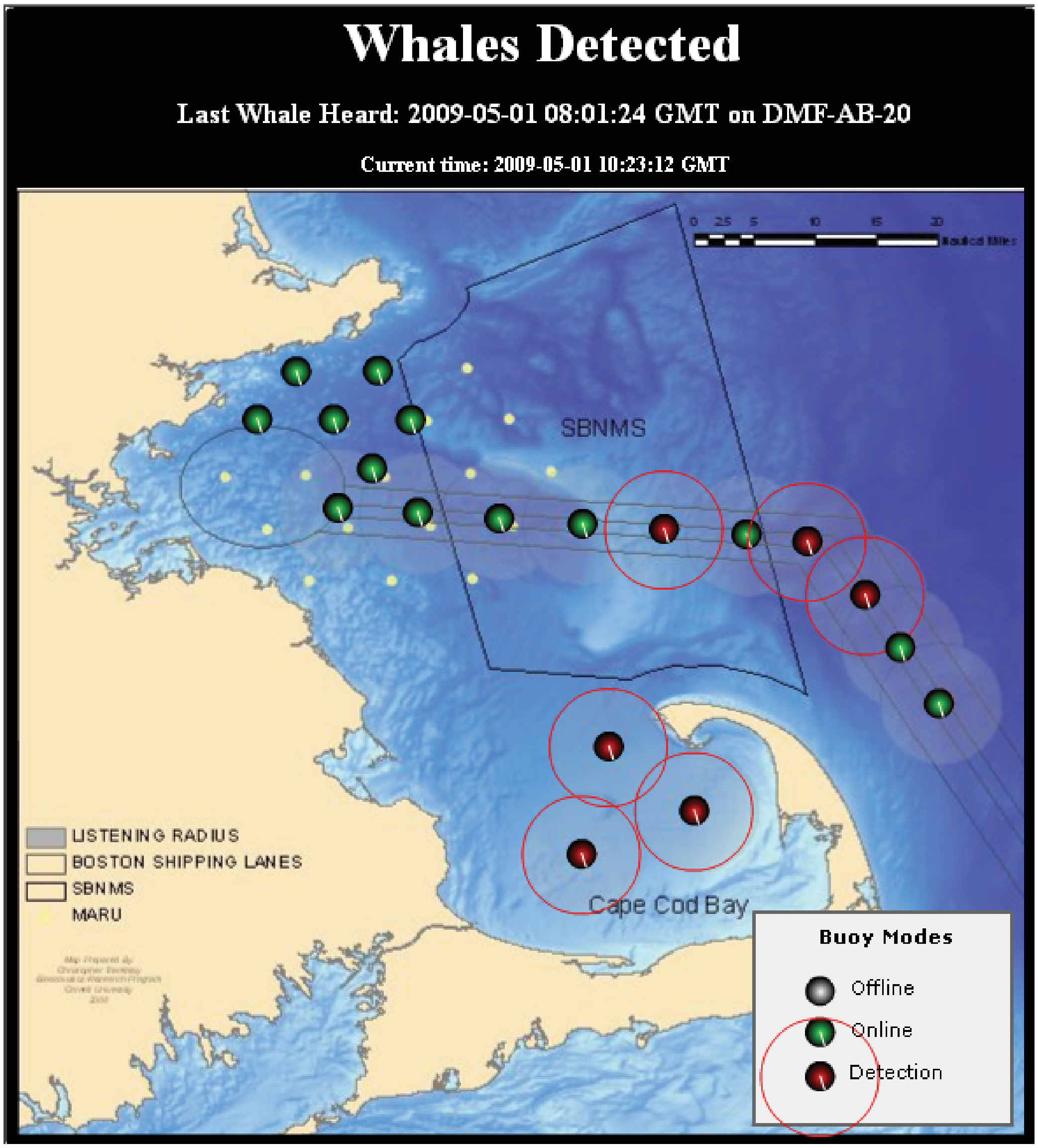


Figure 9: Animated 'Dashboard' from www.nrwbuoys.org on 1 April 2009 showing the status of 10 buoys in the Boston shipping lanes, 3 in Cape Cod Bay, and 6 near Boston Harbor. Red icons indicate a NARW detection in the previous 24 hours. Green icons indicate that data had been recently received from a buoy and that it was functioning. The eventual goal is to provide this type of detection information directly to the navigational displays of ships so that captains reduce speed when entering an area in which whales are detected.

Brief Development History and Cape Cod Bay Deployments:

2005 Deployments:

Cape Cod Bay buoys A, C, and E collected and reported over 8,322 2 second, 2 kHz detection candidate audio clips between 1 April 2005 and 5 July 2005, of which only 256 were confirmed NARW contact calls. These buoys continued to monitor and report detection candidates until early July 2005, but no confirmed calls were detected after 28 April 2005 (Figure 12). The detector clip-score threshold used was 2. In this case, there were no confirmed NARW upsweep calls below a detector score of '7' (Figure 13). The numerical score was assigned by the Doug Gillespie (DG) detector onboard these buoys, the 'approved' vs. 'rejected' assignment was later made by human experts after the clips were transmitted to our servers. These buoys occasionally suffered from firmware lockup issues which required the power to the buoy electronics to be manually cycled.

