

State of Colorado
Risk-Limiting Audit – Final Report
Post-Election Audit Initiative – Grant No. EAC110150E

Table of Contents

History of Post-Election Audits in Colorado3
Goals and Objectives5
Risk-Limiting Audit Process6
Challenges in Implementing RLA8
Arapahoe County RLA Pilot Project8
Lessons Learned8
Summary.....10
Appendix A: Arapahoe County Risk-Limiting Audit.....11
Appendix B: Boulder County Election Audit.....17
Appendix C: Progress Report (12/01/2011 – 05/31/2012)30
Appendix D: Progress Report (05/23/2011 – 11/30/2011)31

History of Post-Election Audits in Colorado

Counties in the State of Colorado have historically been required to use a traditional, fixed-percentage post-election audit to audit the accuracy of election results.¹

In 2009, the Colorado General Assembly passed a law requiring counties to conduct a different type of post-election audit—a risk-limiting audit (RLA)—in accordance with procedures established by the Colorado Secretary of State (SOS). This new legislation required that a statewide RLA be in place by the 2014 General Election.²

A risk-limiting audit is defined by Colorado statute as “an audit protocol that makes use of statistical methods and is designed to limit to acceptable levels the risk of certifying a preliminary election outcome that constitutes an incorrect outcome.”³ In effect, the RLA is a procedure for manually checking a sample of ballots or voter-verifiable paper records from an electronic voting device that will have a large, pre-specified chance of correcting an erroneous election outcome. There are currently two types of risk-limiting audit. A comparison risk-limiting audit is performed by manually comparing randomly selected batches of ballots to the voting machine totals for those ballot batches, continuing until either the comparison gives sufficiently strong statistical evidence that the outcome is correct, or until there has been a complete hand count. A ballot-polling risk-limiting audit is performed by manually tallying randomly selected ballots and continuing until either those ballots give sufficiently strong statistical evidence that the outcome is correct, or until there has been a complete hand count.

The RLA model differs from current Colorado audit practices. Since the existing audit protocol is predicated on the SOS’s random selection for audit of 5% of the optical scan and DRE voting devices used in an election with no provision for expanding the audit to a full count, the chance that the audit will find any errors if the outcome is wrong depends on the contest margins. There is no mechanism by which the audit can correct an incorrect outcome. In addition, the number of ballots to be audited depends on the number of ballots tabulated on the randomly selected voting devices. There is little or no assurance that the current audit methodology will disclose, much less correct, an incorrect preliminary outcome. In a risk-limiting audit, the total number of ballots to be audited takes into account the contest margins and any errors the audit uncovers in a way that yields a pre-determined minimum chance of correcting an incorrect outcome.

Following the legislature’s mandate, in 2010 the SOS tested some elements of a risk-limiting audit in Douglas County with the assistance of Colorado State University. In addition to the SOS’s efforts, the Clerk and Recorder of Boulder County began independently implementing risk-limiting audit procedures

¹ According to post-election audit rules, the Secretary’s staff selects 5% of ballot scanners and 5% of direct recording electronic devices (DREs) used by counties in an election in order to audit every race in an election. The SOS randomly assigns races to audit for each selected device. For each DRE selected, the county clerk audits 100% of the races on that device. For selected ballot scanners, the county clerk randomly selects ballots to audit based on the number of ballots cast. If 499 ballots or fewer were counted on a ballot scanner, then 20% of the ballots are audited. If 500 ballots or more were counted on a ballot scanner, then 100 ballots plus 5% of the difference between the number of ballots counted and 500 are audited, but not more than 500. For example, if the county clerk selects ballot scanner X, and it counted 800 ballots during the election, then the clerk must audit 115 ballots $[100+(0.05)(800-500)]$. The maximum number of ballots that will be audited for any ballot scanner is 500.

² HB 09-1335

³ Section 1-7-515, C.R.S.

for its post-election audit.⁴ Following a review of this initial testing, the SOS began researching effective ways to implement RLA statewide.

In 2011, the SOS applied for and received a grant from the U.S. Election Assistance Commission (EAC) to conduct a two-year post-election audit pilot program. The need for a pilot program in Colorado was demonstrated by the challenge of moving from the traditional post-election audit to an RLA that could be implemented in large or small jurisdictions.

The SOS began its pilot program by selecting six counties – Boulder, Arapahoe, Denver, Eagle, Jefferson and Pitkin – for a potential RLA pilot project. The SOS then began meeting with representatives from these counties, as well as with national experts in the field of RLA—Dr. Philip Stark⁵ and Neal McBurnett⁶—to discuss the RLA process and ideas for moving forward with the pilot project.

Following initial discussions, some participating counties expressed concerns regarding the cost and time constraints of performing a pilot project in their county, along with concerns regarding ballot anonymity during the process.⁷ These concerns stalled progress on the RLA pilot project activities.

In May 2013, the Colorado General Assembly passed additional legislation that extended the deadline to implement a statewide risk-limiting audit from the 2014 General Election to the 2017 Coordinated Election. This legislation alleviated the SOS's urgency in testing and implementing RLA processes in multiple counties during the 2013 election. The SOS moved forward with plans for the pilot project, but modified its scope by concentrating interest in performing a pilot project in just one county.

Arapahoe County agreed to conduct the State's first RLA pilot project during the 2013 General Election.

The SOS then hosted public demonstrations by voting system vendors who presented their risk-limiting audit solutions. The participating vendors included: Everyone Counts, Clear Ballot Group, and Dominion Voting.

Of the three vendors, Clear Ballot Group (CBG) was the only vendor that had a system ready for use in the 2013 Coordinated Election. Everyone Counts and Dominion Voting had systems in development, but those systems would not be ready for testing in the necessary timeframe. As a result, the SOS selected CBG to provide the technology to conduct the RLA pilot project in Arapahoe County in November, 2013.

CBG provided training on its technology to Arapahoe County staff and election judges prior to the election, and assisted the county with its first risk-limiting audit following the election.

The process of exploring methods for implementation of a statewide RLA has been lengthy, and there is still significant work to be done.⁸ This report will outline the SOS's goals and objectives with respect to

⁴ The Boulder County process is not feasible for large scale, multi-jurisdictional implementation due to the time and resources it requires. For a more in-depth look at Boulder County's RLA process, see Boulder County's report at Appendix B: Boulder County Election Audit.

⁵ Dr. Stark is Professor of Statistics at University of California, Berkeley, and is recognized as a leading expert in the field of post-election audit standards. He invented risk-limiting audits and developed all of the methods for risk-limiting audits that have been field-tested.

⁶ Mr. McBurnett is a lecturer in Computer Science at the University of Colorado – Boulder. He is vice-chair of the IEEE Voting Systems Electronic Data Interchange Project 1622, and has expertise in risk-limiting audit theory and processes.

⁷ For a more detailed explanation, see the "Challenges in Implementing RLA" section within this report.

the RLA, describe the RLA process, and outline the lessons learned from the Arapahoe County pilot project that will be used for moving forward to implement a statewide RLA program.

Goals and Objectives

The Colorado General Assembly has declared that “the auditing of election results is necessary to ensure effective election administration and public confidence in the election process. Further, risk-limiting audits provide a more effective manner of conducting audits than traditional audit methods in that risk-limiting audit methods typically require only limited resources for election races with wide margins of victory while investing greater resources in close races.”⁹

The goal of the SOS is to find a feasible statewide risk-limiting audit solution that creates a repeatable post-election audit process and justifies increased confidence that the ballots are being tabulated correctly. In addition, the SOS seeks to reduce the time it takes counties to conduct a post-election audit.

SOS objectives in conducting this risk-limiting audit pilot project mirror the General Assembly’s stated purpose and the SOS’s goals. The SOS hopes to find and implement a solution that:

- Minimizes the number of ballots that must be examined in a post-election audit in order to verify the accuracy of the election outcome within the stated acceptable risk margin; and
- Increases efficiency in the post-election audit process and reduces the county resources and time necessary to ensure accurate election outcomes.

In order to achieve these stated goals and objectives, the SOS researched¹⁰ the RLA process, partnered with experts in the RLA field, and used its grant funds to conduct an RLA pilot project in Arapahoe

⁸ **Colorado Risk-Limiting Audit Implementation: Timeline of Events**

Date	Jurisdiction	Event
August 2010	Douglas County	Colorado State University Pilot Review
November 2010	Boulder County	Boulder County RLA Pilot
May 2011	SOS	SOS Awarded EAC Grant
August 2011	Denver, Jefferson, Eagle, and Pitkin Counties	Pilot County tours
September 2011	San Luis Obispo, CA	Observe the San Luis Obispo County RLA
March 2012	Leon County, FL	Leon County RLA
September 2012	Boulder County	Boulder County RLA Pilot
February – October 2012	SOS	Participated in discussions involving the white paper: Risk-Limiting Post-Election Audits: Why and How
February 2013	Boulder County	Boulder County RLA Pilot
March – April 2013	SOS	Vendor Demonstrations
November 2013	Arapahoe County	Arapahoe County RLA
2014	TBD	RLA in one Colorado county
2015	TBD	RLA in 32 Colorado counties
2016	TBD	RLA in all 64 Colorado counties

See also Appendix C and Appendix D (previous reports to the EAC)

⁹ Section 1-7-515(1)(a), C.R.S.

