Automated Analysis of Election Audit Logs

Patrick Baxter
Clemson University

Anne Edmundson
Cornell University

Keishla Ortiz
University of Puerto Rico-Arecibo

Ana Maria Quevedo
Miami Dade College

Samuel Rodríguez
University of Puerto Rico-Mayagüez

Cynthia Sturton
University of California-Berkeley

David Wagner
University of California-Berkeley

Abstract

The voting audit logs produced by electronic voting systems contain data that could be useful for uncovering procedural errors and election anomalies, but they are currently unwieldy and difficult for election officials to use in post-election audits. In this work, we develop new methods to analyze these audit logs for the detection of both procedural errors and system deficiencies. Our methods can be used to detect votes that were not included in the final tally, machines that may have experienced hardware problems during the election, and polling locations that exhibited long lines. We tested our analyses on data from the South Carolina 2010 elections and were able to uncover, solely through the analysis of audit logs, a variety of problems, including vote miscounts. We created a public web application that applies these methods to uploaded audit logs and generates useful feedback on any detected issues.

1 Introduction

Election officials are tasked with the difficult job of ensuring fair and smooth elections. It is their responsibility to ensure that ballots are cast, collected, and tallied properly and that every registered voter who comes to a polling place to vote is given the opportunity to do so. This requires that every polling location is staffed with well-trained poll workers and provisioned with enough ballots and balloting stations to accommodate all voters. A number of election day events can thwart even the best efforts on the part of election officials; surges of voters all arriving to vote at the same time, malfunctioning machines, and poll worker errors are a few. Information about election day events can help officials, and researchers who study elections, better understand what worked and what did not work and better prepare for the next election.

In the November 2010 U.S. elections, 33% of registered voters were using Direct Recording Electronic (DRE) voting machines [22]. Federal standards require that electronic voting machines generate detailed audit logs for use during post-election audits. Unfortunately, while the logs contain large amounts of data, it is not immediately obvious what sort of useful information can be learned from the data. Furthermore, even simple tallies are cumbersome, time consuming, and prone to human error if done manually. For these reasons, election officials do not regularly perform countywide post-election analysis of the log data.

However, log data contain a trove of information that can shed light on what takes place at the polling place on election day. For example, election officials can use the information to learn about voting machines that may need maintenance, or ways that poll workers and other resources may be better allocated.

In this work, we aim to make DRE audit log analysis more useful and accessible to election officials and other interested parties. We develop new methods to analyze audit logs for the detection of both procedural errors and system deficiencies. We created AuditBear, a public web application that provides our fully automated analyses as a free service for use by election officials or interested third parties.

A strength of our tool is that even in the face of missing data, we are still able to pull out useful information. Our research contributes to the election audit process in the following ways.

- We introduce methods for identifying, solely from publicly available audit logs, potential errors in the software, hardware, and system configuration of DREs.
- We introduce methods for identifying instances of human error by poll workers. Furthermore, we differentiate between random errors and patterns of error that suggest shortcomings in the training election workers receive.

- We introduce a new method for conducting a statistical analysis of voter flow. This allows for improved resource allocation in future elections.

- We conduct a case study using our methods and identify instances of poor worker training, long voting lines, and missing votes during the 2010 South Carolina election.

- Using our experience with the case study, we suggest new content that, if included in election log files, would allow for additional useful analysis.

We implement these methods for the ES&S iVotronic DRE; the 2010 South Carolina data was already publicly available through a previous Freedom of Information Act request and the iVotronic was used in that election. The iVotronic system is a standalone, portable, touchscreen system that records vote totals, ballot images and an event log on internal flash memory. The iVotronic voting machine is one of the most widely deployed DREs in the U.S. In 2010, 422 jurisdictions tallying more than 22 million registered voters used this system [20]. In addition, the types of analyses we identify and our algorithms for analysis are applicable to other DRE voting systems that produce the necessary audit logs.

In this work we assume that DRE audit logs are complete, accurate, trustworthy, and free of accidental or malicious tampering. Many studies have examined the various security weaknesses of DRE machines. DREs have been found to be susceptible to poor software engineering practices leading directly to exploitable vulnerabilities [16, 7], insider attacks [5], viruses that spread between voting machines and the Election Management System server [8, 14], and return-oriented programming exploits [9]. In all these cases, the demonstrated payload is usually a vote-stealing or vote-altering attack and often the associated logs and counters are modified to remove any traces of the attack. The iVotronic may be susceptible to many security exploits, and our tool does not aim to detect or prevent these; detecting and preventing audit log tampering is outside the scope of this work. Rather than making DREs more secure, our tool aims to make them more reliable. While it is crucial to discover machines that experience malicious tampering, finding a number of uncounted votes or learning where voters may be discouraged from voting by long lines is important too. While many states are moving away from the use of DREs precisely because of their security failings, DREs are still in widespread use and our tool provides easy-to-apply techniques that make results and future elections more reliable.

2 Background

2.1 Introduction to the iVotronic DRE

A brief description of the iVotronic's functionality and its main system components follows.

Voting terminal. The voting terminal is a stand-alone touchscreen voting unit. It is equipped with an internal battery, which keeps the unit operational in the event of a power failure. The terminal features three internal flash memories, which store the votes and terminal audit data during the voting process. Three memories are used for redundancy as the three store the same data. A removable compact flash card (CF) is installed in the back of the terminal prior to deployment to the precinct; this is used to store audit data and ballot images (cast vote records). Typically, each polling location is assigned several iVotronic machines as well as one audio (ADA) terminal.

Personalized Electronic Ballot (PEB). The PEB is a proprietary cartridge required to operate the iVotronic terminal. The voting terminal is delivered to the precinct with no ballot style information; that is later supplied by the PEB. The PEBs are programmed at election central with the ballot data for each voting location. At the opening of the polls, poll workers download ballot style information from the PEB's internal flash memory to the terminal. When the PEB is placed in the machine, the terminal and the PEB can communicate through an infrared port. Typically, counties deploy two types of PEBs to the precinct: a) a Master PEB and b) an Activator PEB. They are interchangeable, but poll workers are trained to keep them separate and use them for different purposes.

- Master PEB. Poll workers use the Master PEB to open and close all terminals on election day. The same Master PEB should be used to open all terminals in the polling location. In the same fashion, the Master PEB should be used to close all terminals in the polling location at the end of the voting day. When a terminal is closed, it uploads its vote totals onto the PEB inserted into it. The Master PEB accumulates the precinct totals so that they can later be transported to the tabulation center where the vote totals are uploaded (through PEB readers) and included in the official tally.

- Activator PEBs. Activator PEBs are used by poll workers to activate ballots for voters. Each voter's session with the voting terminal starts with a poll worker inserting an Activator PEB into the terminal. Election officials provide each precinct with multiple Activator PEBs.

