VoTeR Center

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Technological Audits of Optical Scan Voting Systems: Summary for 2007 to 2010 Connecticut Elections

October 19, 2011, Version 1.1

Abstract

Security and integrity concerns regarding the use of electronic voting technologies in elections necessitate comprehensive election audits. Two types of audits are routinely performed in all state-wide elections in Connecticut: random post-election hand-counted audits and technological audits. This report presents the summary of the technological audit results in Connecticut from 2007 to 2010. The technological audits were designed on the request of the Secretary of the State (SOTS) of Connecticut by VoTeR Center and are conducted by the Center before (pre-election) and after (post-election) each state-wide election and selected primaries. The technological audits focus on the information contained on the memory cards used with the AccuVote Optical Scan (AV-OS) tabulators. This report presents the cumulative results of the pre-election and post-election technological audits. The audits examine the correctness of the programming of the memory cards with respect to the specific elections and the usage patterns at the districts in light of the election procedures established by the SOTS Office. The audits also assess the reliability of the memory cards. The conclusions are that districts do not always adhere to the established pre-election procedures. Most notably, in recent elections over 6% of the memory cards are duplicated by the districts, a practice that is not permitted by the SOTS Office; additionally, the number of cards submitted for audits has been substantially lower since 2008. The audits also established that more than 10% of the memory cards may experience data loss between the time they are programmed and the day of the election; this is apparently the reason for card duplication done by the districts. This data loss is most likely caused by the weak batteries on the cards (however, as of this writing it is not clear how long a fresh battery lasts in a memory card as some cards are known to consume substantially more power than others). To provide a better statistical basis for the overall elections landscape in Connecticut, it is recommended that the number of cards examined by the audits is substantially increased.

1   Introduction

In 2006, the AccuVote Optical Scan (AV-OS) ballot tabulation system was chosen to be used in the State of Connecticut elections. An important benefit of using the optical scan technology in electronic voting systems is that it naturally yields a voter-verified paper trail – the actual "bubble sheet" paper ballots marked by the voters. This differentiates optical scan electronic voting from DRE (direct recording electronic) touch-screen voting terminals that provide a digital interface for voting during the elections. At the same time, there exist serious concerns regarding the security vulnerabilities and reliability of electronic voting machines.

We describe how the security and integrity issues are addressed in the State of Connecticut, with the focus on *technological audits* conducted in the State in conjunction with each state-wide election. Additionally, to enhance the integrity of the electoral process, the State implemented explicit chain-of-custody procedures for the electronic voting machines and their removable media, and hand-counted audits of 10% of the districts in each state-wide election.

Background.   The University of Connecticut Center for Voting Technology Research (VoTeR Center) performed an assessment of integrity and security of AV-OS tabulators following their selection. This assessment was performed on the request of the Connecticut Secretary of the State (SOTS) Office. In particular VoTeR Center was asked to evaluate a report[1] that documented a security vulnerability of AV-OS, the so-called "Hursti Hack", and investigate any other vulnerabilities of the system. The investigation by VoTeR Center established that the memory cards used with AV-OS can be tampered with, thus proving the seriousness of the Hursti Hack. VoTeR Center also discovered new security vulnerabilities of AV-OS[2]. We note that if the memory cards or the AV-OS tabulators are left unattended — within or without the tabulator — they can be tampered with in a matter of minutes. The effects of tampering with the AV-OS and memory cards on the election outcome can be devastating: votes cast on ballots can be reassigned to arbitrary candidates, leading to invalid election results. Subsequent reports by VoTeR Center document additional integrity issues with AV-OS systems[3,4,5]. In particular, we determined that *even if the memory card is sealed and pre-election testing is performed, one can carry out a devastating array of attacks against an election* using only off-the-shelf equipment and without having ever to access the card physically or opening the AV-OS system enclosure. For example, the attacks can lead to the following: Neutralizing candidates: The votes cast for a candidate are not recorded; Swapping candidates: The votes cast for two candidates are swapped; Biased Reporting: The votes are counted correctly by the terminal, but they are reported incorrectly using conditionally-triggered biases.

Additionally, more severe threats become possible if the tabulator is left unattended and its internals are tampered with. Note that pre-election testing using vendor-provided methods may not be able to detect tampering (self-auditing is inadmissible, just as it is not admissible in the fiscal realm). The only way to guarantee that the memory cards contain valid data and programming for a particular election, is to directly examine the contents of the cards.

Mitigation: addressing security and integrity in Connecticut.   As the result of these findings, VoTeR Center recommended to the SOTS Office that (a) strict chain-of-custody policies for AV-OS and memory cards need to be implemented, and (b) audits — both technological and hand-counting — need to be performed in conjunction with (at least) each state-wide election. These recommendations have been implemented in Connecticut starting with the November 2007 elections.

The SOTS Office asked the Center to prepare for and implement technological memory card audits for general elections that uses AV-OS terminals in Connecticut. VoTeR Center developed a comprehensive methodology and associ-

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[1]Harri Hursti, Critical Security Issues with Diebold Optical Scan Design, Black Box Voting Project, July 4, 2005 (http://www.blackboxvoting.org/BBVreport.pdf).

[2]VoTeR Center, Security Assessment of the Diebold Optical Scan Voting Terminal, October 30th, 2006 (http://voter.engr.uconn.edu/voter/wp-content/uploads/uconn_report-os.pdf).

[3]A. Kiayias, L. Michel, A.C. Russell, N. Sashidar, A. See, and A.A. Shvartsman, An Authentication and Ballot Layout Attack Against an Optical Scan Voting Terminal, USENIX Electronic Voting Security Workshop (EVT07), Electronic proceedings, August 2007 (http://voter.engr.uconn.edu/voter/wp-content/uploads/evt07.pdf).

