Stereo-DIC Challenge Plate Analysis Discussion Document

Introduction

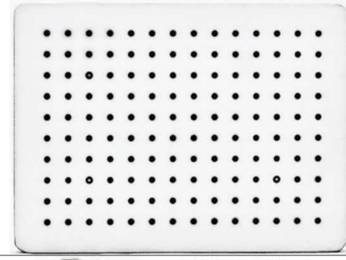
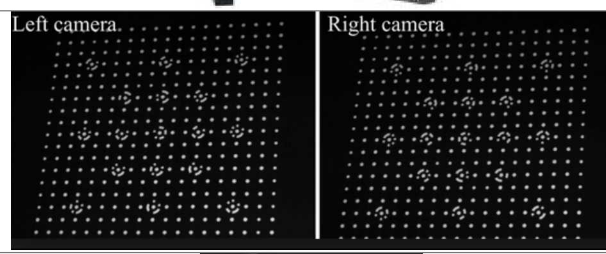
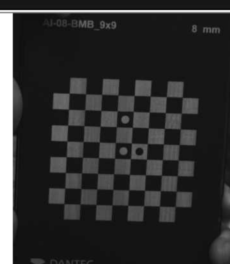
This document outlines the preliminary analysis of the Stereo-DIC Challenge Plate translation test images. The calibration and translation files are contained on Google Drive in folders at: https://drive.google.com/drive/folders/1uLZdQscdt3pWVwNZU7HBaCxNlUx7ByJb?usp=sharing .

The calibration images are broken up by directory based on the vendor calibration target as shown in Table 1. The translation files are contained in the same directory. This document covers ideas for comparing data between the different DIC systems and the laser scan data (available as download with the images). The first step is to get a common coordinate system to do the comparisons. The second step is to get the data at the exact same physical locations for comparison. Approaches to solve both problems are outlined below. Comments and suggestions are welcome on improved approaches. First, we review the experimental setup and acquisition of the calibration images.

Stereo Calibration Images

All the commercial vendors have provided an appropriately sized calibration grid for the plate translation experiment. The list of calibration targets and the corresponding name in the Stereo-Challenge directory is shown in Table 1. Unfortunately, the target from CorreliSTC was not received before the experiment and was not imaged. All other targets were imaged according to the vendors instructions. *Synthetic* images have been created for the bi-level, standard, and checkerboard targets. The GOM targets have not been simulated at this point (we would need the layout specifications for them). The calibration parameters used in the simulation are reported in the provided text file. It uses the standard pinhole model with intrinsic and extrinsic parameters.

Table 1. List of known calibration target types.

Vendor	Calibration Board
Basic Calibration target: 3 special dots Correlated Solutions, MatchID, and… Exp. images: DotGrid10-mm.zip Sim. images: SimDotCal-14x10-10mm.zip	
3D target with dots at 2 levels LaVision Exp. images: LaVision106-10.zip Simulated images: SimTwoLevelCal10mm2.2Dia2mmLevel.zip	
Coded calibration targets GOM/Trilion Exp. images: GOMCP20MV90x72.zip Sim. images: No simulated images.	
Grid Target Dantec Exp. images: DantecAI-08-BMB9x9-8mm.zip Sim. Images: No simulated images.	
Standard checkerboard pattern CorreliSTC Exp. images: Experimental not imaged. Sim. images: SimCheckerBoardCal.zip	

Balcaen Simulator

The simulator that will be used by the stereo challenge was written by Ruben Balcaen, PhD student at KU-Leuven (now at MatchID). The details of the simulator are completely described in [1]. This simulator is independent of all commercial vendors to avoid the appearance of impropriety. It was completed before Ruben joined MatchID.

Stereo Sample 1 and 2 – Translation of plate with known features

Image sets 1 and 2 are a rigid-body translation of a plate with 3D features of known dimensions. Figure 1 shows the dimensions of the as designed plate with features that include two triangles with 45˚ angles, two half cylinders in perpendicular directions and a flat raised section. The features were measured using a laser scanning system after the sample was painted. The laser scanner was a FARO Edge and ScanArm HD system, with an accuracy quoted as ±25 µm. A comma separated file is provided in the experimental directory (LaserData_mm.csv) with the X, Y and Z measured positions in millimeters. A Coordinate Measurement Machine (CMM) was also used to measure the as-built step height, triangle angle, and radius of the cylinder.