  Internally, all PEBs at the precinct are identical. The only difference between them is the color of the rubber band on their exterior. Thus, a Master PEB can be used to activate a voter's ballot and an Activator PEB can be used to open and close terminals; though, as a matter of procedure and training, they should not be used this way. Poll workers are trained so that they put each precinct's Master PEB, CF cards and totals tape in a designated bag that is transported to Election Central after polls close; Activator PEBs may be left behind. Thus, if an Activator PEB is used to close terminals, its vote data may not be uploaded to the aggregated totals on election night.

Removable Compact Flash (CF) card. The CF cards are programmed at Election Central and installed in the back of the voting terminal prior to deployment at the polling location. The CF cards contain graphic (bitmap) files read by the voting terminal during the voting process. The audio files required for the ADA terminals are also stored in the CF cards. The CF cards are also used as an external memory device as the terminal's event log and ballot images are written to the CF card when the terminal is closed for voting. Once the polls close, the CF cards are removed from the back of the terminal and delivered to election headquarters on election night. The CF cards are uploaded to the Election Management System during the canvassing process. Election officials generate the election's ballot image and event log databases from each precinct's set of CF cards. For the remainder of this paper, any reference to the iVotronic logs will refer to the aggregated data from all precincts in a single county.

2.2 iVotronic Audit Data

The ES&S voting solution produces many log files, but in our analysis we focus on three: the event log (EL152.lst), the ballot image file (EL155.lst), and the system log (EL68a.lst). Other files produced by the iVotronic are the Unofficial Precinct Report-Group Details (EL30a.lst), the Official Precinct Report (EL30.lst), the Unofficial Summary Report-Group Details (EL45a.lst), the Official Summary Report (EL45.lst), and the Manual Changes Log Listing (EL68.lst). We did not use these for two primary reasons: first, unofficial data detracts from the validity of our analyses; second, these logs were not available for the majority of counties. There is limited documentation about the iVotronic logs; therefore there may be additional files that have not been released to the public.

The event log (EL152.lst) contains audit log entries from each iVotronic terminal used in the election. The log records, in chronological order, all events that occurred on that machine during the election. It typically begins at election headquarters, before the election, with a "clear and test" of the terminal to delete previous election data from the terminal's memory. It also records all election day events, including polls open, polls closing, and the number of ballots cast. Each event log entry includes the iVotronic's terminal serial number, the PEB's serial number, the date and time, the event that occurred and a description of the event.

The ballot image file (EL155.lst) contains all ballot images saved by the iVotronic terminals during the voting process. An ES&S ballot image is a bit of a misnomer and might more rightfully be called a cast vote record: it is a list of all choices made for each vote cast; it is not a scanned or photographic image. However, we stick with the ES&S terminology and refer to each cast vote record as a ballot image. The ballot images are segregated by precinct and terminal where the votes were cast. The ballots are saved in a random order to protect the privacy of the voter.

The system log listing file (EL68a.lst) chronologically tracks activity in the election reporting database at the election headquarters. Its entries reflect the commands executed by the operators during pre-election testing, election night reporting, post-election testing, and canvassing. It also contains the totals accumulated in the various precincts during election night reporting, as well as any warnings or errors reported by the software during the tabulation process. The system log also tracks the uploading of PEBs and CF cards to the election-reporting database. Manual adjustment of precinct totals are also recorded in the system log file.

2.3 Voter Privacy

Our tool depends on the audit logs being publicly available. It is important that neither the logs themselves, nor our analyses endanger voter privacy.

None of the logs we use in our analyses contain personally identifiable information. The event log contains the times and machines on which votes were cast, but contains no voter information and no form of a ballot image. It simply states that a vote was cast on machine X at time Y. The ballot image file is a record of all cast ballots. Each ballot image depicts the choices a voter made, which machine they used, and which precinct they voted in. In order to protect voter privacy, the system records the ballot images in a random order. As long as no machine was used by only a single voter, the ballot image cannot be traced back to a particular entry in the event log. Because the event log does not contain any cast vote records and the ballot images are randomly ordered, and assuming no machine was used by only a single voter, there is no way to link the two log files to determine how a voter voted. Public information in combination with these logs does not affect voter privacy either; even if a spectator views the order of voters, no voter can be linked to his or her respective ballot image.

The system log only reflects operator actions and vote totals, and therefore has no foreseeable impact on voter privacy.

2.4 Other DRE Audit Logs

Our tool focuses on the iVotronic system, but it can be applicable to other systems, provided their logs contain the information described in Section 3, as well as a way to collect the logs at a central location in an electronic format. Other machines that we considered based on their popularity were the ES&S (formerly Premier Election Solutions) AccuVote-TSX, Sequoia AVC Edge, and Hart eSlate. Both the AccuVote-TSX and AVC Edge lack the ability to export logs to a central location for analysis. Additionally, it is not clear from available documentation that these two machines support file formats that are suitable to our tool. The eSlate DRE machine is more conducive to a tool such as ours. This machine allows for the automatic collection of audit logs to a central location. It also contains the most complete logging of the three systems; it is more likely that the eSlate contains all of the required information necessary to run our analyses. However, it is known that the eSlate contains a weakness in the protection of voter privacy: the audit log includes information that could connect voters to their votes [24]. These are not fundamental limitations of the idea of log analysis, but rather a shortcoming of existing systems, so we scoped our work to reflect this. More details on suggestions to make logging systems more amenable to this type of analysis are discussed in Section 6.

3 Analysis

Our system is structured as a set of analyses, each one designed to shed light on one particular aspect of election-day and post election-day activities. In this section we present a description of our analyses.

3.1 Analyses of Interest

We focus on analyses that we expect to be most useful to election officials or interested third parties. First, since incorrectly set internal clocks on the DREs make analysis of the audit log data more difficult and less reliable, we identify erroneous time stamps in the audit logs. Incorrectly set clocks may also prevent a voting machine from starting up on time [23].

Then, since vote-counting is fundamental to elections, we use the audit logs to detect instances of cast votes being under-counted. We do this by looking for discrepancies between the different log files that indicate some votes have been left out of the final tally.

Third, we use audit logs to identify incidents of lines at polling locations. Long lines in the voting place can negatively affect the fairness of elections. There is a positive correlation between line length and the likelihood of a voter reneging – that is, leaving the polling location without voting [19]. A study conducted by the Voting Rights Institute of the Democratic National Committee found that as many as 3% of voters in the 2004 general election in Ohio reneged [10]. A field study conducted during the 2008 presidential primary in California observed close to 2% of voters leaving the polling location without voting when there were lines [19]. In addition to reneging, voters may be deterred from going to the polling place in the first place if they expect long lines, which is known as balking. A case study of the 2004 presidential election estimates that between 4% and 4.9% of voters in Franklin County, Ohio may have balked for fear of encountering long lines [3]. Finally, incidents of long lines do not occur with equal probability at all precincts. Locations in lower socioeconomic neighborhoods have a higher chance of experiencing long lines on election day [19, 10]. For these reasons, understanding where and how often long lines occur is important for gauging the success and fairness of an election and can help election officials better allocate resources at the next election.