[4]A. Kiayias, L. Michel, A.C. Russell, N. Sashidar, A. See, A.A. Shvartsman, S. Davtyan. Tampering with Special Purpose Trusted Computing Devices: A Case Study in Optical Scan E-Voting. 23rd Annual Computer Security Applications Conference (ACSAC). Electronic proceedings. December 10-14, 2007 (http://voter.engr.uconn.edu/voter/wp-content/uploads/seea-tamperevoting.pdf).

[5]S. Davtyan, S. Kentros, A. Kiayias, L.D. Michel, N.C. Nicolaou, A. Russell, A. See, N. Shashidhar, A.A. Shvartsman: Taking total control of voting systems: firmware manipulations on an optical scan voting terminal. ACM Symposium on Applied Computing (SAC), pages 2049-2053, Honolulu, Hawaii, USA, March 9-12, 2009 (http://voter.engr.uconn.edu/voter/wp-content/uploads/sac09.pdf).

ated tools for performing technological audits[6,7], and performed technological audits in Connecticut in each state-wide election (and some primaries) since 2007.

The Center performs two types of technological audits:

1. Pre-election audit: this technological audit is performed on the memory cards randomly selected at districts for the audit after the pre-election testing conducted at the districts. Ideally, one out of every four memory cards is submitted to the audit by the districts. Pre-election auditing includes integrity checks of the contents of the memory cards that are to be used in the elections, and the analysis of the audit log for adherence to proper election procedures and any unexpected events.

2. Post-election audit: this technological audit is performed on the memory cards that were used in an election and submitted by the districts after the election. Similar to the pre-election auditing, post-election auditing includes integrity checks of the contents of the memory cards that are to be used in the elections, and the analysis of the audit log for adherence to proper election procedures and any unexpected events.

This report deals with the results of the technological audits performed by VoTeR Center in the State of Connecticut on the request of the SOTS Office. (The Center also performs statistical analysis of the hand-counted audits conducted in Connecticut; this series of reports can be found at `http://voter.engr.uconn.edu/voter/reports/`.)

The analysis performed during technological audits yield results that cover the following areas:

• Correctness of memory card programming (both data and code),

• Reliability of memory cards, and

• Adherence of the election officials and poll workers to proper procedures and sequencing of election activities, including: Pre-election testing, Preparation for elections, and Election day procedures and processing.

Additionally, to enhance the integrity of the electoral process, the State implemented the following: (i) explicit chain-of-custody procedures for the electronic voting machines and their removable media[8] , and (ii) hand-count audits of 10% of the districts in each state-wide election[9] . The chain-of-custody procedures and hand count audits are outside of the scope of this report.

Document structure.   The report summarizes the historical data gathered during pre-election and post-election technological audits. Section 2 overviews the technological audit methodology and terminology, and provides details about the audited data contained on the memory cards used with the AV-OS tabulators. Sections 3 presents the results of the audits from 2007 to 2010. Section 4 contains conclusions and recommendations. Most of the detailed statistical results summarized in this report are available on the VoTeR Center website (`http://voter.engr.uconn.edu/voter/reports/`). The report does not deal with technical and engineering issues, and the details of the methodology and automated tools. We refer the reader to the website for additional details and comprehensive technical reports.

2   Technological Audit Description

We now describe the technological audits in greater detail. Post-election and pre-election audits analyze memory cards used with AV-OS optical scan terminals. For each election and each district, the Global Election Management System (GEMS) software is used to define the election. This is done by an external contractor (LHS Associates) based on the election information provided to them from Connecticut. The cards are then programmed by transferring the information from GEMS. Programmed cards are tested by the contractor and then shipped to the districts. Technological audits (both pre-election a post-election) examine the data and code stored on memory cards.

Next we describe how the pre-election and post-election audits are conducted.

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[6]T. Antonyan, S. Davtyan, S. Kentros, A. Kiayias, L. Michel, N. Nicolaou, A. Russell, and A.A. Shvartsman. Automating Voting Terminal Event Log Analysis. Proceedings of the 2009 USENIX/ACCURATE Electronic Voting Workshop (EVT/WOTE 2009), 15 pages, electronic edition, Montreal, Canada, August, 2009 (`http://voter.engr.uconn.edu/voter/wp-content/uploads/evt09.pdf`).

[7]T. Antonyan, S. Davtyan, S. Kentros, A. Kiayias, L. Michel, N. Nikolaou, A. Russell, A. A. Shvartsman. State-wide Elections, Optical Scan Voting Systems, and the Pursuit of Integrity. IEEE Transactions on Information Forensics & Security, vol. 4, issue 4, pp. 597-610, December, 2009 (urlhttp://voter.engr.uconn.edu/voter/wp-content/uploads/ieee.pdf).

[8]For example, see MODERATORS HANDBOOK FOR ELECTIONS AND PRIMARIES: OPTICAL SCAN VOTING TABULATORS, Office of the Secretary of the State, revised October 2009. REVISED OCTOBER 2009.

[9]For the definition of the audit see Connecticut Public Act 07-194 AN ACT CONCERNING THE INTEGRITY AND SECURITY OF THE VOTING PROCESS, approved July 5, 2007.

Pre-Election Technological Audit.   These audits have three primary goals: (i) determine whether or not the memory cards are properly programmed for the specific district and specific election, and (ii) determine whether or not proper pre-election procedures are followed by the election officials, (iii) determine whether or not any technical failures occurred.

Prior to the election, each polling center receives four programmed memory cards from the external contractor. According to the instructions from the SOTS Office, each district is supposed to perform pre-election tests of the four cards. After the testing is complete, they are asked to select *randomly* one memory card per district and send it to VoTeR Center for pre-election technological audit. The procedure for random selection of memory cards applies to district-based tabulators and does not include central absentee ballot tabulation. (Sometimes the cards are submitted for the audit before the pre-election test, and sometimes after the pre-election test – this should be made consistent in the future). When the cards are submitted for the audit after they undergo pre-election testing and preparation for the election, such memory cards should be in "election mode" with all counters set to zero.

