Using *Camera Technology* to "Measure" Golf Launch Parameters?

There are a number of tools available to measure high-speed events, in particular the launch parameters of golf shots. However, the results accuracy produced by any system will depend upon the conditions of measurement, definitions of parameters to be measured, the degree to which accuracy is required for each reported parameter, the system or systems used for measurement, and the skill of testing administrators.

Any tools or systems designed for launch parameter measurement will have some inherent limitations as well as optimal operational specifications. System limitations and operational specifications combine to determine the upper limits of measurement performance that can be achieved by a tool or set of tools. Use of a calibrated system outside of its optimal specs will give you less than desired results, or errors beyond system limitations.

Over the years, High-Speed Camera and/or Stroboscopic Photography Technology have been used by a number of golf equipment manufacturers in the golf ball and golf club development process. As this technology has become increasingly prevalent for launch parameters measurement, the use of high-speed camera images has become represented by many to be an "*accurate measurement*", but is this really the case?

A good example of errors generated by a tool's limitations and its operational ranges is the use of a 2-Dimensional High-Speed Camera or Stroboscopic Photography System for the quantification of golf ball impact analysis and ball flight (and roll) prediction. Measurement errors inherent to 2-D High Speed Camera and Stroboscopic Photography Systems fall into the following categories: Camera Limitations (such as image resolution, focus, and distortion), Set Up Issues (Operator and System), and the Dynamic Variable Range presented with human beings and golf swings. As described herein, these components of measurement error have an interdependent relationship with one another, meaning that each parameter's accuracy depends upon the accuracy of every other parameter. Unfortunately, any error in any given parameter will compound the errors in the other parameters.

HIGH SPEED CAMERA and STROBOSCOPIC PHOTOGRAPHY – THE BASIC SET UP AND INTENDED PURPOSE

In golf ball launch, a 2-D camera system is often used to measure Ball Speed, Launch Angle, back-spin RPMs, and sometimes Azimuth (Degrees of Push or Pull) and Side-Spin RPMs. By accurately measuring these parameters, algorithms shaped by field-testing and calibration can be used to predict golf ball flight (and roll). The camera's purpose is to capture two or more successive images of a high-speed occurrence – a speeding golf ball moving up to 200 MPH with RPMs of up to 12,000 RPMs and launch angles from 0-65 degrees. The images are then processed by Image recognition software or Spatial mapping software, which *calculates* the shot's launch parameters based on the movement of pre-defined markings on the golf ball over the series of images.

To provide Image processing software meaningful images to accurately calculate golf ball launch parameters, orientation of the Camera along the x-, y-, and z-axes spatially, as well as the camera lens' position side to side and/or up and down, for every starting and dynamic ball location, is critical. Otherwise, parallax views will severely limit a camera system's ability to provide representative images of the golf ball launch parameters (3-dimensional occurrence), and thus limit the prediction accuracy of ball flight and roll from such systems. However, even if you get the set-up as close to perfect as possible, the variability of any golfer's shot performance will almost guarantee a parallax view of the event.

SIMPLE EXAMPLES OF INTERDEPENDENT VARIABLES CAUSING ERROR IN ANOTHER (DEPENDENT) VARIABLE with 2-D CAMERA SYSTEM

- *Ball Speed Error Dependent Upon Azimuth* – A good example of parallax view error is illustrated when you are trying to measure ball speed with a 2-D camera positioned at a perpendicular angle to the target line. To better understand the concept of parallax viewing error, image trying to read your automobile's gas gauge from the passenger seat… the Fuel Gauge doesn't appear the same way it does to the driver who is sitting straight on. Trying to measure Ball Speed with non-zero Azimuth when using a camera system is the same way. The graphic below illustrates ball speed error across positive (PUSH) and negative (PULL) azimuth angles. As you can see, only if the ball's direction is 90 degrees to the camera angle view, will you get reliable and accurate results with little to no error. In practical situations, however, rarely does a player hit the ball at Zero Azimuth (perfectly straight), with the feat of recognizing a Zero Azimuth shot by the system and system operator even more rare. In general, shots with a (+) Azimuth, a push traveling towards the camera, will show up with a progressively higher ball speed than actual, while those with a (–) Azimuth, a pull traveling away from the camera, will show up with a progressively lower ball speed than actual. *See Diagram A below.*