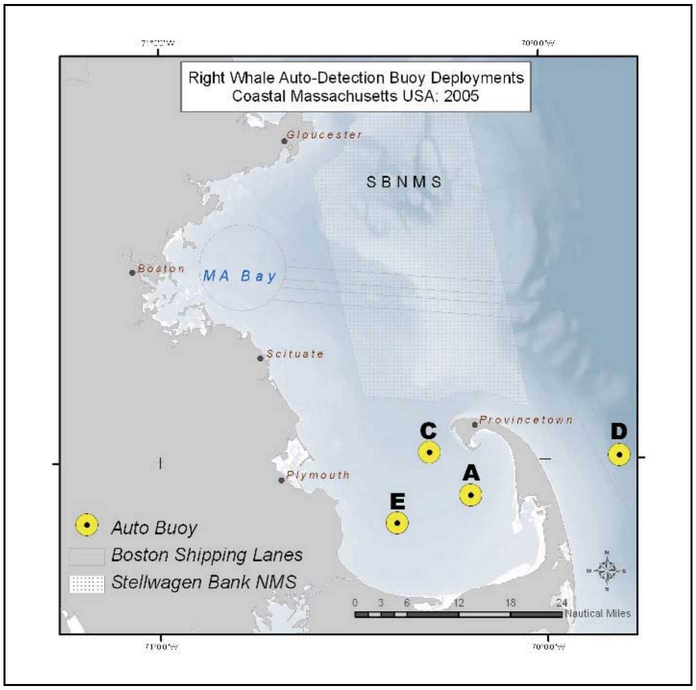


Figure 10: April 2005 Deployments, Buoys A, C, and E reported 250 verified NARW calls between 1 April 2005 and 5 July 2005.

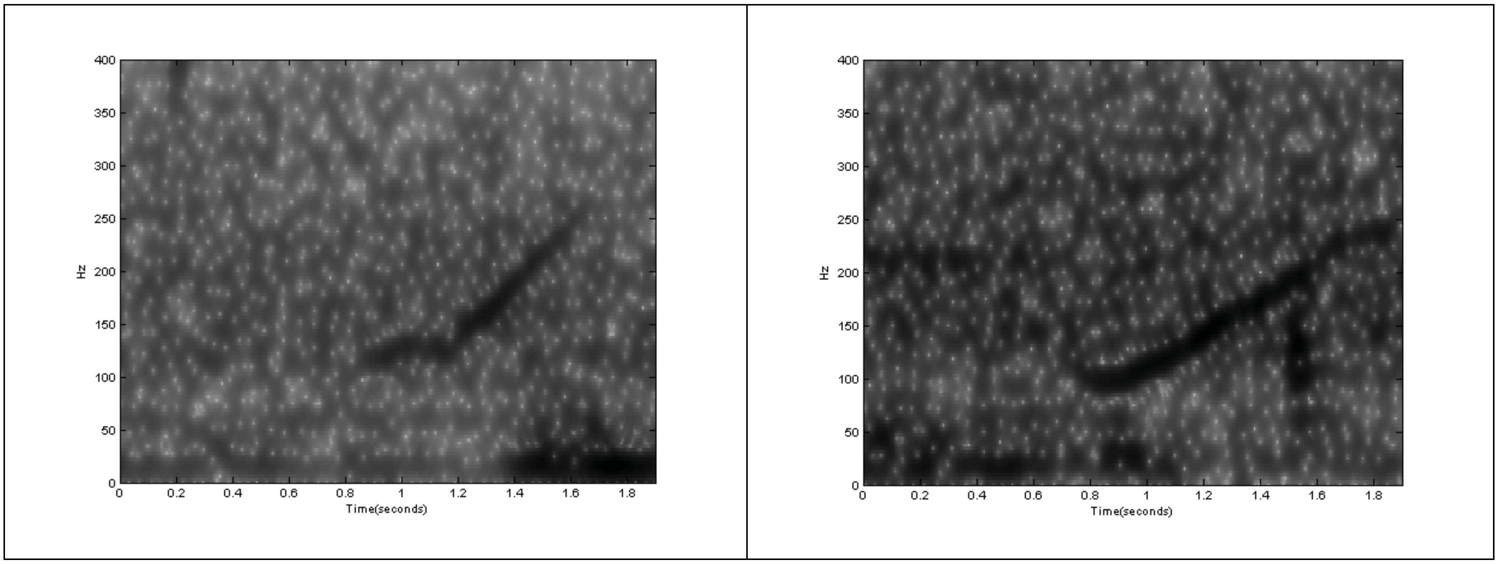


Figure 11: Examples of confirmed NARW upsweep call from session A3 (Wellfleet) 1 April 2005, and from E3 (Sandwich) 7 April 2005.