As the cards arrive from the districts at the Center, the contents of the cards is examined to determine whether the data and code on the cards is correct for the given district and election, and whether the pre-election testing was performed and the cards are set for election. This is done by comparing the card contents to the known baseline data received from the external contractor, and by checking the status of the card and its audit log that should contain the timestamped events that correspond to the cards being programmed, tested, and set for election.

Post-Election Technological Audit.   Post-election audits deal with the memory cards that were used in the election, and have three primary goals: (i) determine whether or not the memory cards are still properly programmed after the election is closed for the specific district and specific election, and (ii) determine whether or not proper pre-election procedures are followed by the election officials, and whether the usage of the cards is consistent with the proper conduct of the election, (iii) determine whether or not any technical failures occurred. The post-election audit employs a procedure similar to the pre-election audit.

The selection of cards for the post-election technological audit differs from the pre-election audit as follows. The SOTS Office randomly selects 10% of the districts that are the subject of post-election hand-counted audit (this audit is not covered in this document). These districts are also asked to submit the cards that were used in the election for the post-election technological audit. Additionally, any district, in principle, is able (and welcome) to submit their cards for the post-election audit.

As the cards arrive from the districts at the Center, the contents of the cards is examined to determine whether the data and code on the cards is correct for the given district and election, and whether the events recorded in the card's audit log correspond to a proper programming, preparation for the election, and conduct of the election. As before, this is done by comparing the card contents to the known baseline, and by checking the status of the card and its audit log.

Description of the Data and Code on Memory Cards.   The cards used in Connecticut have the capacity of 128KB (kilobytes). Occasionally 32KB cards are found. Since AV-OS only uses 32KB, both card sizes can be used, however 32KB cards are not owned by any municipality in Connecticut and they apparently are substituted by the vendor in error. The following information is contented in each memory card.

1. **Header:** The header of the card contains information about the organization of the contents of the card and the identification of the district and the election.

2. **Event Log:** This part contains the audit log that records significant events in life of the card starting with the programming of the card. The log contain selected events relating to pre-election testing, preparation for election, and the conduct of the election.

3. **Election Data:** This data consists of (i) Ballot Data, (ii) Race Data, and (iii) Candidate Data.

4. **Bytecode:** This is the executable AccuBasic (AB) bytecode that governs the reporting procedures associated with an election.

5. **Election Counters:** Here all the election results and statistics are stored, including (i) Race Counters, and (ii) Candidate Counters.

Description of States of the Data Found on Memory Cards.   We now summarize the terminology we use in describing the data collected from the memory cards and to present the results of the technological audits.

- **Usable Cards**: A memory card can either be *usable* or *unusable*. *Usable* cards are those that contain data and code appropriate for the election; these cards can be safely used in the election. Usable cards can further be categorized as follows:

    - **Clean Card:** The content of a clean card is free of any unexpected differences when compared against the corresponding baseline file. This is the desired card type.
    - **Card with Byte Differences:** A card with byte differences can contain one or more unexpected byte differences when compared against baseline data. In most cases the differences are the results of card duplication, or due to last minute changes (e.g., race changes, candidate name changes or substitution). One can also observe a few "specks", that is isolated bytes with unexpected values. These occur outside the area that is used for election data that is normally filled with zeros. These specks are not detected by AV-OS and we have not discovered any cases where they interfere with normal AV-OS operation.

- **Unusable Cards**: *Unusable* cards, are those that cannot be used in the election. Such cards are readily detected by the AV-OS tabulator. Unusable cards fall into the following two categories:

    - **Blank Card:** On a rare occasion a card may contain only the header and the rest is clear (contains 0s). This happens when the card is formatted for programming, but is not programmed for the election.
    - **"Junk" Card:** Such a card lost all information previously contained in it. A "junk" card contains apparently arbitrary sequence of data values. We have determined that weak batteries cause loss of data, however there may be other reasons for this. We are continuing the investigation of the causes.

When examining a card, the technological audit determines whether the card is in the following states and whether its usage is consistent with proper election procedures.

- Size: cards are expected to have capacity 128K bytes, but sometimes cards of 32K bytes appear.

- Election Status: This identifies the last state of the election process when the card was removed from the tabulator.

    - Card Not Programmed (Blank)
    - Not Set for Elections: the tabulator is not set for election.
    - Results Print Aborted: the tabulator was powered down during the print of the results, or improperly powered down at the conclusion of the results print.
    - Election Closed: the election was conducted and closed. This is the expected state for the cards in the post-election audit.
    - Set for Election: the tabulator was prepared for election using this card. This is the expected state for the cards in the pre-election audit.
    - Results Sent/Uploaded: The election results were uploaded to a GEMS system for central tabulation. In Connecticut central tabulation is never used, and the cards must never be in this state.
    - Audit Report Printed: Normally these are not printed, but printing such a report is not a problem.

- Zeroed Counters: This describes whether the election counters on the card are zeroed or not. For the pre-election audit it is expected that the counters are zeroed. For post-election audit the counters are normally not zeroed (provided at least one ballot is cast).

- Election Count: This is an integer that is the number of times the card was prepared for elections.

- Ballot Count: This is an integer that is the number of ballots cast with this card in the tabulator.

- Ballot Correctness: This is determined by the technological audit. By "ballot correct" we mean that card's data matches the election baseline (as recorded in the GEMS file provided for the current election). It can happen that ballot appears incorrect due to a very late change to the ballot; if this is the case, a subsequent analysis is needed to determine whether the ballot is correct with respect to the updated baseline.