To this end, we conduct two analyses. In the first, we find all locations that were open past the official poll closing time and use this as a proxy for the existence of long lines at the end of the day. Election officials might also like to know when lines occurred throughout the day or whether there were lines earlier in the day that had disappeared by closing time. We perform the former analysis for those subset of locations that stayed open late. In other words, for those locations that stayed open late, we are able to show through analysis of the audit logs, at what other times of the day they likely had long lines. In Section 6 we suggest simple improvements to the log data that would make our long lines analysis possible for all precincts, not just those that stayed open late.

In our fourth set of analyses, we identify a number of seemingly small election-day issues that can have a very real, negative effect on the accuracy and fairness of an election. These include: malfunctioning displays that go unnoticed; failure to follow procedures on the part of poll workers; and audit data that was not recorded, but should have been.

Incorrect displays might cause a voter to cast a vote other than as intended. Failing to follow election-day protocol can lead to a loss of votes when a machine is not correctly closed out at the end of the day. Missing audit data is a concern as it makes it difficult for our other analyses to give accurate results. Some of these errors could result in fewer working machines on election day. Fewer machines can mean longer lines at the polling place. Also, the number of machines per voter appears to have an affect on the percentage of votes not included in the final tally due to error: as the number of machines per voter increases, the more likely the cast votes get counted [10].

3.2 Algorithms

We describe here the algorithms used in each of our analyses. For the majority of these we only consider data from election day between the hours of 7 A.M. and 7 P.M., which are the times that polls open and close in South Carolina. In our preliminary analysis, we found examples of log entries with seemingly incorrect time stamps. We identified two types of time stamp errors: errors resulting from incorrectly set clocks and errors resulting from apparent bugs in the time stamp mechanism itself. Given only a time stamp in the logs, it is impossible to know whether it is correct; however, we developed a number of heuristics to find those terminals that likely do have an incorrect clock. We try to minimize the number of false positive reports we give; therefore, we may miss some terminals with an incorrect clock. We provide the user with a report detailing the results of this time stamp analysis.

This analysis is meant only to indicate whether a machine had a noticeably incorrect time; we are not concerned with whether multiple machines in a precinct have synchronized internal clocks. Our analyses never require piecing together the order of events that took place in two different machines; therefore we neither require nor suggest that election officials should synchronize the clocks on different machines. While our tool can tolerate a fair amount of error, we do recommend that the machines be set with a reasonably correct time.

AuditBear detects whether any votes were left out of the tally. We assume the tabulation software is correct and instead use the audit logs to check that all cast votes are entered into the tabulation software. Recall that each voting terminal's vote totals are loaded onto a PEB when polls are closed and then all these PEBs' data are loaded into the election reporting database. There are two points in this process where votes could be omitted: a terminal may be forgotten and never closed, so that no PEB contains its vote totals; or a PEB used to close a terminal might be forgotten and not uploaded to the database. We show how to use the audit logs to detect both of these problems.

In order to find instances of PEBs that were not uploaded, we compared the contents of the event log and ballot image files to that of the system log listing file. We first identify, by parsing the event log, the set of PEBs used to close out all voting terminals in the county and then verify each one appears as uploaded in the system log file. When a PEB is missing from the system log file, we report the case because it signifies that the PEB was not uploaded and the votes may not be in the certified totals. Our tool only has the ability to detect missing PEBs when the corresponding CF card has been uploaded; there may be additional missing votes and audit information that we do not detect.

Looking for terminals that were never closed is a challenging problem: essentially we need to identify events that are missing from the logs. We do this by finding terminals that were opened, but never closed.

AuditBear also reports on polling locations that stayed open late and that had long lines throughout the day. While the totals report for each precinct specifies what time the totals report was printed, it may not be indicative of the time the polls closed for that precinct. For example, a poll worker may work on other closing procedures before printing the totals report; if election officials were to refer to these tapes to identify polling locations open late, they would experience many false positives. Additionally, this allows a more convenient way for election officials to find out which precincts were open after 7 P.M.

In order to identify locations that stayed open past 7 P.M., AuditBear first compiles a list of every terminal in the event log file for which the last vote was cast after 7 P.M. Then, using information from the ballot image file, the algorithm groups terminals by polling location and computes the mean time of the last cast vote for each group. We take the mean in order to account for any chance error in the time stamps. Finally, we report which polling locations stayed open late and also provide, for every county, a chart detailing the number of polling locations that stayed open late and by how long.

Identifying locations that had lines throughout the day is trickier. We start by positing that when there is a line of voters waiting, there will be negligible idle time for each machine between voters. We would like to identify windows of time where this was the case for a particular polling location. (Note that this does not allow us to differentiate between voters standing in line and voters arriving in a steady stream that keeps the machines at maximum capacity. It is a shortcoming of our approach, but seems difficult to avoid given only the log data.) The analysis is complicated however, by the fact that the logs do not record an event when a new ballot is activated for a voter, only when a ballot is cast. Given the time stamps t_1 and t_2 of two cast vote events for voters v_1 and v_2, it could be the case that v_2 walked up to the terminal as soon as v_1 cast her vote and then spent $t_2 - t_1$ minutes marking her ballot before casting her vote. Or, it could be that the terminal was idle for most of $t_2 - t_1$ and at the last moment, voter v_2 approached the terminal, quickly marked her ballot and then cast her vote. If we knew how long the average voter took to mark her ballot we could use that to estimate the length of the idle time between two consecutive cast vote events. We do not know that information directly, but we can infer it from the logs we have. We know which locations were open after 7 P.M. and we also know that a polling location should only stay open late if there are people waiting in line at the official poll closing time. We assume this protocol is followed, and that the line moves efficiently, and therefore the terminals in a given location experience very little idle time between voters after 7 P.M. We also assume the time it takes to mark a ballot is a random variable and these late voters are a random sample of the entire voting population for that precinct. Therefore the average time it takes them to vote represents the time it takes the average voter in the precinct to vote.[1] We then look for other times throughout the day where the time between votes is similar to or less than the time between votes after 7 P.M. Starting at 7 A.M., for each location, we look at each one hour window that starts on the hour and compile the set S_1 of time-between-consecutive-votes for every machine in that location during the window. Next, we compare this set to S_2, the time-between-consecutive-votes for every machine in that location after 7 P.M. If the mean of S_1 is less than the mean of S_2, this suggests times in S_1 were shorter than in S_2 and there possibly were long lines in that window. We then perform the Mann Whitney U statistical test to determine whether the observed difference in mean is likely due to chance error. For windows where the two-tailed p-value is less than 0.05, there is evidence that the difference in mean is real and there possibly were long lines during the window when S_1 was collected. For those precincts open after 7 P.M., we report the hours during the day that possibly experienced long lines.