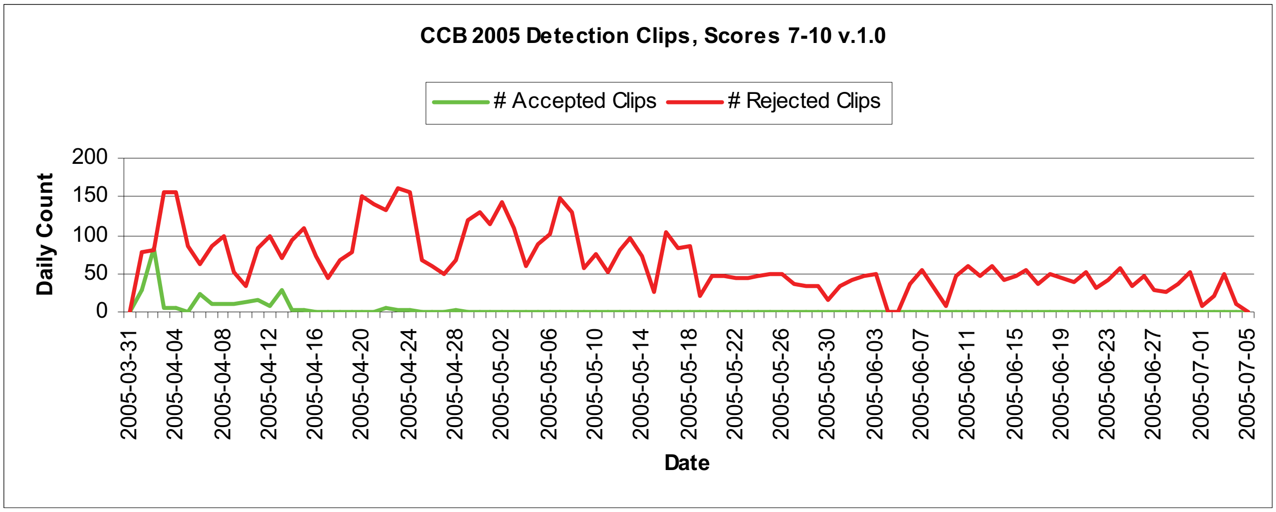
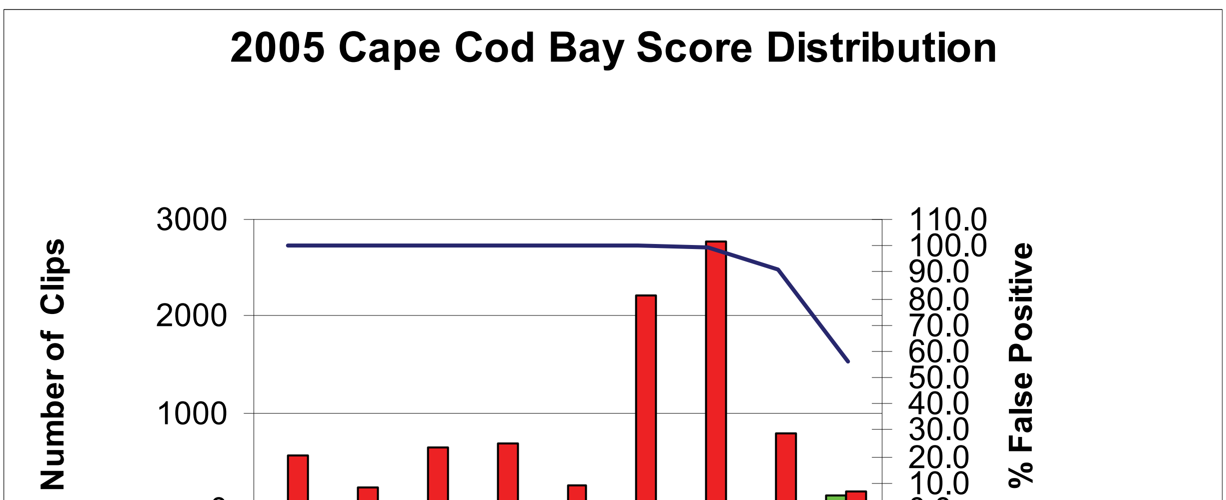


Figure 12: Daily counts of Rejected (false-positive, red line) and Accepted (true-positive, green line) audio clips reported from early CCB buoys for the April-July 2005 period. This plot only includes detection clips of score 7-10 for comparison with future deployments.



	2	3	4	5	6	7	8	9	10
approved	0	0	0	0	0	2	20	79	149
rejected	555	221	640	685	246	2222	2771	794	188
% FP	100.0	100.0	100.0	100.0	100.0	99.9	99.3	91.0	55.8

Figure 13: Distribution of detector-assigned clip scores from 2005 Cape Cod Bay deployments. Each column represents the number of accepted or rejected detection clips, as grouped by detector-assigned score. Although a higher clip score (7+) suggests a greater chance that the clip was an actual NARW call, the majority of received clips were still false-positives.

Figure 14: WELL1 Hydrophone wrapped in open-cell foam within the hydrophone cage, 19 March 2006.

Figure 15: WELL2 entire hydrophone cage wrapped with open-cell foam, 19 March 2006.

2006 – Efforts were made in 2006 to reduce heave-noise on the hydrophone because of the large amount of perceived self-noise experienced during the 2005 deployments. Two buoys were deployed (WELL1, WELL2) within 300m of each other near the previous year's site of Buoy A (Figure 10), each buoy with different configurations of open-cell foam installed around the hydrophone. WELL1 had open-cell foam wrapped around the hydrophone within the cage (Figure 14), and WELL2 which had this foam wrapped around the entire hydrophone cage (Figure 15).

These buoys were deployed with a 4-hour reporting schedule (normally 6 reports/day x 10 clips per report), and the detector score threshold minimum was set at 2. As seen in Figure 16, WELL1 reported a higher number of validated detection clips than WELL2. These buoys suffered from firmware lockups midway through their deployments. These lockups required power cycling, so the comparison was limited to dates when both buoys were operational.