Two stereo-camera pairs were setup to view the plate (see Figure 3), System 1 used 35-mm lenses (Edmund Optics) and System 2 used 16-mm lenses (Tamron). The aperture was set to approximately f/8. All four cameras were FLIR (formerly PointGrey) Grasshopper 2 (Gras-50S5M) cameras with 3.45-µm pixels. As the 16-mm lenses required the cameras to be closer (280 mm stand-off from the plate, 140 mm baseline between the cameras) to have the equivalent field-of-view (FOV) of the 35-mm system, they were positioned slightly above the mid-line of the sample looking down. The 35-mm cameras were further back (648 mm stand-off from the plate, 254 mm baseline between the cameras), positioned below the 16-mm setup and looking up to avoid heat waves from the front cameras. The cameras warmed up for an hour acquiring images before data was taken. The sample was painted with a thin coat of white paint and speckled by hand using a Sharpie marker (laser scan measurements were made *after* painting). Speckle sizes were large enough to ensure that they were not aliased, with average speckle size of 7.7±1.5 pixels (Blob analysis) and 7.1 pixels (auto-correlation) with 32% coverage. LED lights were positioned above and behind the cameras to minimize possible heat waves in the images from the lights. A fan was positioned to blow air across the region between the sample and the cameras, to homogenize the air temperature and reduce errors due to heat waves. The cameras and sample/stage were all mounted on a floating optical table to reduce effects of building vibrations.

The plate was mounted on a 2-axis Aerotech stage with a high-precision linear encoder and feedback control of the position. Measured position accuracy of the stage by the vendor is shown in Figure 2. The stage was setup to translate in the X and Z-directions (U- and W-displacements) in steps of known amounts (see Table 2). The mean and standard deviation of the stage displacement as measured by the stage's optical encoders, along with the corresponding filename are in Table 2. The files are contained in directories labeled by the lens focal length. Stereo file naming conventions with _0 (left camera) and _1 (right camera) for the cameras were used for both the calibration and translation images. Five images were taken at each stage position to be able to calculate the image noise or other statistics. The field-of-view was setup to maintain the entire sample in the image for all translation positions. Total experimental time to acquire images from Step01 to Step18 was approximately 8 minutes. Step18 returned the stage back to the origin and is a measure of the system stability over the test period.

The plate was scanned before testing with both a coordinate measurement machine (CMM) and a laser scanner. Laser scanner surface maps are available with the images as a comma separated file with three columns of X, Y and Z. Dimensions are in millimeters in the uploaded file.

Table 2. Translation plate filenames and amount of translation.

Step	Filename 16-mm	Filename 35-mm	W Mean (mm)	StDev (nm)	U Mean (mm)	StDev (nm)
1	Step01 00,00-sys1-0000_0.tif	Step01 00,00-0000_0.tif	0	6.76	0	7.01
2	Step02 00,-10-sys1-0000_0.tif	Step02 00,-10-0000_0.tif	10	6.16	0	7.69
3	Step03 00,-20-sys1-0000_0.tif	Step03 00,-20-0000_0.tif	20	6.21	0	6.30
4	Step04 00,10-sys1-0000_0.tif	Step04 00,10-0000_0.tif	-10	6.12	0	7.67
5	Step05 00,20-sys1-0000_0.tif	Step05 00,20-0000_0.tif	-20	6.33	0	6.74
6	Step06 10,00-sys1-0000_0.tif	Step06 10,00-0000_0.tif	0	6.83	-10	4.91
7	Step07 20,00-sys1-0000_0.tif	Step07 20,00-0000_0.tif	0	7.27	-20	5.71
8	Step08 -10,00-sys1-0000_0.tif	Step08 -10,00-0000_0.tif	0	6.79	10	6.53
9	Step09 -20,00-sys1-0000_0.tif	Step09 -20,00-0000_0.tif	0	7.37	20	5.69
10	Step10 10,10-sys1-0000_0.tif	Step10 10,10-0000_0.tif	-10	4.57	-10	5.99
11	Step11 20,20-sys1-0000_0.tif	Step11 20,20-0000_0.tif	-20	25.19	-20	14.65
12	Step12 -10,-10-sys1-0000_0.tif	Step12 -10,-10-0000_0.tif	10	6.43	10	7.65
13	Step13 -20,-20-sys1-0000_0.tif	Step13 -20,-20-0000_0.tif	20	6.54	20	6.10
14	Step14 10,-10-sys1-0000_0.tif	Step14 10,-10-0000_0.tif	10	6.08	-10	5.70
15	Step15 20,-20-sys1-0000_0.tif	Step15 20,-20-0000_0.tif	20	6.45	-20	5.14
16	Step16 -10,10-sys1-0000_0.tif	Step16 -10,10-0000_0.tif	-10	5.01	10	6.29
17	Step17 -20,20-sys1-0000_0.tif	Step17 -20,20-0000_0.tif	-20	6.07	20	5.99
18	Step18 00,00-sys1-0000_0.tif	Step18 00,00-0000_0.tif	0	7.59	0	6.36

