Accident Reconstruction Photogrammetry using Zoomed Images from Digital Cameras

Lee F. DeChant
J Rolly Kinney P.E.

Images that were zoomed from consumer grade digital cameras are often the only source of evidence for accomplishing measurements related to vehicle collisions. It is well known in close-range photogrammetry (CRP) that when the camera's lens is zoomed, the lens distortion values change and are generally unknown, making accuracy of the computed XYZ points prone to error. The traditional method of working with zoomed digital camera images has been solving the cameras inner parameters and exterior orientation, if enough 3-D control points are present in the images.

This traditional process of solving the camera's parameters for zoomed imagery is usually labor intensive, and most reconstruction practitioners have found the process difficult to accomplish and only use it as a "last resort".

This article discusses a new camera calibration computational algorithm called "Zoom-Dependant" (Z-D), that affords a reconstruction practitioner the option of using zoomed imagery through the standard process of reference marking perspective view images. Z-D metrically calibrates the digital camera throughout the entire telephoto zoom range, making the full capability of modern digital cameras easily accessible for accurate photogrammetric mensuration. Z-D corrects for the lens distortion, principal point offsets and focal length. Described in this article, are the requirements for calibrating, together with a comparative study of consumer grade Digital Single Lens Reflex (DSLR) cameras and Point and Shoot (PAS) cameras, metrically calibrated using *iWitnessPRO*^{TM}. Accuracy tests of the study are accomplished using the front end of a 1986 Porsche Carrera. The Z-D data are compared to a reference control network. Additionally, photogrammetric processing of zoomed imagery using only the EXIF (meta tag) focal length to characterize the camera was also used for comparison.

INTRODUCTION

Z-D camera calibration is expected to open up many new opportunities working with digital camera images that were zoomed, and not initially intended for photogrammetrical analysis. To date, the constraint of working with images of known camera parameters meant the camera's lens was typically calibration at a fixed focal length, prior to accomplishing the computer analytics within the Close-Range Photogrammetry (CRP) software. In the case of imagery zoomed from a telephoto lens, the "zooming" also changes the lens distortion parameters and usually makes the photogrammetric data much less accurate than image analysis based on metric camera calibration.

The Zoom-Dependent (Z-D) process described eliminates the fixed focal length requirements that have been traditionally assumed in CRP software programs.

The CRP calibration software solves for the interior orientation properties of the camera and lens combination automatically from the imagery of calibration targets yielding the Focal Length; Xp, Yp Principal Point Offsets; and K1, K2, and K3 radial lens distortion coefficients. So the application of Z-D analysis can extract the coordinates of important feature points from images sets that could not otherwise be solved, would require much more effort if the solution was possible, and the resulting accuracy will be significantly better than solutions using only the EXIF focal length with no correction for lens distortion.

Overview of Zoom-Dependent (Z-D) camera calibration

The zoom-dependent calibration process models the variation of camera calibration parameters as functions of the nominal zoom focal length shown in the EXIF header of the image file. The functions describe variations in the interior orientation parameters of principal distance and principal point offset, and in the coefficient of the cubic expression utilized to model radial lens distortion. For most lenses the function is a power curve but linear functions are needed for some lenses. The interior parameters are interpolated from the calibration functions for the focal length shown in the EXIF file of each image. The Z-D calibration range includes four zoom/focus settings, nominally the widest and narrowest fields of views, plus two intermediate settings about equally spaced within the range.

Photogrammetric Study using Z-D

The goal of the study was to compare different DSLR cameras and PAS cameras to a control network. In the study, four different make/model PAS cameras and two different model DSLR cameras (total 3 DSLRs) were employed in the field work. The 3-dimensional coordinates and residuals of all photogrammetric networks were compared to a control network established from a self-calibrated Olympus E420 with 14-42mm lens, with lens fixed to 14mm and manually focused to infinity.

Seven cameras were calibrated for this study using the Z-D process:

1. (Qty 1) Olympus E-420 DSLR with 14-42mm lens set to 14mm – [This was the photogrammetry reference device and was calibrated only at 14mm.]