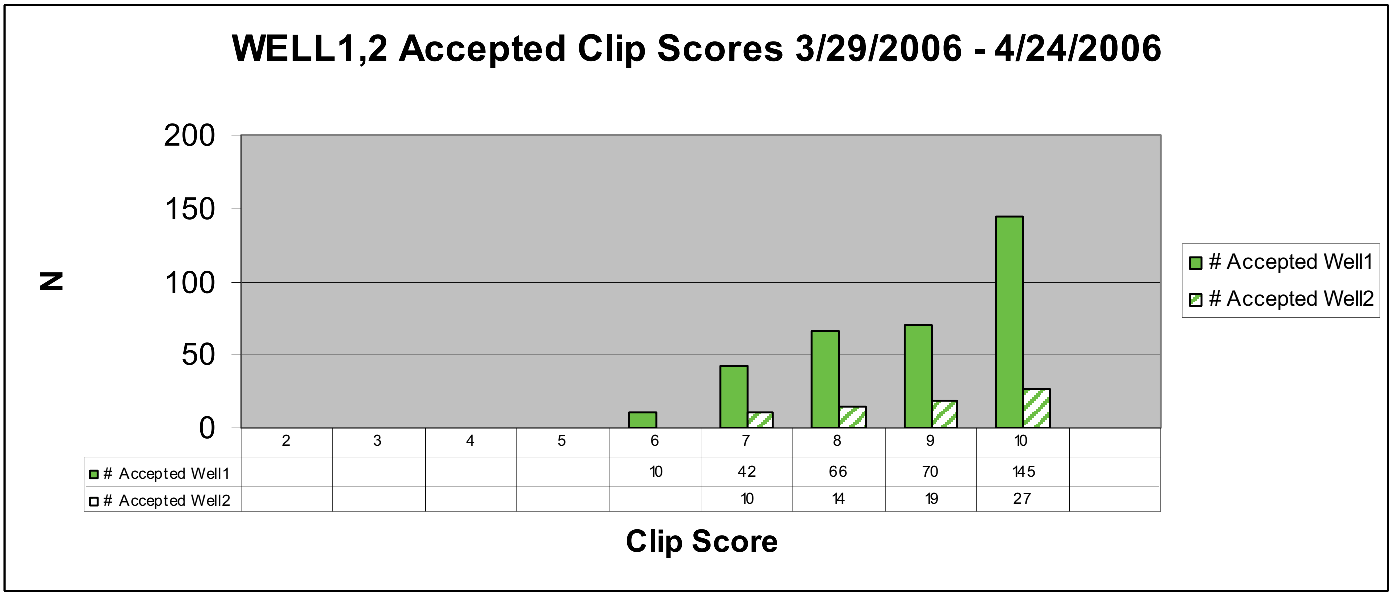


Figure 16: Comparison of NARW detection numbers made with two different hydrophone/open-cell foam configurations in 2006.

2007 - To further reduce water movement across the hydrophone a new mooring type was designed to include a stretchable, flexible rubber hose that is referred to as a "Gumby" hose. The first deployment with this new mooring type, the 'GUMBY1' deployment, occurred in March 2007 (subsurface components in Figure 17). This mooring also introduced a floatation sphere to create a bottom-moored hydrophone system that was under tension to keep the hydrophone stationary in the water column. This sphere was connected to the surface buoy with the 'Gumby' hose, so that the movements of the surface buoy were mechanically decouple from the sphere and hydrophone. The hydrophone cable within this rubber hose was helically-coiled, keeping it strain-free within the stretching range of the Gumby hose. Noise profiles from the GUMBY1 deployment are shown in Figure 18.

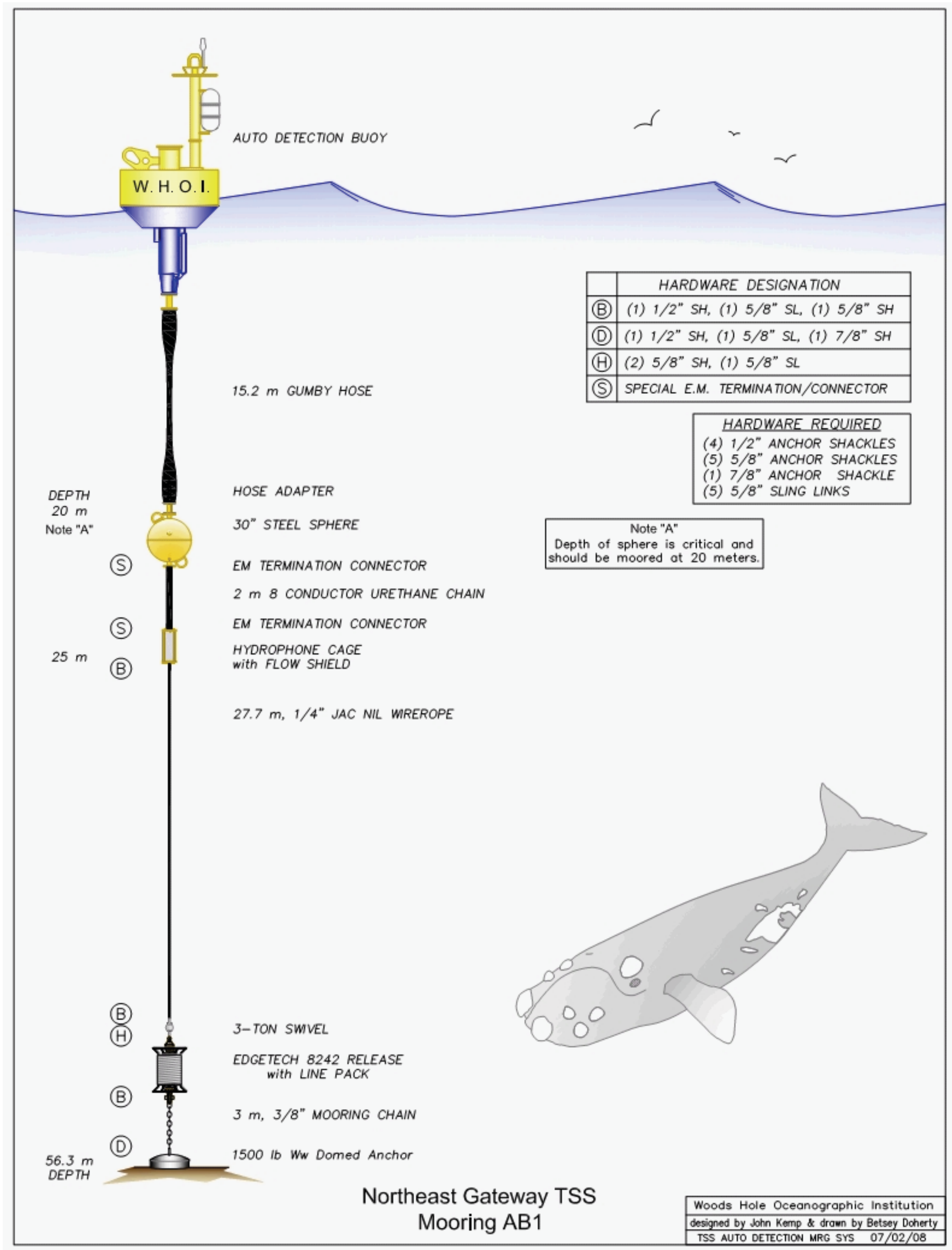


Figure 17: WHOI's 'GUMBY'–hose and subsurface mooring system used in deployments 2007-present. The surface buoy type shown here was used 2008-present.