Note that we only perform this analysis on locations that were open after 7 P.M. This analysis would be useful to perform on all locations; after all, it is possible a polling place had long lines early in the day, but was still able to close on time. One way to do that would be to define S_2 to be the time-between-consecutive-votes after 7 P.M. for every machine in *every* location that is open late and then separately compare each location's S_1 set to the global S_2. However, doing so assumes that the late voters are a random sample of the entire voting population across all precincts in the county and have a representative average time-to-vote; this is not a safe assumption. The average time to vote depends on a number of factors that can vary widely from precinct to precinct, including: the number of issues on the ballot, the clarity and length of the writing on the ballot, and the socioeconomic level of the polling location [19, 3]. Between locations, the average time to vote can vary by as much as 1.5 minutes [19]. In order to make the long lines analysis applicable to all voting locations, one would have to correct for each of these confounding factors. How one might do so is an interesting open question, and we feel that extending the long lines analysis to all voting locations might be amenable to deeper analysis.

We also report on machines that had an uncalibrated display at the time when a vote was cast; there is the possibility that those votes may not have been cast as intended. When detecting votes cast on uncalibrated machines, we looked for three specific events in the event log: a machine uncalibrated event, a vote cast event, and a machine recalibrated event. We used a simple finite state machine with states = {uncalibrated machine with no votes cast, uncalibrated machine with at least one vote cast, calibrated machine} and tracked the current state of each terminal as we iterated through the event log. We then report any machine that had ever been in the state "uncalibrated machine with at least one vote cast."

The procedural errors we are concerned with are: not printing zero tapes, casting votes with Master PEBs, and opening and closing a machine with different PEBs. For each polling location, we check that every machine in the location recorded printing zero tapes, that each machine was opened and closed with the same PEB, and that no PEB used to open or close a machine was also used to cast a vote.

Last, we consider how to detect missing data: audit data that was not recorded, but should have been. In some cases, this may be impossible; if there is no trace of a terminal in any of the logs, we have no way of knowing that its data is missing given only the logs. We focus on the audit data for cast votes and find votes for which

[1] It is possible that voters who arrive later in the day are from a particular population that has a different average time-to-vote than voters who arrive earlier in the day; however, in their field study of the California 2008 primary, Spencer and Markovitz found that, at a given location, the average time to vote was constant throughout the day [19], so we feel our assumption is not unreasonable.

either the cast vote event was missing or the ballot image was missing. We can not detect a cast vote which is missing both the cast vote event and the ballot image. For each voting terminal, we compare the number of cast vote events in the event log with the number of ballot images in the system log. We report those terminals where the two values are not equal as the logs must be missing data from those machines.

4 Implementation

We built a web application called AuditBear to give election officials and advocacy groups easy access to our toolset. AuditBear requires the user to upload an event log and a ballot image file; we strongly suggest they also submit the system log to take advantage of the full range of analyses our tool provides.

AuditBear uses only publicly available log data and does not store any information from the logs. In the case that there is a malicious person with access to the tool, no harm can be done because the logs do not contain any private information and it cannot be derived from the use of multiple logs or public information. Additionally, voter privacy will not be harmed if there is a web security breach in the log upload process for the same reasons. Therefore, the storage and distribution of these logs does not pose a risk to voter privacy.

AuditBear produces reports that warn election officials about possible miscounts or procedural errors. Each report provides details about the errors found and explains the possible consequences of the error and suggests, where applicable, steps the election officials might take to address the error.

5 Results

This section discusses our findings after running our tool on the audit logs from the South Carolina 2010 General Election. We tested our analysis using log files downloaded from the website titled South Carolina Voting Information.[2]

While we report the anomalies AuditBear detects, there are limited resources for confirmation. There is no plausible way to confirm long lines or problematic machines in the 2010 elections. As we do not handle malicious tampering of the logs, we assume that they are correct. While we do detect incomplete logs, we have no means to know whether there are errors in the FOIA request. With the assumption that the logs are correct, we can compare our detected number of missing votes to the number found in a previous study for corroboration.

[2] www.scvotinginfo.com

5.1 Date/Time Errors

AuditBear found 1465 out of 4994 machines across 12 counties whose date was changed during election day voting. Figure 1 shows an example of a 1-hour time change for Georgetown County. This county had 125 out of 140 machines adjusted nearly exactly one hour back in time. This suggests the wrong Daylight Savings Time algorithm was in use, as mentioned in previous audits [6].

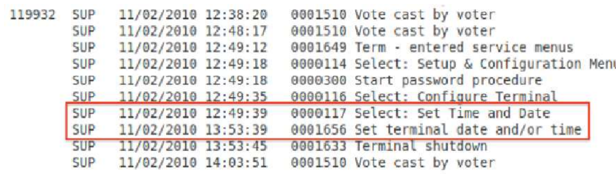

```
119932  SUP  11/02/2010 12:38:20  0001510 Vote cast by voter
        SUP  11/02/2010 12:48:17  0001510 Vote cast by voter
        SUP  11/02/2010 12:49:12  0001649 Term - entered service menus
        SUP  11/02/2010 12:49:18  0000114 Select: Setup & Configuration Menu
        SUP  11/02/2010 12:49:18  0000300 Start password procedure
        SUP  11/02/2010 12:49:35  0000116 Select: Configure Terminal
        SUP  11/02/2010 12:49:39  0000117 Select: Set Time and Date
        SUP  11/02/2010 13:53:39  0001656 Set terminal date and/or time
        SUP  11/02/2010 13:53:45  0001633 Terminal shutdown
        SUP  11/02/2010 14:03:51  0001510 Vote cast by voter
```

Figure 1: Event log entry for resetting an iVotronic clock by one hour in Georgetown County.

Anomalous time changes were detected in 18 machines. An anomaly is any occurrence of an unexplained date change while a machine is open for voting. Figure 2 is an example that occurred in Richland County. The machine was manually corrected about 30 minutes later.

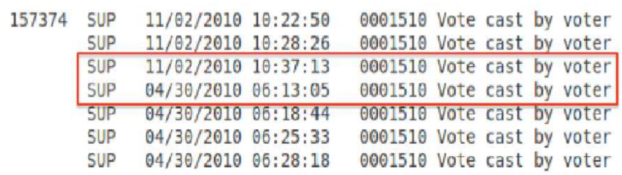

```
157374  SUP  11/02/2010 10:22:50  0001510 Vote cast by voter
        SUP  11/02/2010 10:28:26  0001510 Vote cast by voter
        SUP  11/02/2010 10:37:13  0001510 Vote cast by voter
        SUP  04/30/2010 06:13:05  0001510 Vote cast by voter
        SUP  04/30/2010 06:18:44  0001510 Vote cast by voter
        SUP  04/30/2010 06:25:33  0001510 Vote cast by voter
        SUP  04/30/2010 06:28:18  0001510 Vote cast by voter
```

Figure 2: The event log shows a seemingly random date anomaly, which occurred in Richland County during the election day.

5.2 Missing Votes

Our analysis shows that a total of 15 PEBs containing 2082 votes were not uploaded from the 14 counties that we audited in South Carolina. Figure 3 summarizes the PEBs not uploaded during the General 2010 elections.