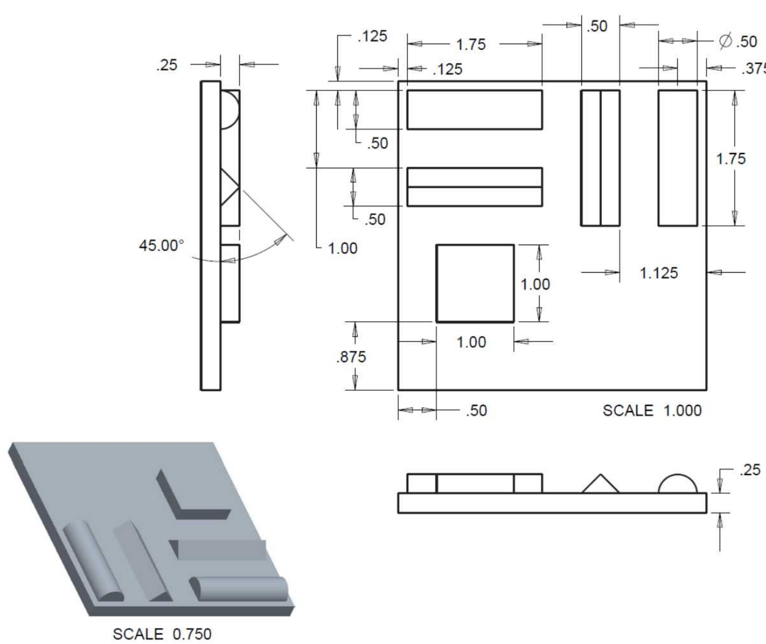


Figure 1. As designed dimensions of translated plate. All units are in inches.