- Timing and Sequencing: This is established by comparing the events that correspond to the actions performed by the districts to the expected proper sequencing of events with respect to the election period timing.

- Unexpected Events: The audits determine whether or not any unexpected events occurred (such as card resets, power failures, and card duplication).

3 Results of Technological Audits

In this section we present the summary of the results of technological audits, first for the pre-election audits, then for the post-election audits, and concluding with general timing and sequencing issues. In the next two sections, the pre-election and post-election summaries are presented in Tables 1 and Table 2 respectively. The rows of the tables correspond to various characteristics of the audits, and columns correspond to the specific elections (or primaries). Each table contains the following four parts.

(a) Card Format: Here we give statistics for audited cards in the following categories (i) *Usable, Clean Card*, (ii) *Usable, Byte Differences*, (iii) *Unusable, Not Programmed (Blank)*, and (iv) *Unusable, "Junk" Data.*

(b) Card Status: In this part we give statistics on the last status of the card prior to the audit. (i) *Not Set for Election*, (ii) *Set for Election*, (iii) *Results Print Aborted*, (iv) *Election Closed*, (v) *Results Sent/Uploaded*, and (vi) *Audit Report Printed.*

(c) Counter Status: We give statistics for the following card status and counters categories: (i) *Not Set for Election, Non-Zero Counters*, (ii) *Not Set for Election, Zero Counters*, (iii) *Set for Election, Non-Zero Counters*, (iv) *Set for Election, Zero Counters*, (v) *Election Closed, Non-Zero Counters*, (vi) *Election Closed, Zero Counters*, (vii) *Results Print Aborted, Non-Zero Counters*, and (vii) *Results Print Aborted, Zero Counters.*

(d) Card Duplication: In Connecticut the election procedures do not allow cards to be duplicated. Here we give statistics on card duplication: (i) *Master Card* used for duplication, (ii) *Copy Card* produced by duplication, (iii) *Master + Copy Totals*, showing the total number of cards involved in duplication.

The first column in each table provides additional annotation that describes certain conditions, such as expected or preferred card states, procedural deviations, and card states that raise concerns. In particular, we use the following annotation.

- Star "$\star$" denotes an expected or preferred state.

- A blank indicates an unexpected state that is easily detectable and does not raise an integrity concern.

- Letter "p" indicates a procedural deviation from the expected state that does not raise an integrity concern. For these cases it is recommended that SOTS reiterates the importance of adhering to proper procedures.

- Annotation "x!" denotes an unexpected state indicating that an unauthorized procedure was performed at a district that may raise integrity/security concerns. SOTS follow up is recommended for such cases (if any). The first such case is when a card is set for election with non-zero counters. If poll workers forget/neglect to zero the counters, the election results will be inaccurate. This is normally prevented by the requirement that zero reports are printed and signed. The second such case is unauthorized card duplication (discussed in more detail later in the section).

3.1 Pre-Election Audit Results

Table 1 presents the summary of the results for pre-election audits of memory cards conducted in Connecticut for November 2007, August 2008 (primary), November 2008, November 2009, August 2010 (primary), and November 2010 elections.

First we note that all usable memory cards contained correct ballot data and expected executable code. See lines 1 and 2 of Table 1. In the cases where small differences were found in the ballot data (line 2), these were either due to last minute authorized election changes or due to small differences in the unused part of the memory cards.

We now describe the most important observations and most significant trends dealing with pre-election audit coverage, adherence to pre-election procedures, memory card duplication, and card reliability.

Pre-Election Audit Coverage.   The pre-election audits ideally are performed on one card randomly selected in each district. Thus the number of audited cards can be as high as the number of districts. For November 2007, November 2008, and November 2009 elections, the audit response was very good, with about 500-600 cards audited. For November 2010 elections, the response was surprisingly *very low*, with only 55 cards audited. See line 5 of Table 1.

This is a concern, as such a small audit coverage does not allow one to obtain a statistically accurate view of the pre-election landscape in Connecticut.

		Audit Type: Election/Primary Date:	Pre-Election Nov. 2007		Pre-Election Aug. 2008		Pre-Election Nov. 2008		Pre-Election Nov. 2009		Pre-Election Aug. 2010		Pre-Election Nov. 2010	
			Num	%	Num	%	Num	%	Num	%	Num	%	Num	%
		(a) Card Format												
1	⋆	Usable, Clean Card	501	94.9%	174	94.1%	541	87%	419	85.2%	173	77.6%	48	87.3%
2		Usable, Byte Differences	8	1.5%	1	0.5%	24	3.8%	29	5.9%	16	7.2%	0	0%
3		Unusable, Not Programmed (Blank)	1	0.2%	0	0%	1	0.2%	1	0.2%	3	1.3%	0	0%
4		Unusable, Junk Data	18	3.4%	10	5.4%	56	9%	43	8.7%	31	13.9%	7	12.7%
5		Totals:	528	100%	185	100%	622	100%	492	100%	223	100%	55	100%
		(b) Card Status												
6	p	Not Set for Election	222	43.6%	175	100%	559	98.9%	173	38.6%	68	36%	26	54.2%
7	⋆	Set for Election	234	46%	0	0%	6	1.1%	272	60.7%	118	62.4%	20	41.6%
8	p	Results Print Aborted	11	2.2%	0	0%	0	0%	0	0%	0	0%	1	2.1%
9	p	Election Closed	42	8.2%	0	0%	0	0%	3	0.7%	3	1.6%	1	2.1%
10	x	Results Sent/Uploaded	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
11	p	Audit Report Printed	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
12		Totals:	509	100%	175	100%	565	100%	448	100%	189	100%	48	100%
		(c) Counter Status												
13	p	Not Set for Election, Non-0 Counters	168	33%	175	100%	508	89.9%	165	36.8%	57	30.2%	25	52.1%
14	p	Not Set for Election, 0-Counters	54	10.6%	0	0%	51	9%	8	1.8%	11	5.8%	1	2.1%
15	x!	Set for Election, Non-0 Counters	1	0.2%	0	0%	0	0%	0	0%	0	0%	0	0%
16	⋆	Set for Election, 0-Counters	233	45.8%	0	0%	6	1.1%	272	60.7%	118	62.4%	20	41.6%
17	p	Election Closed, Non-0 Counters	42	8.2%	0	0%	0	0%	3	0.7%	3	1.6%	1	2.1%
18	p	Election Closed, 0-Counters	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
19	p	Results Print Abort, Non-0 Counters	11	2.2%	0	0%	0	0%	0	0%	0	0%	1	2.1%
20	p	Results Print Abort, 0-Counters	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
21		Totals:	509	100%	175	100%	565	100%	448	100%	189	100%	48	100%
		(d) Card Duplication												
22	x!	Master Card Duplicated	0	0%	0	0%	16	2.6%	17	3.5%	14	6.3%	0	0%
23	x!	Copy Card	0	0%	1	0.5%	6	0.9%	4	0.8%	2	0.9%	0	0%
24	x!	Master + Copy Totals	0	0%	1	0.5%	22	3.5%	21	4.3%	16	7.2%	0	0%