¹⁰Risk-Limiting Audits Working Group (2012, October). Risk-Limiting Post-Election Audits: Why and How. Retrieved December 6, 2013, from <http://www.stat.berkeley.edu/~stark/Preprints/RLAwhitepaper12.pdf>.

County. The remainder of this report outlines the RLA process, lists the challenges of implementing RLA in Colorado, and summarizes the findings of the SOS related to the Arapahoe County pilot project.

Risk-Limiting Audit Process

The following steps outline the RLA process:

1. Conducting a risk-limiting audit requires that jurisdictions have a sound ballot accounting process. In an efficient risk-limiting audit, a batch size of one ballot is used, which requires that a cast vote record (CVR) exist and be available and retrievable for each individual ballot. The CVR is the output of a scanned paper ballot, which can be produced by a voting system or other technology. DREs do not allow for individual CVRs, so the DRE VVPAT record is treated as a batch.
2. The risk-limiting audit process begins by obtaining the vote results for each batch of ballots cast and then selecting the specific contests to audit.
3. Once the contests have been selected, the number of ballots to select initially is calculated by using the risk limit¹¹ and the margin of the contests.¹²
4. The ballots are then randomly selected and each ballot's vote marking is compared by hand to the CVR for that ballot.
5. If sufficiently few errors are found, the audit ends; otherwise, additional ballots are audited.

Colorado is proposing two different solutions for conducting risk-limiting audits: (1) a tested solution (parallel scanning); and (2) an ideal solution (single scan).

While parallel scanning has been performed in Colorado¹³, a single scan solution has yet to be tested. Ideally, Colorado will use a single scan solution moving forward, because it is more efficient. The single scan solution would imprint the ballot with a unique identifier that would be traceable to the CVR and the scanned ballot image, so that ballot position within a batch is not the only way to locate the ballot. The following diagram provides a visual side-by-side comparison of the steps to conduct a risk-limiting audit by single scan versus parallel scan.

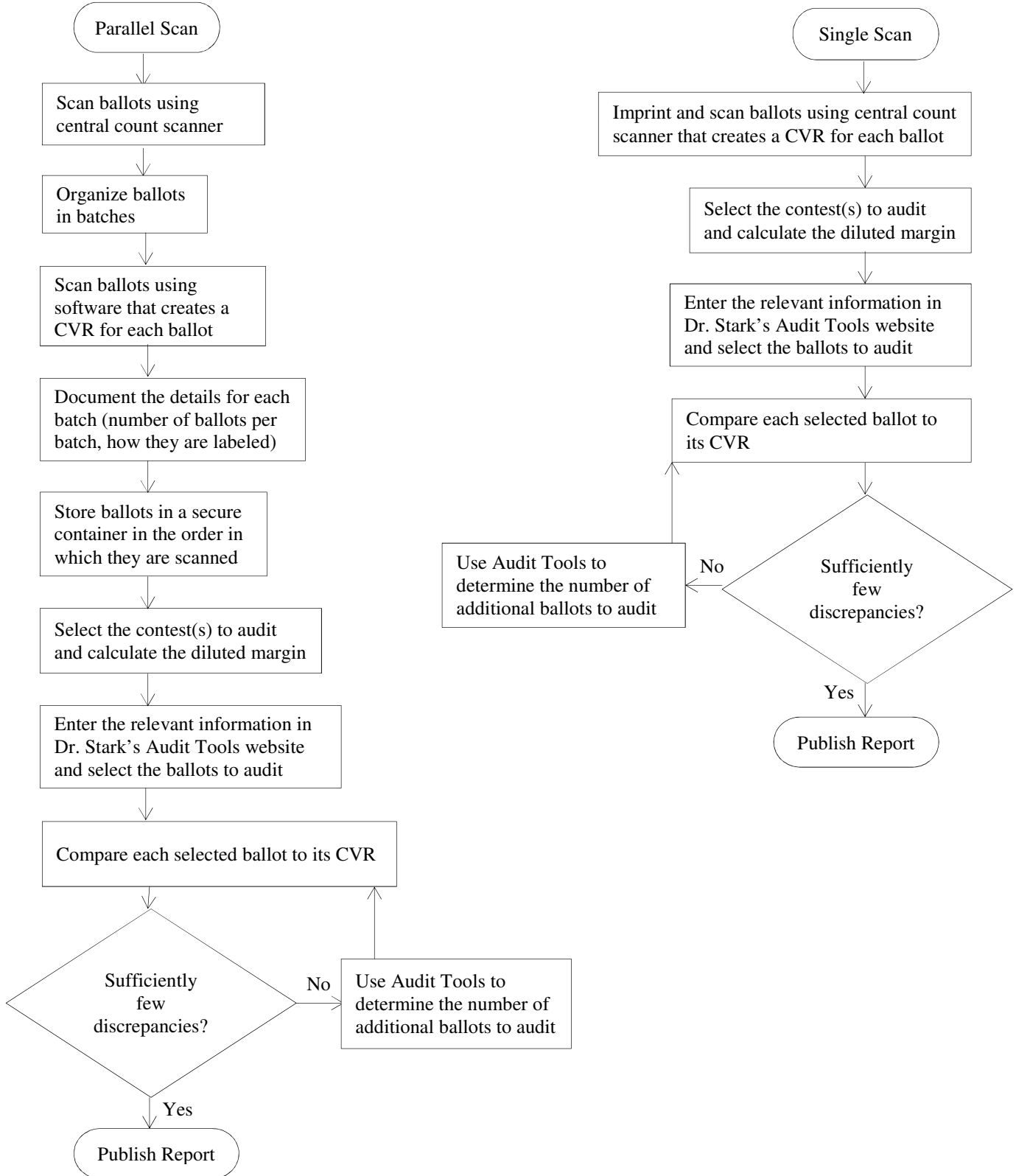
Stark, P.B. and Wagner, D.A. (2012, May 8). Evidence-Based Elections. Retrieved January 24, 2014, from <http://www.stat.berkeley.edu/~stark/Preprints/evidenceVote12.pdf>.

¹¹ The risk limit is the largest chance that an incorrect outcome of a contest will not be corrected by the audit. A risk limit of 5% means that there is at least a 95% chance that an audit will lead to a full hand count that corrects the outcome, if the outcome is incorrect. The smaller the risk limit, the greater the number of ballots to initially audit. A 10% risk limit is the generally accepted risk limit based on risk-limiting audits conducted in jurisdictions around the U.S.

¹² The margin of a contest is a factor that determines how many ballots will be audited (the smaller the margin, the greater the number of ballots to audit).

¹³ See Appendix A: Arapahoe County Risk-Limiting Audit.

Parallel Scan and Single Scan Solutions



Challenges in Implementing RLA

During this project, the SOS encountered a number of challenges in implementing RLA statewide. Those challenges included:

- **Lack of necessary technology for certified voting systems in Colorado.** The key elements in conducting a risk-limiting audit are to obtain a CVR of each ballot and match each paper ballot to its CVR. Currently, most of Colorado's certified voting systems cannot meet this requirement due to the lack of available technology at the time they were designed.
- **Uncertainty regarding the risk-limiting audit process.** Colorado has only recently been introduced to risk-limiting audits, which caused some uncertainty among SOS and county staff. Interested parties raised questions about the definition of a risk-limiting audit, how to conduct an audit, the cost to conduct an audit, the time it would take to conduct an audit, and what to expect from the audit. Some of these questions could only be answered by performing a risk-limiting audit. Additional testing at counties of various sizes will need to be performed in order to fully understand the impact risk-limiting audits will have on the counties statewide.
- **Legal issues regarding the Colorado Open Records Act.** The project came to a standstill at one point in the process, because the SOS and counties became uncertain of whether or not a ballot would be subject to the Colorado Open Records Act.¹⁴ The counties that initially volunteered for the RLA pilot project were reluctant to participate if it meant that ballots or ballot images would be available for inspection by the public without any safeguarding of voter anonymity. The issue was resolved months later by State legislation¹⁵, but the timing was such that the scope of the pilot had to be changed from testing in multiple counties to testing in only one county.
- **Timing of the project in relation to the election cycle.** Timing had the biggest impact on the progress of the project. County officials work on election matters for several months before and after each election, and have few resources to implement new processes during that time period. Implementing and testing new processes during non-election periods would have been ideal, but such a time period was not available as a result of the grant time period.

Arapahoe County RLA Pilot Project

Arapahoe County volunteered to coordinate with the SOS for an RLA pilot project for the November 2013 General Election using CBG's parallel scanning solution. A detailed report of the Arapahoe County RLA can be found in Appendix A. The following information summarizes the findings of SOS staff following completion of the RLA.

Lessons Learned

SOS staff learned several lessons regarding the benefits and pitfalls of risk-limiting audits using the parallel scanning solution during the RLA pilot project:

¹⁴ Section 24-72-201 *et seq.*, C.R.S.