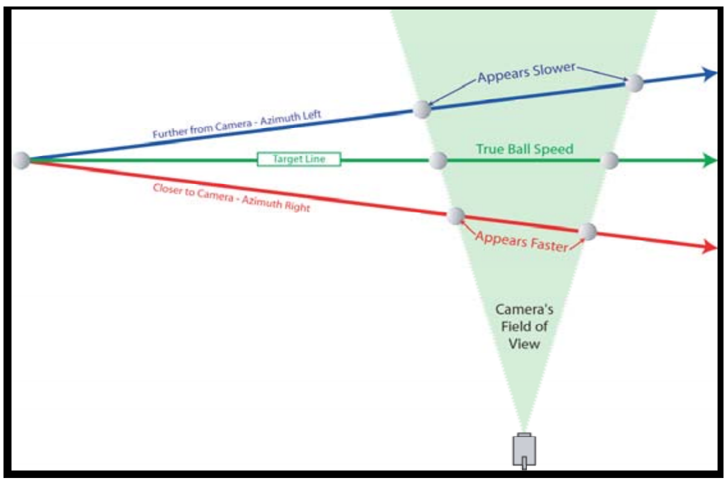


Diagram A: Ball Speed Measurement Calculation Dependent Upon Ball Azimuth Angle

- *Launch Angle Error Dependent Upon Azimuth* – As demonstrated in *Diagram B (below)*, Non-Zero Azimuth shots introduce parallax error into the camera's launch angle measurements too! While the camera will see the three shots depicted in the image as having the same launch angle, the shot with positive azimuth traveling towards the camera will actually have a lower than reported launch angle, while the shot with negative azimuth traveling away from the camera will have a higher than reported launch angle.

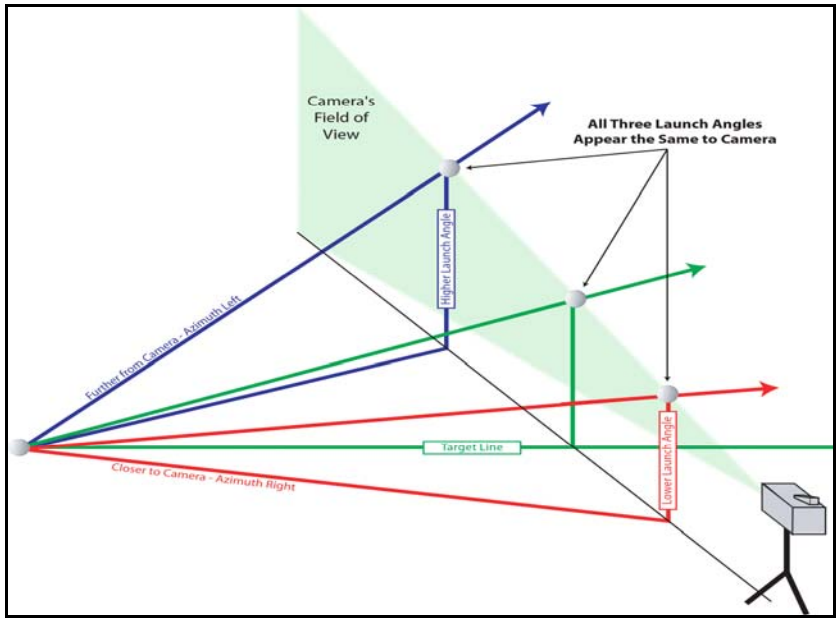
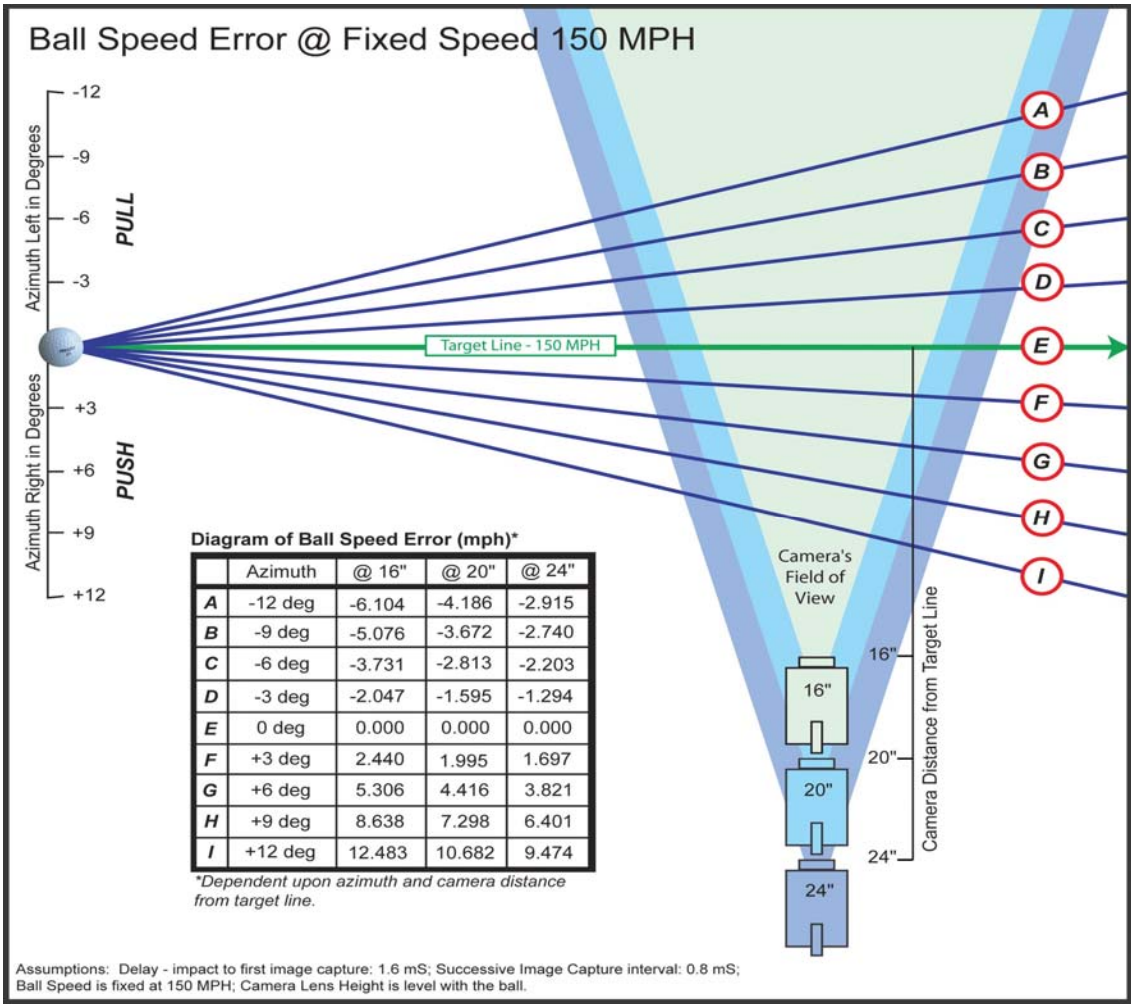


Diagram B: Launch Angle Measurement Calculation Dependent Upon Ball Azimuth Angle

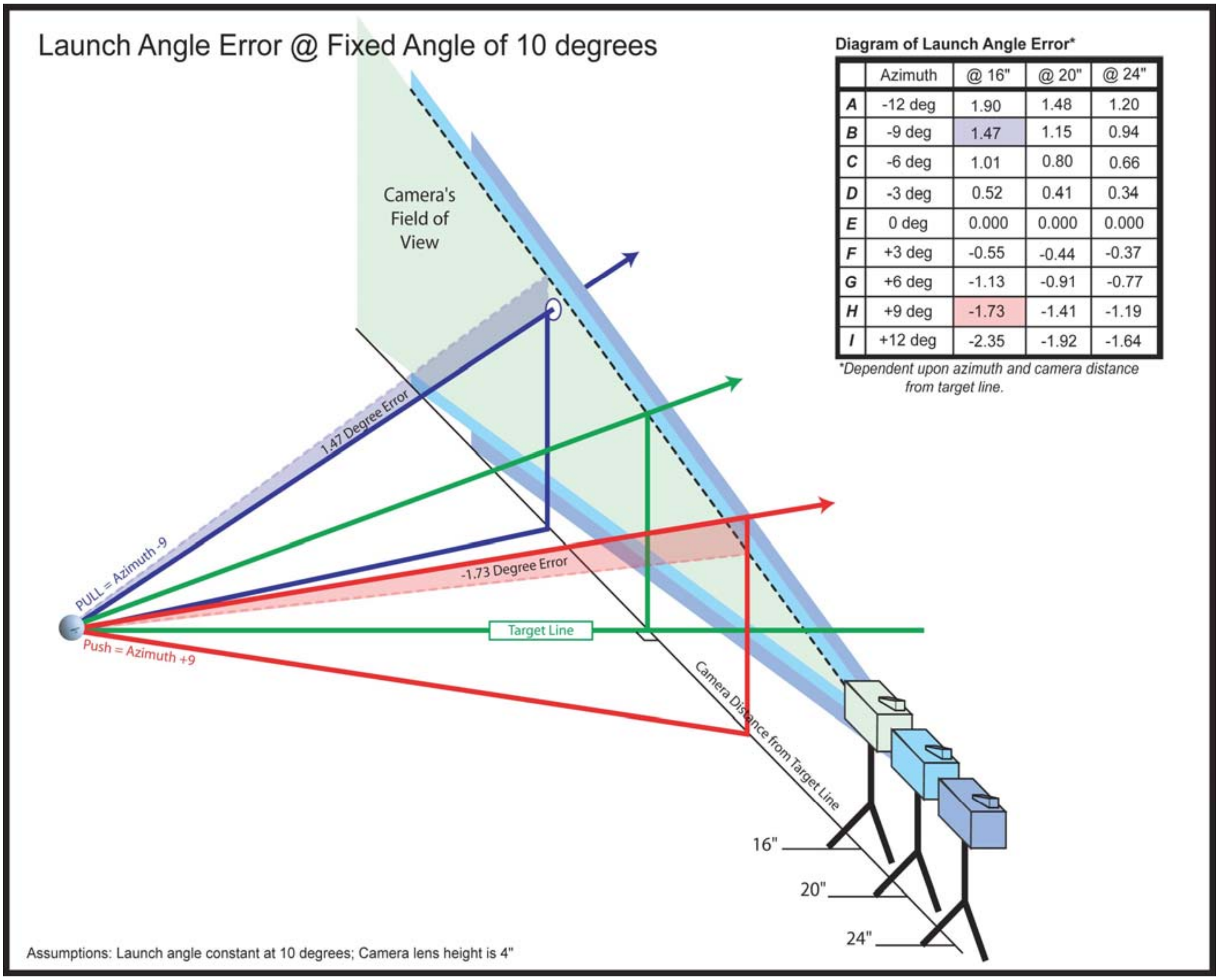
- *Ball Speed Error Dependent Upon Distance between Camera to Intended Target Line and Ball Azimuth Angle. See Diagram C below.*
  - *In general, Ball Speed Error is reduced as Camera Position moves further away from the Intended Target Line.*
  - *In general, Ball Speed Error increases with the greater the Ball Azimuth Angle (+ or -).*
  - *As Diagram C demonstrates, CAMERA Error for a golf shot moving 150 MPH at –6 Degrees Azimuth (PULL) is –2.813 MPH and at +6 Degrees Azimuth (Push) is +4.416 MPH, assuming Camera Distance from Intended Target Line at 20 inches. The Camera Reported MPH Range at +/-6 Degrees Azimuth for a ball traveling at 150 MPH is 147.187MPH to 154.416 MPH!*



	Azimuth	@ 16"	@ 20"	@ 24"
A	-12 deg	-6.104	-4.186	-2.915
B	-9 deg	-5.076	-3.672	-2.740
C	-6 deg	-3.731	-2.813	-2.203
D	-3 deg	-2.047	-1.595	-1.294
E	0 deg	0.000	0.000	0.000
F	+3 deg	2.440	1.995	1.697
G	+6 deg	5.306	4.416	3.821
H	+9 deg	8.638	7.298	6.401
I	+12 deg	12.483	10.682	9.474

Diagram C: Ball Speed Measurement Error as a function of Camera Distance to Target Line and Ball Azimuth Angle

- *Launch Angle Error Dependent Upon Distance between Camera to Intended Target Line and Ball Azimuth Angle. See Diagram D below.*
    - *In general, Launch Angle Error is reduced as Camera Position moves further away from the Intended Target Line.*
    - *In general, Launch Angle Error increases with the greater the Ball Azimuth Angle (+ or -).*
    - *As Diagram D demonstrates, CAMERA Launch Angle Error for a 10 degree launch angle golf shot launched at –9 Degrees Azimuth (PULL) is –1.47 Degrees and at +9 Degrees Azimuth (Push) is +1.73 Degrees, assuming Camera Distance from Intended Target Line at 16 inches. The Camera Reported Launch Angle Range at +/-9 Degrees Azimuth for a ball traveling at 10 Degrees Launch is 8.53 Degrees to 11.73 Degrees!*



	Azimuth	@ 16"	@ 20"	@ 24"
A	-12 deg	1.90	1.48	1.20
B	-9 deg	1.47	1.15	0.94
C	-6 deg	1.01	0.80	0.66
D	-3 deg	0.52	0.41	0.34
E	0 deg	0.000	0.000	0.000
F	+3 deg	-0.55	-0.44	-0.37
G	+6 deg	-1.13	-0.91	-0.77
H	+9 deg	-1.73	-1.41	-1.19
I	+12 deg	-2.35	-1.92	-1.64

Diagram D: Ball Launch Angle Measurement Error as a Function of Camera Distance to Target Line and Ball Azimuth Angle

- *Launch Angle Error Dependent Upon Camera Height Relative to Ball Flight Path when keeping Distance between Camera to Intended Target Line Constant. See Diagram E below.*
    - *In general, Launch Angle Error increases as the camera lens height relative to ball flight path increases.*
    - *As Diagram E demonstrates, CAMERA Launch Angle Error for a 10 degrees launch angle golf shot launched at –9 Degrees Azimuth (PULL) is –1.47 Degrees and at +9 Degrees Azimuth (Push) is +1.73 Degrees, assuming Camera Distance from Intended Target Line at 16 inches and Camera Height at 4 inches. The Camera Reported Launch Angle Range at +/-9 Degrees Azimuth for a ball traveling at 10 Degrees Launch is 8.53 Degrees to 11.73 Degrees! If the Camera is actually 6" high, the Range increases to 7.46 Degrees to 12.83 Degrees. At 8" high, the Range increases to 6.39 Degrees to 13.93 Degrees.*

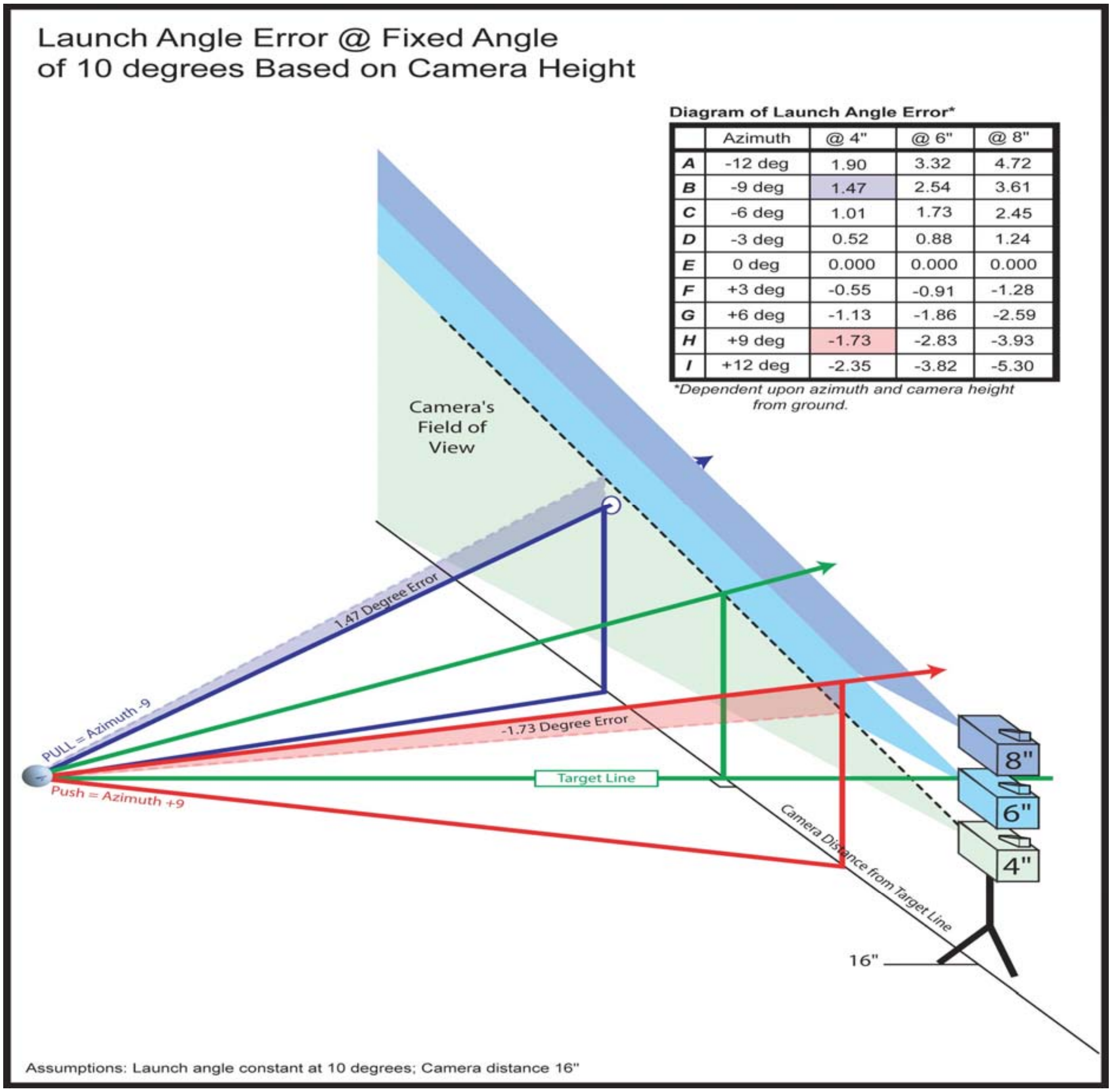


Diagram E: Ball Launch Angle Measurement Error as a Function of Camera Height and Ball Azimuth Angle

Two-Dimensional Camera Image Limitations

Inherent to the design of the camera, the following may be hardware limitations of a Camera System:

- Two-Dimensional (side-view only)
- Pixels of resolution; Image Sensors
    - In Limiting Ball Speed error by increasing Distance of Camera Lens to Target line, one reduces the image resolution of the ball, thereby reducing a system's ability to accurately assess Azimuth. In this case, correcting ball speed for incorrect Azimuth reading further complicates the Ball Speed errors.
- Lens Distortion and De-Focusing
- Height of Camera Lens relative to ball
    - Having its biggest effect on Launch Angle calculation, this error becomes further pronounced with Ball Azimuth variables.
- Time Interval between image capture

  - The right time interval settings need to be implemented to optimally measure Ball Speed.
- Distance between Sequential Ball Images
- Distance between Camera Lens to Target Line
  - The further away the camera from the intended target line, the more one reduces Ball Speed and Launch Angle Errors due to Azimuth Variables, however, moving further from the Intended Target Line further complicates a system's ability to assess the actual Azimuth Results, thereby making it more difficult to correctly report Ball Speed and Launch Angle Calculations.
- Lighting Conditions, which affect Image Blurring, Focusing, and Resolution

Error Introduced by Operator Set Up (Intentional and Unintentional)

Among the difficulties in obtaining proper Camera set up prior to measurement include the following:

- *Set-Up/Determining Precise Zero Camera Azimuth*
- *Set-Up/Determining Precise Camera Leveling*
- *Height of the Camera Adjusted for the Different Launch Angles? Different Launch Angles require different optimum set up positions to minimize errors*
- *Distance Between Camera Lens to Target Line exactly as recommended by the System Manufacturer. As shown earlier, the parametric calculations are highly dependent upon this distance.*
- *Time Delay and Time Interval Settings; thus, the distance between sequential images of the golf ball.*
- *The Camera Lens is not typically perfect in eliminating image distortion – e.g. fish eye image and/or edge distortion*

Dynamic Variables

The variability of golf shot results from any player due to player skill level and capability limitations, along with the randomness of any single golf shot, while keeping in mind the compounding effects of problems added by *Operator Set Up Errors (as described above),* means that a High Speed Camera or Stroboscopic Photography system will rarely be in the optimal position to record a golf shot's launch parameters. Shot results randomness from golfers in the following parameters makes High Speed Camera Set-up Positioning very difficult, while making golf ball measurement less accurate:

- *Ball Azimuth Angle.* Unless a straight shot of 0 Degrees Azimuth is achieved, a camera system will have parallax error spill into Ball Speed and Launch Angle calculations (as shown earlier in Diagrams A and B). What's more, when using correction formulas for Azimuth errors effect on other parameters, the Azimuth Angle is often miscalculated or inaccurate due to difficulty of producing accurate Azimuth calculation. This results in ill-applied correction formulas, producing even higher Ball Speed and Launch Angle errors, not to mention the original error in Azimuth calculation.
  - When hitting indoors into a net, very few facilities will offer sufficient target indicators for the zero Azimuth target line and a Zero Azimuth set up with a camera system. Thus, indoor testing with a camera system can make it even more difficult to assess actual Azimuth (minimum error conditions).
- *Ball Launch Angle*. Unless the shot has a zero Azimuth *and* is captured with the ball flight at camera lens height, there is parallax error (as shown earlier in Diagrams B, D, and E). So, the system operator should change the camera height to minimize error if a golfer wants to hit Driver, 6-iron, Sand Wedge, not to mention trying to account for shots that might be hit thin (lower) or with an open face (higher).
  - Setting the system up for an expected set of launch parameters is difficult because golfers rarely exhibit such refined talent so as to repeat a shot two times in a row.