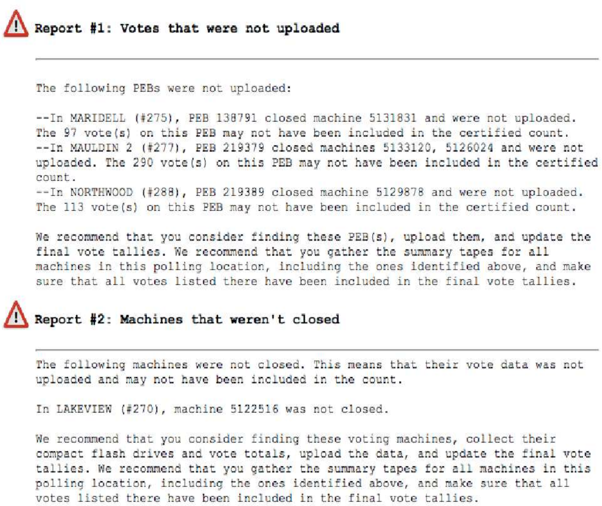
AuditBear also identified a few instances of machines not being closed. A machine must be closed in order to collect the votes and audit data from that machine. There was a single machine that was not closed in each of the following counties: Greenville County, Horry County, and Sumter County. If this was a close election, information such as this could be cause for an extensive audit or recount of the votes. In this particular case, we know from previous audits that the missing data amounts

County	PEBs used to collect votes	PEBs not uploaded	Votes not uploaded
Anderson	77	1	163
Colleton	36	1	122
Georgetown	36	1	92
Greenville	154	3	500
Horry	121	2	189
Richland	128	5	648
Sumter	60	2	368

Figure 3: The number of PEBs and their corresponding votes per county that were not uploaded.

to 2082 missing votes, which would not have affected the outcome for any of the races in the South Carolina 2010 elections [18].

Figure 4 shows some of AuditBear's output on Greenville County's log files.



Report #1: Votes that were not uploaded

The following PEBs were not uploaded:

--In MARIDELL (#275), PEB 138791 closed machine 5131831 and were not uploaded. The 97 vote(s) on this PEB may not have been included in the certified count.
--In MAULDIN 2 (#277), PEB 219379 closed machines 5133120, 5126024 and were not uploaded. The 290 vote(s) on this PEB may not have been included in the certified count.
--In NORTHWOOD (#288), PEB 219389 closed machine 5129878 and were not uploaded. The 113 vote(s) on this PEB may not have been included in the certified count.

We recommend that you consider finding these PEB(s), upload them, and update the final vote tallies. We recommend that you gather the summary tapes for all machines in this polling location, including the ones identified above, and make sure that all votes listed there have been included in the final vote tallies.

Report #2: Machines that weren't closed

The following machines were not closed. This means that their vote data was not uploaded and may not have been included in the count.

In LAKEVIEW (#270), machine 5122516 was not closed.

We recommend that you consider finding these voting machines, collect their compact flash drives and vote totals, upload the data, and update the final vote tallies. We recommend that you gather the summary tapes for all machines in this polling location, including the ones identified above, and make sure that all votes listed there have been included in the final vote tallies.

Figure 4: Feedback generated by AuditBear for officials when detecting that some votes were not uploaded.

5.3 Long Lines

We found 671 out of a total of 942 South Carolina precincts stayed open late. Berkeley County had the highest incidence of delayed closing times with 93% of polling locations closing after 7 P.M. Figure 5 depicts the precincts that closed late in Berkeley County. In the future, resources could be allocated to those polling locations that stayed open the latest to help move their lines more quickly. To detect possible lines before 7 P.M., we looked at only the precincts that were open late. Figure 6 shows the time periods when the Berkeley County precincts experienced long lines before 7 P.M. Figure 7 shows the details of the results of the Mann Whitney U statistical test for long lines.

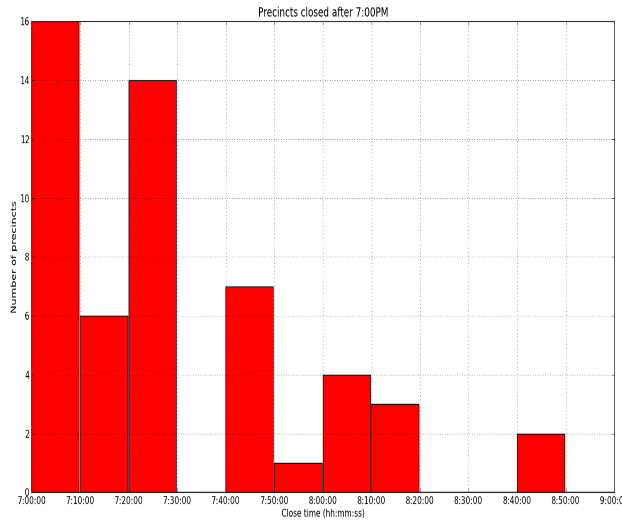


Figure 5: The number of precincts that closed within certain time intervals after 7:00 P.M. (late) in Berkeley County.

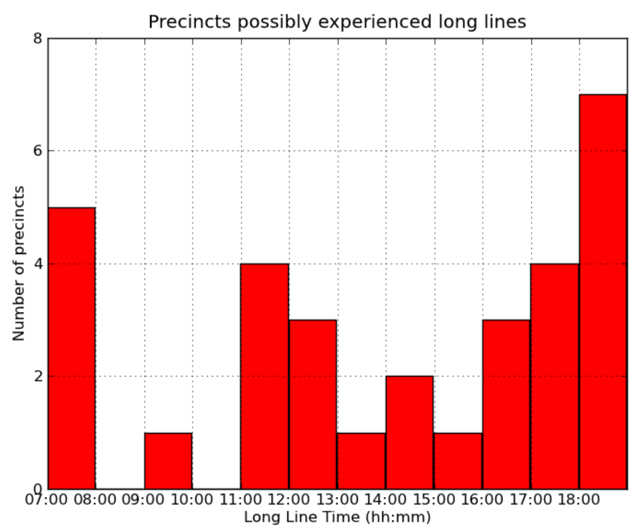


Figure 6: The number of precincts that may have experience long lines within certain time intervals in Berkeley County.