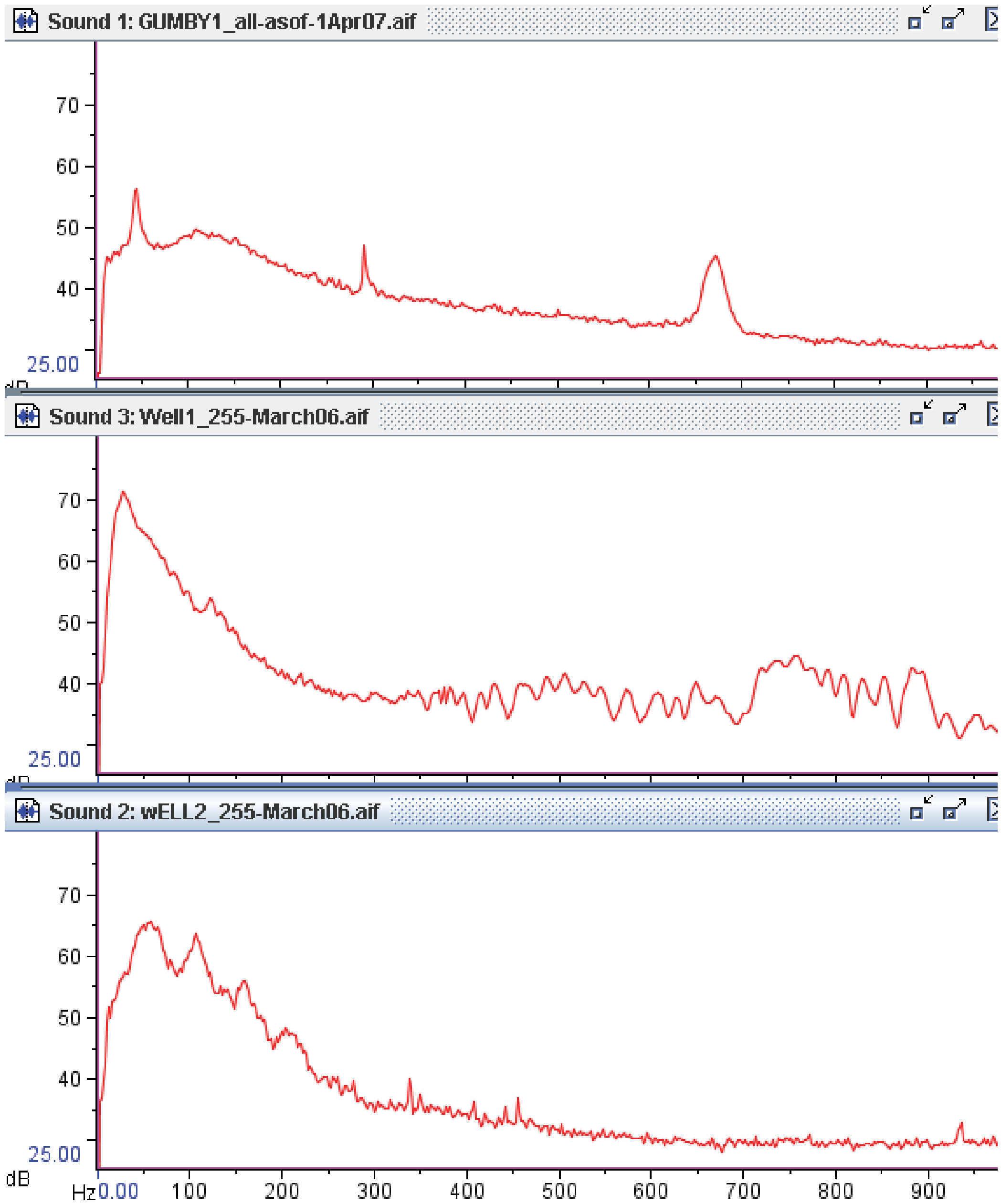


Figure 18: Frequency-intensity distribution plots comparing noise levels from the Gumby buoy designed to eliminate self noise (top panel, "GUMBY1"), the spring 2006 auto-buoy with inner-cage noise-isolation foam (middle panel, "WELL1"), and the spring 2006 auto-buoy with outer-cage noise-isolation foam (bottom panel, "WELL2").

Second Generation (2008 – present):

Satellite Telemetry:

In an effort to help mitigate ship-strikes through the timely notification of ship-captains, the shipping lanes in Massachusetts Bay were instrumented with a fleet of 10 of our automatic-detection buoys. The requirement to deploy detection buoys within the Transportation Separation Scheme (TSS) (Figure 9), and the lack of reliable cell-phone reception at the proposed sites led to the development of a satellite-capable telemetry system. Initial experiments with Globalstar-based systems demonstrated that the degraded state of the satellite constellation (only ~15 mins per 70 minute window guaranteed) was inadequate for our goal of detecting a NARW contact call, transmitting, annotating, and alerting ship-captains within 30 minutes. As a result, we reluctantly implemented a slow (2400 baud), but surprisingly reliable, Iridium-based system, that required a bank of analog telephone lines, modems, and Kermit processes. In January 2008, 10 buoys using this new telemetry system were deployed in the TSS.