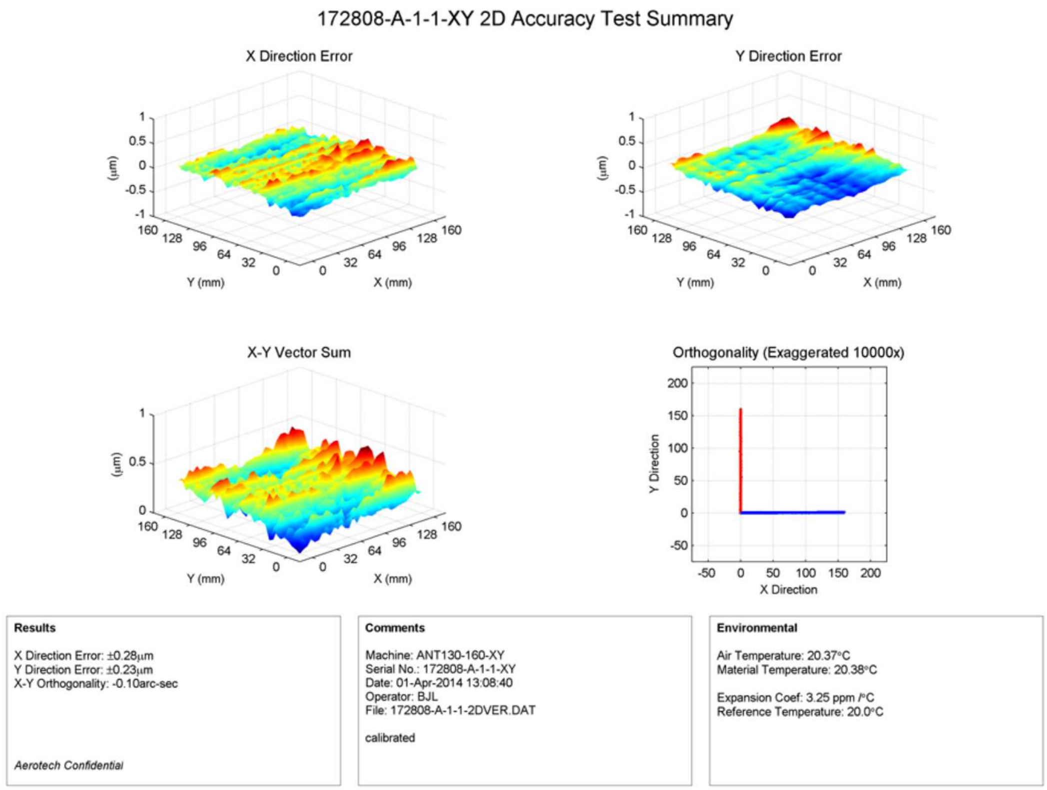


Figure 2. Measured positional accuracy of the Aerotech stage used for the experiment. Not shown: Linear stage flatness peak-peak better than 1.36 µm.

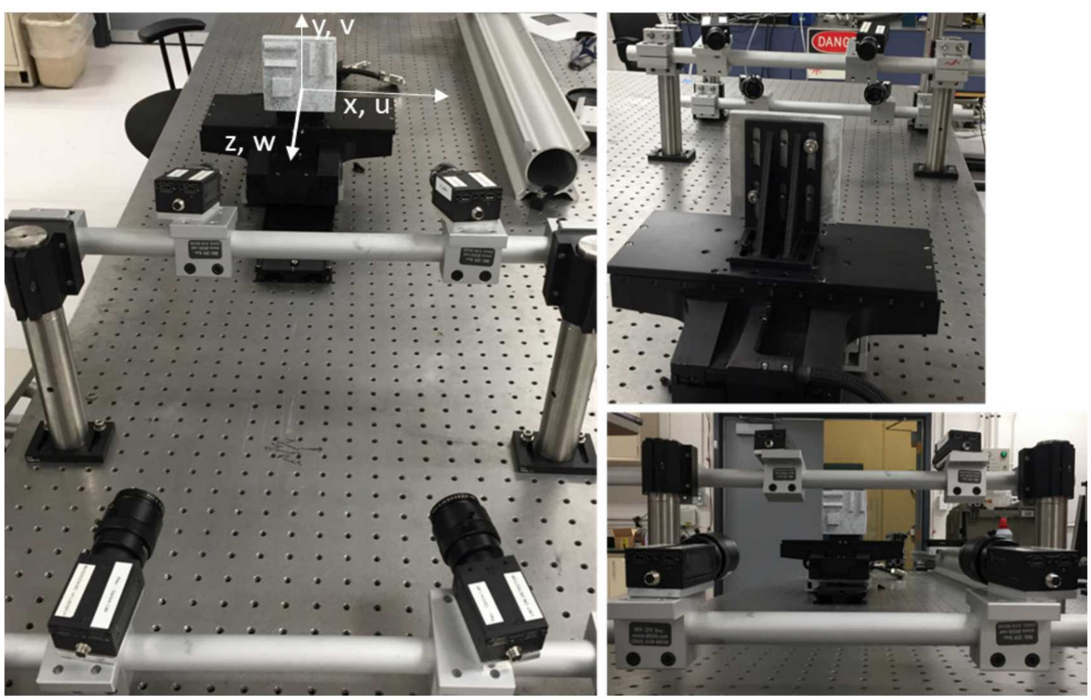


Figure 3. Aerotech stage setup with the two DIC systems. 16-mm lenses in the front and 35-mm lenses in the back. Coordinate system is shown.

Calibration

We acquired many (>50) images spread throughout the calibration volume and with a wide variety of motions including: twist about the X-axis (ca. +/- 20 degrees), tilt about the Y-axis (ca. +/- 20 degrees), plunge in the Z-direction (ca. +/- 25 mm), and translation in X- and Y-directions to ensure the calibration target filled the FOV. We also rotated the calibration target 90 degrees about the Z-axis and repeated some of the motions. We captured two sets of calibration images, one with the target's nominal orientation angled slightly down towards the 35-mm cameras and one set with the target's nominal orientation angled slightly up towards the 16-mm cameras. For vendors who provided specific orientations/locations, we captured those images as well and they are supplied in the zip folder in no particular order. The calibration target was held by hand, but the image exposure was less than 25 ms to minimize motion blur. Calibration scores were within expected values as measured by Vic3D and MatchID. In the calibration folder, the nominal parameters for the basic calibration target (14x10-10mm) are listed in a semicolon delimited text file.