¹⁵ HB 12-1036

- **Documentation:** The audit process must be clearly documented by the county conducting the audit, including how ballots are organized. The county must create procedures for publishing audit data. Clear documentation will provide transparency and instill confidence in the process while also preserving anonymity.
- **Ballot location and retrieval:** Locating and retrieving the selected ballots by hand and using one scanner with the CBG system was a cumbersome process given the large batch size. The ballot retrieval process could be more efficient by using the same number of scanners for ballot location that were used for creating the CVRs to count ballot pages within a batch. A table paper counter is a solution that could also be used to more efficiently count ballots and keep them in order.
- **Training:** CBG provided a half-day training session to Arapahoe County staff and election judges. Though helpful, SOS staff recommends more detailed training and system documentation to assist county staff and judges with understanding the RLA process and the technology.
- **Parallel scanning:** Parallel scanning using the CBG system is significantly more time-consuming than Colorado's current post-election audit process, and requires that ballots stay in the same order in which they are scanned. This requirement allows significant opportunity for human error. As a result, parallel scanning does not promote the SOS's stated goals and objectives.
- **Ballot accounting:** One selected ballot could not be verified against its CVR, and it did not match the ballot image on the CBG system. The correct ballot existed, but finding that ballot within the batch would have required rescanning the batch and recreating a CVR for each ballot in that batch. It is essential that all ballots are accounted for and are easily retrievable.
- **Communication:** Communication with all of the participating parties is crucial to the success of a risk-limiting audit. The county must have a well-organized, concise agenda for each meeting, clearly define the expectations, ensure that everyone is on the same page and has access to all of the information needed for the audit.
- **Human error:** Human error can occur whether ballots are hand counted or counted by a scanner. SOS staff has observed human error in both instances. For hand counting, the most common error is miscounting the number of ballots in each stack of ballots. For scanning, the most common error is failing to store ballots in the same order in which they are scanned. Risk-limiting audits rely heavily on accuracy, and as a result, unintended errors greatly impact the time it takes to conduct the audit.
- **Workload:** The workload for performing a risk-limiting audit will vary from election to election due to the volume of ballots to be scanned and the contest margins of selected races.
- **Discrepancies:** The SOS must develop best practices and tools to address any discrepancies with ballot selection, when a ballot does not match a CVR, and when there is a hand count.
- **Standardization:** The SOS must develop a standard CVR format.
- **Batch size:** A batch size of 50 ballots or fewer would be optimal for searching and ballot accounting. Having batch sizes of approximately 1,000 ballots made the pilot project process more time consuming, difficult to search for selected ballots, and made the selection process more susceptible to errors.

- **Ballot order:** The ballots should be imprinted with a unique audit batch and ballot number as they are scanned. The search for a particular ballot would be simplified by not having to count ballots within a particular batch to locate the desired ballot. Keeping the ballots in order would still be desirable, but an out-of-order batch would not result in the inability to locate a particular ballot.

Summary

The SOS successfully coordinated with Arapahoe County – one of the largest counties in Colorado – to conduct a risk-limiting audit for the 2013 Coordinated Election. The audit proved the effectiveness of using statistics to ensure the accuracy of an election, and provided the SOS with learning opportunities to make risk-limiting audits more efficient.

The SOS plans to conduct additional testing and analysis, but conducting this audit made great strides toward implementing statewide risk-limiting audits in Colorado.

With the extension of the deadline for completion of a statewide RLA and the knowledge gained over the past three years, the SOS is better equipped to implement a statewide risk-limiting audit by the 2017 Coordinated Election.

Testing will need to continue on risk-limiting audits. For instance, Colorado plans to conduct testing on risk-limiting audit methods (ballot comparison vs. ballot polling¹⁶), contests with margins of 5% or less, and scanning hardware and software. Analysis and optimization of ballot accounting and scanning processes will also continue.

The SOS's goal is to perform risk-limiting audits in at least one county in 2014, approximately 32 counties in 2015, and all counties in the 2016 General Election.

¹⁶ Stark, P.B. (2012, August 24). Ballot-polling Risk-limiting Audits in Two Pages (± 1). Retrieved March 13, 2014, from <http://www.stat.berkeley.edu/~stark/Preprints/bpa2pp.pdf>

Appendix A: Arapahoe County Risk-Limiting Audit

Timeline

October 24, 2013 – Clear Ballot Group (CBG) provided training to Arapahoe County staff.

October 28, 2013 – Arapahoe County staff began scanning ballots.

November 7, 2013 – Risk-limiting audit participants selected the contests to be audited.

November 14, 2013 – Risk-limiting audit conducted at Arapahoe County.

November 18, 2013 – Risk-limiting audit completed at Arapahoe County.

Participants

Arapahoe County: Matt Crane – County Clerk and Recorder, Wayne Munster – Director of Elections, Corene Henage – Elections Manager, Jim Dunst – Election Specialist

Clear Ballot Group: Tim Halvorsen – Chief Information Officer, Ana Quevedo – Sales Engineer

Colorado Secretary of State: Christi Coburn – Voting Systems Program Manager, Danny Casias – Voting Systems Specialist, Jerome Lovato – Voting Systems Specialist

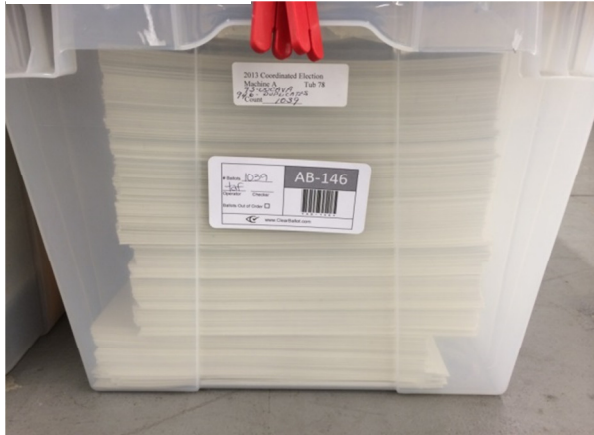
Consultants: Dr. Philip B. Stark, Neal McBurnett

Pre-Audit Ballot Scanning

Upon receiving ballots, Arapahoe County staff created batches of 250 ballots to be scanned in the Sequoia 400-C optical scanner. A batch audit log was assigned to each batch of ballots. After a batch was scanned in the Sequoia 400-C, the ballots were consolidated into batches of approximately 1,000 ballots and scanned in the CBG system to produce a CVR for each ballot. This additional scanning was necessary because the Sequoia 400-C produces CVRs that cannot confidently be matched to the corresponding ballot within the batch.

Arapahoe County assigned two temporary staff workers to run the CBG system. These temporary staffers were responsible for storing the ballots in the same order in which they were scanned. After being scanned in the CBG system, the ballots were placed in boxes (containing approximately 1,000 ballots per box) which were given a CBG box label (*e.g.* AB-XXX). A total of 146 batches consisting of 139,821 ballots were scanned and stored in boxes in numerical order in the Arapahoe County Elections Warehouse, as shown in the photographs below.

CBG Box Label



Box Organization



Setup

On the day of the risk-limiting audit, CBG provided Dr. Stark and Mr. McBurnett with CVR files from the CBG system. The Elections Manager provided Dr. Stark with the results from the seven DREs (581 ballots) that were used in the 2013 Coordinated Election, which Dr. Stark incorporated with the CBG results.

Dr. Stark then wrote an SQL script to make the CVR content human-readable and searchable for the relevant contests. Dr. Stark entered the total ballots cast for the election and the contests to be audited, and the votes for each contest into his online tool for comparison risk-limiting audits.¹⁷

The contests comprised two statewide ballot measures - Amendment 66 and Proposition AA - and one county race - City of Centennial Mayor.

Data was entered for:

- Ballots cast in all contests
- Contest names
- Candidate names
- Votes for each candidate
- Votes for each contest
- Risk limit
- Expected rate of difference for 1-vote overstatement
- Expected rate of difference for 2-vote overstatement
- Expected rate of difference for 1-vote understatement
- Expected rate of difference for 1-vote understatement
- Whether to round up the starting sample size for 1-vote differences
- Whether to round up the starting sample size for 2-vote differences

¹⁷<http://www.stat.berkeley.edu/~stark/Vote/auditTools.htm>

Ballot Selection

Based on the diluted margin (the vote margin divided by the total number of ballots cast), 44 ballots were selected for the audit.