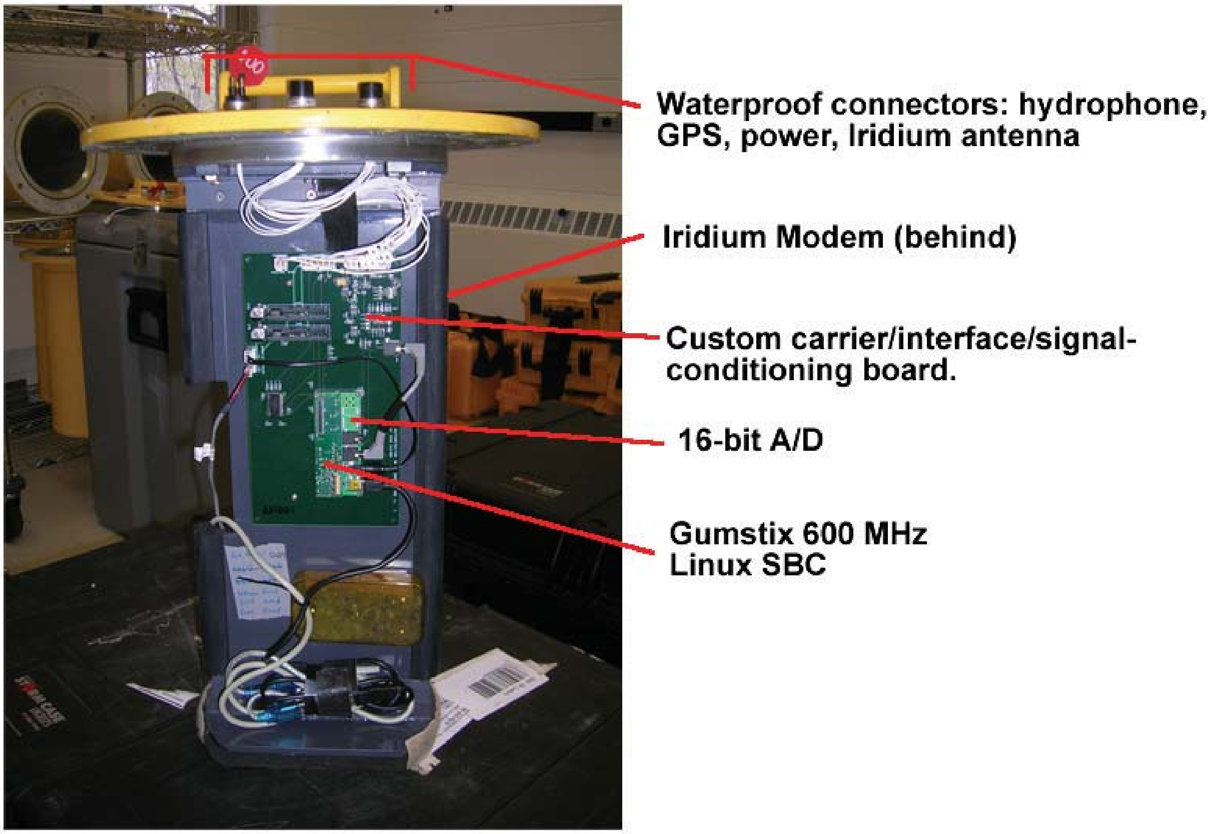


Figure 19: Current version of the buoy electronics, deployed 9-2008 – present.

Previous versions of the buoy electronics which relied on the cell modem to provide TCP/IP and error correction via cell-modem needed a way to reliably relay detection reports via a dial-up Iridium satellite modem. As a result, we added a Gumstix (www.gumstix.com) Linux computer to capture the serial data from the DSK, and we used CKermit's file transfer protocol to drive the Iridium modem and its scripting language to provide command and control. Because the detection process was still implemented on the DSK, this version also suffered from DSK-lockup issues.

Detection Hardware/Firmware:
It was determined that both the communications and the DG detector process could be ported completely from the DSK to the Gumstix, which would provide a simpler design, the ability to update detector parameters and behavior remotely, and would reduce power consumption. After inconsistent performance, we decided that our vehicular-grade GPS receivers were unreliable, and we switched to the server's clock for timing information. We implemented more flexibility in the reporting system so that a buoy's reporting schedule and reporting behavior can now be set remotely (e.g., a 20-minute reporting mode for ship-transit times and a 6-hr reporting intervals for downtimes). In addition, we implemented a 'rapid-notification' mode which programs the buoy to report its data when a detection

occurs instead of needing to wait for a scheduled transmission. As a result, we found our typical buoy deployments were doubled from 3 to 6 months, with the buoy electronics averaging approximately ~2 Watts when reporting 40, 2 sec audio clips per day, with the Iridium modem being powered on only during reports.

Detector Algorithm Bug Fix:
The performance of early implementations of the fixed-point "Gillespie" algorithm suffered from an overflow bug which effectively ruined the background energy estimate. The estimate is calculated using a weighted average (3x3 Gaussian smoothing kernel), which is implemented via a multiply-accumulate step. In the original implementation, no overflow checking was performed for this step, and high-amplitude input could cause the sign to become negative. Since the smoothing filter was computed without any pre-scaling, the 3x3 Gaussian kernel ([1 2 1; 2 4 2; 1 2 1] in MATLAB matrix notation) which has sum 16, meant that the background only needed to reach approximately 1/16th of full-scale to effect this change of sign. The net effect was a drastic reduction of detector performance during high-amplitude conditions due to the proliferation of false detection candidates passed to the recognition step. In practice, the input gain was set very low, making this condition occur infrequently, but as a result, the recorded sounds were of low quality, with typical amplitudes on the order of 100 or so, or using only the least-significant 8 bits of the 16-bit converter.

Parameter Optimization:
Since we had not been able to record the raw data as seen by the buoys – it was not feasible to tune the detector to the exact conditions experienced by the buoy's hydrophone. However, we were able to compare detection performance on recordings made by BRP's marine autonomous recording units ('pop-ups' or MARUs) to that of human analysts, and search the parameter space of the detector to find more effective settings.

We accomplished this by creating a simulation environment in MATLAB, using the XBAT tool [2], which enabled us to run stored sound data through the same detection algorithm used on our on-board Gumstix SBC. Using XBAT's annotation facilities and extensibility, we compared automatic annotations made by the "Gillespie" detector with manual selections by our expert analysts. We then followed a technique based on the method of Urazghildiiev [3] to visualize the operating points of the detector in the same coordinate system of true detection percentage against false positive percentage. Based on the curves generated, we were able to choose operating points and revise our set of detector parameters.