# Precinct	Long Lines Time	Sample Size	Median Time	U-value	Two-tailed p-value
All precincts	7:00 p.m. - closing time	1257	3.57	N/A	N/A
26 Huger	4:00 p.m. - 5:00 p.m.	37	2.88	15,759	0.0
	6:00 p.m. - 7:00 p.m.	39	2.70	14,741.5	0.0
10 Cordesville	12:00 m. - 1:00 p.m.	32	3.16	14,765.5	0.01
24 Hilton Cross Rd	12:00 m. - 1:00 p.m.	53	2.98	24,407	0.0
	5:00 p.m. - 6:00 p.m.	52	3.21	24,332.5	0.0
20 Hanahan 1	5:00 p.m. - 6:00 p.m.	48	3.28	24,968	0.04
58 Medway	7:00 a.m. - 8:00 a.m.	51	3.02	23,965.5	0.0
	6:00 p.m. - 7:00 p.m.	68	2.73	30,245	0.0
34 Moncks Corner 4	4:00 p.m. - 5:00 p.m.	84	3.26	45,274	0.03
37 Russellville	11:00 a.m. - 12:00 m.	47	3.02	22,496.5	0.0
	1:00 p.m. - 2:00 p.m.	34	3.04	15,691	0.0
	2:00 p.m. - 3:00 p.m.	44	2.92	17,490	0.0
	3:00 p.m. - 4:00 p.m.	60	2.48	20,789.5	0.0
	4:00 p.m. - 5:00 p.m.	50	3.20	25,064	0.02
	6:00 p.m. - 7:00 p.m.	51	2.88	20,709.5	0.0
29 Macedonia	7:00 a.m. - 8:00 a.m.	42	3.07	19,821	0.0
45 Stratford 2	7:00 a.m. - 8:00 a.m.	68	3.06	31,825	0.0
	12:00 m. - 1:00 p.m.	78	3.21	42,027	0.03
7 Cainhoy	2:00 p.m. - 3:00 p.m.	51	3.25	26,770.5	0.046
	6:00 p.m. - 7:00 p.m.	59	2.78	22,364.5	0.0
60 Whitesville 2	7:00 a.m. - 8:00 a.m.	32	2.83	12,105	0.0
	6:00 p.m. - 7:00 p.m.	51	3.25	26,361.5	0.03
57 Liberty Hall	6:00 p.m. - 7:00 p.m.	49	2.98	24,473	0.01
39 Sangaree 2	6:00 p.m. - 7:00 p.m.	86	2.99	41,377.5	0.0
49 Wassamassaw 2	5:00 p.m. - 6:00 p.m.	110	3.28	60,667.5	0.03
35 Pimlico	7:00 a.m. - 8:00 a.m.	58	2.83	22,526	0.0
	5:00 p.m. - 6:00 p.m.	68	3.0	32,026	0.0
11 Cross	9:00 a.m. - 10:00 a.m.	97	3.37	51,907.5	0.01
	11:00 a.m. - 12:00 m.	85	3.17	46,088	0.03
12 Daniel Island 1	11:00 a.m. - 12:00 m.	125	3.35	70,085.5	0.046
13 Daniel Island 2	11:00 a.m. - 12:00 m.	138	3.3	76,555	0.02

Figure 7: Times when there were likely long lines in Berkeley County on a per-precinct basis.

5.4 Calibration Errors

We found seven counties where at least one machine was possibly not calibrated when votes were cast on that machine. An uncalibrated display could potentially cause votes to not be cast as intended. Our report suggests an election official or technician inspect these machines for possible calibration issues; see Figure 8.

Report #1: Votes cast when the voting machine screen may not have been calibrated

The following machines may have recorded votes being cast while the terminal screen seemed to have calibration problems. You may wish to find these machines and check whether their screen is properly calibrated and verify the votes.

In Red Bank (#18),	machine 5123670 had votes cast when it was possibly not calibrated.
In Pilgrim Church (#64),	machine 5130458 had votes cast when it was possibly not calibrated.
In Lexington #3 (#70),	machine 5123550 had votes cast when it was possibly not calibrated.

Figure 8: Feedback generated by AuditBear for election officials when calibration issues are detected.

5.5 Procedural Errors

Our findings reveal the need for improvements in poll worker training. When opening and closing a machine, the same Master PEB should be used, but in 11 counties there were machines opened and closed with different PEBs. Our results showed an association between this error and certain precincts where poll workers made those mistakes repeatedly. When this error is made multiple times at a single precinct, it indicates that perhaps the poll workers do not know the procedures, whereas a random distribution of these errors across polling locations probably means a mistake was made. Colleton County had five instances of this procedural error, but four of those instances took place at one polling location. Figure 9 shows this report from Colleton County.

A poll worker assigns each voter a PEB to use when it is that voter's turn. When voters cast votes, they should not do so with a Master PEB. For most precincts in Florence County, this error never occurred, however, four precincts had large numbers of this error; Mill Branch had this error on 56 out of 540 votes, Pamplico 2 had this error on 82 out of 579 votes, McAllister Hill had this error on 102 out of 749 votes, and Effingham had this error on 86 out of 591 votes. This pattern of errors again suggests certain poll workers did not know the proper procedure. Figure 10 shows this relationship in Florence County.

Report #9: Machines opened and closed with different PEBs

The following machines were opened and closed with different PEBs. You may wish to review your poll worker training manual.

In Mashawville (#15),	machine 5138893 was opened with PEB 156178 and closed with PEB 156226.
In Walterboro No 4 (#32),	machine 5129946 was opened with PEB 155914 and closed with PEB 155925.
In Walterboro No 4 (#32),	machine 5133679 was opened with PEB 155914 and closed with PEB 155925.
In Walterboro No 4 (#32),	machine 5138439 was opened with PEB 155914 and closed with PEB 155925.
In Walterboro No 4 (#32),	machine 5138563 was opened with PEB 155914 and closed with PEB 155925.

Figure 9: An example response when AuditBear reports machines that were opened and closed with different PEBs.

5.6 Audit Data

In several counties, the audit logs appeared to be incomplete. Our analysis detected six counties that did not have the same set of machines in both the event log and ballot image file. Florence County had the most inconsistencies with 65 machines that had votes cast on them according to the event log, but no ballot images. We also saw cases where there were ballot images for votes cast on machines that did not record any events on the event log. In addition to an unusually large amount of missing data, the analysis of Florence County showed machines that did not have the same number of votes cast as ballot images. See Figure 11 for example output from AuditBear.

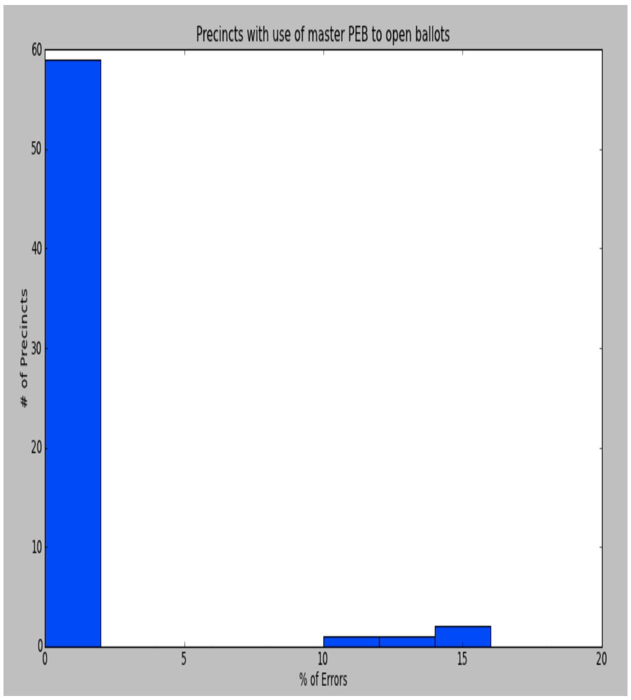


Figure 10: This histogram shows the percentage of votes at each precinct that were cast with a Master PEB. The precincts that showed the highest percentages had between 56 and 102 instances of this error.

Report #3: Machines whose vote count differed between files

The following machines appear to have inconsistencies across the audit data. We recommend that you gather vote data from the following machines, upload it, and update the audit data. From the data provided, we cannot infer the locations of the machines.