2. (Qty 2) Olympus E450 DSLR with 14-42mm lens, at 10 megapixels

3. (Qty 2) Kodak C142 “Easyshare” PAS, at 10 megapixels

4. (Qty 1) Nikon S510 “Coolpix” PAS, at 12.2 megapixels

5 (Qty 1) Canon SD 1300 IS “Powershot” PAS, at 12.1 megapixels

The steps in the study described here were:

1. Accomplish Z-D calibration for each of the cameras at four different focal lengths.

2. Capture one or two image sets of the vehicle with each camera.

3. Process the imagery from the cameras with *iWitnessPRO* to obtain the network of selected points for:

    a. The fixed lens (control network) for the E-420 imagery as the reference in the study.

    b. The Z-D network based on the Z-D calibration of the image camera.

    c. The network based on the EXIF focal length only.

d. The Z-D solution based on the Z-D calibration, but used on the images of an *exemplar* camera of the same make/model.

e. The FOOM (**F**ocal length Fr**o**m **O**ne I**m**age) process used to orient the camera(s) and solve the network.

4. Compare the Z-D Network solutions to the E-420 Control Network solution on the basis of the RMS errors and also the error range of 3D affine coordinate transformation.

The Z-D Calibration Procedure

To Z-D calibrate a camera with a zoom lens, four different focal lengths are required; the widest field of view (FOV), two other intermediate focal lengths, and the Narrowest FOV. The Z-D calibration is usually more accurate when the Auto-Focus is turned off –when the camera has the ability to turn the focus to a manual setting. Most PAS cameras do not allow the focus to be manually set, so the PAS camera is typically calibrated and used in the Auto-Focus Mode. Precise intermediate focal lengths zoom chosen for the Z-D calibration are not important, and should be about equally spaced between the Widest and Narrowest FOV's. For example, if a PAS camera has a zoom range of 5mm to 20mm, advancing the cameras electronic "zoom slider bar" about one third and also two-thirds from the lens's widest FOV, is a good practice.

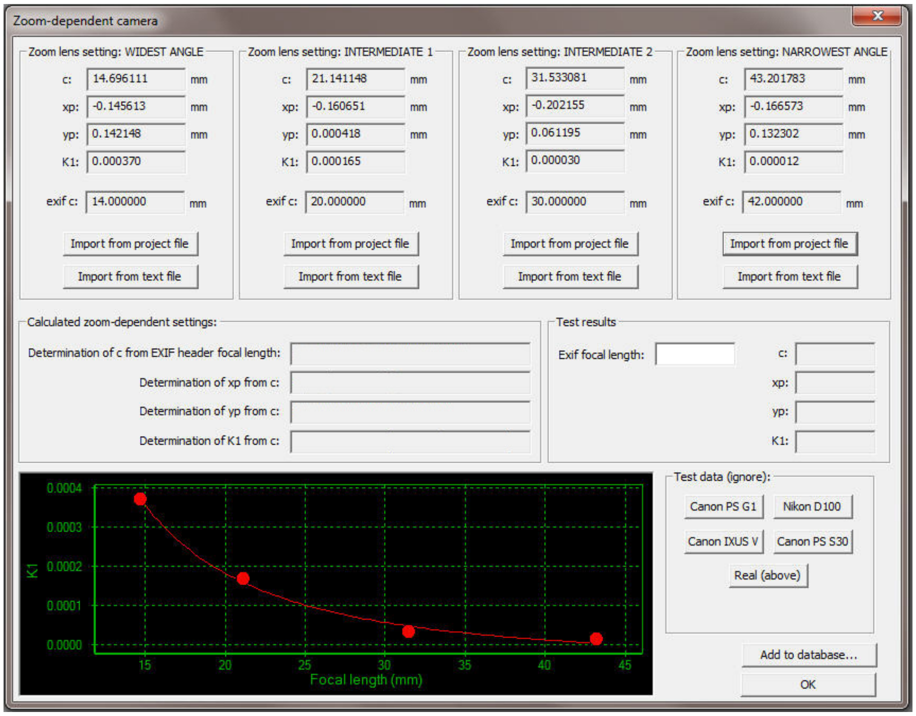
The first step in the Z-D calibration procedure was to obtain about 12 images for each focal length, from strong perspective camera viewpoints, of a target array attached to a vertical wall surface over an area of about 5' high x 8' wide. Figure 1 illustrates the Z-D calibration target array used in this study. The camera's onboard flash was required on all Z-D calibrations for automatically marking the red coded targets. A few coded targets were mounted off the plane of the wall to improve the initial relative-orientation process of the cameras during calibration. The maximum distance of the camera to calibration target array was about 24' for the Narrowest FOV images.