- *Ball Speed.* It is difficult to set up the camera time interval in anticipation of ball speed. For every ball speed, there is an optimal set of interval and delay time settings for the camera. For every mile an hour, there is an optimal setting to minimize error. Unfortunately, most good golfers will vary in their ball speed by more than 5 MPH from shot to shot, while the average golfer will have variance of +/- 10 MPH, or a range of some 20 MPH. It is impractical to assume one can predict and cover the entire range of ball speeds with only a few optimal settings for interval and delay.
- Ball Starting x, y, and z coordinates – After the system operator takes great care and time to set up the system on the precise spatial coordinates, a golfer may take one huge divot producing swing, thus rendering the optimal ball position useless. The operator will need to move the camera to account for the new ball position for optimal results. If the camera is not moved but the ball is, the operator will introduce unwanted measurement error by operating the camera system from outside of the optimal operational specifications.
- Human Swings provide unavoidably inconsistent results. These inconsistencies are affected by skill level, physical conditions, mental state, and/or equipment used.

THE MOST IMPORTANT PARAMETERS IN PREDICTING BALL FLIGHT AND ROLL – Why is the Inherent Camera Image Error so Significant?

As this article demonstrates, camera error from parallax views causes accuracy issues in all shots having non-zero Azimuth. Although some camera systems attempt to reconcile the Ball Speed and Launch Angle Errors with Azimuth estimation and Correction formulas, the typically-used camera's limitation provides accuracy limited to +/-3 degrees Azimuth, or a 6-degrees error variance. Simply put, a wrongful use of the Azimuth correction formula can easily result in a 5+ MPH Ball Speed error and a 3+ Degrees Launch Angle Error.

Yet, Camera Systems do have their perceived strengths in "measuring" the RPMs of golf shots. Unfortunately, the impact of RPMs on the overall performance of golf shots has been largely misunderstood by those using and selling camera systems. Further, this misunderstanding has been amplified to the golfing consumer.

While all launch monitors are developed to help us understand ball flight better, keep in mind, there are four main physical parameters most affecting the landing spot of any golf shot: Ball Speed, Azimuth, Launch Angle, and RPMs, in that order of importance. Obviously, factors such as wind, humidity, ball condition, and altitude play a great role, but we can eliminate these as variables by testing only under controlled conditions. It is in this manner that one quickly learns the priorities of importance in golf shot parameters. For example, if we start with a shot at 150 MPH Ball Speed, 15 degrees of Launch Angle, 0 Degrees Azimuth, and 2,000 RPMs Back Spin (0 side spin), we will result a carry distance of approximately 240 yards. If we manipulate the RPMs by +1000 RPMs to make 3000 RPMs (+50% change), carry distance is reduced by approximately 1 yard, for a net result of approximately 239 yards. If we increase Ball Speed MPH by one to 151 MPH (+0.67% change), 15 Degrees Launch Angle, and 2000 RPMs shot, we will positively affect carry distance by the same one yard, for a net result of approximately 241 yards. If we increase Launch Angle from 15 to 16 degrees (+6.7%), while keeping 150 MPH Ball Speed and backspin at 2000, we maintain the carry distance at approximately 240 yards. Based on this practical example of a good player, we can see that it requires approximately 1000 RPMs, or a 50% change in RPMs, to create the same carry distance difference as with just one MPH in Ball Speed, or less than a 1% change. Based on the example above, we can easily see how Ball Speed can be nearly 100 times more important than RPMs in predicting carry distance. In summary, Ball Speed is the most important predictor of a golf shot's carry distance. This means that the inherent errors of High Speed Camera and/or Stroboscopic Photography Systems introduce substantial measurement calculation errors and difficulty in the accurate prediction of golf ball carry distance. Therefore, tedious arrangement and detailed calculations are required to minimize such errors for optimal use of camera systems.