Table 1: Pre-Election memory card audit analysis summary for November 2007, August 2008 (primary), November 2008, November 2009, August 2010 (primary), and November 2010 Connecticut Elections

Adherence to Pre-Election Procedures. Once the districts receive the cards for the election, they are instructed to perform pre-election testing, and set the cards for election with zero counters. Following the testing, one out of each four cards is to be submitted for the pre-election audit. The districts follow this procedure in about 40% to 60% of the cases; see lines 7 and 16 of Table 1 (with the exception of August and November 2008, when the cards were received directly from the external contractor). We observe that about 40% to 50% of the cards are not set for elections, indicating that they were sent for the pre-election audit *before* the pre-election testing, and not after testing as instructed; see lines 6, 13, and 16 of Table 1 (again, with the exception of August and November 2008, when the cards were received directly from the external contractor). This is a deviation from the expected procedure, but this does not raise an integrity/security concerns. However, to obtain a comprehensive view of the pre-election testing, it is recommended that the districts follow the SOTS instructions and submit the cards for the audit *after* the completion of the pre-election testing.

Memory Card Duplication. The only authorized source of the card programming in Connecticut is the external contractor, LHS Associates. Card duplications are performed using the AV-OS voting tabulator; one can make a copy (duplicate) of a card on any other card by using the tabulator's duplication function. SOTS policies do not allow the districts to produce their own cards by means of card duplication. We observe that card duplication is on the increase, with over 7% of memory cards being involved in duplication for August 2010 (primary) elections. (There is no reported duplication for November 2010 elections, but it appears that the districts were advised not to send duplicated cards for audit; this needs to be checked.) See lines 22–24 of Table 1.

This is a concern, as there is no guarantee that duplication faithfully reproduces cards, and it masks the problem with card reliability (also see below). Additionally, it is impossible to determine who and why resorted to unauthorized card duplication. Given the SOTS policies, the districts must not be producing their cards locally. If a district finds it necessary to duplicate cards, they need to make records of this activity and bring this to the attention of SOTS Office.

Memory Card Reliability and Junk Data. The memory cards used with AV-OS tabulators are powered by batteries. We have determined that weak batteries cause the memory cards to lose their data; the result being that pseudo-random or arbitrary (or "junk") data is found on the cards. There may be other reasons for cards to lose their data, and we are continuing the investigation. When the batteries are renewed, they may last for several months, however we found that

some cards consume power at substantially higher levels, thus they may keep their data for only a few weeks. This may not be enough to guarantee high reliability of the cards in the elections.

In recent elections, the number of cards that lost their data (junk cards) is over 10%. See line 4 of of Table 1. Such high failure rates are unacceptable for electronic components. We also note that apparently some districts duplicate cards when a card fails during the pre-election testing. As we pointed out above, this masks some of the problems with card unreliability, and gives the districts a false sense of security, since a card that lost its data is very likely to lose its data again in a few days.

This is a concern. We note that in 2009 elections, there was one district where all four cards failed on the election day. In order to better identify this problem and explore possible solutions, it is important to have a reasonably large number of cards for testing and to have substantially higher number of cards submitted for audits.

3.2   Post-Election Audit Results

Table 2 presents the summary of the results for post-election audits of memory cards conducted in Connecticut for November 2007, February 2008 (primary), August 2008 (primary), November 2008, November 2009, August 2010 (primary), and November 2010 elections.