The next step in the study was to open each set of camera images in *iWitnessPRO* and obtain the camera calibration for the set using fully automatic coded targets (specialized red/black dot placards). Also shown in Figure 1, adjacent to the coded targets, were six printed 8.5" x 11" sheets with a quantity of three, 1.25" black dots. These relatively larger black dots were needed for PAS camera images when the telephoto zoom was set in the Intermediate 2 and Narrowest zoom settings, because the reflective red-coded targets could not be automatically detected and measured due to 'target image blooming' from the camera's onboard flash. *iWitnessPRO* automatically "Z-D calibrated" the DSLR cameras successfully, measuring the red coded targets for all four focal lengths. The PAS cameras worked satisfactorily for automatic measurement in the Widest FOV and Intermediate 1 FOV focal lengths; but the Intermediate 2, and Narrowest FOV's required user-assisted measurement through photogrammetric referencing of the paper sheet's black dots. The Z-D calibration for each image set was saved as a unique *project*.iwpro file for the corresponding camera and lens setting.

FIGURE 1 – Z-D calibration targets for DSLR and PAS cameras

After the four Z-D calibrations for a camera had been completed, a new project was opened in *iWitnessPRO* and the four camera calibration project files imported, e.g. "*project1*.iwpro" through "*project4*.iwpro. *iWitnessPRO* automatically computed the Z-D camera description from the four focal length projects. Figure 2 shows the Z-D calibration data displayed for the Olympus E420 w/ 14-42mm lens, with the power curve for the K1 distortion shown on the left. The Z-D calibrated camera was then named a 'unique ID' and saved for later use on projects that utilize the specific camera. If a camera doesn't employ in-camera lens distortion correction, the Z-D calibration is based on the Power-ZD mode.

FIGURE 2 – Z-D calibration dialog box with computed results for the Olympus E420

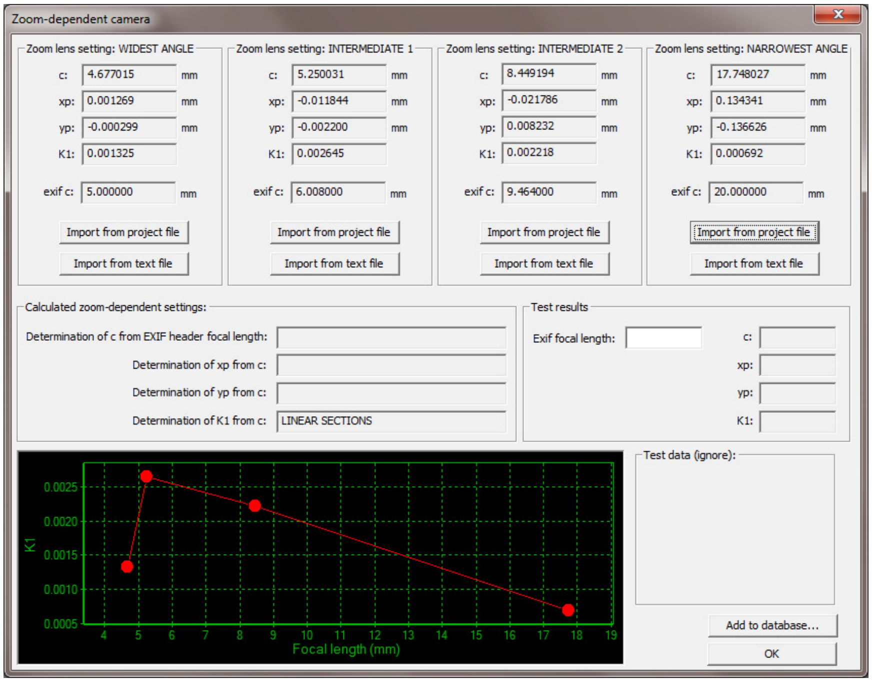


Zoom-dependent camera

	Zoom lens setting: WIDEST ANGLE	Zoom lens setting: INTERMEDIATE 1	Zoom lens setting: INTERMEDIATE 2	Zoom lens setting: NARROWEST ANGLE
c:	14.696111 mm	21.141148 mm	31.533081 mm	43.201783 mm
xp:	-0.145613 mm	-0.160651 mm	-0.202155 mm	-0.166573 mm
yp:	0.142148 mm	0.000418 mm	0.061195 mm	0.132302 mm
K1:	0.000370	0.000165	0.000030	0.000012
exif c:	14.000000 mm	20.000000 mm	30.000000 mm	42.000000 mm

In the event the camera has in-camera lens distortion, the user needs no prior knowledge of the camera's "distortion correction" before the Z-D calibration process. *iWitnessPRO* determines this automatically, immediately following the importation of all four Z-D calibration networks. Figure 3 shows the Z-D dialog for the Canon SD 1300 IS Powershot that utilized in-camera lens distortion correction. The line at the bottom of the figure was not a proper fit to a power curve, so *iWitnessPRO* 'forced' the calibration to follow the Linear-ZD model, and the screen displayed a message that the mode had been switched.

FIGURE 3 – Z-D calibration dialog box with Linear-ZD computed result



	Zoom lens setting: WIDEST ANGLE	Zoom lens setting: INTERMEDIATE 1	Zoom lens setting: INTERMEDIATE 2	Zoom lens setting: NARROWEST ANGLE
c:	4.677015 mm	5.250031 mm	8.449194 mm	17.748027 mm
xp:	0.001269 mm	-0.011844 mm	-0.021786 mm	0.134341 mm
yp:	-0.000299 mm	-0.002200 mm	0.008232 mm	-0.136626 mm
K1:	0.001325	0.002645	0.002218	0.000692
exif c:	5.000000 mm	6.008000 mm	9.464000 mm	20.000000 mm

Calculated zoom-dependent settings:

Determination of c from EXIF header focal length:
Determination of xp from c:
Determination of yp from c:
Determination of K1 from c: LINEAR SECTIONS

Test results

Exif focal length:
c:
xp:
yp:
K1:

Test data (ignore):

Network Measurement of the Porsche 911 Vehicle

To compare the capability of various cameras and Z-D calibrations on a small scale project, targets were placed on and around the vehicle, and image sets were captured. Imagery was obtained with each camera, and then processed in *iWitnessPRO,* for various calibration schemes, and the results compared to the 3D coordinate positions of the Control Network obtained with the fixed lens Olympus E-420 camera.

The first step was to create a control network of the 3D points by applying around the front end of the vehicle with adhesive-backed passive-style red photogrammetric strip tape and single dot targets on the bumper, hood, and windshield illustrated in Figure 4. Three precision scale bars were used; two scale bars were placed on the ground in front of the vehicle, and one scale bar, was tripod mounted and placed on the vehicle's roof. Twenty-eight coded targets were randomly placed on the vehicle and fanned-out on the ground (mostly in front of the vehicle's front bumper).

A total of 91 targets on the vehicle were measured for each network; but for this study only a subset of 19 spatially separated XYZ points were the basis for the tables presented.

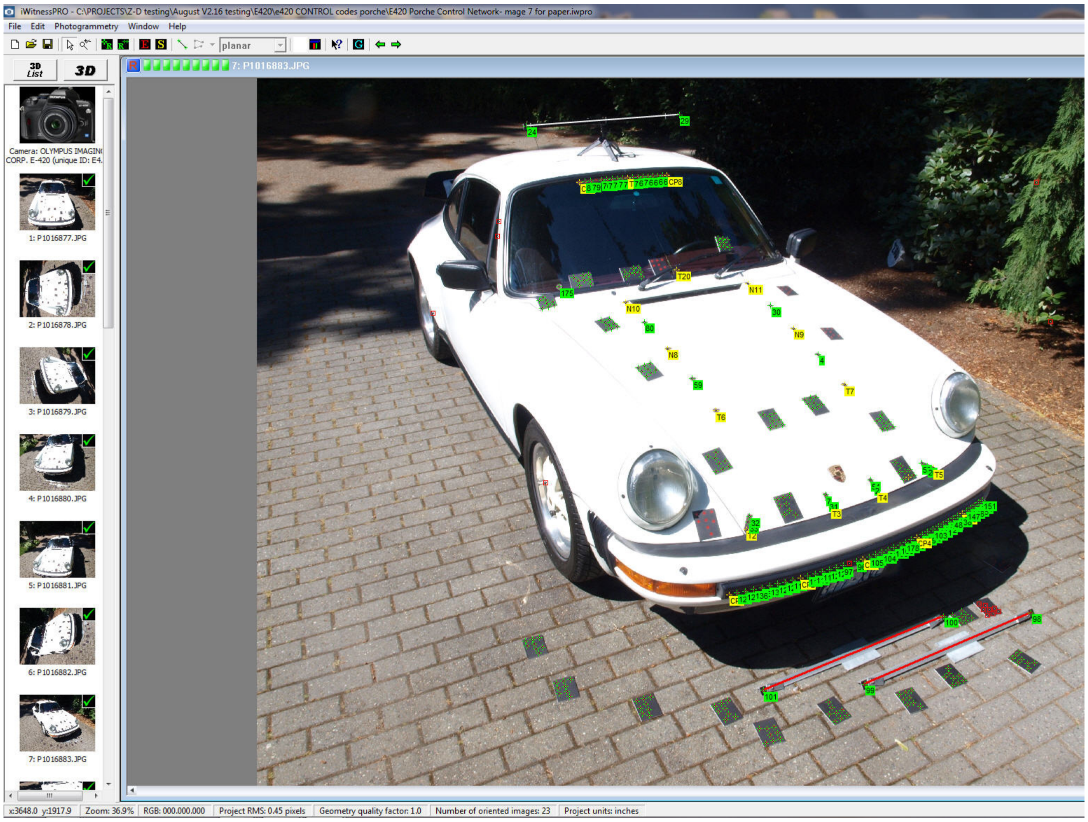
The second step was to record images with each study camera from four camera positions, where all the cameras positions and camera aim points were generally the same locations for all of the measurement networks. The minimum intersection angle was approximately 40 degrees, while the maximum was 70 degrees for all computed 3D points. For Z-D testing, the lens was a different focal length in all four camera positions used, with one of the four being at the lens widest FOV. The control network was obtained with an Olympus E420 with 14-42mm lens, from twenty-three camera stations and a mix of both landscape and portrait orientation shots.

iWitnessPRO processed twenty-three images in the E-420 control network in approximately 60 seconds, computing a quantity of 315 object points (i.e., the temporary applied red-dot passive targets and coded targets).

The imagery for each study camera was processed as a Z-D Network. In addition, one E-450 Network and one Kodak C142 Network were each computed using the Z-D calibration *for the other camera of the same model*. All targets on the hood were manually referenced in *iWitnessPRO*, but referencing was fully automatic 'target centroid' measurement for all other red/black synthetic targets that were applied.

Finally, comparisons were made between the vehicle results. The E-420 control network, with an internal accuracy estimate of 0.006" RMS, (or 1:18000 of object size) was used as the reference base. The object space "check distance" (scale bar) satisfactorily agreed with the internal measurement estimates within the control network. The coordinate system was defined from one of the codes on the ground, adjacent to the passenger front tire and all Z-D and EXIF networks were later placed into the same coordinate reference system by using the least squares coordinate transformation feature called "*Transformation to Control*" within *iWitnessPRO*.

Figure 4 Vehicle Target Pattern



iWitnessPRO - C:\PROJECTS\Z-D testing\August V2.16 testing\E420\e420 CONTROL codes porche\E420 Porche Control Network- mage 7 for paper.iwpro

x:3648.0 y:1917.9 | Zoom: 36.9% | RGB: 000.000.000 | Project RMS: 0.45 pixels | Geometry quality factor: 1.0 | Number of oriented images: 23 | Project units: inches

Figure 5: The 19 points of the E-420 Control Network:

Location	Point Name
Front Bumper (Passenger side)	C1
Front Bumper	C2
Front Bumper	C3
Front Bumper	C4
Front Bumper (Drivers side)	C5
Hood Leading edge	T2
Hood Leading edge	T3
Hood Leading edge	T4
Hood Leading edge	T5
Hood	T6
Hood	N8
Hood	N10
Hood	N11
Hood	N9
Hood	T7
Windshield Base Center	T20
Windshield Upper Passenger side	CP7
Windshield Upper Center	T1
Windshield Upper Driver side	CP8

Discussion of the vehicle Z-D Networks

Six networks were evaluated for the two Olympus E-450 cameras, seven networks for the two Kodak C-142 cameras, two networks for the Nikon S510, and two networks for the Canon SD 1300IS.

The Olympus E-450 lens were zoomed to the "tick-marks" on the lens body for the widest FOV at focal length 14mm, plus approximately 20mm, 25mm and 30mm.

The two Kodak C142 Easyshare cameras displayed an electronic zoom slider bar (through rotating the optical zoom lever), that was subjectively adjusted to "*set*" intermediate focal lengths at 6mm, then approximately 9mm and 14mm, plus the narrowest FOV at 17mm.

The Nikon Coolpix S510 zoom control was similar to the Kodak, and was set at approximately 5mm 8mm, 10mm, and 17mm.

The Canon SD1300 IS Powershot was set to four focal lengths of approximately, 5mm, 8mm, 14mm, and the narrowest at17mm.

One image set for each test camera was processed with the *iWitnessPRO* software using the Z-D camera calibration and a second image set using the 'approximate' focal length as read from the image EXIF meta tag. Both the Z-D and EXIF networks were then compared to the Olympus E420 Control Network as a measure of accuracy. Comparison between the Z-D and EXIF networks illustrate the difference of zoomed imagery from a metrically calibrated camera versus zoomed imagery from a non-calibrated camera.

The networks from the pairs of *exemplar* cameras, the two Olympus E450 DSLR's and the two Kodak C142 PAS cameras, represent a situation where the camera that captured the available imagery cannot be obtained for Z-D calibration but an exemplar camera can be. Comparison of the networks obtained using the camera that captured the imagery, but using the Z-D calibration for an exemplar camera illustrates the variation possible among PAS and DSLR cameras of the same model.

Lack of EXIF information

In some situations digital images are the only evidence of a vehicle or scene and the EXIF meta tag information does not exist in the file. The only reliable approach to determine the camera's inner orientation parameters is the traditional process of solving for the *camera absolute orientation* (i.e., back-calculation of the camera position and camera aim through measurement of known control points). The **FOOM** (**F**ocal length Fr**o**m **O**ne I**m**age) function in *iWitnessPRO* is one proven method to obtain the camera absolute orientation. An example of the **FOOM** process is included here using the four images from one of the Kodak C142 cameras, with their EXIF data removed, making the images appear to be from "unknown" camera(s)). FOOM requires independent knowledge of the XYZ coordinates of eight or more points in each image in order to solve the focal length, principal points and K1 radial distortion. Marking and analysis of the FOOM network typically requires about twice as long as compared to a Z-D network.

The first row of each coordinate comparison table shows the ***RMS Error** (in inches)* for all the points in the network, expressed as residual vectors in the X-Axis (VX) Y-Axis (VY), and Z-Axis (VZ) columns, and the Total RMS error under the "*Discrepancy Vector*" column. The second row in each comparison table shows the ***Error Range** (inches)* of the 3D affine coordinate transformation (*read from the iWitnessPRO "3D Transformation to Control" dialog*). The coordinate system was defined relative to one of the iWitnessPRO codes arbitrarily placed on the ground, with the coordinate axes +X in the general pointing direction of forward to aft of the vehicle, +Y from the driver side toward the passenger's side and +Z upward. All numbers in the tables were rounded to two decimal places.

Vehicle Test Results for the two Olympus E-450 Cameras

Vehicle Errors for Camera #9914 imagery using its Z-D calibration:

Camera #9914	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.04	0.05	0.02	0.07
Error Range (inches)	-0.01 – 0.04	-0.00 – 0.02	-0.02 – 0.08	0.08

Vehicle Errors for Camera #9914 imagery using the Z-D calibration of camera #9896:

Camera #9914	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.04	0.04	0.32	0.07
Error Range (inches)	-0.02 – 0.11	-0.06 – 0.03	-0.07 – 0.06	0.06

Vehicle Errors for Camera #9914 imagery using EXIF recorded Focal Lengths:

Camera #9914	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.26	0.35	0.08	0.45
Error Range (inches)	-1.15 – 2.76	-0.49 – 0.63	-0.47 – 1.05	1.04

Vehicle Errors for Camera #9896 imagery using its Z-D calibration:

Camera #9896	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.06	0.01	0.02	0.06
Error Range (inches)	-0.12 – 0.09	-0.02 – 0.03	-0.03 – 0.06	0.04

Vehicle Errors for Camera #9896 imagery using the Z-D calibration of camera #9914:

Camera #9896	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.07	0.017	0.02	0.07
Error Range (inches)	-0.11 – 0.15	-0.03 – 0.04	-0.05 – 0.03	0.04

Vehicle Errors for Camera #9896 imagery using EXIF recorded Focal Lengths:

Camera #9896	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.39	0.22	0.07	0.46
Error Range (inches)	-1.00 – .75	-0.57 – 0.73	-0.04 – .73	0.76

Vehicle Test Results for the two Kodak C142 Easyshare cameras

Vehicle Errors for Camera DCS imagery using its Z-D calibration:

Camera DCS	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.03	0.03	0.02	0.05
Error Range (inches)	-0.07 – 0.17	-0.04 – 0.05	-0.03 – 0.09	0.05

Vehicle Errors for Camera DCS imagery using the Z-D calibration of camera AFI:

Camera DCS	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.085	0.18	0.05	0.21
Error Range (inches)	-0.76 – 1.75	-0.08 – 0.29	-0.31 – 0.66	0.64

Vehicle Errors for Camera DCS imagery using EXIF focal length only:

Camera DCS	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.27	0.28	0.07	0.40
Error Range (inches)	-0.98 – 2.34	-0.14 – 0.40	-0.37 – 0.94	0.91

Vehicle Errors for Camera DCS imagery using FOOM:

Camera DCS	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.11	0.07	0.02	0.13
Error Range (inches)	-0.13 – 0.14	-0.13 – 0.13	-0.05 – 0.04	0.07

Vehicle Errors for Camera AFI imagery using its Z-D calibration:

Camera AFI	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.06	0.09	0.02	0.1

Error Range (inches)	-0.22 – 0.52	-0.05 – 0.08	-0.09 – 0.21	0.2

Vehicle Errors for Camera AFI imagery using the Z-D calibration of camera DCS:

Camera AFI	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.085	0.18	0.05	0.21
Error Range (inches)	-0.67 – 0.37	-0.06 – 0.06	-0.33 – 0.15	0.34

Vehicle Errors for Camera AFI imagery using EXIF focal length only:

Camera DCS	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.14	0.09	0.02	0.16
Error Range (inches)	-0.36 – 0.88	-0.19 – 0.19	-0.15 – .034	0.33

Vehicle Test Results for the Nikon S510

Vehicle Errors for Camera Nikon S510 Coolpix imagery using its Z-D calibration:

Camera DCS	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.84	0.08	0.27	0.12
Error Range (inches)	-0.24 – 0.60	-0.05 – .08	-0.08 – 0.13	0.21

Vehicle Errors for Camera Nikon S510 Coolpix imagery using EXIF focal length only:

Camera DCS	VX	VY	VZ	Discrepancy Vector
RMS Error (Inches)	0.52	0.52	0.29	0.79
Error Range (inches)	-3.2 – 1.4	-0.6 – 0.37	-1.2 – 0.59	1.22

Vehicle Test Results for the Canon SD 1300IS

NOTE: the Canon camera had "in-camera lens distortion correction". The Linear Z-D mode was required for the Canon SD 1300 IS. All other cameras in the study used the Power-ZD mode. The correct Z-D mode was determined automatically by iWitnessPRO.

Vehicle Errors for Camera Canon SD1300 IS imagery using its Z-D calibration:

Camera Canon	VX	VY	VZ	Discrepancy
RMS Error (Inches)	0.09	0.08	0.02	0.12
Error Range (inches)	-0.23 – 0.53	-0.03 – 0.06	-0.1 – 0.21	0.20

Vehicle Errors for Camera Canon SD1300 IS imagery using EXIF focal length only:

Camera Canon	VX	VY	VZ	Discrepancy
RMS Error (Inches)	0.33	0.11	0.16	0.38
Error Range (inches)	-5.34 – 2.13	-1.32 – 1.57	-2.09 – 0.86	2.12

Results of Study

The tests of the two Olympus E-450 DSLRs showed the Z-D based networks matched the control network better than 0.1" RMS. Similarly, the two networks which used the Z-D calibrations from the other camera, matched the control network of the Olympus E-420 better than 0.1" RMS, which suggests that using the Z-D calibration from exemplar DSLR cameras might not adversely affect small scale or vehicle crush reconstruction analysis The maximum errors for Z-D based networks for the DSLR cameras were less than 0.2 inches.

The tests of the two Olympus E-450 DSLRs EXIF based networks (using only the approximate focal length for the camera parameters) were significantly less accurate and produced RMS errors six or more times larger than the Z-D calibration networks. The largest EXIF based network errors for the two cameras ranged from about 0.76 inches to 1.04 inches. While the use of an EXIF focal length based network might seem to be acceptable in some small scale situations, there is insufficient empirical or theoretical bases to support that application, and it is not recommended.

The tests of the two Kodak C-142 PAS cameras showed the Z-D based networks also matched the control network within 0.1" RMS. The Kodak Z-D RMS error was a bit larger than the DSLR Z-D RMS error and showed considerable variation between the individual Kodak cameras, but was impressive for an inexpensive camera, when its Z-D calibration was used. The maximum absolute errors for Z-D based networks for the Kodak cameras were less than 0.7 inches, which is small compared to the uncertainty of other variables in a vehicle crush analysis. The accuracy of two Kodak networks which used the Z-D calibrations from the other Kodak camera, were comparable to the Kodak EXIF based networks, which do not have an empirical or theoretical basis, so neither exemplar Z-D or EXIF based networks are recommended for PAS cameras.

The tests of the two Kodak C-142 PAS, EXIF based networks (using only the approximate focal length for the camera parameters) were significantly less accurate and up to 16 times larger in the discrepancy error range than their Z-D calibration networks.

The test of one Kodak C-142 network, treated as an unknown camera with focal lengths and lens distortion parameters determined by the *iWitnessPRO* FOOM method, produced errors comparable to the Z-D calibration network for the same camera. The test demonstrates the capability of the FOOM, but it requires significantly more 3D knowledge within the image and greater effort.

The small scale tests of the Nikon S510 PAS camera showed the Z-D based network accuracy was comparable to the Kodak C-142 PAS camera Z-D networks. However, the Nikon EXIF based network errors were several times larger than the Kodak EXIF network errors.

The tests of the Canon SD 1300 IS PAS camera showed the Z-D based network accuracy was comparable to the Kodak C-142 PAS camera Z-D networks. However, the Canon EXIF based network errors were as much as 6 times larger than the Kodak EXIF network errors. The Canon imagery had in-camera correction for lens distortion so the Z-D calibration was linear rather than a power function.

It has been demonstrated by the camera parameters used, and resulting data presented in the *Vehicle Test Result Tables,* that significantly larger errors for the EXIF based network occurred when the principal point and K1 radial distortion are "defaulted" to zero (0) for the camera's inner orientation parameters, and the fact that the EXIF focal length is only 'approximate' rather than an accurate metric calibration of these same parameters using Z-D.

Conclusions and Recommendations:

Zoom-Dependent Camera Calibration provides a method to efficiently and reliably obtain 3-dimensional measurements from consumer grade DSLR and PAS digital camera images, without restricting the full use of a zoom lens capability. The accuracy of Z-D networks has been demonstrated to be suitable for accident reconstruction analysis projects.

Obtaining a Z-D calibration for a camera involves a reasonable initial effort and negligible additional processing effort for subsequent networks, in return for removal of the traditional ‘fixed’ zoom lens restriction in close-range photogrammetry.

Network analysis based on Z-D calibration has a provable basis to be a valuable tool for image-based measurement in accident reconstruction applications.

The tests support Z-D as a much more efficient, but equally accurate, alternative (*or an additional method available*) to the more traditional photogrammetrical means requiring control points, e.g. FOOM.

The accuracy of a Z-D based network was comparable to a FOOM based network while the EXIF based networks in this study were much less accurate. Z-D calibration of the imagery camera provides an empirical basis for confidence in the accuracy of a Z-D based network, while there is no equivalent support for an EXIF based network and its use is not recommended because it is unpredictable.

Radial distortion is present in varying degrees in consumer grade digital cameras but its magnitude is not identified in readily available camera specifications. The importance of determining the radial distortion and correcting the network to account for that distortion had been demonstrated by others, along with corrective schemes. A Z-D calibrated camera determines and corrects for the radial distortion, focal length and principal point offsets automatically throughout the full zoom range of a digital camera’s telephoto lens.