2009 Deployments:

In addition to the 10 TSS and 6 Boston Harbor buoys, three buoys were again deployed near the previously used 3 Cape Cod Bay sites (Figure 20). The time series of accepted and rejected clips can be seen in Figure 21.

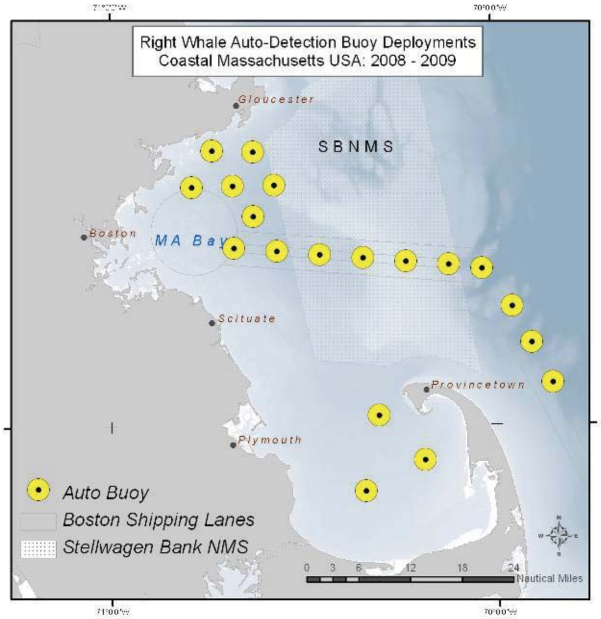


Figure 20: Coastal Massachusetts Deployments Deployed Between 2008 - 2009.

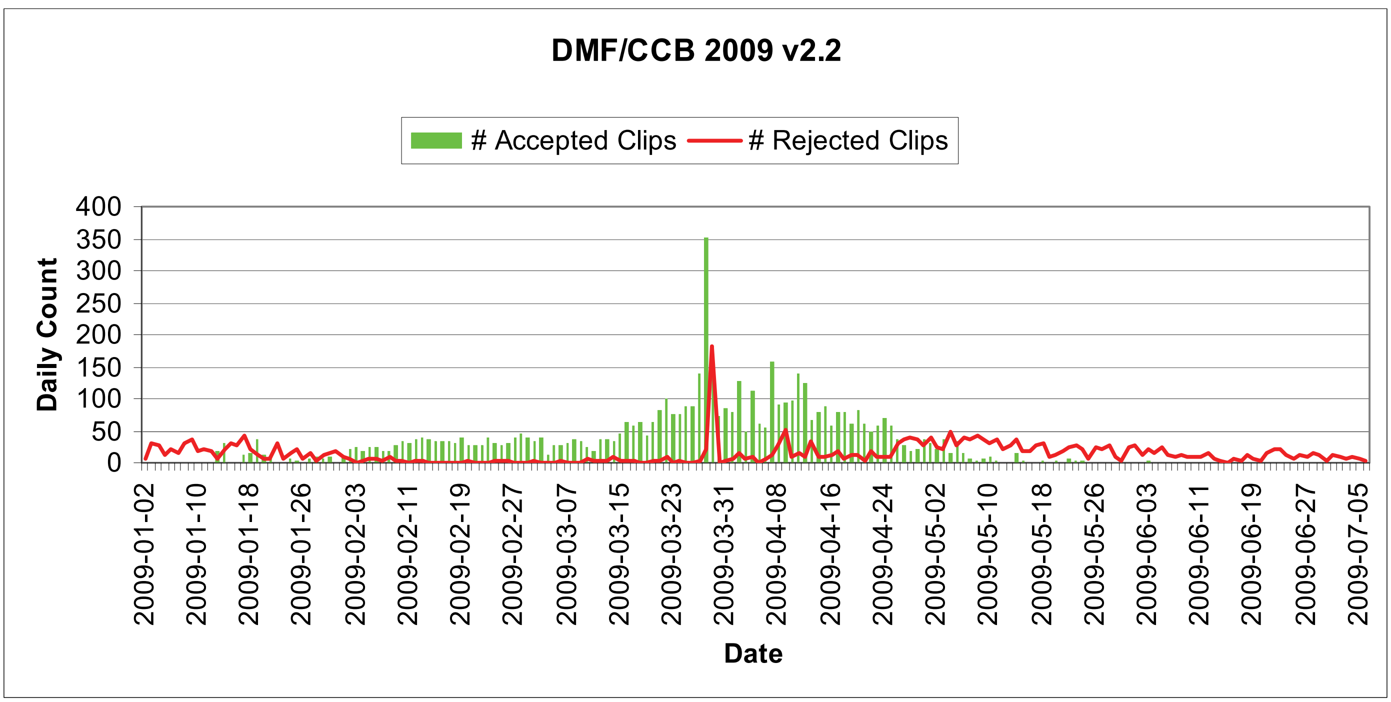


Figure 21: Reported audio clips from 3 Auto-Detection Buoys (DMF-19, 20, and 21) deployed in Cape Cod Bay, 2009. This version of the system had remotely settable reporting capability. The spikes at ~28 March 2009 in both accepted and rejected clips was due to buoy DMF-19 accidentally resetting into 10-minute reporting mode for a day before being reprogrammed for 6-hour reporting.

System Performance comparison, Cape Cod Bay:

Since 2005, a series of improvements have been made that have increased auto-buoy detection performance. This includes:

1. adding open-celled foam around the hydrophone (2006),
2. mechanically decoupling the surface buoy from the hydrophone by switching to WHOI's 'Gumby' mooring system (2007),
3. adding additional high-pass filtering (2008),
4. eliminating a firmware bug that influenced background noise estimation (2008), and
5. refining the Gillespie detector parameters (2008).

