Automating Data Acquisition on a Mechanical Equal-Arm Balance Used in Large Mass Calibrations

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Abstract

This paper focuses on efforts by the Mass and Force Group at the National Institute of Standards and Technology (NIST) to enhance the data taking operations of an approximately 40 year-old mechanical two-pan equal-arm balance used for high-precision mass comparisons in the range from approximately 50 kg to 1134 kg (110 lb to 2500 lb). The repeatability and sensitivity of this manually operated balance (called the Russell balance) has not been found to be matched or surpassed by current digital comparator technology. Therefore, the balance remains a core component of the NIST large mass laboratory. In order to enhance the data taking procedure and reduce the potential uncertainties inherent with human involvement in the data collection process, an automated system was designed and installed to obtain the turning points of the balance taken during calibration that ultimately are used to convert scale units to SI mass units. This paper discusses the advantages of the improved system, the challenges that had to be overcome, and the design, operation, and verification of the automated system.

1. Introduction

As part of the mission of the NIST Mass and Force Group, the Mass section has the responsibility of disseminating the SI unit of mass to its customers, with calibration services that span a range from 1 mg to 30 000 kilograms. While NIST uses digital mass comparators for calibrations of artifacts up to approximately 50 kg, digital comparator technology has yet to meet or exceed the repeatability and sensitivity of NIST's mechanical balances beyond the 50 kg threshold. While this paper discusses equipment used only in the range from 50 kg to 1134 kg, there is the potential for future application of the system to that equipment used in calibrations performed at NIST up through 30 000 kg.

The mechanical two-pan equal-arm balance used at NIST for high-precision mass comparisons in the 50 kg to 1134 kg range is called the Russell balance[1] and has been in service for more than 40 years. Section 2 provides an overview of the Russell balance, discusses how measurements are manually performed, and gives insight as to the reasons for automating these measurements.

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[1] Certain commercial equipment, instruments, software, or materials are identified in this paper. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Section 3 outlines the automated approach to taking data on the Russell balance and the advantages to doing so. Section 4 compares the results computed, using data sets acquired simultaneously by the traditional "manual" method and the overlaid automated data acquisition system, prior to putting the new system into service. Section 5 summarizes with conclusions and explores adapting the system to NIST's largest mechanical balance. The purpose of this paper is to describe a new way to take measurements on an existing balance that reduces the uncertainties inherent in the current level of human interaction in the data-collection process while preserving the desirable qualities of these types of mechanical balances. Refer to the publications listed in the references (Section 7) for more detail and discussion regarding the intricacies of mass calibrations and general mass metrology [1-3].

2. Overview and Operation of the NIST Russell balance

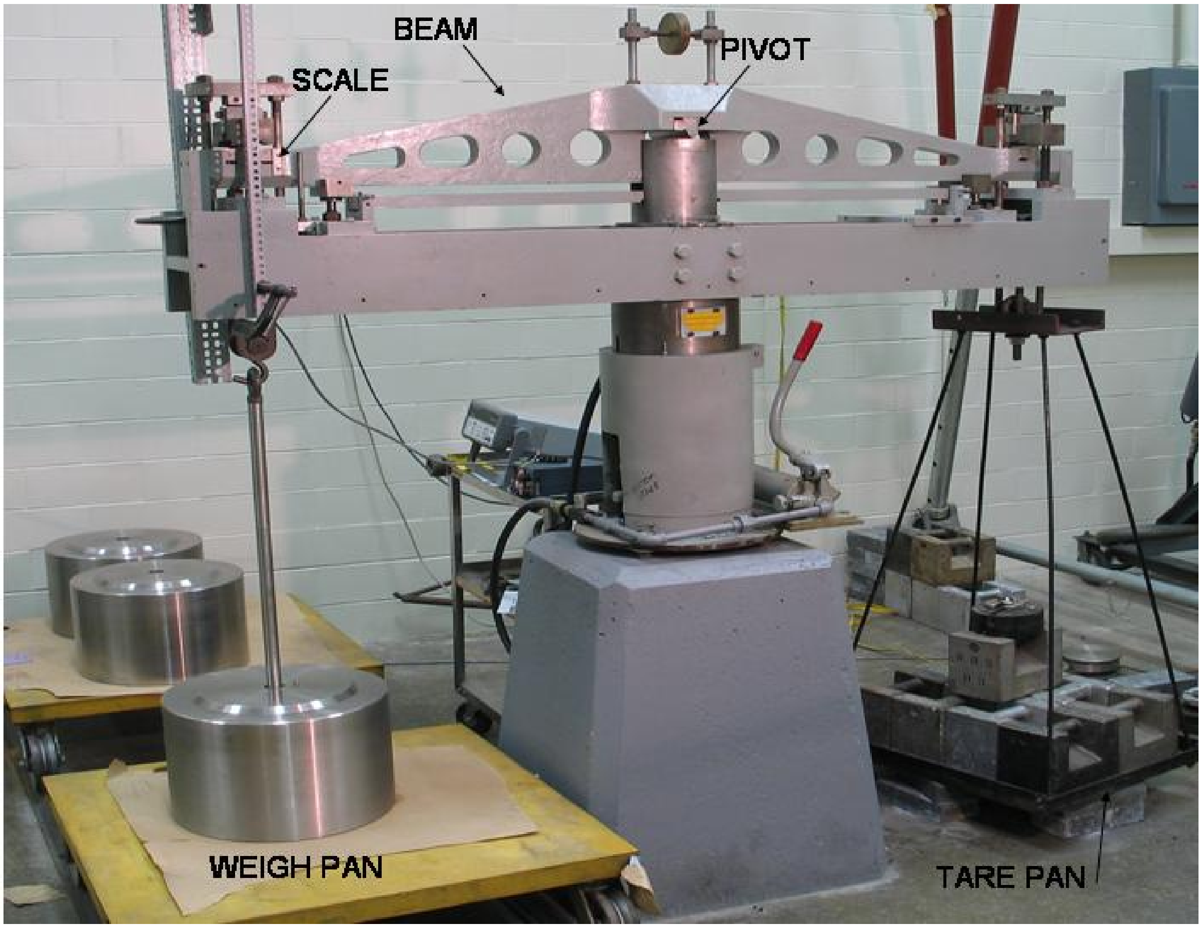


Figure 1. Photograph showing the Russell balance with a 226.8 kg (500 lb) stainless steel weight on the weigh pan.

The Russell balance is a mechanical two-pan equal-arm balance used for high precision mass comparisons. To setup and use the balance as a comparator, one pan (sometimes called the tare pan or the counterpoise) of the balance is loaded with enough counterweight to match (or balance) the opposing pan (weigh pan) which is interchanged between reference standards and a weight for which a mass value will be assigned, sometimes called the unknown (see figure 1).

The beam when properly balanced will oscillate (or pivot up and down) about the center knife edge and will eventually come to rest after a potentially long time interval. The damping of the beam oscillation is usually quite slow since there is minimal friction through the knife edges of the balance. Therefore, in order to determine a deflection (or reading) from the balance as it is performing this oscillating motion, one can read the magnitude of these oscillations with a pointer indicating on a scale (located on the fixed frame of the balance) as the end of the beam travels up and down in the vertical plane (see figure 2). Rather than wait for the beam to come to rest and taking a static reading on the scale (which likely wouldn't be prudent anyway due to friction sticking), it is more practical and accurate to record the highest and lowest readings of the beam travel while the beam is changing direction during it's oscillation. These peak readings are referred to as turning points. Once the swing is induced, the operator usually waits at least one complete oscillation before beginning to record turning points. As turning points are recorded, the operator must ensure that the points are valid by determining if the balance is in "decay," meaning the amplitude of the oscillation is getting smaller (or converging to the final resting place). Sometimes the balance will accelerate (meaning the last top reading was greater than the previous top reading for example) and requires the discarding of these points and waiting until the balance renders a consistent pattern of decay. Once valid turning points are taken, the operator then takes consecutive Bottom Top Bottom (BTB) readings (or Top Bottom Top readings (TBT)) and averages the two Bottom readings (or two top readings if TBT) and adds it to the reading taken in between. The result is then divided by two and is called the computed mean. Enough valid turning points are taken to ensure that at least three computed means are calculated. The computed means are averaged to obtain the final average computed mean (where the balance would stop if left to decay long enough).

At NIST, mass comparisons in this range are generally performed using the "double substitution" method that entails a comparison between a reference mass and an unknown mass and requires the use of a sensitivity weight [1]. The purpose of the sensitivity weight is to measure the scale deflection per unit mass, or in other words relate scale units to mass units. During setup, with the unknown placed on the weigh pan, the beam oscillation is adjusted to keep the pointer "on scale" by adjusting the counter mass on the tare pan. The sensitivity weight, which is a small reference weight, is then added to the weigh pan to ensure that even with the increased deflection due to the additional mass, the turning points remain "on scale." After these initial adjustments of the tare pan resulting in an average computed mean somewhere near the scale's midpoint, no additional adjustments are made to the tare pan for the rest of the comparison process. Each double substitution comparison requires four weighings on the balance. Additionally, a weighing design is chosen that incorporates a series of these difference measurements that, by fixing the value of the reference standard, allows one to solve for the mass of the unknown by using the method of least squares [4]. These methods were developed at NIST by Cameron et al. in 1979. A full description can be found in Ref. [4]. The weighing design used throughout this paper is referred to as a "3-1" indicating that it involves three masses of equal nominal mass. In this design, the third mass used in the comparison is another reference standard called a "check standard" and it is treated as an unknown (meaning in this case that the mass value is not fixed in the calculations).

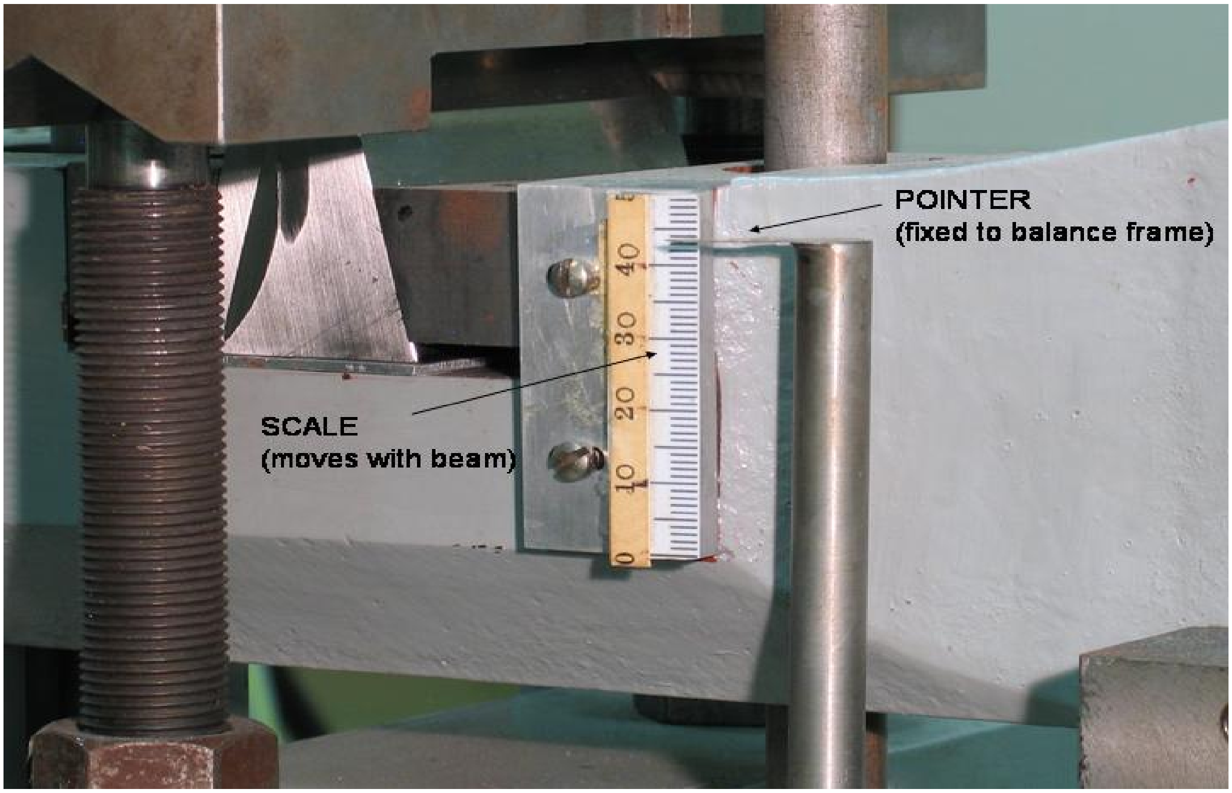


Figure 2. Photograph showing the detail of the scale/pointer assembly that is used when manual measurements are taken.

Once all masses being used in the weighing design are adjusted to produce “on scale” readings, the operator can then execute the proper sequence of the weighing design by interchanging, on the weigh pan, the unknown, the reference standard, the check standard, and all combinations with sensitivity weights.

As one can see, the process for one comparison involves numerous time consuming measurements. For example, a typical 3-1 weighing design will require twelve changes to the weigh pan, meaning that there are twelve separate average computed means recorded (requiring about 100 turning points all together). Additional time is needed for changing weights, hydraulically raising or lowering the balance, changing lifting hardware, etc. Operators cannot be interchanged during this comparison to avoid possibly introducing an operator bias due to different operator stance, height, optical characteristics, and operating convention. Therefore, the operator can suffer fatigue and eye strain and actually introduce a bias due to becoming restless and changing body stance which ultimately affects the optical alignment of the eyes with the scale (parallax due to changing lens location). A misread reading and/or changing posture of the operator can lead to poor repeatability and/or increased standard deviations in the readings. Additionally, all measurements are hand written during this procedure, increasing the odds of a transcription error and the possibility that the measurements could have to be repeated.

3. Automating the Reading of Turning Points

A solution to the aforementioned problems regarding manual measurements has been accomplished by removing the human aspect of physically reading the scale. An automated system was designed and installed on the balance using a laser measurement sensor to determine the turning points of the balance. A picture of the laser sensor setup is shown in Figure 3. The sensor applies the principle of triangulation and uses a laser beam reflected off of the top knife edge assembly near the end of the beam to relate the displacement of the beam relative to the fixed sensor, much like the mechanical pointer. However, the same beam displacement is correlated to an analog voltage that can be read at a much higher resolution and more consistently than one could achieve manually by eye. For example, the manual process using the scale and pointer divides the vertical travel of the balance into approximately 300 divisions (the scale shown in Figure 2 is only usable between 10 and 40 due to mechanical stops). On the other hand, in addition to having a better resolution, the laser sensor is located slightly further out on the beam and gains some additional travel in its measuring range. Therefore, the laser sensor can divide the measuring range into about 1600 divisions, a significant improvement in resolution over the manual system.

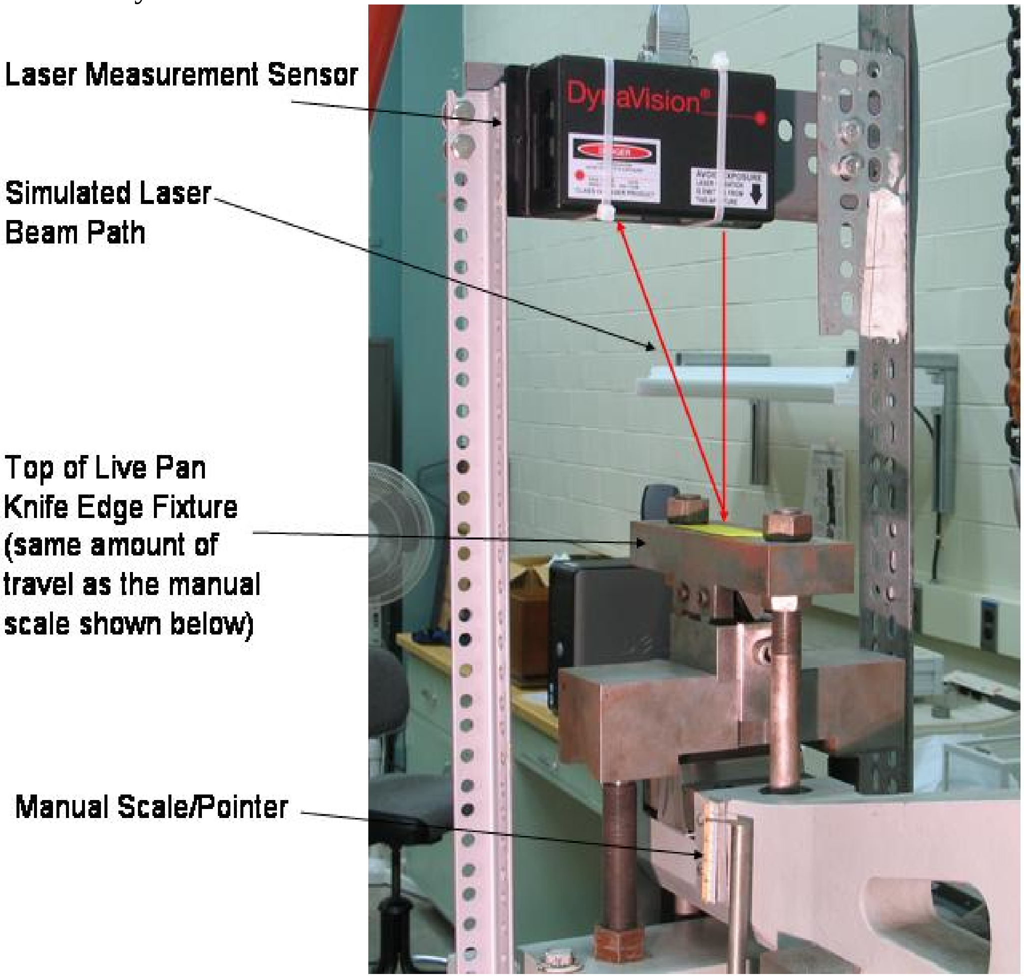
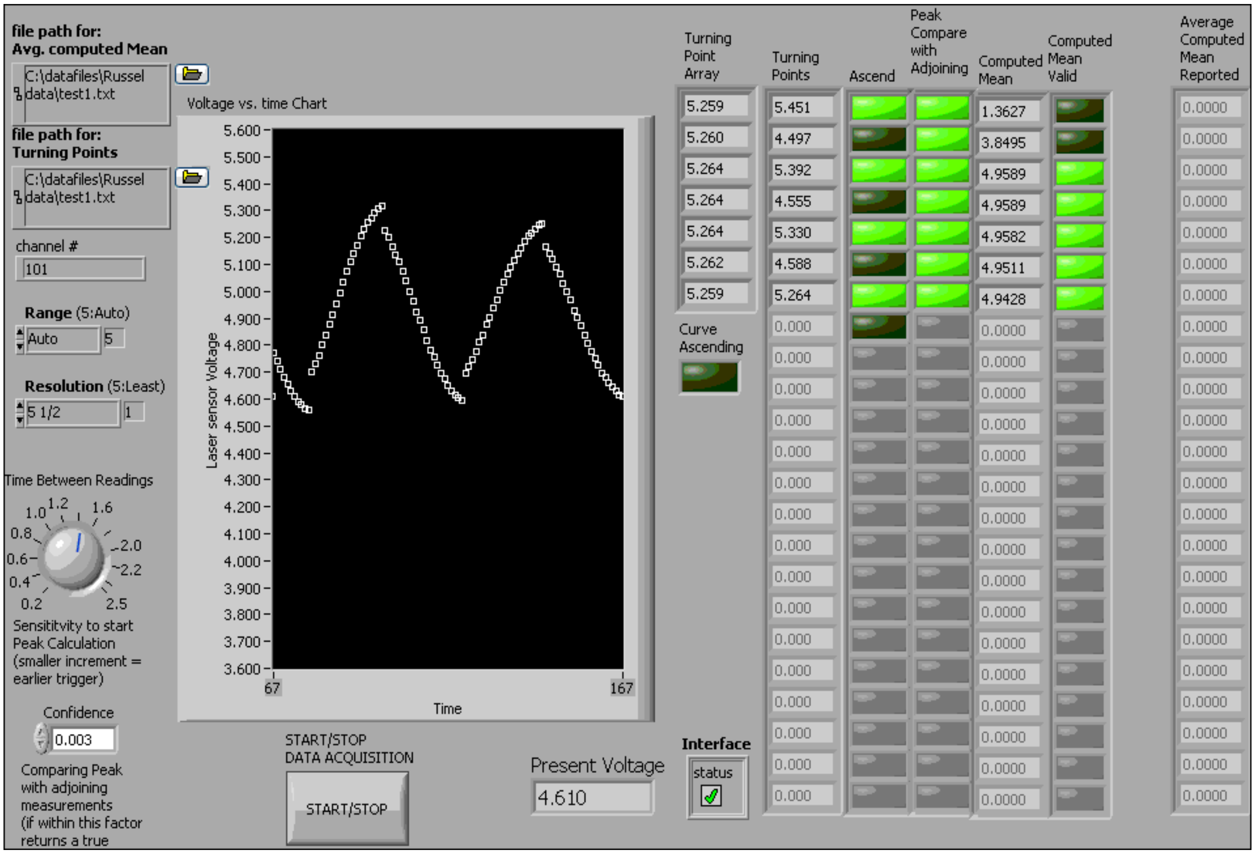


Figure 3. Photograph showing the laser measurement sensor with simulated laser beam path. As the balance beam oscillates up and down, the laser measurement sensor triangulates the height (correlated from a DC voltage) from the fixed sensor to the moving balance beam.

The sensitivity weight is still used to correlate the scale units to mass units, in this case to correlate a voltage to mass units. The laser measurement sensor is a DynaVision Model SPR04. A standard 15 Volt DC power supply is used to power the laser while the analog output voltage is read by an Agilent 34970 Data Acquisition and Control Unit containing a precision 5-1/2 Digit Digital Multi-Meter (DMM) capable of adequately reading the resolution of the sensor which is 1 mV. The digital signal is then read by a laptop running a LabView program communicating through a National Instruments Universal Serial Bus (USB)/General Purpose Interface Bus (GPIB) interface.

In order to determine the turning points using this system, the operator uses a LabView program to take voltage readings from the sensor as the beam is oscillating. The time between readings of the voltage is adjustable by a control on the user interface of the program (See Figure 4). This allows the operator to find a sufficient reading rate based on how fast the beam is traveling (which has been found to vary under different load conditions). The program then determines if the beam is ascending or descending by comparing the current reading with the previous. As the beam loses momentum and nears a direction change (turning point), the voltage measurements do not change nearly as much. When this condition occurs, the LabView program triggers the DMM to take voltage measurements at a very high rate (50 readings per second) throughout the period while the balance is changing direction. From this group of readings, the program determines the maximum/minimum (depending on which direction the beam is traveling) and uses that peak value as the turning point. To ensure no errant peak readings were recorded, the program compares the peak reading to several of the adjoining readings taken on both sides of the peak to see if they agree within a specified amount. If it exceeds the prescribed amount, the program determines that the turning point is invalid and does not use it in calculating a computed mean. Additionally, as more turning points are gathered, the program determines whether the balance is in proper decay, hence whether the turning point can be used in calculating a valid computed mean. When the program determines that it has had three consecutive valid turning points, the computed mean is calculated and displayed. The operator then can simply watch the screen and determine when enough valid computed means are acquired (usually three) and can stop data acquisition at this point. Another screen then appears allowing the operator to choose which valid computed means are to be used in calculating the average computed mean for that measurement. The average computed means are then stored in a separate file for incorporation into the final mass calculations which eliminates the need to manually transcribe the data. While the operator still needs to be an active part of the data acquisition process and still must manipulate the balance and weights, the strain of staring at a scale for several hours, calculating means on the fly, and properly recording data, is now eliminated and the likelihood of having to repeat measurements is greatly reduced.



file path for:
Avg. computed Mean
C:\datafiles\Russel data\test1.txt

file path for:
Turning Points
C:\datafiles\Russel data\test1.txt

channel # 101

Range (5:Auto) Auto 5

Resolution (5:Least) 5 1/2 1

Sensititvity to start Peak Calculation (smaller increment = earlier trigger)

Confidence 0.003

Comparing Peak with adjoining measurements (if within this factor returns a true

Present Voltage 4.610

status ☑

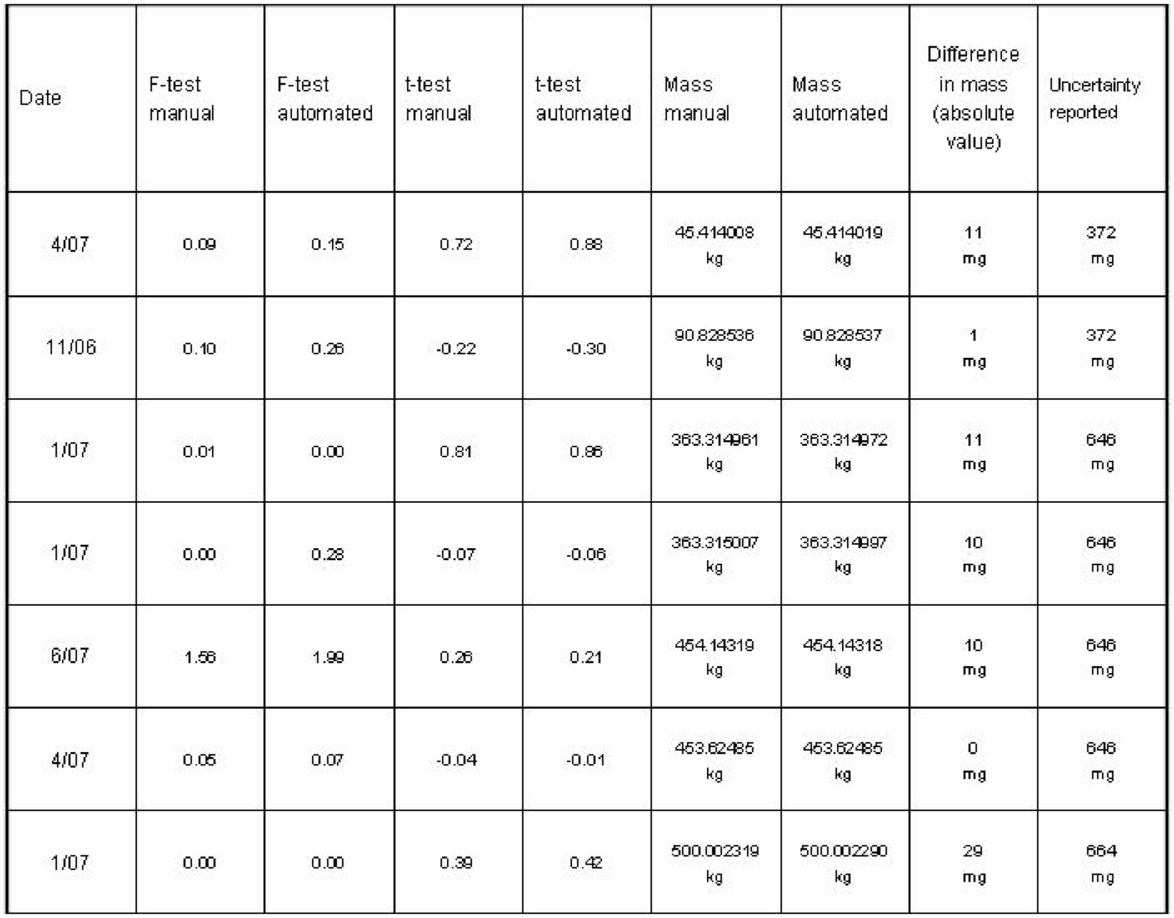
Turning Point Array	Turning Points	Ascend	Peak Compare with Adjoining	Computed Mean	Computed Mean Valid	Average Computed Mean Reported
5.259	5.451	🟩	🟩	1.3627	■	0.0000
5.260	4.497	■	🟩	3.8495	■	0.0000
5.264	5.392	🟩	🟩	4.9589	🟩	0.0000
5.264	4.555	■	🟩	4.9589	🟩	0.0000
5.264	5.330	🟩	🟩	4.9582	🟩	0.0000
5.262	4.588	■	🟩	4.9511	🟩	0.0000
5.259	5.264	🟩	🟩	4.9428	🟩	0.0000
	0.000	■	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000
	0.000	□	□	0.0000	□	0.0000

Figure 4. Snapshot of LabView program that controls the data acquisition and calculates the turning points, computed means, and the average computed mean. Note: Chart does not show what one may expect as the typical sine wave due to the program not updating the chart while the high speed acquisitions of the turning point data are being gathered.

4. Validation and Verification of the Automated System

The automated system did not require any changes to the mechanical readout system that was already in place. Therefore, verification of the automated system could easily be done by direct comparison with manual data taken concurrently under identical conditions. Numerous comparisons were completed in this manner using a 3-1 weighing design. The results of the comparisons can be seen in Table 1.

Table 1. Results showing comparisons between the manual method and the automated method. Automated and manual data were taken simultaneously for each individual comparison using a 3-1 weighing design.



Date	F-test manual	F-test automated	t-test manual	t-test automated	Mass manual	Mass automated	Difference in mass (absolute value)	Uncertainty reported
4/07	0.09	0.15	0.72	0.88	45.414008 kg	45.414019 kg	11 mg	372 mg
11/06	0.10	0.26	-0.22	-0.30	90.828536 kg	90.828537 kg	1 mg	372 mg
1/07	0.01	0.00	0.81	0.86	363.314961 kg	363.314972 kg	11 mg	646 mg
1/07	0.00	0.28	-0.07	-0.06	363.315007 kg	363.314997 kg	10 mg	646 mg
6/07	1.56	1.99	0.26	0.21	454.14319 kg	454.14318 kg	10 mg	646 mg
4/07	0.05	0.07	-0.04	-0.01	453.62485 kg	453.62485 kg	0 mg	646 mg
1/07	0.00	0.00	0.39	0.42	500.002319 kg	500.002290 kg	29 mg	664 mg

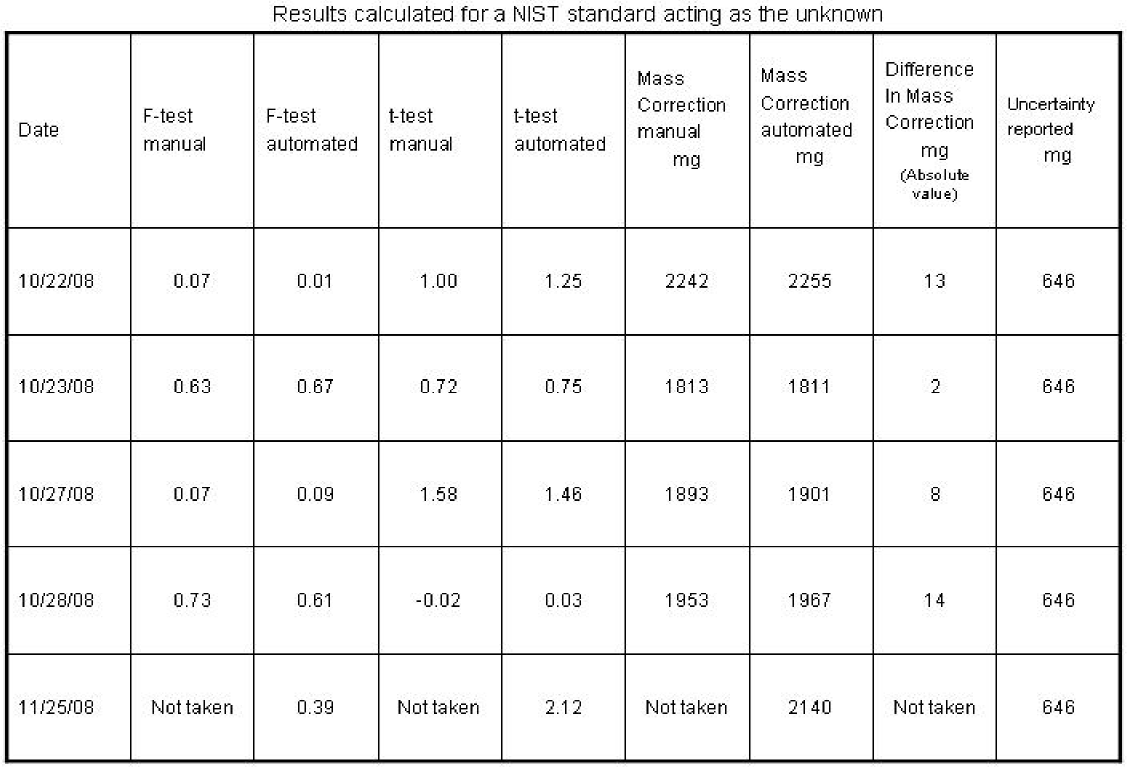
As indicated in the table, verification was performed using the same statistical tests (metrics) and by direct comparison of the mass and uncertainties calculated from each correlating set of data. Briefly, one metric used is the "F-test" or "F-ratio" which is used to analyze balance performance during a comparison (more detail can be referenced in [1]). Basically, the standard deviation of the current data set is checked for consistency with the long-term standard deviation of the balance at a 95 % confidence interval (k=2). Therefore, if the automated data compares well with the manual data in each test, then it is safe to assume that it agrees with the long-term performance of the balance. The magnitude of the difference between the automated and manual data for the F-test is small (average = 0.14) and establishes that the data collected using the automated system is consistent with that collected using the manual system and also is in statistical control with the long-term history of the balance.