The online tool was used to randomly select the ballots based on a random number seed, as shown by the exhibits below. Dr. Stark presented the group with nine uniquely colored translucent, 10-sided dice to create the random number seed. The County Clerk and Recorder rolled all nine dice twice followed by rolling two die to obtain a 20-digit seed. Dr. Stark entered the 20-digit seed into his online tool, which produced the 44 ballots that were selected for auditing. (See Table 1, below)

Audited Contests

Initial sample size	
Contest information	
Ballots cast in all contests: <input type="text" value="140402"/> Smallest margin (votes): 15,509. Diluted margin: 11.05%.	
Contest 1. Contest name: <input type="text" value="Mayor of Centennial"/>	
Winners: <input type="text" value="1"/>	
Reported votes:	
Candidate 1 Name: <input type="text" value="Noon"/>	Votes: <input type="text" value="23157"/>
Candidate 2 Name: <input type="text" value="Bromley"/>	Votes: <input type="text" value="7648"/>
<input type="button" value="Add candidate to contest 1"/> <input type="button" value="Remove last candidate from contest 1"/>	
Contest 2. Contest name: <input type="text" value="Amendment 66"/>	
Winners: <input type="text" value="1"/>	
Reported votes:	
Candidate 1 Name: <input type="text" value="No"/>	Votes: <input type="text" value="91039"/>
Candidate 2 Name: <input type="text" value="Yes"/>	Votes: <input type="text" value="48301"/>
<input type="button" value="Add candidate to contest 2"/> <input type="button" value="Remove last candidate from contest 2"/>	
Contest 3. Contest name: <input type="text" value="Proposition AA"/>	
Winners: <input type="text" value="1"/>	
Reported votes:	
Candidate 1 Name: <input type="text" value="No"/>	Votes: <input type="text" value="46291"/>
Candidate 2 Name: <input type="text" value="Yes"/>	Votes: <input type="text" value="91118"/>
<input type="button" value="Add candidate to contest 3"/> <input type="button" value="Remove last candidate from contest 3"/>	
<input type="button" value="Add contest"/> <input type="button" value="Remove last contest"/>	

Dice Displaying Random Seed



Audit Parameters and Seed

Audit parameters	
Risk limit:	<input type="text" value="10%"/>
Expected rates of differences (as decimal numbers):	
Overstatements. 1-vote:	<input type="text" value="0.00"/> 2-vote: <input type="text" value="0.000"/>
Understatements. 1-vote:	<input type="text" value="0.00"/> 2-vote: <input type="text" value="0.000"/>
Starting size	
<input checked="" type="checkbox"/> Round up 1-vote differences.	<input type="checkbox"/> Round up 2-vote differences. <input type="button" value="Calculate size"/> 44
Random sampling	
Pseudo-Random Sample of Ballots	
Seed:	<input type="text" value="27405096441431501170"/>
Number of ballots:	<input type="text" value="140402"/>

Table 1 – Selected Ballots

sorted_number	ballot	batch_label	which_ballot_in_batch	sorted_number	ballot	batch_label	which_ballot_in_batch
1	1257	AB-001	676	23	54268	AB-058	65
2	3441	AB-005	123	24	57795	AB-061	613
3	6673	AB-008	590	25	58687	AB-062	511
4	7624	AB-009	557	26	60188	AB-064	46
5	7747	AB-009	680	27	64184	AB-068	85
6	8389	AB-010	355	28	65740	AB-069	647
7	9344	AB-011	481	29	66408	AB-070	325
8	11695	AB-013	877	30	69158	AB-073	115
9	19138	AB-021	442	31	69564	AB-073	521
10	19892	AB-022	211	32	69883	AB-073	840
11	23897	AB-026	423	33	84920	AB-089	279
12	24834	AB-027	377	34	85217	AB-089	576
13	24939	AB-027	482	35	87378	AB-091	759
14	25290	AB-027	833	36	91361	AB-095	777
15	25636	AB-028	201	37	92067	AB-096	494
16	26170	AB-028	735	38	97246	AB-101	833
17	28176	AB-030	772	39	108960	AB-113	874
18	32281	AB-035	26	40	110460	AB-115	414
19	34495	AB-037	281	41	122470	AB-128	364
20	36282	AB-039	125	42	126759	AB-132	731
21	38568	AB-041	440	43	126977	AB-132	949
22	45056	AB-048	164	44	135551	AB-141	716

The selected ballots were found using three different methods in order to determine the most efficient method: hand selecting, the CBG scanner, and the Sequoia 400-C. Twenty-four ballots were selected by hand, 18 ballots were selected by the CBG scanner, and two ballots were selected by the Sequoia 400-C. For all three methods, it was essential that all of the ballots be kept in the same order in which they were selected, because the CVR for each ballot was obtained by using the CBG system and the ballots were not uniquely identifiable. If the ballots were not kept in order then they would not match the CVR, and that batch would have to be rescanned into the CBG system. Using the Sequoia 400-C as a paper counter was ultimately found to be the fastest method for finding the selected ballots. However, as shown by Table 2 below, there are pros and cons for using each method.

Table 2 – Ballot Selection

Method	Pros	Cons
Hand Selecting	<ul style="list-style-type: none">• Not susceptible to machine error• 1 to 3 people per batch (1 person per batch was found to be sufficient)	<ul style="list-style-type: none">• Took three times as long as a scanner to locate a ballot• Not repeatable• Susceptible to human error: miscounting a ballot• Requires additional manpower as the number of ballots increases due to the time needed to locate a ballot
CBG Scanner	<ul style="list-style-type: none">• Can select ballots faster than a single human selector• Repeatable results counting ballots• Additional manpower is required only if additional scanners are needed (2 people per machine)	<ul style="list-style-type: none">• Susceptible to: paper jams, miscounting a ballot, causing ballot fatigue• Susceptible to human error: scanning ballots in the wrong order
Sequoia 400-C	<ul style="list-style-type: none">• Can select ballots at about a three times faster rate than the CBG scanner• Additional manpower is required only if additional scanners are needed (2 people per machine)	<ul style="list-style-type: none">• Susceptible to: paper jams, miscounting a ballot, causing ballot fatigue• Susceptible to human error: ballots can get out of order; scanning ballots in the wrong order

Hand Selecting

Hand selecting involved a manual count of the ballots until the desired ballot was located. The ballot table (Table 1) was arranged in ascending order based on where it was located in a batch (*e.g.* batch AB-035, ballot 26; batch AB-064, ballot 46). The hand selectors were given a sheet of paper listing the batch and ballot numbers. The first group of hand selectors (three selectors per batch) counted down to the selected ballot. For example, the hand selectors selected batch AB-068, ballot 85 by counting 84 ballots. The second group of hand selectors - one selector per batch - counted ballots in stacks of 25 ballots. The second method of hand selecting was found to be the more efficient method for hand selecting ballots, especially when the ballot to be located was several hundred from the beginning of the batch.

CBG Scanner

The CBG Scanner was used to count ballots until the desired ballot was located. Again using Table 1, county and CBG staff first selected batches that contained multiple ballots (*e.g.* batch AB-073, ballots 115, 521, and 840) then proceeded to batches that contained a ballot in the middle of the batch (*e.g.* batch AB-096, ballot 494). CBG’s Chief Information Officer entered the batch and ballot information into the CBG software, and county staff loaded the CGB scanner with approximately 150 ballots until the selected ballot was found. When searching for multiple ballots within a batch, care had to be taken to correctly account for how many ballots had already been scanned and how many more ballots would need to be scanned to find the next ballot. The CBG system associates each ballot in the CVR with a unique identifier consisting of the batch label (*e.g.* AB-067) and an image sequence number. Since each ballot image is associated with a high-quality image, it is possible to check if the randomly selected ballot matches the corresponding CVR using the unique Ballot ID.

Sequoia 400-C

Due to time constraints on the day of the risk-limiting audit, the final two ballots (batch AB-008, ballot 590 and batch AB-062, ballot 511) were audited on November 18, 2013. At this time the CBG scanner

was no longer in Arapahoe County's possession so the county Election Specialist configured the Sequoia 400-C to run in scan-only mode and scanned the ballots from the bottom of the batch until within a few ballots of the selected ballot. For example, there were 982 ballots in batch AB-062. In reverse order starting with the last ballot in the batch, the county Election Specialist scanned 465 ballots while the county Elections Manager ensured that the ballots stayed in the same order in which they were scanned. After the 465 ballots were scanned, six additional ballots were hand-counted to get to the 472nd ballot, which was ballot 511. SOS staff compared the selected ballots to the CVRs produced by the CBG system. Both ballots matched their CVRs.

Ballot Auditing

After a ballot was retrieved, the selector brought the ballot to SOS staff, who called out the results of each selected contest to Dr. Stark, who verified that the results matched the CVR. Additional contests on the ballot were given to Mr. McBurnett for further verification. When a ballot did not match the CVR, the selector would take the ballot back to the batch and recount the ballots. The selectors were able to find the correct ballot in all but one case using this process.

Two batches were found to be out of order. Ballot 26 in batch AB-035 was found to be ballot 25 in that batch. After performing a search for the selected ballot, it was determined that the ballots were out of order starting at Ballot 21. Ballot 647 in batch AB-069 did not match the CVR because the ballots in batch AB-069 were out of order.

Ballots were verified by comparing the ballot to the ballot image of the expected ballot on CBG's system. When the ballot image did not match, it was easy to look at the ballot images around the expected one to determine if the ballot order of the selected ballot and surrounding ballots could be correlated with the images.

Summary

This was the first time the SOS assisted with the performance of a risk-limiting audit for a live election in Colorado. As expected with a pilot project, there were unknowns and lessons to be learned by all of the parties involved. Having the full cooperation of Arapahoe County was essential in making this audit a success, and based on the results, the risk-limiting audit at Arapahoe County was a success.

Appendix B: Boulder County Election Audit¹⁸

Overview

The Election Audit is a quality assurance procedure that checks the accuracy of the machine tally of ballots (*Ref 6*). Ballots for a contest are sampled, hand counted and the results checked against the vote tabulation. In the risk-minimizing approach that we use, the sample is specifically constructed so as to minimize the risk of confirming an incorrect election outcome (*Ref 7*).

The Election Audit is one of the two quality assurance procedures we use when certifying the election. The other is the Election Reconcile which investigates the conduct of the election. It compares the number of voters, the ballot inventory, the ballots voted and the vote credit assigned. The results of both of these procedures are primary inputs to the Election Canvass.

We are fortunate that we can piggyback on an excellent audit strategy employed in 2008 (*Ref 1*). Because of that effort we have some experience in statistical audit techniques that form the foundation for this audit process.

Audit Requirements - Colorado Law & SOS Rules

The audit must conform to current state statute and SOS rules:

- CRS 1-7.514 (Random Audit) manual audit of 5% of voting devices or, for central count counties, a “specified” percentage of ballots counted in the county. Or, use any method that provides a higher level of statistical confidence.
- SOS Rule 11.5.4 (Post Election Audit for Central Count counties) random selection of one Central Count scanner (all races on no more than 500 ballots) and 5% of DREs (all races on all of the paper trails).

Boulder County will use a risk-minimizing audit (*Ref 7*) -- an option that meets the “higher level of statistical confidence” part of CRS 1-7.514. Risk-minimizing audits typically require limited resources for races with wide margins of victory while investing greater resources in close races. The technique increases coverage and reduces expense.

State law also provides provisions for an automatic recount (CRS 1-10.5-101). Since the need for a recount is only determined after the election is certified, there are no direct interactions between the audit and the recount. However, if a contest is likely to be included in a recount, to minimize risk to the paper ballots and VVPAT paper trails, we will postpone any audit of the contest until after the recount.

Audit Procedure Highlights

At a high level, the audit procedure is straightforward: select some contests to audit, select groups of ballots on which to hand count those contests, compare the hand count with the machine count of those same ballots.

Selecting Contests

When audit resources are limited, it’s useful to statistically avoid selecting contests that have wide margins or are uncontested. This focuses the audit on the contests where the outcome may be in question. As was done in the 2008 General Election (*Ref 1*) and in the 2009 Coordinated Election (*Ref 9*), we can do this by selecting contests with a probability proportional to the inverse of the contests’ margin. Close contests, those with a small margin, are more likely to be selected.

¹⁸ Webb, C., *Boulder County Election Audit* (Nov. 7, 2013)

We don't require that all contests be selected in this manner. For example, we may be mandated by the SOS to audit a particular contest. Or, it could be that there is a national or statewide contest that is particularly heated and public interest suggests that the contest should be audited. However, the majority of contests need to be selected statistically, as above, since there is higher confidence in the election when no contest is immune from being audited.

Selecting Ballots (selecting audit units)

Audit units are groups of ballots that are selected for hand counting a contest. Audit units, in general, must adhere to two requirements: (1) that the ballots can be retrieved as a group and be available for the hand-count and (2) that a machine count of the group is available for comparison.

Because election results are eventually reported by precinct, it would be nice if the audit unit could be all of the ballots associated with a precinct. However in our central count system, ballots are grouped as they arrive back in the Elections Department and are not resorted into precincts. It would be difficult to use precinct ballots as the audit unit.

In Boulder, voted ballots that arrive back in the Elections Department are grouped, processed (i.e., scanned and resolved), aggregated with other groups and counted. These aggregates are called MBBs and they have exactly the characteristics we need in an audit unit – groups of ballots, archived together and with a machine count¹⁹. In the 2008 election there were over 525 MBBs, each containing between 1 and 1760 ballots. The audit consisted of randomly identifying a set of MBBs, hand counting them and comparing with the MBB's tabulated results. The 2008 audit hand counted select contests on 24 MBBs for a total of 69 MBB-contest pairs. In 2009 a similar methodology picked 21815 votes from 20 contests and 78 MBBs out of a total of 425 MBBs.

So, how many audit units do you randomly select to have a statistically valid audit? You could select a fixed percentage of the audit units. California uses this approach and audits all contests on a fixed 1% of the ballots. Or, you could have a tiered approach like what was proposed in HR 811: (1) if vote margin is less than 1% then audit 10% of the audit units, (2) if the margin is more than 1% but less than 2% then audit 5%, (3) otherwise audit a fixed 3% of the audit units. We choose to use a risk-minimizing statistical approach (Ref 3, 4, 6, 7) because of its improved efficiency. This approach focuses on the fewest number of audit units to achieve a specified statistical confidence, or probability, that an outcome-affecting error would be detected. This choice gives us an opportunity to audit more contests for the same audit cost.

Our audit unit selection relies on the NegExp algorithm detailed in *Reference 4*. It uses the contest's margin, the size (number of ballots) of the audit unit and a parameter that define the rigor of the algorithm to select audit units. The algorithm is well suited to large, complex elections in that selected audit units can be used across several contests, thus minimizing some of the administrative overhead of running an audit. This is an active area of research and in the two years since NegExp has been published, more robust algorithms have been developed and are being investigated for future audits.

Comparing Results

Once the hand count of the selected MBBs for a contest is completed, the results are compared to the machine count of the same ballots. If the difference between the hand count and the machine count differ by $\lceil 0.5\% \rceil$ or more of the ballots hand counted, the audit is escalated. This "escalation trigger" prescribes a sequence of troubleshooting activities which help (1) to identify the source and extent of the problem with the contest and (2) whether other contests are impacted.

¹⁹ It's time consuming to produce individual MBB results during the conduct of the election. Instead, we produce cumulative MBB results which are processed after the election to produce the individual MBB tally results.

Confirm that there is a discrepancy

- Verify that the MBB is complete. Confirm that the hand counters and the Ballot Now and Tally systems saw the same number of ballots.
- Re-verify the hand count, perhaps using a different hand count team.

Look for “unusual” ballots as source of discrepancy

- Manually inspect the ballots. Identify any that are “unusual” – i.e., have stray marks, or are incorrectly marked, or are inconsistently marked -- and compare how the election night Resolution Team resolved them. If the discrepancy is due to a difference of opinion between the hand count team and the election night Resolution Team, document the difference and de-escalate.
- Visually inspect the scanned images. Using the Ballot Now Resolution Screen, compare image quality and resolution of the contest on all ballots on the MBB. Look carefully at ballot fold lines. If the Ballot Now and hand count resolutions agree, yet the tally of the MBB doesn't, investigate Tally as the source of the discrepancy and proceed to “Investigating Tally Discrepancies”.

Investigate resolution differences

- Folding in the results of other MBB-Contest audits, look for trends across scanners and contests. Consider re-scanning the MBB using a different scanner. If this resolves the discrepancy then investigate how the original scanner was used during the election. Investigate any discrepancies in the MBBs that have already been audited and that used this scanner. Decide if non-audited MBBs from this scanner need to be re-scanned.
- If the discrepancies seem to relate to this particular contest and the discrepancies cannot be resolved by re-scanning on different scanners, increase the number of MBBs audited for this contest. If needed, this escalation may result in a complete hand count of the contest across all MBBs. If this doesn't resolve the discrepancy (i.e., total discrepancies be within $\lceil 0.5\% \rceil$) then consider reinstalling the Ballot Now Trusted Build, re-scanning and re-tallying.

Investigate Tally Differences

- When the election night resolutions and the hand count resolutions are identical yet Tally shows different election results, you have to suspect Tally or the MBB. Inspect the MBB to see if there was a fault writing to it. In diagnosing this, see if Tally can “recover” the MBB.
- As a last resort, securely archive the Tally hardware and software for later scrutiny and, with SOS support, re-run the tally of all MBBs on a different, trusted Tally system. Compare the election results from the trusted Tally against the hand counts.

Audit Schedule

The schedule for the audit is tight. Ideally, it would be best to wait as late as possible after Election Day so that all ballots are considered in the audit. However, audit results are a major input to the Canvass Board, which is required to certify the election within 13 calendar days of a Primary (or 18 days for other elections). With those two constraints in mind, the audit fits into a narrow window that starts on the Friday following the election. With this early snapshot of the election, it is likely that some small portion of provisional ballots and mail-in cures will be missed. The schedule for the 2010 Primary is as follows:

Week 1	Tuesday	Election Day
	Late Thursday (8/12)	Take snapshot of Score and Tally as the basis of the Election Audit and the Canvass.
	Late Friday (8/13)	Publish Audit Setup information.
	Saturday (8/14)	Meet with Audit Board to select audit parameters, select contests, select MBBs.
Week 2	Early Monday (8/16)	Make available selected MBBs for hand counting.
	Mon-Fri (8/16-8/20)	Hand count the selected MBBs – Monday noon through Friday.
	Late Thurs (8/19)	Canvass Board begins assessment with non-audit aspects of the election.
	Late Sunday (8/22)	Publish Audit Report.
Week 3	Early Monday (8/23)	Canvass wrap-up.
	Mon EOD (8/23)	Certify election.

Audit Budget

The audit budget covers the hand count and escalation of an estimated 3% of the expected ballot-contests in the election. As contests are selected, their ballot-contest estimates will be deducted from the budget. Contests will be selected as long as there are resources left in the budget to audit them.

If the auditing of randomly selected contests concludes before the budgeted time is up, we will accept nominations from the community for additional MBB-contest pairs to audit. The selections will be made by the audit team, as time permits.

Acknowledgments

This plan is a derivative of the Boulder County 2008 General Election audit that was lead by Neal McBurnett. Neal’s subsequent discussions and comments on drafts of this plan have been greatly appreciated.

References/Resources

1. Boulder County 2008 General Election Audit, Neal McBurnett, <http://bcn.boulder.co.us/~neal/elections/boulder-audit-08-11>.
2. In Consideration of Ohio Audits in 2008, Feb 19, 2008, Ohio Joint Audit Working Group, http://www.caseohio.org/Documents/Reports/Ohio_Audit_White_Paper_Feb_2008.pdf.
3. Recommended Audit Procedures, June 2, 2008, Ohio Joint Audit Working Group, http://www.caseohio.org/PageDetails/Audits/Ohio_Recommended_Audit_Procedures.pdf.
4. On Auditing Elections When Precincts Have Different Sizes, Aslam, Popa, Rivest, *Proceedings of the 2008 USENIX/ACCURATE Electronic Voting Technology Workshop (EVT)*. July 2008, http://www.usenix.org/event/evt08/tech/full_papers/aslam/aslam_html. See also, slides at <http://www.usenix.org/event/evt08/tech/popa-slides.pdf>.
5. Checking Election Outcome Accuracy. Post-Election Audit Sampling, Kathy Dopp, July 18, 2009, <http://kathydopp.com/serendipity/index.php?/archives/44-RELEASE-New-improved-methods-for-post-election-audit-sampling.html>.

6. [Implementing Risk-Limiting Post-Election Audits in California](http://www.usenix.org/event/evtwote09/tech/full_papers/hall.pdf), Hall, et al, August 10-11, 2009, http://www.usenix.org/event/evtwote09/tech/full_papers/hall.pdf.
7. Best Practices: Risk Limiting Audits, ElectionAudits.org, <http://www.electionaudits.org/bp-risklimiting>.
8. A “Sum of Square Roots” (SSR) Pseudorandom Sampling Method For Election Audits, Ronald Rivest, April 25, 2008, <http://people.csail.mit.edu/rivest/Rivest-ASumOfSquareRootsSSRPseudorandomSamplingMethodForElectionAudits.pdf>.
9. Post-Election Audit Report, 2009 Coordinated Election – Boulder County, November 29, 2009, <http://www.bouldercounty.org/clerk/elections/Audit%20Files/2009%20Audit%20Report.pdf>.

Inputs

1. MBB Cumulative Reports from Hart Tally.
2. Contest margins when contest extends beyond the county.

Outputs

1. Election Audit report

Change History

Month Day, Year i.e. (March 27, 2009)	Description of change i.e. (Initial Issue)
August XX, 2009	Initial draft
September XX, 2009	Second draft
October 21, 2009	Version 1.0
August 9, 2010	Version 2.0 for 2010 Primary
October 27, 2011	Details to further clarify Audit Setup #1
June 13, 2012	Insert Audit Setup step 3 to clarify how the setup spreadsheet is initially populated

Election Audit Process Details

A trustworthy audit requires transparency. The audit plan and the uncertified election results (per audit unit) need to be published and available before the audit is conducted. Software tools need to be transparent as well; the use of tools to expedite portions of the audit are acceptable but auditors need to be able to manually verify the output generated by any tool. While this is particularly true for third-party software, even use of off-the-shelf office software like spreadsheets needs to be open and review-able. Verification steps are built into the audit details described below. How extensive these steps are pursued is left up to the discretion of the audit team.

Audit Setup

The audit process below uses a spreadsheet for automation of the statistical methods used therein. An example of this spreadsheet as used for the 2011 Coordinated Election Audit can be found at G:\CRELED\2011 Coordinated Election\2011 Audit\02 - Audit Setup\2011 Coordinated Audit Setup.xls. Step 1 sets up the election data needed for the spreadsheet. Subsequent steps are referenced by blue comment boxes in the spreadsheet. Prior to starting this process, a template directory structure for the audit should be set up in the current election directory, similar to the 2011 Coordinated Election structure, and a copy of the setup spreadsheet saved there.

1. [Elections Staff] Construct Individual MBBs from Hart Cumulative MBBs

The statistical algorithms used in the audit require election results by MBB. However, individual MBB reports are time consuming to produce and impractical to get while ballots are being counted. But cumulative MBB reports are available. A cumulative MBB report contains the MBB's election results summed with all previously tallied MBBs. Individual MBBs reports can be constructed by subtracting the successive cumulative reports.

The timing of when to start the audit may be an issue. On one hand, we would like to wait until all ballots are processed and are accounted for in an MBB. However, the results of the audit are a major input into the election certification process, which statutorily has a short fuse. This means that the audit may have to proceed before all ballots are processed. In the past this meant that Provisional Ballots weren't included.

The first step in setting up the audit is to create Individual MBB reports from Cumulative MBB reports, using some third party software tools. The resulting Individual MBBs will be verified for correctness when the audit team is assembled.

- a) Copy the Hart Tally directory containing the MBB cumulative xml reports. This directory should contain pdf and xls/csv files as well as a directory containing an xml for each cumulative report.
- b) Check ballot issues to see if there are any special characters in the contest choices. For example, look for names that have "accents" (as would be used in non-English languages). If these special characters are not replaced, then step C below will error with a "wide character" error message.

If there are special characters, then they must be replaced with standard English characters. To do this, use NotePad++ software, which is free and available from <http://notepad-plus-plus.org/>. Open NotePad++ and use the Search/Find in Files option to find and replace the names with special characters. This feature will search and replace in all files under the directory which you have specified, so it does not need to be run for each MBB. For example, the name "José Smith" needs to be replaced with "Jose Smith". Also look for seemingly "normal" characters which may need to be replaced. An example of this is an apostrophe "d'Amore" which needs to be replaced with a regular apostrophe "d'Amore". If you continue to receive "wide character" error messages, then there are other non-standard character values in the files.

Note: editing the files to replace special characters changes the timestamp on the files. This will need to be explained during the audit if necessary.

- c) Execute the perl script "SpotMissingFiles.pl", redirecting output to "MissingFileCheck.csv" ("perl bin/SpotMissingFiles.pl OriginalMBBs >MissingFileCheck.csv"). Given a directory containing the "raw" Tally cumulative reports (as in Step 1), this program generates a report that is useful to determine if any xml files are missing. Generating the Tally cumulative reports are tedious and, consequently, error prone. Sometimes pdf or xls versions of a cumulative report will be saved but the xml save is missed. The SpotMissingFiles.pl program summarizes the files in the directory in a way that highlights when an xml file is missing.

When reviewing the MissingFileCheck.csv file, check each XML and PDF time stamp that is blank (missing). Go to the appropriate directory and check to see that the file names are all correct. There could be errors in the MBB's directory name, the original MBB file name, and/or the PDF file name.

- d) From the "03 - Create Individual MBBs" directory, execute the perl script "SimplifyCumulativeMBBs.pl" ("perl bin/SimplifyCumulativeMBBs.pl OriginalMBBs SimplifiedMBBs"). This program creates a simplified, uniform version of the more complicated

xml produced by Tally. Two parameters are required – the input directory created above, and an output directory where the simplified, cumulative MBBs will be written.

- e) Identify a county-wide contest which can be used as a baseline for ballot counts. Then edit the file CumulativeSortOrder.pl program file in the bin directory and change the \$countywideContestNumber to the value of the contest (e.g. if the county/state-wide contest is the 25th contest defined, then this parameter is assigned the value of 25). Note: because landowner ballots contain only the special district contest and not count-wide contests, they will not be detected by this program and must be accounted for later.
- f) Determine the order that the cumulative MBBs were tallied by executing the perl script “CumulativeSortOrder.pl” and redirecting output to “SortOrder.csv” - “perl bin/CumulativeSortOrder.pl SimplifiedCumMBBdir >SortOrder.csv”. This program inspects each simplified cumulative MBB and outputs relevant statistics on each. In particular, there are three fields associated with each cumulative MBB that should be reviewed: MBB sequence number, cumulative file creation time and cumulative cast votes. Open SortOrder.csv as a spreadsheet and, using these three fields, re-sort it so that the order reflects the order that the MBBs were read into Tally. Once resorted, save the file as a csv.
- g) If several Tally databases were used, you will have to divide the SortOrder.csv file csv file by database and execute step H below separately for each file.
- h) Create individual xml MBBs by deconstructing the cumulative xml MBBs according to the tally order determined above. Execute the perl script “CreateIndividualMBBs.pl” with the following command line parameters (1) the tally order csv file created above, (2) the directory containing the simplified cumulative xml MBBs and (3) an output directory where the individual xml MBBs will be written. If more than one Tally database was used, then this program needs to be run for each one, e.g.: “perl bin/CreateIndividualMBBs.pl SortOrder_j.csv SimplifiedMBBs IndividualMBB”
- i) To test the integrity of the individual MBBs, execute the perl script “RecreateCumulativeMBB.pl” with command line parameters (1) the tally order csv file created above, (2) the directory containing the individual MBBs and (3) a new output directory where the recreated cumulative MBBs will be written. Verify that the last recreated cumulative MBB agrees with the results captured in the original Tally cumulative pdf.\
- j) ***placeholder – how to identify landowner ballots on an MBB – affects total ballots on voter counts, combined MBBs, and summary tab

2. [Elections Staff] Determine In-County Voters per Contest

The number of voters per contest is equal to the number of ballots received – usually this is the number cast votes plus overvotes plus undervotes. Calculate this for each contest on each MBB by executing the perl script “VoterCounts.pl”. Pass as a parameter the directory containing the Individual MBBs and redirect output to “VoterCounts.csv” (e.g. “perl bin/VoterCounts.pl IndividualMBBs >VoterCounts.csv”). The csv file contains the number of ballots or voters per MBB per contest as well as the county’s grand total margin of victory between the top two candidates.

3. [Election Staff] Build Audit Setup Spreadsheet

All of the subsequent setup work for the audit happens in the Audit Setup spreadsheet. This spreadsheet can be copied from one election to the next. After doing a “save as” on a setup spreadsheet from a previous election, copy the contents of the VoterCounts.csv file into both the VoterCounts and CombineSmallMBBs tabs of the setup spreadsheet. Be sure to adjust any calculated columns as needed:

- “Num Ballots on MBB” should refer to a column with a county-wide contest on it. Set this up in the first row of voter counts and then drag down all the way to the “Countywide Voters” row at the bottom of the spreadsheet.
- At the bottom right-hand corner of the spreadsheet are calculated formulas for minimum, maximum, and average ballots per MBB – make sure all these formulas reference the complete span of rows of MBBs (but not the Countywide voters row mentioned above).
- Below the MBB statistics are calculations for ballot-contests and contests per ballot. Make sure that these calculations also reference the correct cells.
- Vote for N – VoterCounts.csv will have sum of votes not voters; on CombineSmallMBBs sheet, point these columns to another column for that same district that does NOT have vote for N. For example, for Boulder City Council vote for 5, point to a ballot question for the City of Boulder. If the district has no other contest, then ???

4. [Election Staff] Protect Voter Privacy in Small DRE MBBs

When reporting election results we protect the privacy of voters by ensuring that the precinct reports don't include small sample sizes. Results showing 25 or fewer voters are combined protect the secrecy of each individual's vote.

In the CombineSmallMBBs tab of the setup spreadsheet, manually combine MBBs when the number of voters for a countywide contest is less than 25. Note: since manually combining these numbers could be error-prone, consider inserting a row, right above the 2 being combined, then using formulas to perform the calculations and dragging the formulas across the spreadsheet.

5. [Election Staff] Adjust Margins for Multi-County Contests

The risk-minimizing algorithms we use require an absolute margin, not a countywide margin, between the winner and loser. For multi-county contests, find the absolute margins and total voter counts and adjust the setup spreadsheet accordingly.

Formulas that must be propagated on this sheet include rows 3 – 13 – all formulas must be propagated to the right across all contests. After the formulas are propagated, the following overrides must be made to specific contests:

- a) Multi-county/statewide contests – margin in row 6 must be manually updated to be the multi-county/statewide margin
- b) Vote for n contests – margin in row 4 must be manually updated to be the difference between the (n)th and the (n+1)th candidates.

Note: needed here is a sub-procedure for collecting and updating multi-county information in the spreadsheet. The collecting part includes:

- Identifying multi-county contests, including which counties are involved (pre-election)
- Gathering multi-county results, including overvotes, in order to populate the spreadsheet with the margin and voter information for the multi-county contests.

The multi-county worksheet can be used to help collect this information.

6. [Elections Staff] Determine Contest Selection Probabilities

Efficient audits statistically avoid auditing contests that have wide margins. This is done by selecting contests with a probability proportional to the inverse of their margin. In this step, probabilities are assigned to each contest so that when the audit is conducted, dice can be used to select contests.

Formulas in the spreadsheet perform the following calculations, and must be propagated for all columns (contests) across the sheet:

- a) Row 4 – Inverse Relative Margin = Absolute Voters V/Absolute Margin M; this value must be overridden to 0 for unopposed contests.
- b) Row 5 – Weighted contest selection probability = the proportion of this contest’s Inverse Fractional Margin to the total (contest’s Inverse Relative Margin/sum of all Inverse Relative Margins).
- c) Row 6 - To facilitate a random selection using dice, iteratively sum the probabilities to construct a running cumulative probability for each contest.

7. [Elections Staff] Determine MBB Selection Probabilities

After a contest is selected, MBBs for hand count need to be selected. The selection is probabilistic, with probabilities assigned by an algorithm that depends on the number of voters per MBB (Step 3, above), the absolute margins (Step 4, above) and the statistical confidence desired in the algorithm. Higher confidence translates higher likelihood that an error, if present, will be detected.

We will use the NegExp algorithm described in detail in *Reference 4* to calculate these probabilities. A detailed summary is contained in Attachment 1. This algorithm is flexible and is our algorithm of choice for large elections. For transparency the NegExp algorithm will be implemented in a spreadsheet so that the audit team can inspect formulas and test the implementation.

8. [Election Staff] Generate Pseudorandom Numbers Using SSR Algorithm

The algorithm for selecting MBBs requires random numbers and the above probability tables. Using the SSR pseudorandom algorithm of *Reference 8*, provide a spreadsheet that takes a 15-digit seed and produces a large number of pseudorandom numbers.

9. [Elections Staff] Publish Audit Details

For transparency, the results of the above audit setup will be published on the county website so that the public can confirm the work done so far. Include the following information along with SHA1 checksums (<http://support.microsoft.com/kb/841290>):

- VoterCounts.csv
- Margin adjustments for multi-county contests
- Contest Selection probabilities
- MBB selection probabilities for NegExp
- SSR pseudorandom number generator
- A zip containing the Hart Cumulative MBB pdf and xml files
- A zip containing the Individual MBBs xml files produced in Step 1, above.
- This Audit Procedure document

Conducting the Audit

10. [Elections Staff] Convene the Audit Team

Convene the audit team and have them sign an affidavit stating that they will honor the privacy of the ballot and protect the materials they’ll be working with. Give them an overview of the process. Emphasize that they will be working in pairs from different political parties and will need to verify each other’s work.

11. [Election Staff and Audit Team] Confirm the Generation of Individual MBBs

If necessary download the audit setup information published in Step 8. Recalculate the SHA1 checksum and verify that the checksums haven’t changed.

Test the integrity of the tools used to create the individual MBBs. Have audit team members select several individual MBBs at random and a contest. Provide them with (1) Tally's cumulative pdf report for this MBB, (2) the cumulative pdf report from the preceding MBB, and (3) a print of the individual MBB xml. The audit team should verify that the individual MBB is correct for the contest(s) selected.

12. [Elections Coordinator and Audit Team] Establish MBB Selection Parameters

For each contest, determine the level of confidence desired for each contest. Audit confidence, in this context, is loosely defined as the likelihood that the audit will be strong enough to detect an results-impacting error in the contest if one exists. This parameter along with contest margin determines the work load of the audit – specifically how many ballots will be hand counted.

In 2008 we picked 99% confidence for state contests and 75% for local contests. In 2009 we raised the local contests to 80%. It's useful to plug these numbers into the MBB selection spreadsheet (Step 10, above) to get a feel for the impact that different confidence levels can make.

13. [Elections Coordinator and Audit Team] Select Contests to Audit

First, determine if the SOS has mandated that certain contests be audited. Then, eliminate uncontested contests and contests that are targeted by the SOS for a re-count.

Select additional contests randomly, as follows:

- Construct a random number x , where $0 \leq x < 1$. The number can be the result of rolling 4 die. Or, the audit team may decide to just grab a block of pseudorandom numbers that were constructed in Step 7.
- Using x , scan the ordered Contest Selection probabilities table, selecting the contest having a cumulative probability immediately greater than the value x .

For each contest selected, estimate the workload on the audit team. Workload is the number of ballots that the team will scrutinize for each contest. It's pretty easy to estimate workload using the NegExp algorithm. See *Reference 4* for details.

14. [Elections Staff] Prepare Hand Count Tally Sheets

For each contest selected, prepare tally worksheets for the hand count.

15. [Elections Staff and Audit Team] Select MBBs for Each Contest

The NegExp algorithm has a nice property that MBB probabilities can be combined for the selected contests, allowing the MBB selection to cover all selected contests. To combine NegExp probabilities so that a single set of MBBs can be used to audit several contests:

- The combined NegExp probability for an MBB is the maximum of the NegExp probability for each selected contest.
- Do this for each MBB.

Select MBBs for NegExp (NegExp #6 in Attachment 1):

- Use four dice or the pseudorandom numbers created in Step 7 to construct a random number x , where $0 \leq x < 1$.
- If x is less than the combined NegExp probability for the MBB, select the MBB for auditing.
- Do this for each MBB.

With the number of MBBs approaching a thousand, NegExp will require a lot of random dice throws. Alternatively, the audit team may choose to use the SSR random number table saved in Step 7. If this is

the case, the team should use the dice to construct a single random 15-digit seed which then randomly select the MBBs.

16. [Audit Team] Audit the MBBs

For each selected batch, an individual hand count is performed for the selected contests. Hand counts use 4-person teams. One person (the Caller) reads the ballot for the target contest and calls out the vote. A second person (the Witness) observes the Caller for accuracy. Two people (Tallier #1 and Tallier #2) separately record the vote. The talliers compare their results periodically and investigate if there are discrepancies.

It is important that the counting be done “blind”. But since the Individual MBB reports are published before the counting begins, this is somewhat problematic. Where possible, the MBBs will be split between two counting teams so that no one team will be responsible for the entire MBB hand count.