Simulated Calibration Images

Simulated calibration images are provided for the different calibration targets as discussed previously. The scores and results from the simulated standard calibration images were checked against the physical experiments and provided similar results. The simulated calibration images are:

1. Checkerboard with 10-mm spacing
2. Simulated dot 14×10-10mm spacing
3. Two-level Grid 106-10 target; 10mm spacing, 2.2mm dots and 2mm level

Simulated Translation Images

A surface mesh of the as designed specimen was created and translated according to Table 2. Simulated images corresponding to the movements are available. The speckle pattern used was from an image of a printed speckle pattern. This pattern was then morphed to fit the as-designed shape of the plate and then numerically translated according to the commanded displacements.

Example Results for Experimental System 1 and System 2

A minimal analysis was done on both Systems 1 and 2. Figure 4 shows the displacement results of the two DIC systems, averaged over the entire DIC region (lines dashed and solid), as well as the average displacements measured by the optical encoder on the stage (point and "X"). The U and W motion compares at this scale exactly with the stage results. There is some vertical displacement, well above the stage specifications, correlated with the motion. This may indicate some coordinate system misalignment. Because of this, displacement magnitudes (the vector sum of the U, V and W) are used for a comparison. Figure 5 shows the difference between the stage encoder and each of the DIC systems, as well as the difference between the two DIC systems. The difference between the DIC systems is less than the difference between the stage and each DIC system. However, the plate upon returning to the home location, does not have any rigid-body-offset from zero as shown in Figure 6. Not sure of the cause at this time.

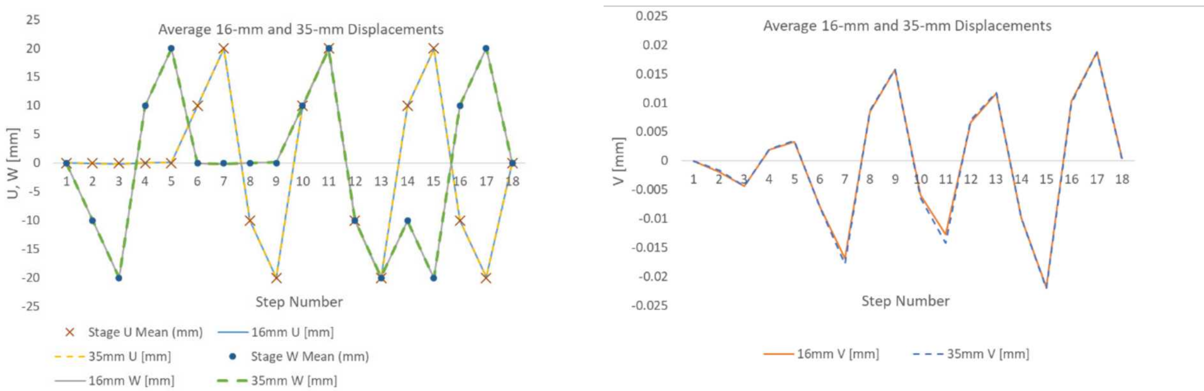


Figure 4. Translation comparison between DIC and Aerotech displacements. Lines are from the DIC results. Points are from the stage displacement. U and W are on the primary axis, and V is on the secondary axis.