A casual comparison of the score distributions from 2005 (Figure 13) vs. 2009 (Figure 22) shows that our improvements have decreased the percentage of false positives in the upper score range and have made the arbitrary detection score number a more useful parameter for limiting the number of false positives.

Because none of these systems stored continuous data, we are unable to easily evaluate the true and false negative detections of the complete system. Instead we have had to rely on similar recordings made by BRP's marine autonomous recording units. Unfortunately, these recordings do not contain the actual noise events experienced by the auto-buoy's hydrophone. We will be adding continuous data storage to future versions of the system to enable this type of analysis, provide better assessments of self-noise, and assist us in improving both the sensitivity and specificity of our detection system.

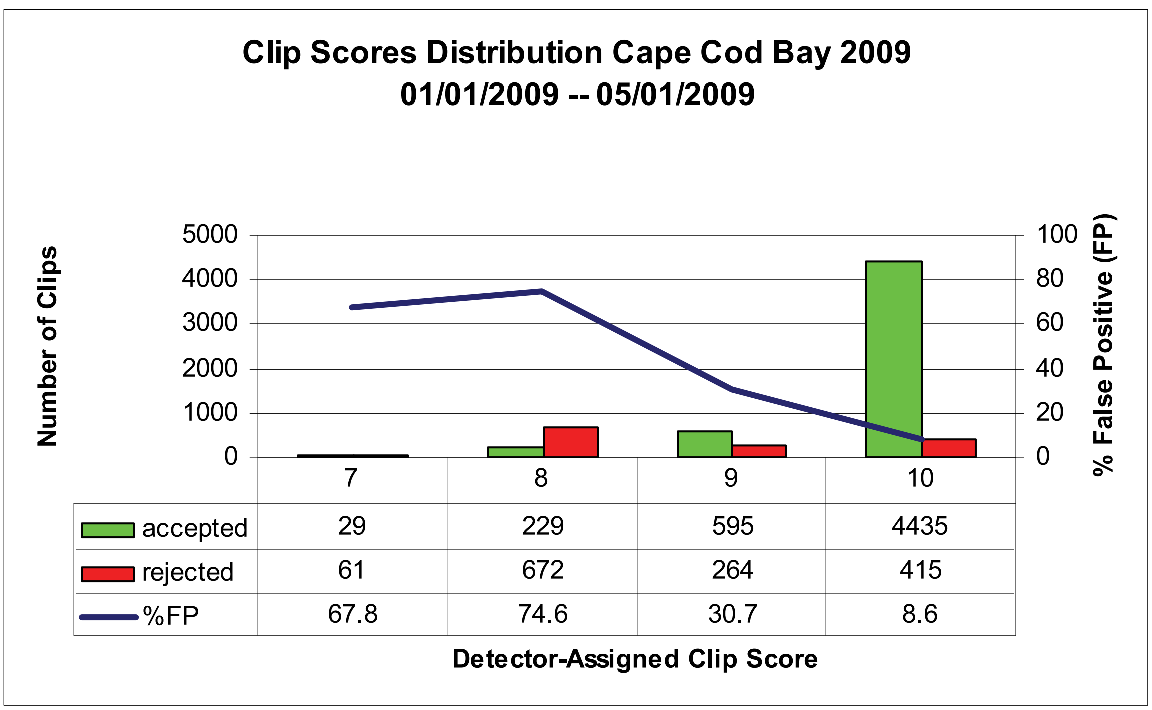


Figure 22: Distribution of detection clip scores from the 3 Cape Cod Bay buoys, spring of 2009. The same version of the system is currently deployed in the TSS shipping lanes, Cape Cod Bay, and Boston Harbor.

Future Work:

The goal of this project is to reduce ship strikes of whales, and therefore we would like all the detection information from our buoy system to be made available in a visually appropriate way to ship-captains. Some of the important technical tasks we are implementing or will be implementing include:

1. AIS broadcast of buoy data to ships. We are collaborating with Kurt Schwehr of University of New Hampshire to broadcast buoy information and detection data as properly formatted AIS alerts to the Massachusetts Bay area using Coast Guard transmitters, giving ship-captains real-time situational awareness of our NARW detections.
2. Potential to locate calling whales. We intend to re-implement the precision timing functionality, which will give us the ability to locate a calling whale when three or more buoys detect the call (requires the appropriate buoy array geometry).
3. Report ambient noise data. We intend to re-implement the computation and reporting of noise level data to measure local changes in the acoustic environment.
4. Additional efforts will be made to characterize, understand, and improve the detector performance. Ideally, it would be nice if we could refine the onboard detector to the point where transmitting raw audio and human validation was unnecessary.
5. Properly calibrate buoy electronics so that we may use our systems for absolute sound level measurements.
6. Implement detectors for non-NARW signals, initially using template detector techniques, thereby allowing us to detect arbitrary signals.
7. Perform calibrated playback experiments to allow us to quantify detection range.
8. Calibrate and use each buoy’s thermistor to sample and report water temperature.
9. Replace the buoy’s alkaline battery pack power source with some sort of regenerative power source, allowing for longer deployments and possibly increasing our power budget for additional detectors, telemetry, and onboard storage.

Acknowledgements:

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XBAT: Harold Figueroa
Raven: Tim Krein, Harold Mills, Dean Hawthorne, Dounan Hu, Laura Strickman, Scott Nelson
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Northeast Fisheries Science Center
New England Aquarium, Boston MA
Cornell University, Bioacoustics Research Program at the Cornell Lab of Ornithology, Ithaca NY (BRP)
Woods Hole Oceanographic Institution, Woods Hole, MA (WHOI)
Provincetown Center for Coastal Studies
International Fund for Animal Welfare
North Atlantic Right Whale Consortium

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[1] Gillespie, D. 2004. Detection and classification of right whale calls using an "edge" detector operating on a smoothed spectrogram. Can. Acoust. **32**, 39–47.

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Monitoring Site Demo: