ASSESSING THE ACCURACY OF THE PHOTO FINISH: AUTOMATIC TIMING ANDROID APP

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Abstract

This study presents an in-depth evaluation of Photo Finish: Automatic Timing [1], an innovative sports timing app developed for Android smartphones. The primary focus was on assessing the accuracy of this system for various starting modes and a wide array of different phone models. We also included a comparison with an ordinary light barrier system, where Photo Finish demonstrated significantly higher accuracy due to its chest detection algorithm. In all tested configurations, three-quarters of all measurements of Photo Finish were accurate within 10 milliseconds or less. Furthermore, 95% of the measurements fell within a 15-millisecond margin, and all recorded times were consistently within 20 milliseconds of the times obtained through manual video evaluation. Thus, we conclude that the Photo Finish system offers a highly accurate, cost-effective, and accessible solution for timing in sports, demonstrating an accuracy level of less than 0.02 seconds under the test conditions.

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1 Introduction

Photo Finish: Automatic Timing is a smartphone application designed to meet the demands of accurate timing in various sports. The app leverages the capabilities of modern smartphones to offer a practical yet sophisticated solution for measuring sports performance.

Photo Finish performs automatic detection of the exact position of the athlete's chest, using the phone's camera. This approach aims to address the timing inaccuracies commonly found in traditional systems such as light barriers, which may be inadvertently triggered by non-target parts of an athlete's body like the knee or hands.

The focus of this study is to rigorously evaluate the accuracy of the Photo Finish app. Through a series of multiple experiments, we aim to establish not only its effectiveness in accurate timing but also to compare its precision against a commercial light barrier system, the SpeedTech S-003 Wireless Laser Timing System [2].

1.1 Setups

Four distinct experiments have been selected for their direct relevance to real-world applications. These scenarios were chosen due to their common occurrence in training for competitive sports and their ability to provide a comprehensive evaluation of the timing app's accuracy across a range of setup conditions. The tests were conducted on a track and field course during daylight to ensure optimal lighting conditions for Photo Finish.

1. 30-meter flying sprint
   A common test in athletics is to measure an athlete's top-end speed. The corresponding test setup is explained in *2.1.*

2. 40-yard dash without reaction time
   The 40-yard dash is a staple in evaluating an athlete's acceleration and speed, particularly in sports like American football. This test, incorporating reaction time, is pivotal in assessing an athlete's quickness off the mark. The corresponding test setup is explained in *2.3*.

3. 40-yard dash with touchpad trigger.
   In this variation of the 40-yard dash, the start is triggered the moment the athlete lifts his thumb from a starting touchpad. The corresponding test setup is *Touch Start with two connected phones*.

4. 100m sprint with a start gun
   The 100-meter sprint, often initiated with a start gun, is a quintessential track event testing an athlete's explosive speed and endurance. The corresponding test setup is *Sound Detection Start with two connected phones*.

1.2 Phone Pairings

Additionally, we intend to demonstrate that Photo Finish operates with precision across a diverse range of smartphones, including cheaper ones. Therefore, for each of the four experimental setups, seven different phone pairings were chosen from the following list of 12 different phone models:

Manufacturer	**Model**
Samsung	Galaxy S20 FE
Samsung	Galaxy S8
Samsung	Galaxy A52
Huawei	P30 Pro
Huawei	P30 Lite
Huawei	P8 Lite
Google	Pixel 3 XL
One Plus	Nord CE2
Xiaomi	Poco
Xiaomi	Redmi Note 9s
Cubot	Note 20 Pro
Realme	C3

2 Analysis Setup

In each of the setups discussed in this chapter, we tested seven phone pairings. For every pairing, 8 measurements were conducted, totaling 4x7x8 = 224 individual measurements. In Flying Start Mode, we also compared Photo Finish against a commercial light barrier timing system, the SpeedTech S-003 Wireless Laser Timing System [2], for which we also determined the measurement error.
The study was performed on two consecutive days. Two male test subjects aged 30 and 32 alternated in performing the runs for the required measurements. We used Version 3.3.1 of Photo Finish: Automatic Timing which was installed on all phones before the experiments. The tests were conducted from around 11 am to 4 pm with overcast weather intermixed with occasional sunshine.

To analyze the experiments, we used a high-speed smartphone camera capable of continuous audio and video capture at 240 frames per second to analyze the Photo Finish app's performance. On day two of the study, we also adjusted the font size on the phones to be extra large, ensuring that the times recorded by Photo Finish were visible in the high-speed camera's video feed. This enables interested readers to independently verify the measurements using the original video material which can be requested via email. The video footage was then analyzed using the Da Vinci Resolve Video editing software [3].

Note that the Start and Finish Phones are close by in the setups described below. In practical scenarios, they would typically be placed further apart, such as in a 30m flying sprint test. However, for this experiment, we positioned the Start and Finish Phones on the same line to allow for the use of a single high-speed camera that captures both the start and the finish of each run. This arrangement does not impact the app's precision, as the times are transmitted over the internet and the phones synchronize their clocks upon initial connection. Further technical details are discussed in Section 3.

The alignment of the whole setup for Photo Finish, the laser timing system, and the camera evaluation was thoroughly checked to allow for a measurement accuracy of one millisecond. The alignment was rechecked after every phone swap.
This means, that at an expected speed of 5m/s or higher of the passing test subjects, the laser beam must be aimed precisely perpendicular to the track and the end of the laser beam and may deviate at most 5m/s * 1/1000 s = 5mm from the exact middle at both ends. To be able to precisely determine the vertical plane of crossing on the high-speed camera image, a rectangular wooden triangle was constructed and placed in the background at the measurement line (Figure 1).

The camera has a resolution of 1280x720 pixels at a 35° horizontal field of view. The total distance between the laser sensors is kept at 4m. This results in a theoretical timing resolution of the camera at a running pace of 5m/s or higher of

$$35/720 \ \times \frac{\pi}{180} \frac{4m}{5m/s} \approx 0.7ms$$

The almost perfectly linear movement of an athlete in 2 consecutive frames of 240fps video footage allows for frame interpolation from 240 to 1000fps using the built-in frame interpolation algorithm of The Da Vinci Resolve video editing software to allow for easy and precise analysis, see Figure 2:

Figure 1: Flying Start Measurement Setup. A wooden triangle is placed at the starting line to enable precise video analysis. Two timing gates are placed opposing each other on the same measurement line. An Additional Smartphone films the complete setup at 240fps for later video analysis.

Figure 2: 1000fps video analysis. The timestamp of the frame where the chest is exactly at the height of the wooden beam is evaluated for every run. The right 3 images show detail views 1ms before, at, and 1ms after the crossing, showing both the need for precise alignment of the equipment as well as the large influence of triggering on the legs or the arms when assessing runs with millisecond precision.

2.1 Flying Start Measurement Setup

The Flying Start mode in Photo Finish starts the clock when an athlete passes a starting phone after a runup and finishes when it passes the last measurement line. With additional phones, as many measurement points as desired can be added. This mode therefore allows for direct comparison with a laser timing system.
The experimental setup is depicted in Figure 3. For a single measurement, the test subject, acting as an athlete, runs past the ***Start Phone*** and the ***Start Light Barrier***, triggering the start of the timer. They then turn around and sprint past the ***Finish Phone*** and the ***Finish Light Barrier***, which stops the timer and completes the measurement.
We used the following seven phone pairings, with eight measurements per pairing (See Appendix 1):

Start Phone	Finish Phone
Samsung Galaxy S20 FE	Huawei P30 Pro
Samsung Galaxy S8	Huawei P30 Pro
Realme C3	Huawei P30 Pro
Xiaomi Redmi Note 9S	Huawei P30 Pro
Huawei P30 Lite	Google Pixel 3XL
Samsung Galaxy A52	Google Pixel 3XL
Samsung Galaxy S20 FE	Huawei P30 Pro

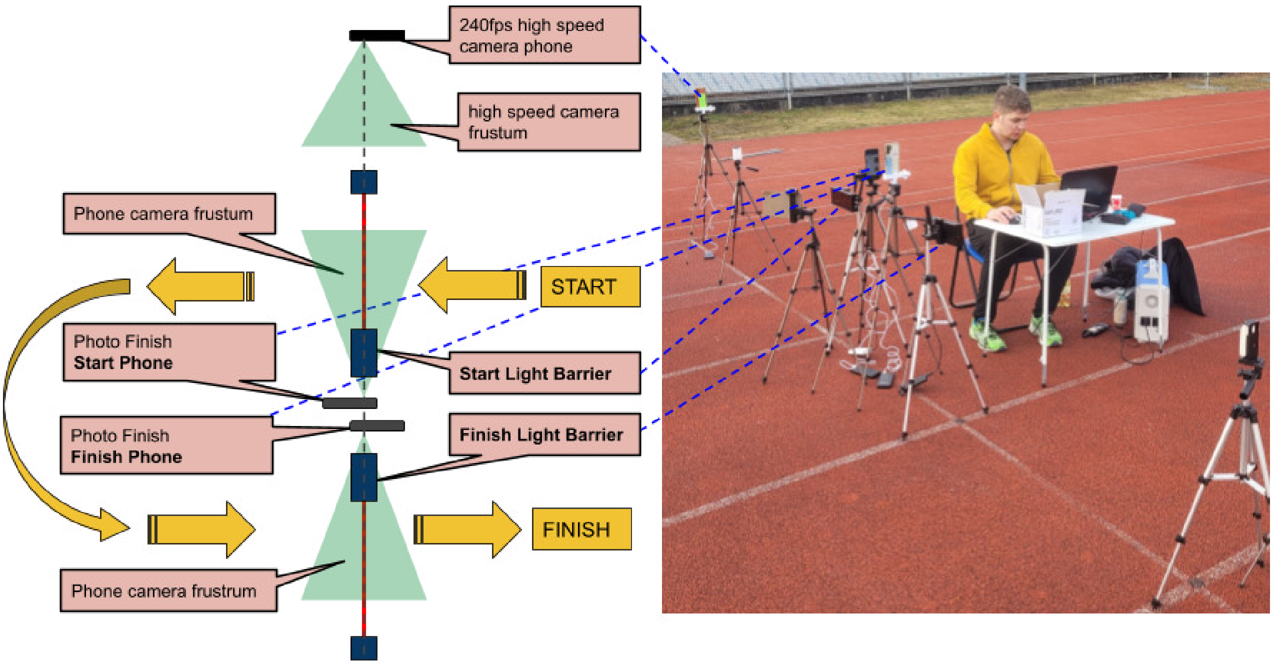

Figure 3: Two Smartphones are connected in Flying Start mode and placed back to back on a single line. The light barrier timing system is placed on the same line. The high-speed camera is also placed on the same line and aligned such that it can accurately monitor the passing of an athlete on both sides.

2.2 Touch Start Measurement Setup

Photo Finish's touch start mode allows for low start sprint measurements without reaction time, for example, the 40-yard dash. The athlete places his thumb on the phone and the timer is started as soon as the thumb is lifted from the touchscreen.
The setup for the Touch Start experiment is shown in Figure 4. In this test, first, a finger is placed on the touch screen of the ***Start Phone***. The measurement then begins once the touch screen is released by lifting the finger. The test subject then starts his run and the measurement once again concludes as he crosses the measurement line of the ***Finish Phone***.

We used the following seven phone pairings, with eight measurements per pairing (See Appendix 2):

Start Phone	Finish Phone
Samsung Galaxy S20 FE	Huawei P30 Pro
Samsung Galaxy S8	Huawei P30 Pro
Realme C3	Huawei P30 Pro
Xiaomi Redmi Note 9S	Huawei P30 Pro
Google Pixel 3 XL	Huawei P30 Pro
Samsung Galaxy A52	Huawei P30 Pro
One Plus Nord CE 2	Huawei P30 Pro

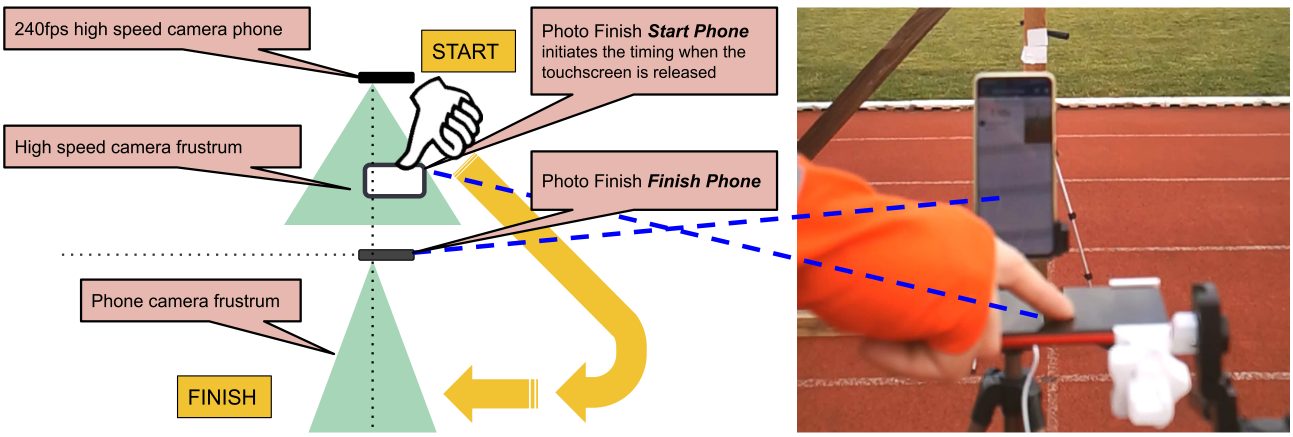

Figure 4: Two smartphones are connected in Touch Start mode. The Start Phone is mounted on a tripod within the field of view of the high-speed camera. This setup allows for precise determination of the moment when the finger is released from the screen. The Finish Phone is aligned along the same line as the high-speed camera.

2.3 Beep Start Measurement Setup

Photo Finish has several starting sequences that end with a 3 kHz beep sound initiating the start. This can either happen after a random delay ("Ready-Set-Go!" mode) to test the athlete's reaction or after a predictable fixed delay to eliminate reaction time ("3-2-1-Go!" mode). Photo Finish uses a beep signal instead of imitating a gunshot sound for two reasons: The small smartphone speakers are able to play a beep sound at a much higher volume, and the beep sound allows for frequency analysis of the microphone input to robustly determine the exact moment the sound was played independent of possible delays (i.e. through Bluetooth speakers) and loud wind noises.
The setup for the Beep Start experiment is shown in Figure 5. In this test, a single measurement begins with the press of the start button on the ***Start Phone***, which then emits a beep sound signaling the start of the run. The athlete runs past the ***Finish Phone***, at a distance of approximately 1.5 meters. The measurement concludes as the runner crosses the measurement line of the *Finish Phone*.

We used the following seven phone pairings, with eight measurements per pairing (See Appendix 3):

Start Phone	**Finish Phone**
Samsung Galaxy S20 FE	Huawei P30 Pro
Samsung Galaxy S8	Huawei P30 Pro
Huawei P8 Lite	Huawei P30 Pro
Xiaomi Redmi Note 9S	Huawei P30 Pro
Google Pixel 3 XL	Huawei P30 Pro
OnePlus Nord CE 2	Huawei P30 Pro
Xiaomi Poco	Huawei P30 Pro

Please note that the last measurement is missing for the Pixel 3 XL / P30 Pro combination due to an oversight.

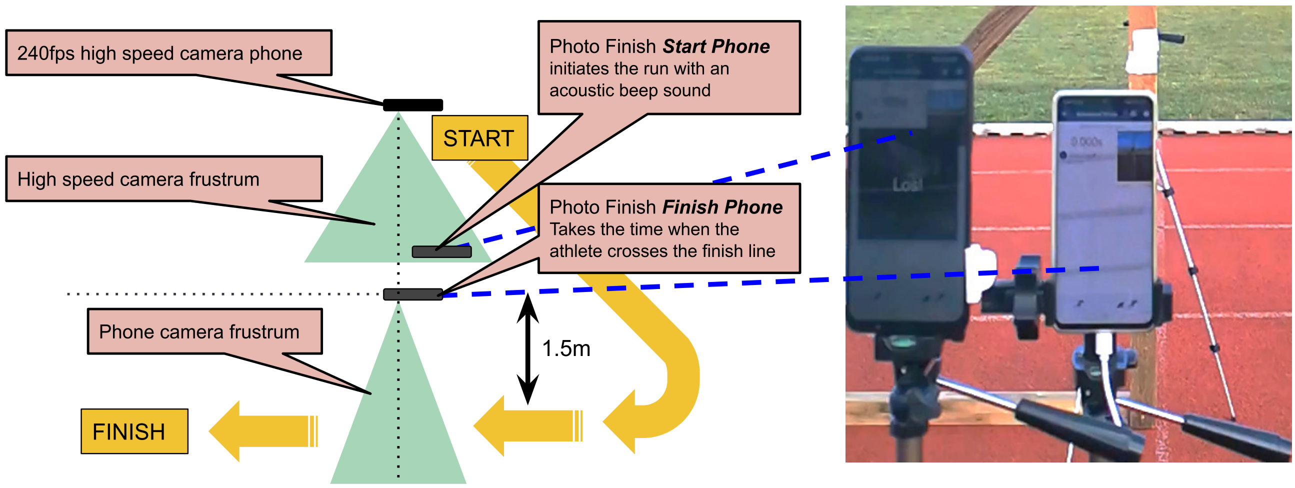

Figure 5: In Beep Start mode, two smartphones are connected. The Start Phone is placed within 0.5 meters of the high-speed camera, its specific location being less critical as long as it is close to the high-speed camera to make sound travel time irrelevant. The Finish Phone is aligned on the same line as the high-speed camera.

2.4 Sound Detection Start Measurement Setup

Photo Finish can also trigger on a loud external sound, such as a starting clapper, a starting gun, or simply a clap with the hands.
The setup for the Sound Detection Start experiment is shown in Figure 6. In this test, a single measurement begins when two metal rods are struck against each other. This emits a loud sound which is detected by the ***Start Phone***, which then starts the timer. The athlete then runs past the ***Finish Phone***, again at a distance of approximately 1.5 meters. The measurement concludes as the runner crosses the measurement line of the ***Finish Phone***, upon which it takes the final time.

We used the following seven phone pairings, with eight measurements per pairing (See Appendix 4):

Start Phone (Sound Detection)	Finish Phone
Huawei P30 Lite	Google Pixel 3XL
Samsung Galaxy S20 FE	Google Pixel 3XL
Xiaomi POCO	Samsung Galaxy S20 FE
Xiaomi Redmi Note 9S	Huawei P30 Pro
Huawei P30 Lite	Huawei P30 Pro
Huawei P30 Pro	Google Pixel 3 XL
Cubot Note 20 Pro	Google Pixel 3XL

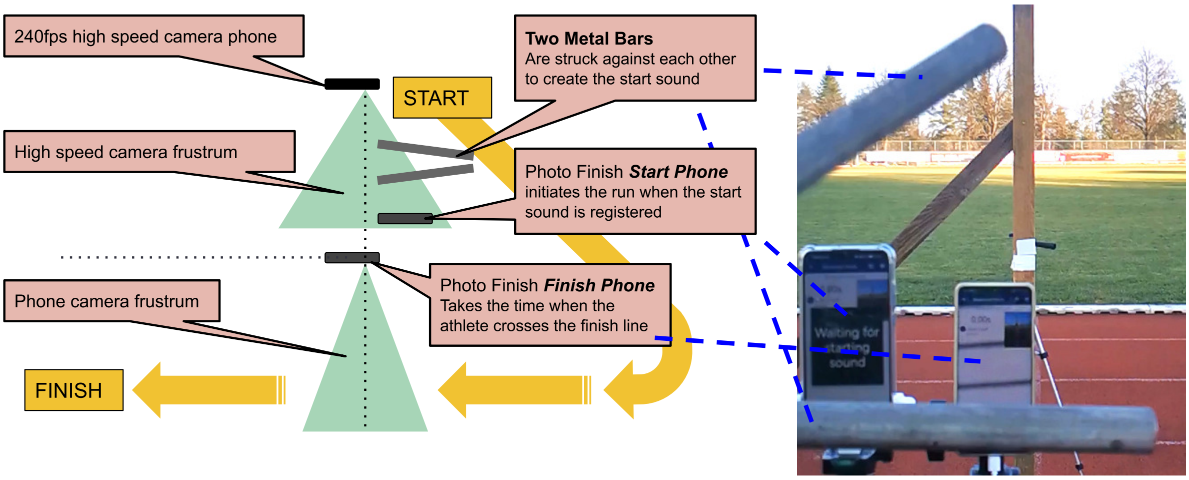

*Figure 6: In Sound Detection Start mode, two smartphones are connected. The **Start Phone** is placed within 0.5 meters of the high-speed camera, its specific location being less critical as long as it is close to the high-speed camera to make sound travel time irrelevant. The **Finish Phone** is aligned on the same line as the high-speed camera. To start a measurement, two metal bars are struck against each other. The emitted sound is detected by the Start Phone, which then starts the timer. The two metal rods also allow for a precise alignment of the audio and video tracks of the high-speed camera.*

2.5 Audio and Video Synchronization

For the analysis of the Beep and Sound Start modes, accurate audio and video synchronization is paramount. The high-speed camera already captures an audio signal at a 48khz sampling rate during video recording. However, the audio and video signals are not accurately synchronized by default. A starter clapper was intended to be used for accurate synchronization: During the video analysis, the audio track is aligned such that the peak of the clap sound happens precisely at the frame when both halves of the clapper touch. Preliminary tests, however, showed that a typical start clapper is unsuitable for the desired precision, as it bends during the clapping movement and emits several sound waves over the span of roughly three to five milliseconds (See Figure 7). Therefore, two iron rods were used instead. At the end of each run, the iron rods were triggered a second time to verify that the tracks were still synchronized and apply a potential offset correction.
The speed of sound at ground level is roughly 34cm per millisecond [6]. Since the phone and the clapper are positioned at roughly the same distance from the camera, the synchronization offset cancels out and the synchronized audio and video tracks of the high-speed camera can be directly used for measuring the time between the Photo Finish start sound and the athlete finish crossing for an overall measurement accuracy of ±1 millisecond.

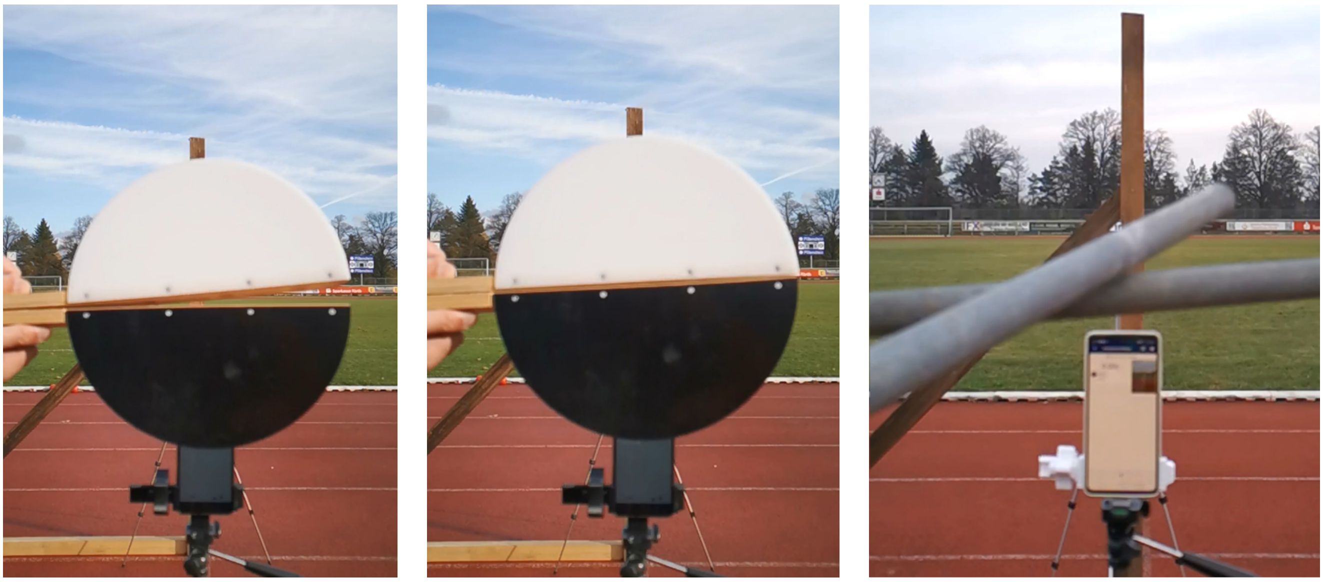

Figure 7: A typical start clapper is unsuitable for precise audio and video alignment as it bends during clapping and emits sound over several milliseconds. We therefore used two metal rods.

3 Results and Discussion

The video analysis shows very high accuracy of Photo Finish across all tested modes of less than 0.02 seconds and notable performance benefits in comparison to the laser timing system. In Flying Start mode, 75% of Photo Finish measurements were within 10 milliseconds or less of the manual video evaluation time, 95% were within 14 milliseconds, and all measurements were within 19ms of the video evaluation time. In contrast, the laser timing system exhibited 75, 95, and 100 Percentile errors of 26, 43, and 47 milliseconds respectively, which are further discussed below. In total, Photo Finish is about two and a half times more accurate than the laser timing system (See Appendix 1).

In the Touch Start mode, the results were similar with 75% of Photo Finish's measurements differing by less than 7 milliseconds, 95% by less than 10 milliseconds, and the maximum error being 19 milliseconds (See Appendix 2). The laser timing system does not have a comparable mode which we were able to evaluate. It's important to note that our evaluation accuracy was slightly lower in Touch Start mode, as even with quick movement of the finger the exact moment of the finger lifting from the touchscreen is hard to determine in the video footage because the finger accelerates from rest instead of a linear movement like the chest on the finish line. During the first 2milliseconds, the finger typically still touches the screen somewhat to its elasticity but with less pressure. Therefore, in this mode, our video analysis measurements themselves are subject to up to 3 millisecond error.

In the Beep- and Sound Start modes, the results are similar with 75% being within 10 milliseconds and all measurements equal or less than 20 milliseconds off from the video evaluation time. (See Appendix 3 and Appendix 4). The Laser timing system does also have an additional Loudspeaker which can be triggered by a button and start the clock. We tested this mode and saw a very large timing offset of around 450 milliseconds (See first phone pairing in Appendix 4) which was even noticeable during the measurements without any video evaluation tools. We did contact the manufacturer about this and were informed that the timing system automatically subtracts 150ms from the measurements in this mode to eliminate the reaction time. This, however, was nowhere mentioned in the manual and also does only explain less than half of the offset, so we assume that there is some calibration error internally. We therefore excluded the speaker mode of the laser timing system from further measurements.

In the Flying Start measurements, the comparatively lower accuracy of the laser timing system can be primarily attributed to its mechanism of triggering: Any part of the athlete's body rather than just their torsos can trigger the laser- typically a runner's knee or hand. This detection method introduces variability, as the exact moment an athlete's torso crosses the finish line—the relevant measure in sprinting events—is not directly measured. This is also clearly visible in the video evaluation footage, see Figure 8.

These resulting measurement errors are also relevant for training environments. As shown by the video analysis, these errors can be up to 0.05s, which are significant for short sprint measurements such as 30m flying, where Chu (1996) for example divides athletes into sprinting ability categories and where the width of categories is as low as 0.20s in total.

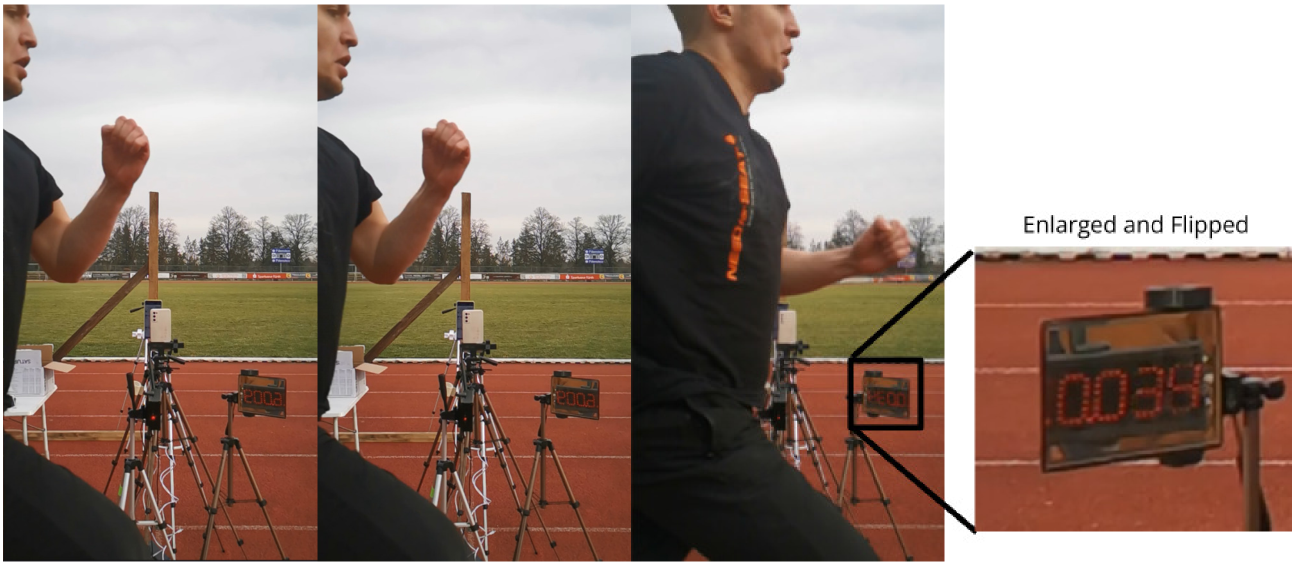

Figure 8: Early triggering of the Laser timing on the thigh instead of the torso. The left image and middle image show the moment the laser was broken and the clock was started, visible as the laser light dims significantly because it is not being reflected by the mirror anymore. When the chest of the passing runner has reached the measurement line/wooden beam, the timer on the Laser timing system already shows 34 milliseconds even though there is an additional screen latency.

Despite all the possible error sources that a smartphone-based timing system using wireless connection faces discussed in Section 4, Photo Finish manages to surpass the accuracy of light barrier timing due to its chest detection algorithm, offering a more precise, accessible, and cost-effective solution for amateur and professional sports timing as well as performance evaluation.

At this point, we also want to emphasize that despite its primary intended use for running sports, Photo Finish can also be used in a variety of other athletic disciplines such as mountain biking and skiing. The chest detection algorithm has been calibrated specifically for running, such that for example it also detects the chest of a cyclist instead of triggering on the frontmost part of the front wheel. This leads to slight, but mostly constant differences in timing, which depending on the application can either be ignored or just added or subtracted from the measurements to still get automatic timing results that are vastly more accurate than manual timing in a variety of sports.

Gender	Excellent	Above Average	Average	Below Average	Poor
Male	<2.6 secs	2.6 - 2.9 secs	2.9 - 3.1 secs	3.1 - 3.3 secs	>3.3 secs
Female	<3.0 secs	3.0 - 3.3 secs	3.3 - 3.5 secs	3.5 - 3.7 secs	>3.7 secs

Figure 9: 30m flying sprint normative data from Chu (1996)

4 Technical Details and Potential Error Sources

In the previous chapters, the overall accuracy of the Photo Finish Timing App in the various modes has been established. In this chapter, we want to discuss how we managed to achieve this level of precision despite the limitations of the Android operating system and smartphone technology in general and what the sources of the remaining errors are, while also stating the preliminary conditions that ensure that these are kept as low as possible.

4.1 Bluetooth Synchronization Accuracy

Photo Finish uses the Bluetooth protocol to synchronize the smartphones. Photo Finish initiates multiple connection attempts and uses the one with the lowest measured ping. The resulting typical synchronization latency ranges between 20-40 milliseconds, potentially introducing an error margin of up to half the ping. However, our preliminary analysis, which involved multiple trials with a high-speed camera setup like in Section 2.1 and alternating start and finish positions, indicated that the actual impact on accuracy is minimal. We observed that Bluetooth ping is typically highly symmetrical, resulting in a synchronization accuracy that is generally under 5 milliseconds. However, due to the large range of possible phone conditions and vendors, a higher ping with other phone combinations can't be ruled out.

4.2 Smartphone Clock Drift

The internal quartz oscillators of smartphones are subject to clock drift post-synchronization. According to Chu Luo et al (2017), the worst-case drift scenario is approximately 2 parts per million (ppm), equating to a potential error of about 7 milliseconds per hour. To counteract this, Photo Finish implements a re-synchronization protocol every 5 minutes, therefore negating the impact of the clock drift on short-time measurements such as sprints and interval training. The resynchronization is however only successful if the phones are within Bluetooth range, which is up to 40m in an open area. If the phones are placed further apart, such as in a 100m sprint, or for long-range timings such as marathon runs, Photo Finish accuracy is expected to decrease by up to 0.01s/hour since the session was started.

Since the quartz oscillator of the smartphone camera used for the high-speed analysis is equally subject to these fluctuations, all individual runs were kept to a length of fewer than 20 seconds so that the clock drift was negligible for the analysis.

4.3 Camera Timestamps

Every time the smartphone camera captures an image, the time at the beginning of the exposure is noted down. This timestamp can however be off by a significant margin due to different delays and interruptions in the Android operating system. Our investigation into the timestamp accuracy of smartphone cameras encompassed over 15 different models spanning various release years. We found that models released within the last 8 years generally maintained timestamp accuracy within less than 10 milliseconds. An outlier, the Huawei P8 Lite from 2015, demonstrated a video timestamp deviation of approximately 20 to 30 milliseconds which did significantly impact this phone's accuracy. The table in the appendix contains the measurements with this phone, showing an overall error of up to 30ms. We, therefore, excluded this phone from the analysis and recommend using more recent phone models. Note that the achieved accuracy still excels the light barrier system even on this outdated smartphone.

4.4 Exposure Duration

Photo Finish image capture rate of 30 frames per second dictates that camera exposure duration can vary based on lighting conditions, ranging from approximately 0.5 to a maximum of 33 milliseconds. Our empirical research showed that in lower light conditions (such as dusk or indoor environments), Photo Finish's chest detection algorithm triggers between the middle and the end of a blurred image section. Photo Finish therefore automatically optimizes measurement accuracy in low light conditions by adding three-quarters of the exposure duration to the video frame timestamp. For this study, we confined our accuracy tests to bright daylight conditions which keep the exposure length to around one millisecond to ensure optimal accuracy.

5.5 Chest Detection Algorithm

The chest detection algorithm is a critical component for accurate measurements. Challenges arise when there is low color contrast between the athlete and the background, potentially leading to missed detections or slight misplacements of the chest marker. In our study, we mitigated this risk by using brightly colored shirts (See Figure 10). Additionally, Photo Finish's feature of saving and displaying captured images with chest markers facilitates easy verification of accurate athlete capture.

4.6 Touch Screen and Microphone Latencies

Android smartphones, not inherently designed for high-speed, real-time applications, exhibit notable latencies in sound playback, microphone buffering, and touchscreen responsiveness. Sound playback latency is additionally unpredictable and can, depending on the phone model, be occasionally as high as 400ms or more. Luckily, touchscreen and microphone latencies are constant, as otherwise, this would lead to corrupted microphone data and/or missed touchscreen events.

Photo Finish therefore uses the microphone to determine the exact moment in time when the start sound is emitted. This still requires knowing the exact microphone latency, which also varies from phone model to phone model. We successfully developed a calibration routine to calculate these latencies and subtract them from the measurements, which the user is requested to perform before using Photo Finish for the first time.

Figure 10: Typical recording of Photo Finish. The white markers show where the chest detection algorithm triggered. The final time on the top right is calculated by linear interpolation of the frame timestamps and the distance of the chest marker from the measurement line (wooden beam in the background).

References

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Appendix 1: Flying Start Measurements

Phone Pairing	Run	Photo Finish Measurement (seconds)	Laser Timing System Measurement (seconds)	High-Speed Camera Manual Evaluation	**Error Photo Finish (ms)**	**Error Laser Timing System (ms)**
Samsung Galaxy S20 FE / Huawei P30 Pro	1	7.623	7.613	7.612	**11**	**1**
	2	7.410	7.411	7.398	**12**	**13**
	3	9.301	9.333	9.296	**5**	**37**
	4	6.634	6.650	6.630	**4**	**20**
	5	8.489	8.476	8.484	**5**	**-8**
	6	9.648	9.653	9.648	**0**	**5**
	7	9.946	9.930	9.944	**2**	**-14**
	8	11.081	11.114	11.089	**-8**	**25**
Galaxy S8 / Huawei P30 Pro	1	7.753	7.741	7.748	**5**	**-7**
	2	8.704	8.721	8.699	**5**	**22**
	3	9.412	9.385	9.402	**10**	**-17**
	4	8.200	8.207	8.188	**12**	**19**
	5	9.849	9.881	9.849	**0**	**32**
	6	11.564	11.545	11.551	**13**	**-6**
	7	15.239	15.199	15.220	**19**	**-21**
	8	11.109	11.090	11.104	**5**	**-14**
Realme C3 / Huawei P30 Pro	1	10.401	10.389	10.392	**9**	**-3**
	2	9.943	9.927	9.933	**10**	**-6**
	3	11.518	11.523	11.511	**7**	**12**
	4	10.111	10.096	10.103	**8**	**-7**
	5	11.311	11.306	11.311	**0**	**-5**
	6	7.970	7.961	7.962	**8**	**-1**
	7	9.432	9.443	9.427	**5**	**16**
	8	10.802	10.770	10.796	**6**	**-26**
Xiaomi Redmi Note 9S / Huawei P30 Pro	1	7.061	7.107	7.060	**1**	**47**
	2	7.401	7.372	7.399	**2**	**-27**
	3	9.736	9.745	9.733	**3**	**12**
	4	8.744	8.714	8.740	**4**	**-26**
	5	9.451	9.461	9.448	**3**	**13**
	6	10.306	10.286	10.305	**1**	**-19**
	7	13.340	13.307	13.338	**2**	**-31**
	8	5.626	5.655	5.622	**4**	**33**
Huawei P30 Lite / Google Pixel 3XL	1	8.510	8.531	8.513	**-3**	**18**
	2	7.302	7.286	7.297	**5**	**-11**
	3	11.278	11.292	11.277	**1**	**15**
	4	13.269	13.308	13.273	**-4**	**35**
	5	10.934	10.960	10.935	**-1**	**25**
	6	12.222	12.223	12.227	**-5**	**-4**
	7	10.936	10.917	10.934	**2**	**-17**
	8	12.219	12.262	12.220	**-1**	**42**
Samsung Galaxy A52 / Google Pixel 3XL	1	8.177	8.167	8.168	**9**	**-1**
	2	9.092	9.094	9.081	**11**	**13**
	3	13.402	13.392	13.399	**3**	**-7**
	4	12.084	12.061	12.068	**16**	**-7**
	5	9.977	9.951	9.966	**11**	**-15**
	6	9.647	9.636	9.644	**3**	**-8**
	7	8.686	8.633	8.676	**10**	**-43**
	8	7.195	7.180	7.181	**14**	**-1**
Samsung Galaxy S20 FE / Huawei P30 Pro	1	5.773	5.765	5.771	**2**	**-6**
	2	6.863	6.838	6.853	**10**	**-15**
	3	6.061	6.009	6.050	**11**	**-41**
	4	6.411	6.388	6.397	**14**	**-9**
	5	6.031	5.982	6.027	**4**	**-45**
	6	6.852	6.797	6.842	**10**	**-45**
	7	8.043	8.015	8.028	**15**	**-13**
	8	6.187	6.148	6.178	**9**	**-30**
				75th Percentile Error (ms):	**10.0**	**26.0**
				95th Percentile Error (ms):	**14.3**	**43.5**
				Maximum Error (ms):	**19.0**	**47.0**

Appendix 2: Touch Start Measurements

Phone Pairing	Run	Photo Finish Measurement (seconds)	High-Speed Camera Manual Evaluation	**Error Photo Finish (ms)**
Samsung Galaxy S20 FE / Huawei P30Pro	1	3.879	3.872	**7**
	2	4.151	4.152	**-1**
	3	4.145	4.145	**0**
	4	4.368	4.371	**-3**
	5	4.528	4.532	**-4**
	6	3.023	3.020	**3**
	7	3.623	3.619	**4**
	8	3.194	3.193	**1**
Galaxy S8 / Huawei P30 Pro	1	4.182	4.175	**7**
	2	3.336	3.335	**1**
	3	3.446	3.438	**8**
	4	3.409	3.408	**1**
	5	3.614	3.605	**9**
	6	3.316	3.308	**8**
	7	4.286	4.279	**7**
	8	4.024	4.015	**9**
Realme C3 / Huawei P30Pro	1	4.626	4.625	**1**
	2	3.470	3.467	**3**
	3	3.840	3.840	**0**
	4	3.682	3.663	**19**
	5	3.145	3.145	**0**
	6	2.930	2.925	**5**
	7	4.153	4.148	**5**
	8	3.622	3.623	**-1**
Xiaomi Redmi Note 9S / Huawei P30Pro	1	10.767	10.760	**7**
	2	3.628	3.633	**-5**
	3	4.370	4.363	**7**
	4	4.129	4.125	**4**
	5	4.004	4.008	**-4**
	6	4.061	4.053	**8**
	7	4.648	4.646	**2**
	8	3.713	3.694	**19**
Google Pixel 3 XL / Huawei P30 Pro	1	6.071	6.068	**3**
	2	3.241	3.231	**10**
	3	3.402	3.392	**10**
	4	3.255	3.253	**2**
	5	4.337	4.331	**6**
	6	4.230	4.232	**-2**
	7	3.979	3.971	**8**
	8	3.692	3.694	**-2**
Samsung Galaxy A52 / Huawei P30 Pro	1	6.674	6.675	**-1**
	2	4.705	4.712	**-7**
	3	4.254	4.258	**-4**
	4	4.335	4.345	**-10**
	5	4.181	4.189	**-8**
	6	4.452	4.460	**-8**
	7	4.304	4.308	**-4**
	8	3.495	3.502	**-7**
OnePlus Nord CE 2 / Huawei P30 Pro	1	3.495	3.494	**1**
	2	3.099	3.101	**-2**
	3	4.198	4.194	**4**
	4	4.061	4.062	**-1**
	5	3.439	3.435	**4**
	6	3.662	3.667	**-5**
	7	3.689	3.687	**2**
	8	3.442	3.443	**-1**
			75th Percentile Error (ms):	**7.0**
			95th Percentile Error (ms):	**10.0**
			Maximum Error (ms):	**19.0**

Appendix 3: Beep Start Measurements

Phone Pairing	Run	Photo Finish Measurement (seconds)	High-Speed Camera Manual Evaluation	**Error Photo Finish (ms)**
Samsung Galaxy S20 FE / Huawei P30 Pro	1	5.111	5.111	**0**
	2	5.112	5.107	**5**
	3	3.998	3.996	**2**
	4	4.760	4.755	**5**
	5	4.734	4.735	**-1**
	6	6.102	6.091	**11**
	7	6.027	6.028	**-1**
	8	5.144	5.143	**1**
Samsung Galaxy S8 / P30 Pro	1	4.321	4.321	**0**
	2	4.239	4.240	**-1**
	3	3.875	3.867	**9**
	4	3.045	3.047	**-2**
	5	4.899	4.898	**1**
	6	5.005	5.000	**5**
	7	4.316	4.302	**14**
	8	4.039	4.038	**1**
P8 Lite / Huawei P30 Pro	1	3.317	3.318	**-1**
	2	3.619	3.618	**1**
	3	3.765	3.773	**-8**
	4	3.596	3.590	**6**
	5	4.005	4.014	**-9**
	6	3.995	4.005	**-10**
	7	3.983	3.995	**-12**
	8	3.756	3.767	**-11**
Xiaomi Redmi Note 9S / Huawei P30 Pro	1	4.367	4.366	**1**
	2	4.445	4.454	**-9**
	3	4.214	4.219	**-5**
	4	4.300	4.308	**-8**
	5	4.862	4.864	**-2**
	6	3.189	3.193	**-4**
	7	4.220	4.221	**-1**
	8	3.830	3.837	**-7**
Pixel 3 XL / Huawei P30 Pro	1	4.158	4.157	**1**
	2	5.392	5.392	**0**
	3	4.537	4.537	**0**
	4	4.604	4.603	**1**
	5	6.525	6.522	**3**
	6	4.063	4.066	**-3**
	7	5.143	5.143	**0**
	8	Measurement missing due to an oversight		
OnePlus Nord CE 2 / Huawei P30 Pro	1	4.503	4.502	**1**
	2	4.298	4.295	**3**
	3	4.384	4.385	**-1**
	4	4.473	4.469	**4**
	5	4.246	4.233	**13**
	6	4.505	4.505	**0**
	7	5.268	5.264	**4**
	8	4.348	4.348	**0**
Xiaomi POCO / Huawei P30 Pro	1	4.677	4.676	**1**
	2	4.140	4.145	**-5**
	3	5.075	5.074	**1**
	4	4.259	4.260	**-1**
	5	4.669	4.670	**-1**
	6	4.121	4.119	**2**
	7	4.239	4.239	**0**
	8	4.090	4.093	**-3**
			75th Percentile Error (ms):	**5.3**
			95th Percentile Error (ms):	**11.3**
			Maximum Error (ms):	**13.7**

Appendix 4: Sound Start Measurements

Phone Pairing	Run	Photo Finish Measurement (seconds)	Laser Timing System Measurement (seconds)	High-Speed Camera Manual Evaluation	**Error Photo Finish (ms)**	**Error Laser Timing System (ms)**
Huawei P30 Lite / Google Pixel 3XL	1	4.283	3.816	4.284	**-1**	**-468**
	2	4.369	3.913	4.369	**0**	**-456**
	3	7.858	7.394	7.858	**0**	**-464**
	4	8.506	8.032	8.504	**2**	**-472**
	5	9.068	8.619	9.075	**-7**	**-456**
	6	11.573	11.119	11.581	**-8**	**-462**
	7	10.129	9.721	10.127	**2**	**-406**
	8	8.748	8.321	8.755	**-7**	**-434**
Samsung Galaxy S20 FE / Google Pixel 3XL	1	8.175	Laser Timing System was excluded from further measurements because of obvious large systematic error (See Chapter 3)	8.189	**-14**	Laser Timing System was excluded from further measurements because of obvious large systematic error (See Chapter 3)
	2	4.308		4.312	**-4**	
	3	3.173		3.182	**-9**	
	4	3.217		3.221	**-4**	
	5	4.682		4.694	**-12**	
	6	3.373		3.376	**-3**	
	7	3.809		3.826	**-17**	
	8	4.345		4.348	**-3**	
Xiaomi POCO / Samsung Galaxy S20 FE	1	23.219		23.230	**-11**	
	2	3.359		3.371	**-12**	
	3	3.054		3.068	**-14**	
	4	4.881		4.890	**-9**	
	5	3.622		3.639	**-17**	
	6	4.357		4.366	**-9**	
	7	2.926		2.936	**-10**	
	8	4.103		4.114	**-11**	
Xiaomi Redmi Note 9S / Huawei P30 Pro	1	4.419		4.422	**-3**	
	2	3.974		3.980	**-6**	
	3	3.715		3.718	**-3**	
	4	4.103		4.108	**-5**	
	5	4.200		4.194	**6**	
	6	4.257		4.264	**-7**	
	7	4.265		4.268	**-3**	
	8	4.060		4.071	**-11**	
Huawei P30 Lite / Huawei P30 Pro	1	4.764		4.770	**-6**	
	2	4.717		4.725	**-8**	
	3	4.079		4.086	**-7**	
	4	4.064		4.071	**-7**	
	5	3.616		3.618	**-2**	
	6	5.024		5.021	**3**	
	7	4.174		4.176	**-2**	
	8	4.333		4.330	**3**	
Huawei P30 Pro / Google Pixel 3 XL	1	7.203		7.214	**-11**	
	2	4.605		4.612	**-7**	
	3	4.233		4.240	**-7**	
	4	4.801		4.810	**-8**	
	5	3.895		3.901	**-6**	
	6	3.986		3.993	**-7**	
	7	4.588		4.592	**-4**	
	8	3.367		3.387	**-20**	
Cubot Note 20 Pro / Google Pixel 3XL	1	5.543		5.550	**-7**	
	2	3.427		3.432	**-5**	
	3	5.605		5.606	**-1**	
	4	4.936		4.946	**-9**	
	5	5.253		5.258	**-5**	
	6	5.210		5.220	**-9**	
	7	3.657		3.671	**-14**	
	8	4.643		4.657	**-14**	
				75th Percentile Error (ms):	**9.6**	-
				95th Percentile Error (ms):	**14.7**	-
				Maximum Error (ms):	**20.0**	-

Appendix 5: Additional Measurements with an Older Smartphone

Phone Pairing	Run	Photo Finish Measurement (seconds)	Laser Timing System Measurement (seconds)	High-Speed Camera Manual Evaluation	**Error Photo Finish (ms)**	**Error Laser Timing System (ms)**
Huawei P8 Lite / Huawei P30 Pro	1	7.328	7.346	7.349	**-21**	**-3**
	2	8.632	8.677	8.653	**-21**	**24**
	3	8.307	8.304	8.333	**-26**	**-29**
	4	8.383	8.405	8.401	**-18**	**4**
	5	8.506	8.478	8.527	**-21**	**-49**
	6	11.933	11.975	11.956	**-23**	**19**
	7	8.097	8.110	8.127	**-30**	**-17**
	8	6.868	6.898	6.888	**-20**	**10**
				75th Percentile Error (ms):	**23.8**	**25.3**
				Maximum Error (ms):	**30.0**	**49.0**