		Audit Type: Election/Primary Date:	Post-Election Nov. 2007		Post-Election Feb. 2008		Post-Election Aug. 2008		Post-Election Nov. 2008		Post-Election Nov. 2009		Post-Election Aug. 2010		Post-Election Nov. 2010	
			Num	%	Num	%	Num	%	Num	%	Num	%	Num	%	Num	%
		(a) Card Format (all cards)														
1	⋆	Usable, Clean Card	120	90.9%	196	93.3%	231	82.5%	350	75.7%	99	80.5%	125	80.1%	122	82.4%
2		Usable, Byte Differences	1	0.8%	3	1.4%	6	2.1%	71	15.4%	7	5.7%	10	6.4%	9	6.1%
3		Unusable, Not Programmed (Blank)	1	0.8%	0	0%	0	0%	0	0%	2	1.6%	0	0%	0	0%
4		Unusable, Junk Data	10	7.5%	11	5.3%	43	15.4%	41	8.9%	15	12.2%	21	13.5%	17	11.5%
5		Total:	132	100%	210	100%	280	100%	462	100%	123	100%	156	100%	148	100%
		(b) Card Status (usable cards)														
6	p	Not Set for Election	31	25.6%	19	9.6%	1	0.4%	52	12.4%	8	7.5%	30	22.2%	18	13.7%
7	⋆	Set for Election	54	44.6%	43	21.6%	83	35%	90	21.4%	49	46.2%	42	31.1%	41	31.3%
8	p	Results Print Aborted	4	3.3%	10	5%	9	3.8%	20	4.7%	4	3.8%	5	3.7%	6	4.6%
9	⋆	Election Closed	32	26.5%	127	63.8%	144	60.8%	259	61.5%	45	42.5%	58	43%	66	50.4%
10	p	Results Sent/Uploaded	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
11	p	Audit Report Printed	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
12		Totals:	121	100%	199	100%	237	100%	421	100%	106	100%	135	100%	131	100%
		(c) Counter Status (usable cards)														
13	p	Not Set for Election, Non-0 Counters	29	24%	18	9.1%	1	0.4%	41	9.7%	8	7.5%	29	21.5%	17	13%
14	p	Not Set for Election, 0-Counters	2	1.6%	1	0.5%	0	0%	11	2.6%	0	0%	1	0.7%	1	0.7%
15	x!	Set for Election, Non-0 Counters	1	0.8%	0	0%	0	0%	2	0.5%	0	0%	0	0%	0	0%
16	⋆	Set for Election, 0-Counters	53	43.8%	43	21.6%	83	35%	88	20.9%	49	46.2%	42	31.1%	41	31.3%
17	⋆	Election Closed, Non-0 Counters	32	26.5%	126	63.3%	141	59.5%	259	61.5%	45	42.5%	58	43%	66	50.4%
18		Election Closed, 0-Counters	0	0%	1	0.5%	3	1.3%	0	0%	0	0%	0	0%	0	0%
19	p	Results Print Abort, Non-0 Counters	4	3.3%	10	5%	9	3.8%	20	4.8%	4	3.8%	5	3.7%	6	4.6%
20	p	Results Print Abort, 0-Counters	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
21		Totals:	121	100%	199	100%	237	100%	421	100%	106	100%	135	100%	131	100%
		(d) Card Duplication (usable cards)														
22	x!	Master Card Duplicated	0	0%	2	0.9%	1	0.4%	32	6.9%	3	2.4%	10	6.4%	8	5.4%
23	x!	Copy Card	0	0%	1	0.5%	0	0%	9	1.9%	1	0.8%	0	0%	1	0.7%
24	x!	Master + Copy Totals	0	0%	3	1.4%	1	0.4%	41	8.8%	4	3.2%	10	6.4%	9	6.1%

Table 2: Post-Election memory card audit analysis summary for November 2007, February 2008, August 2008, November 2008, November 2009, August 2010, and November 2010 Connecticut Elections

First we note that, as with the pre-election audits, all usable memory cards contained correct ballot data and expected executable code. See lines 1 and 2 of Table 2. In the cases where small differences were found in the ballot data (line 2), these were either due to last minute authorized election changes or due to small differences in the unused part of the memory cards.

We now describe the most important observations and most significant trends dealing with post-election audit coverage, adherence to election procedures, memory card duplication, and card reliability.

Post-Election Audit Coverage.   The post-election audits ideally are performed on one card from each district or polling place. It is recommended that this is made explicit in the instructions from SOTS to municipalities. In recent elections, although the intent has always been to broaden the audit coverage, mostly the cards from the municipalities selected for hand-counted audits were submitted for post-election audits. Thus the sample of audited cards corresponds

to approximately 10% of the municipalities randomly selected by SOTS for hand-counted audits. We also note that in recent years only about one half of all cards were actually used in the elections; the other half are the "spare" cards that were not used (having such spare cards in the audit is not a problem, however these cards are not post-election cards).

The largest number of cards that were used in the elections were audited for February 2008 (primary) elections, August 2008 (primary) elections, and for November 2008 elections; here we audited 137, 153, and 279 cards respectively. These totals corresponds to the sums of lines 8 and 9 from Table 2.

In recent elections for November 2009, August 2010 (primary), and November 2010 elections, the post-election audit was performed on only 49, 63, and 72 cards respectively that were acutally used in the elections. These totals again corresponds to the sums of lines 8 and 9 from Table 2.

This is a concern, as such audit coverage does not allow one to obtain a statistically accurate view of the post-election landscape in Connecticut.

Adherence to Election Procedures.   Here the audit examines how the cards are used, and whether or not they usage of the cards is consistent with the proper election procedures.

The post-election audit includes cards from two broad categories (as mentioned above): cards that were used in the elections, and cards that were not used in the elections. The latter group of cards must consist only of the cards that are set for election. The audit observes that there is still a non-trivial fraction of the cards that are *not* set for elections, e.g., 22.2% for August 2010, and 13.7% for November 2010. See lines 6, 13, and 14 of Table 2. This shows that not all districts are adhering to the pre-election and election procedures. This is a concern, as it is expected that all cards are prepared for election according to the pre-election procedures.

Among the cards that were used in the election, a small percentage of cards indicate that the results print was aborted. See line 8, 19, and 20 of Table 2. We have determined that, although aborting the print of the election results will cause this status, it is normally the incorrect tabulator shut-down sequence following the print that causes this status being recorded on the cards. Although this does not raise a concern, it is important for the election officials to follow the established procedures.

Memory Card Duplication.   As in the pre-election audits, we observe that memory card duplication is a problem, with over 6% of the cards being involved in duplication in the 2010 elections. See lines 22–24 of Table 2.

This is a concern, as there is no guarantee that duplication faithfully reproduces cards, and it masks the problem with card reliability (also see below). Given the SOTS policies, the districts must not be producing their cards locally. If a district finds it necessary to duplicate cards, they need to make records of this activity and bring this to the attention of SOTS Office.