17. [Election Staff and Audit Team] Compare the Hand Count and the Machine Count

When contest hand counting is completed, the elections staff will collect the hand count results in a spreadsheet and compare to the individual MBB tallies.

We are executing the audit to detect errors that may impact the election outcome. If any of the numbers differ by $\lceil 0.5\% \rceil$ or more of the ballots cast for the contest on the MBB, then the hand count for the MBB-Contest is escalated through a series of troubleshooting steps until the discrepancy is resolved or the scope of the problem is understood and fixed:

Confirm that there is a discrepancy

- Verify that the MBB is complete. Confirm that the hand counters and the Ballot Now and Tally systems saw the same number of ballots.
- Re-verify the hand count, perhaps using a different hand count team.

Look for “unusual” ballots as source of discrepancy

- Manually inspect the ballots. Identify any that are “unusual” and compare how the election night Resolution Team resolved them. If the discrepancy is due to a difference of opinion between the hand count team and the election night Resolution Team, document the difference and de-escalate.
- Visually inspect the scanned images. Using the Ballot Now Resolution Screen, compare image quality and resolution of the contest on all ballots on the MBB. Look carefully at ballot fold lines. If the election night and hand count resolutions agree, yet the tally of the MBB doesn't, investigate Tally as the source of the discrepancy and proceed to “Investigating Tally Discrepancies”.

Investigate resolution differences

- Folding in the results of other MBB-Contest audits, look for trends across scanners and contests. Consider re-scanning the MBB using a different scanner. If this resolves the discrepancy then investigate how the original scanner was used during the election. Investigate any discrepancies in the MBBs that have already been audited and that used this scanner. Decide if non-audited MBBs from this scanner need to be re-scanned.
- If the discrepancies seem to relate to this particular contest and the discrepancies cannot be resolved by re-scanning on different scanners, increase the number of MBBs audited for this contest. If needed, this escalation may result in a complete handcount of the contest across all MBBs. If this doesn't resolve the discrepancy (i.e., total discrepancies be within $\lceil 0.5\% \rceil$) then consider reinstalling the Ballot Now Trusted Build, re-scanning and re-tallying.

Investigate Tally Differences

- When the election night resolutions and the hand count resolutions are identical yet Tally shows different election results, you have to suspect Tally or the MBB. Inspect the MBB to see if there was a fault writing to it. In diagnosing this, see if Tally can “recover” the MBB.
- As a last resort, securely archive the Tally hardware and software for later scrutiny and, with SOS support, re-run the tally of all MBBs on a different, trusted Tally system. Compare the election results from the trusted Tally against the hand counts.

18. [Election Staff] Audit Report

The election staff will prepare the audit report and publish it to the public.

Using the NEGEXP audit procedure for variable-sized precincts.

1. [**Gather data**] Determine n , the number of precincts, and v_i , the number of votes cast in precinct i , for $1 \leq i \leq n$. Let r_{ij} denote the number of (electronic) votes reported cast for candidate j in precinct i .
2. [**Tally electronic votes**] Let R_j denote the total number of (electronic) votes reported cast for candidate j . Let j_1 denote the candidate with the largest reported vote count, and let j_2 denote the runner-up. Determine M , the overall margin of victory in the electronic tallies: $M = R_{j_1} - R_{j_2}$.
3. [**Choose audit parameters**] Choose a value for s , the assumed maximum within-precinct-miscount (e.g. $s = 0.20$). Choose a value for α , the significance level desired for this audit (e.g. $\alpha = 0.05$).
4. [**Compute error bounds**] For $1 \leq i \leq n$: Determine the error bound for precinct i :

$$e_i = \min(2sv_i, M, v_i + r_{ij_1} - \min_j r_{ij}) .$$

(It is OK just to use the first term, so that $e_i = 2sv_i$.) Also compute the total error bound: $E = \sum_{1 \leq i \leq n} e_i$. (Check that $M < E$; if not, then let $s = (M + 1)/2V$ and repeat this step.)

5. [**Determine per-precinct selection probabilities**] Determine the probability of auditing each precinct:

$$p_i = 1 - \alpha^{e_i/M} \quad \text{for } 1 \leq i \leq n .$$

6. [**Select precincts to be audited**] For each precinct P_i , determine whether to audit it as follows:
 - (a) Roll four decimal dice to obtain four decimal digits d_1, d_2, d_3, d_4 ; combine them to obtain a fraction $x = 0.d_1d_2d_3d_4$ (so that $0 \leq x < 1$).
 - (b) If $x < p_i$, mark precinct P_i for auditing.
7. [**Audit selected precincts**] For each precinct P_i marked for auditing in the preceding step, hand-count its paper ballots to determine the actual number a_{ij} of (paper) votes for each candidate j .
8. [**Terminate or escalate**] If no significant discrepancies are discovered, terminate the audit and announce that no significant discrepancies were discovered. Otherwise, escalate the audit.

²⁰ Lifted from “On Auditing Elections When Precincts Have Different Sizes”, Aslam, Popa, Rivest.

Appendix C: Progress Report (12/01/2011 – 05/31/2012)
Reporting Period December 1, 2011 through May 31, 2012

On June 16, 2011, the Colorado Department of State (CDOS) hosted the Colorado Risk-Limiting Audit (CORLA) Kick-Off meeting. In attendance were CDOS staff, consultants, and representatives from the five Colorado pilot counties (Boulder, Denver, Eagle, Jefferson, Pitkin). Consultant Dr. Stark presented his work on risk-limiting audits, and the group drafted a road map for conducting risk-limiting audit tests for the 2011 Coordinated Election.

Throughout the 2011 summer, CDOS staff drafted Statements of Work for each participant, conducted conference calls with the participants, and engaged in agreements with consultants and counties.

Four of the five pilot counties were visited on August 22-23 by Dr. Stark and CDOS staff, Jerome Lovato and Danny Casias. The purpose of the visits was to observe how ballots are processed at each of the counties, and to identify the best way to a conduct risk-limiting audit test for the 2011 Coordinated Election. The counties' staff was also educated on risk-limiting audits.

Jerome traveled to San Luis Obispo, CA on September 12-13 to observe a pilot risk-limiting audit, which was conducted by Dr. Stark and a graduate student at UC-San Diego. A similar audit was to be conducted in Pitkin County for the 2011 Coordinated Election. However, the CORLA project experienced an unforeseen roadblock while plans were being made to conduct pilot tests at Eagle and Pitkin Counties. A dispute about ballot images being made available to the public temporarily halted the project. The dispute was resolved and pilot tests are scheduled to take place in mid-February 2012.

During this reporting period, CDOS expended \$1,435.31 in federal grant funds for CDOS staff to travel within the state and to San Luis Obispo, California. Approximately \$45,075 of State in-kind funds (for staff salaries) was also expended.

San Luis Obispo county Pilot Risk-limiting Audit Report

San Luis Obispo County (SLO) in California tabulated 10,689 ballots for a local election that occurred in September 2011. SLO tabulated the ballots using Premier Central Count Optical Scanners and GEMS software. (This is the same equipment used in several Colorado counties, including Pitkin County.)

After scanning the ballots into the Premier scanners, SLO election officials scanned the 10,689 ballots in 200-ballot batches using a Kyocera 420i copier/printer/scanner. The scanned images were sent to the graduate student at UC-San Diego who used software he had developed to obtain the cast vote records of the scanned ballots.

Two races were audited in the SLO election; the margin of victory for both races was about 45%. By law, California counties are required to report to the Secretary of State the results of a 1% manual tally conducted after each election. SLO had to manually tally approximately 107 ballots to meet the requirement. Conversely, SLO had to audit 16 ballots for the risk-limiting audit (based on the formula $7/.45$ [margin of victory]).

Interested parties were invited to view the risk-limiting audit process. With observer participation, Dr. Stark obtained an 8-digit random number which was used as a seed for a random number generator to randomly select 16 ballots. Once a ballot was selected, the observers were able to view the ballot and the cast vote record associated with the ballot. No mistakes were found in the review of the ballots.

It is expected that Colorado will be able to implement a similar pilot audit in Pitkin County.

Appendix D: Progress Report (05/23/2011 – 11/30/2011)
Reporting Period May 23, 2011 through November 30, 2011

Work on the risk-limiting audit in Colorado came to a brief halt in the fall of 2011. This roadblock was a result of a dispute about ballot images being made available to the public under the Colorado Open Records Act (CORA). This issue was eventually resolved by the passing of Colorado House Bill 12-1036.

After the aforementioned delay, the SOS began researching alternative solutions for performing a risk-limiting audit in the pilot counties. The SOS wanted a solution that would: 1) reduce the time that the county spent on conducting their post-election audit, and 2) provide ease of use. At the recommendation of Dr. Philip Stark, the SOS began talks with the Clear Ballot Group.

On March 12, 2012, the SOS and representatives from three of the five pilot counties (Boulder, Denver, and Jefferson) traveled to Tallahassee, FL to observe a risk-limiting audit conducted by the Clear Ballot Group at the Leon County Election Department. The representatives drafted a report of their visit (attached).

The SOS drafted a revised project roadmap to implement a risk-limiting audit for the 2014 General Election. The SOS will conduct meetings with the pilot counties and consultants during the risk-limiting audit test preparation period (summer and fall of 2012). The SOS and pilot counties will conduct tests after the 2012 General Election.