A second statistical check used to help verify the automated system is the "t-test" (more detail can be referenced in [1]). Each comparison uses at least two standards in addition to the unknown. One reference standard (the "restraint") is used to calibrate the unknown and also the remaining reference standard (check standard). The newly derived value for the check standard is then compared to the long-term average of the check standard. Any statistically significant difference in the two values usually indicates a physical change in one (or both) of the standards or, more commonly, there was an error made during the comparison. The average t-value difference between the automated and the manual data is 0.05 and further indicates that the automated system is consistent with the manual system.

The last check used to verify the automated system was by directly comparing the calculated mass and uncertainty of the unknown as derived by both methods. As can be seen in Table 1, the differences in the calculated masses are at a minimum of 23 times smaller than the uncertainty in the measurement itself with an average of 104 times smaller (or about 1.8 % of the measurement uncertainty). The magnitude of these differences provide the last step in confirming the precision, consistency, accuracy, and the validation of the automated system in comparison to the manual system.

Additionally, repeatability and reproducibility comparisons were completed in a 3-1 weighing design that used several NIST stainless steel reference standards. The comparison was repeated over several days using the same identical weights, weighing design, and setup. Results of the repeatability tests are shown in Table 2.

Table 2. Repeatability/Reproducibility test using NIST stainless steel reference standards in a 3-1 weighing design.



Results calculated for a NIST standard acting as the unknown

Date	F-test manual	F-test automated	t-test manual	t-test automated	Mass Correction manual mg	Mass Correction automated mg	Difference In Mass Correction mg (Absolute value)	Uncertainty reported mg
10/22/08	0.07	0.01	1.00	1.25	2242	2255	13	646
10/23/08	0.63	0.67	0.72	0.75	1813	1811	2	646
10/27/08	0.07	0.09	1.58	1.46	1893	1901	8	646
10/28/08	0.73	0.61	-0.02	0.03	1953	1967	14	646
11/25/08	Not taken	0.39	Not taken	2.12	Not taken	2140	Not taken	646

The same metrics for examining the data are used for this comparison, keeping in mind that one of NIST's stainless steel standards is acting as the unknown. As can be seen in Table 2, the F-test and t-test comparisons indicate that the automated and manual data are consistent and in statistical control. Table 2 also shows that the differences in the calculated mass corrections (from a nominal mass) are at a minimum of 46 times smaller than the uncertainty in the measurement itself with an average of 125 times smaller (or 1.4 % of the measurement uncertainty). Additionally, the last line of the table only shows data taken by the automated system because no manual readings were taken during this comparison.

5. Conclusions

The automated data gathering system for the Russell balance is a marked improvement to the data taking procedure for this mass measurement range. It improves the operator efficiency and comfort as well as eliminating many human factors in the measurement process. Thus, the possibility of introducing random uncertainties inherent with human data-reading/logging are reduced without compromising the advantages of mechanical balances used in these weight ranges. Although the balance characteristics limit a large gain in repeatability from the increased sensitivity of the laser sensor, the system shows enough benefits to warrant possible adaptation to the NIST 30 000 kg balance, a single beam balance that incorporates reading turning points as well.

6. Acknowledgments

The author gratefully acknowledges valuable input and direction from Dr. Zeina Jabbour and Mr. Brian Scace of the NIST Mass and Force Group.

7. References

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