Memory Card Reliability and Junk Data.   Consistently with pre-election audits, in recent elections the number of cards that lost their data (junk cards) is over 10%. See line 4 of of Table 2. Such high failure rates are unacceptable for electronic components. We also note that apparently some districts duplicate cards when a card fails during the pre-election testing. As we pointed out above, this masks some of the problems with card unreliability, and gives the districts a false sense of security, since a card that lost its data is very likely to lose its data again in a few days.

This is a concern. In order to better identify this problem and explore possible solutions, it is important to have a reasonably large number of cards for testing and to have substantially higher number of cards submitted for audits.

3.3   General Timing, Sequencing, and Unexpected Events Issues

There are several issues that relate to the overall conduct of the elections using the AV-OS tabulators that are observed during the technological audits with sufficient frequency to address them in more detail.

Times and Dates.   The audit log of AV-OS tabulator contains a time-stamped and dated audit log. These time-stamps depend on the correct setting of the tabulator's time and date. In a small number of cases the audits observed that the tabulator's clocks are not set accurately. For example, in one case the month field was one digit off, with the resulting appearance that the election was held in October instead of November.

It is important that, in the cases where time and date need to be set or changed on the tabulators, the election officials do this accurately, and preserve a record of their actions for SOTS Office, should questions arise.

Sequencing of Events.	Technological audit checks the sequence of the events recorded in the audit log of a memory card, expecting to find a sequence of events corresponding to the following stages:

- *Card initialization and programming*: this normally occurs anywhere from two months before the elections to two weeks before the elections.

- *Test elections*: this normally is done between two weeks before the elections to four days before the elections.

- *Preparation for the elections* is done immediately after the test election is performed.

- *The elections* occur, of course, on Election Day.

Deviations from this sequencing of events may be a sign of a problem, e.g., card initialization on Election Day, missing test election, the election held on a wrong date, or multiple elections.

It is important for SOTS Office to establish an explicit timeline for each election. This can then be used by the technological audits to better identify deviations from the prescribed procedures. It is also important for election workers to maintain a record of any needed changes to the expected timeline for SOTS Office, should questions arise.

Unexpected Events and Multiple Events.	We identified several events that either should not be occurring during an election or that may occur normally a small number of times. Table 3 lists such events along with the expected number of appearances and suggested maximums (here the number 10 was chosen arbitrarily to help quickly identify noteworthy exceptions).

Action Name	Expected No.	Suggested Max.	Description
SESSION START	≥ 3	10	Tabulator is turned on (e.g., 3 times: for initialization, testing, and election)
POWER FAIL	0	10	Tabulator switches to backup battery as the result of a main power failure
COUNT RESTARTED	0	0	Tabulator is restarted while in election mode and counting is resumed
MEMORY CARD RESET	0	0	The card is reset to a pre-election state following/during an election
DUPLICATE	0	0	The contents of the memory card are copied to another card

Table 3: Events in an election timeline that may indicate a problem.

When an event from Table 3 occurs more than the expected number of times, the technological audit can issue a warning that should ultimately lead to SOTS Office follow up with the involved district.

We have implemented a refined version of audit log analysis for August 2010 and November 2010 elections. The results are in Tables 4 and 5. In each table the headers of the numeric columns are as follows:

- "# Warn" is the number of warnings issued by the technological audit.

- "% Warn" is the percentage among all warnings.

- "# Cards" is the number of memory cards involved.

- "% Usable" is the percentage among all usable cards.

We next provide additional details for pre-election and post-election audits for August 2010 and November 2010 elections.

Pre-Election Event Analysis for August 2010 and November 2010 Elections.	Table 4 summarizes the unexpected timing and events identified in 2010 pre-election audits.

For the Unexpected Dates warnings, the following was observed. Initialization warning occurred because the initialization was performed less then two weeks before the election date. Test elections and preparations for elections were performed 4 or fewer days before the election. Thus none of this raises concerns, although the timing is closer to the day of the election than expected.

Regarding the Many Instances warnings, the following is observed. In the case of SESSION START events, this is normally the result of multiple test elections. However, if a districts experiences a problem requiring many starts, it is advisable that this is brought to the attention of the SOTS Office.

We discussed duplication earlier. DUPLICATE events signify card duplication and this is not permitted by SOTS rules. (There are no duplication events in the pre-election audit for November 2010 because apparently such cards were not submitted for the audit.)

	Pre-Election Audit August 2010				Pre-Election Audit November 2010			
	# Warn	% Warn	# Cards	% Usable	# Warn	% Warn	# Cards	% Usable
(a) Unexpected Dates								
Initialization	18	13.1%	18	9.5%	4	21.1%	4	8.3%
Test Election	1	0.7%	1	0.5%	3	15.8%	3	6.3%
Prepare For Election	1	0.7%	1	0.5%	2	10.5%	2	4.2%
(b) Many Instances (allowed)								
SESSION START (10)	4	2.9%	4	2.1%	0	0%	0	0%
POWER FAIL (10)	0	0%	0	0%	0	0%	0	0%
DUPLICATE (0)	16	11.7%	16	8.5%	0	0%	0	0%
MEMORY CARD RESET (0)	3	2.2%	3	1.6%	0	0%	0	0%

Table 4: Pre-Election Audit Log analysis summary for August 2010 and November 2010 Connecticut Elections

MEMORY CARD RESET events in all cases are the results of running an election instead of a test election, or preparing for election, then resetting the cards before the actual election date. (This would be a concern only if it occurred during an election.)

Post-Election Event Analysis for August 2010 and November 2010 Elections.   Table 5 summarizes the unexpected timing and events identified in 2010 post-election audits.