Machine Serial #	Votes according to event log	Votes according to ballot images
5130310	4	0

Figure 11: Feedback generated by AuditBear when incomplete audit data is detected.

6 Future Voting Systems Suggestions

We believe the following recommendations will make audit files more usable.

Voting systems should support automatic generation and collection of audit logs in a central location. While many other DRE systems do capture data in their audit logs similar to what the iVotronic does, no other widely deployed voting system makes it as easy to gather all the audit logs from all of the voting machines into a single place. As a result, while our methods are in principle applicable to other deployed voting systems, in practice this would require additional effort from election officials. In addition, audit logs should have a universal electronic file format. This would allow for a more extendable tool.

Vendors should document the meaning of all events. We found audit logs with event messages, such as "UNKNOWN," "Warning PEB I/O flag set," and "Warning I/O flagged PEB will be used," which sound ominous, however we could not determine the gravity of the issue. Despite combing through all of ES&S's publicly available information about the iVotronic, the meaning of these events still remain a mystery [21, 12, 13].

Accuracy of date and time logging needs improvement. When the machine has an incorrect clock, time stamps are inaccurate and it becomes difficult to recreate election day events. In addition, some audit log analyses, such as the open late analysis, are made more difficult by unreliable time stamps.

Make system manuals available to the public. Voting machine audit logs are public information. The general public can request them under the Freedom of Information Act. In the same fashion, we recommend that voting system manuals be made freely available. This would allow the public to see for themselves if there were any problems that should be addressed.

Capture the ballot activation event. Recording the time each ballot is activated (as opposed to only recording when the ballot is cast) would make it easier to learn when the voting machines were heavily used and when they were idle. As the ballot image file is still randomized, there is still no way to connect a voter to his or her vote. Even if a spectator watches the polling location and records how long each voter spends in the voting booth, there are hundreds (if not thousands) of ballot images in the ballot image file. It is unlikely that a malicious person could use this information in order to determine a voter's choice. This is a simple change that would not compromise voter privacy, and would make it easier for an automated tool such as AuditBear to extract information about long lines during the day.

Future voting system standards introduce stronger requirements for audit logs; this could make it easier to apply our analyses to other voting systems [24]. The current standards require voting systems to keep a permanent record of audit data, but does not specify a particular format. These standards also address the matter of time stamps; they state "All systems shall include a real-time clock as part of the systems hardware. The system shall maintain an absolute record of the time and date or a record relative to some event whose time and data are known and recorded" [1]. Newly proposed, but not yet approved standards, make additional requirements: voting systems must produce electronic records that are exportable and transmitted to the Election Management System. Another proposal under these standards is that voter privacy be maintained even when reports are combined [2]. Many of these standards align with our suggestions for future voting systems.

7 Related Work

Two recent studies used event logs from the iVotronic voting system to audit elections [6, 17]. Buell et al. [6] analyzed the same South Carolina elections that we did and also discovered votes not included in the certified counts and problems with the audit data. By consulting additional audit materials, such as the printed results tapes, the authors were able to offer possible explanations for why the problems occurred. Our work takes a slightly different approach. We focus on developing an automated analysis of the publicly available audit log data that can be used by anyone to detect other possible errors in addition to missing votes.

Sandler et al. [17] analyzed vote tallies by comparing each machine's protected vote count to the printed results tapes. Their report also finds time stamps that were most likely inaccurate. With further investigation, they concluded that the machine hardware clock was incorrect. Our research provides analyses to identify similar problems, but in a way that can be automated.

There has also been research on using the audit logs to analyze election-day procedure and activity. Antonyan et al. showed how event logs could be used to determine if a machine acted "normally" on election day [4]. They built a finite state machine that models the sequences of events that a well-behaved AccuVote-OS scanner might produce and used it to analyze AccuVote-OS logs. This type of analysis could be useful for the iVotronic systems that we studied, too.

Other work has focused specifically on detecting or predicting long lines. Formal models adapted from queuing theory and simulations of voter queues can be used to better understand the factors that affect the length and duration of lines at the polling place [3, 11]. Our work is complementary, and in fact information about election day events gathered by AuditBear can be used to inform the queuing models. A field study, such as that done by Spencer and Markovitz [19], can provide ground truth about the occurrence of long lines on election day, but in the absence of that ideal, our analysis can provide some information about the time and duration of long lines.

Voter Verified Paper Audit Trails (VVPATs) are a different type of audit log. Unlike the audit logs we used in our analyses, VVPATs are viewed and verified by the voter and are more suited to audits concerning a DRE incorrectly capturing a voters intent. Our work is more concerned with identifying cases of cast votes not being included in the final count, or issues at the polling place that might prevent the voter from casting their vote in the first place. With VVPATs, as long as a certain percentage of voters do check their paper ballot [15], the voting machine need not be assumed correct, whereas our analyses do make this assumption.

8 Conclusion

This paper develops methods to analyze audit data from DRE voting machines. It introduces new methods for extracting information about election-day activities and post-election anomalies from audit data. We conduct an audit on the 2010 South Carolina election using these methods and are able to detect instances of missing votes, procedural errors, and likely instances of lines throughout the day. With this information, election officials can improve poll worker training, resource allocation, election tabulation procedures, and voting machine preparation testing. Based on our experience during this research, we make suggestions for future audit logs that would make an automated analysis such as ours even more informative.

We built a web application, AuditBear, to perform these analyses. Users can upload the iVotronic log files to our website and run the analyses. By automating our analyses we can provide intelligent feedback to election officials during the canvassing process and help them quickly correct any problems in order to produce accurate election results. AuditBear is freely available online.