	Post-Election Audit August 2010				Post-Election Audit November 2010			
	# Warn	% Warn	# Cards	% Usable	# Warn	% Warn	# Cards	% Usable
(a) Unexpected Dates								
Initialization	6	7.2%	6	4.4%	3	5.4%	3	2.3%
Test Election	4	4.8%	4	3%	1	1.8%	1	0.8%
Prepare For Election	2	2.4%	2	1.5%	1	1.8%	1	0.8%
Election	20	24.1%	20	14.8%	16	28.6%	16	12.2%
(b) Many Instances (allowed)								
SESSION START (10)	6	7.2%	6	4.4%	9	16.1%	9	6.9%
POWER FAIL (10)	0	0%	0	0%	0	0%	0	0%
DUPLICATE (0)	10	12.1%	10	7.4%	9	16.1%	9	6.9%
MEMORY CARD RESET (0)	4	4.8%	4	3%	1	1.8%	1	0.8%
COUNT RESTARTED (0)	1	1.2%	1	0.7%	5	8.9%	3	2.3%

Table 5: Post-Election Audit Log analysis summary for August 2010 and November 2010 Connecticut Elections

For the Unexpected Dates warnings, the following was observed (this is similar to the pre-election warnings). Initialization warning occurred because the initialization was performed less then two weeks before the election date. Test elections and preparations for elections were performed 4 or fewer days before the election. Thus none of this raise concerns, although the timing is closer to the day of the election than expected.

For the cases where election day warnings, this is due to elections being done before the election day. Closer examination of these cases determined that in all cases districts ran elections instead of test election as a part of pre-election preparation. This is not a major concern, but it does show deviations from the prescribed pre-election testing procedures.

Regarding the Many Instances warnings, the following is observed. In the case of SESSION START events, this is normally the result of multiple test elections. However, if a districts experiences a problem requiring many starts, it is advisable that this is brought to the attention of the SOTS Office.

We discussed duplication earlier. DUPLICATE events signify card duplication and this is not permitted by the SOTS Office rules.

MEMORY CARD RESET events in all cases are the results of running an election instead of a test election, or preparing for election, then resetting the cards before the actual election date. This would be a concern only if it occurred during an election.

3.4   Bytecode Analysis Results for the Usable Cards

We have analyzed the AccuBasic bytecode that is loaded into each programmed memory card. Based on the analysis we conclude that the bytecode provided by LHS Associates for the elections is safe to use. The bytecode performs

the expected reporting functions. Note that it is not possible to overwrite the contents of the card with the AccuBasic bytecode, however, if the bytecode is tampered with it is possible that incorrect election results are reported. Thus it is crucial to analyze the bytecode. If and when a new version of GEMS and the AV-OS firmware will be used in Connecticut, the AccuBasic bytecode analysis support will need to be updated to correspond.

4   Conclusions

We presented the summary of the technological pre-election and post-election audits conducted in Connecticut from 2007 to 2010. The technological audits were designed on the request of the Secretary of the State (SOTS) of Connecticut by VoTeR Center and are conducted by the Center in conjunction with each state-wide election and selected primaries. The audits examine the correctness of the programming of the memory cards with respect to the specific elections and the usage patterns at the districts in light of the election procedures established by the SOTS Office. The audits also assess the reliability of the memory cards. We make the following conclusions and recommendations.

1. Correctness of Card Programming: The audits determined that 100% of the cards actually used in the election showed correct programming in terms of both the election description data and the executable code on the cards. In the case of the pre-election cards, in all cases where small discrepancies in the election description data were discovered, these differences were due to the very late changes, such as candidate name changes, substitutions, and race changes.

2. Audit Coverage: The number of memory cards submitted for audits fell substantially in 2010. We understand that in some cases districts were advised to not submit cards for audit in an apparent effort to occlude the fact that memory cards were duplicated. It is recommended that the SOTS Office encourages the districts to always submit one out four cards for pre-election audit and all of their used cards for post-election audit. The number of cards examined by the audits needs to be substantially increased in future elections to provide a better statistical basis for the overall election landscape in Connecticut. Not only this will help ensure proper programming of the cards, but it will also help address the reliability problem of the memory cards.

3. Memory Card Reliability: In recent elections more than 10% of the memory cards experienced data loss between the time they are programmed and the day of the election; this is apparently the reason why districts may perform card duplication. This data loss is most likely caused by the weak batteries on the cards (however, as of this writing it is not clear how long a fresh battery lasts in a memory card). We are continuing to examine this issue. Increasing audit coverage will enable us to obtain and evaluate more cards that failed in search for a solution. In particular, we know that some cards drain batteries much faster than most; when we identify such cards it is recommended that they are removed from circulation. Longer term solution may be to develop replacement cards that use non-volatile memory technology.

4. Memory Card Duplication: In recent elections more then 6% of the cards were involved in duplication. We note that the only authorized entity to provide card programming for election in Connecticut is LHS Associates. There is no guarantee that cards duplication done by the districts correctly reproduces data and programming on the copy cards. Additionally, if duplicated cards are not submitted for audits it increases the risk of using incorrect cards in elections. It is recommended that the SOTS Office reinforces its policy that prohibits card duplication.

5. Adherence to Election Procedures: The technological audits established that the districts do not always adhere to the established pre-election procedures. Most notably, in recent elections over 6% of the memory cards are duplicated by the districts, a practice that is not permitted by the SOTS Office. Additionally, some districts do not prepare all of their cards for elections and/or prepare for elections by running elections instead of running test elections. It is recommended that the SOTS Office reiterates the importance of following the prescribed election procedures. Lastly, some districts send cards for pre-election audit before they test the cards, while other districts send cards after they test the cards. For the pre-election audit to be most effective, it is recommended that districts uniformly send cards after the cards are tested and prepared for elections.