9 Acknowledgments

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A Event Log File

Votronic	PEB#	Type	Date	Time	Event
5124751	151386	SUP	11/02/2010	08:25:24	0001510 Vote cast by voter
		SUP	11/02/2010	08:30:34	0001510 Vote cast by voter
	137507	SUP	11/02/2010	08:36:59	0001510 Vote cast by voter
	151386	SUP	11/02/2010	08:42:37	0001510 Vote cast by voter
		SUP	11/02/2010	08:47:07	0001510 Vote cast by voter
		SUP	11/02/2010	08:52:06	0001510 Vote cast by voter
		SUP	11/02/2010	08:55:06	0001510 Vote cast by voter
	137507	SUP	11/02/2010	09:01:30	0001510 Vote cast by voter
	151386	SUP	11/02/2010	09:05:33	0001510 Vote cast by voter
	137507	SUP	11/02/2010	09:12:19	0001510 Vote cast by voter
		SUP	11/02/2010	09:16:40	0001510 Vote cast by voter
		SUP	11/02/2010	09:18:52	0001510 Vote cast by voter
	155466	SUP	11/02/2010	09:19:52	0001721 PEB pulled while getting PEB type
		SUP	11/02/2010	09:19:52	0002405 Failed to get PEB type
		SUP	11/02/2010	09:19:52	0002400 PEB access failed
	137507	SUP	11/02/2010	09:21:20	0001515 Vote canceled - voter left before ballot
		SUP	11/02/2010	09:24:17	0001516 Vote cancelled - voter request
		SUP	11/02/2010	09:29:25	0001510 Vote cast by voter
		SUP	11/02/2010	09:32:33	0001516 Vote cancelled - voter request
		SUP	11/02/2010	09:36:18	0001510 Vote cast by voter
		SUP	11/02/2010	09:40:17	0001510 Vote cast by voter
		SUP	11/02/2010	09:43:32	0001510 Vote cast by voter
	155466	SUP	11/02/2010	09:45:26	0001510 Vote cast by voter
	151386	SUP	11/02/2010	09:51:45	0001510 Vote cast by voter
	137507	SUP	11/02/2010	09:56:10	0001510 Vote cast by voter
	151386	SUP	11/02/2010	10:04:22	0001510 Vote cast by voter
		SUP	11/02/2010	10:09:17	0001516 Vote cancelled - voter request
		SUP	11/02/2010	10:12:03	0001510 Vote cast by voter
	155466	SUP	11/02/2010	10:13:32	0001516 Vote cancelled - voter request
		SUP	11/02/2010	10:17:36	0001510 Vote cast by voter
	137507	SUP	11/02/2010	10:21:52	0001511 Vote cast by poll worker
		SUP	11/02/2010	10:27:24	0001510 Vote cast by voter
		SUP	11/02/2010	10:30:35	0001510 Vote cast by voter
		SUP	11/02/2010	10:37:13	0001510 Vote cast by voter
		SUP	11/02/2010	10:40:29	0001510 Vote cast by voter
		SUP	11/02/2010	10:45:26	0001510 Vote cast by voter
		SUP	11/02/2010	10:50:07	0001510 Vote cast by voter
		SUP	11/02/2010	10:52:48	0001510 Vote cast by voter
	151386	SUP	11/02/2010	10:58:06	0001510 Vote cast by voter
		SUP	11/02/2010	11:04:08	0001510 Vote cast by voter
	137507	SUP	11/02/2010	11:14:11	0001510 Vote cast by voter

B Ballot Image File

RUN DATE:03/30/11 08:05 AM   PRECINCT 57 - Liberty Hall   ELECTION ID: 08110210

VOTR.	B/I	CANDIDATES RECEIVING A VOTE	
5129343	2	46 Tom E Elliott	Commissioner of Agriculture
5129343	2	49 Tom Clements	U.S. Senate
5129343	2	57 Ben Frasier	CONG001 U.S. House of Rep. Dist 1
5129343	2	66 Bill Crosby	HOU0117 State House of Rep Dist 117
5129343	2	72 Wayne Dewitt	Sheriff
5129343	2	75 Keith Kornahrens	Probate Judge
5129343	2	78 Mary P Brown	Clerk of Court
5129343	2	88 Diane Edwins	Soil and Water District Commission
5129343	2	92 Yes	Amendment 1
5129343	2	95 Yes	Amendment 2
5129343	2	98 Yes	Amendment 3
5129343	2	101 Yes	Amendment 4
5129343	2	104 Yes	Local Question
5129343	2 *	11 Vincent A Sheheen	Governor
5129343	2	19 Mark Hammond	Secretary of State
5129343	2	24 W/I MICKEY MOUSE	State Treasurer
5129343	2	28 Matthew Richardson	Attorney General
5129343	2	32 Robert Barber	Comptroller General
5129343	2	38 Frank Holleman	State Superintendent of Education
5129343	2	43 W/I MARTIN SHEEN	Adjutant General
5129343	2	46 Tom E Elliott	Commissioner of Agriculture
5129343	2	51 Alvin M Greene	U.S. Senate
5129343	2	57 Ben Frasier	CONG001 U.S. House of Rep. Dist 1
5129343	2	92 Yes	Amendment 1
5129343	2	95 Yes	Amendment 2
5129343	2	99 No	Amendment 3
5129343	2	101 Yes	Amendment 4
5129343	2	104 Yes	Local Question
5129343	2 *	4 Democratic	STRAIGHT PARTY
5129343	2	11 Vincent A Sheheen	Governor
5129343	2	16 Ashley Cooper	Lieutenant Governor
5129343	2	20 Marjorie L Johnson	Secretary of State
5129343	2	23 Curtis Loftis	State Treasurer
5129343	2	28 Matthew Richardson	Attorney General
5129343	2	32 Robert Barber	Comptroller General
5129343	2	38 Frank Holleman	State Superintendent of Education
5129343	2	42 Bob Livingston	Adjutant General
5129343	2	46 Tom E Elliott	Commissioner of Agriculture
5129343	2	51 Alvin M Greene	U.S. Senate

C System Log File

```
11-02  09:03 pm  START PACK ACCUMULATION  (Replace Mode - restarting)
11-02  09:03 pm  0023-Time stamp mismatch (Reply was: Update)
11-02  09:03 pm                                                  PRC 0023 PACK RECEIVED VTR  (BALS=728  TOT=728)
11-02  09:03 pm  0040-Time stamp mismatch (Reply was: Update)
11-02  09:03 pm                                                  PRC 0040 PACK RECEIVED VTR  (BALS=816  TOT=816)
11-02  09:03 pm  0049-Time stamp mismatch (Reply was: Update)
11-02  09:03 pm                                                  PRC 0049 PACK RECEIVED VTR  (BALS=1093  TOT=1093)
11-02  09:03 pm  0043-Time stamp mismatch (Reply was: Update)
11-02  09:03 pm                                                  PRC 0043 PACK RECEIVED VTR  (BALS=604  TOT=604)
11-02  09:03 pm  0044-Time stamp mismatch (Reply was: Update)
11-02  09:03 pm                                                  PRC 0044 PACK RECEIVED VTR  (BALS=739  TOT=739)
11-02  09:03 pm  0044-Time stamp mismatch (Reply was: Update)
11-02  09:03 pm  0044-Precinct already updated (Pack suspended)
11-02  09:03 pm  0058-Time stamp mismatch (Reply was: Update)
11-02  09:03 pm                                                  PRC 0058 PACK RECEIVED VTR  (BALS=833  TOT=833)
11-02  09:03 pm  STOP PACK ACCUMULATION
11-02  09:03 pm  START PROCESS PEBS
11-02  09:07 pm  PEB votes retrieved for P0137152
11-02  09:07 pm  SPP file record created for P0137152
11-02  09:07 pm  PEB votes retrieved for P0137152
11-02  09:07 pm  SPP file record created for P0137152
11-02  09:07 pm  PEB votes retrieved for P0147256
11-02  09:07 pm  SPP file record created for P0147256
11-02  09:08 pm  PEB votes retrieved for P0147585
11-02  09:08 pm  SPP file record created for P0147585
11-02  09:08 pm  STOP PROCESS PEBS
11-02  09:09 pm  iVotronic GROUP 3 SELECTED FOR UPDATE
                 EQUIPMENT TYPE VTR - UPDATE PRECINCTS COUNTED:Y
```