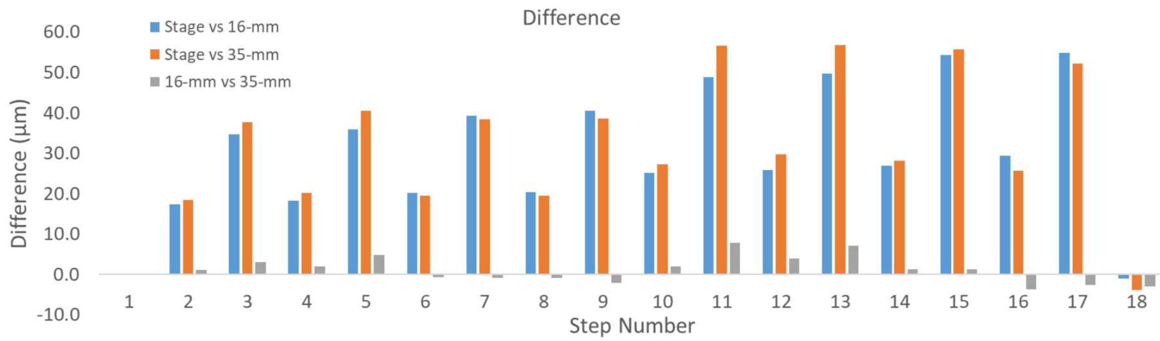


Figure 5. Difference in displacement magnitudes between the stage and each of the DIC systems, as well as the difference between the two DIC systems (16-mm and 35-mm systems).

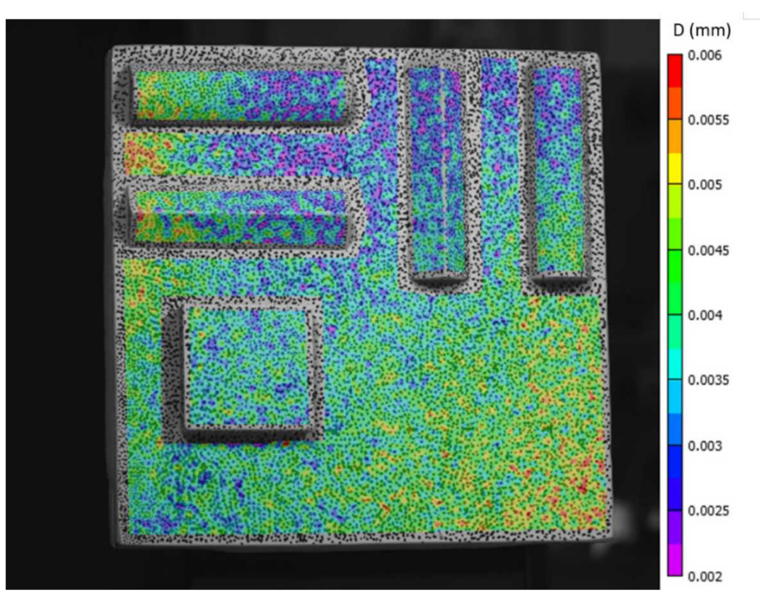


Figure 6. Residual displacement magnitude at the final step position (35-mm system).

Figure 7 presents a 3D plot of the laser scan data. A vertical line cut was taken from the laser scan and from the full-field DIC data (both experimental and simulated DIC data), and these line cuts are plotted in Figure 8. At this point, registration of the three sets of full-field data is only approximate. We are currently investigating the use of iterative closest point (ICP) algorithms to register different sets of full-field data exactly, based on the shapes of the features on the plate, but other suggestions are welcome. There is generally good agreement between the laser scan, the simulated DIC, and the experimental DIC results, but a more careful analysis must wait until the data registration is improved.

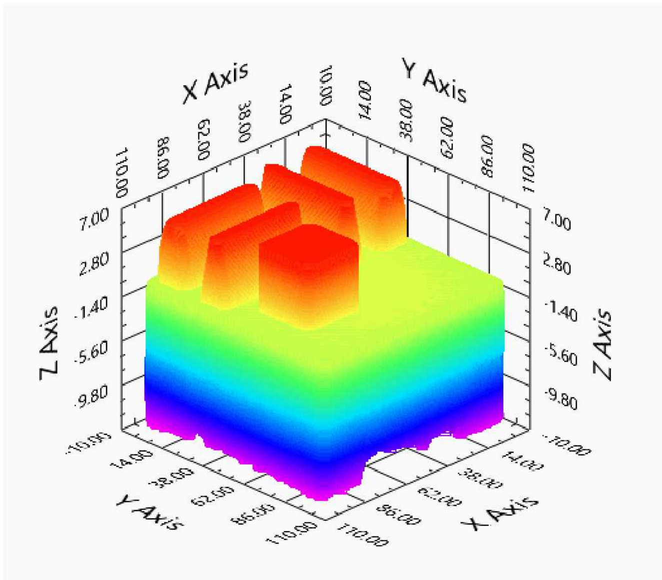


Figure 7. Laser scan data in millimeters.

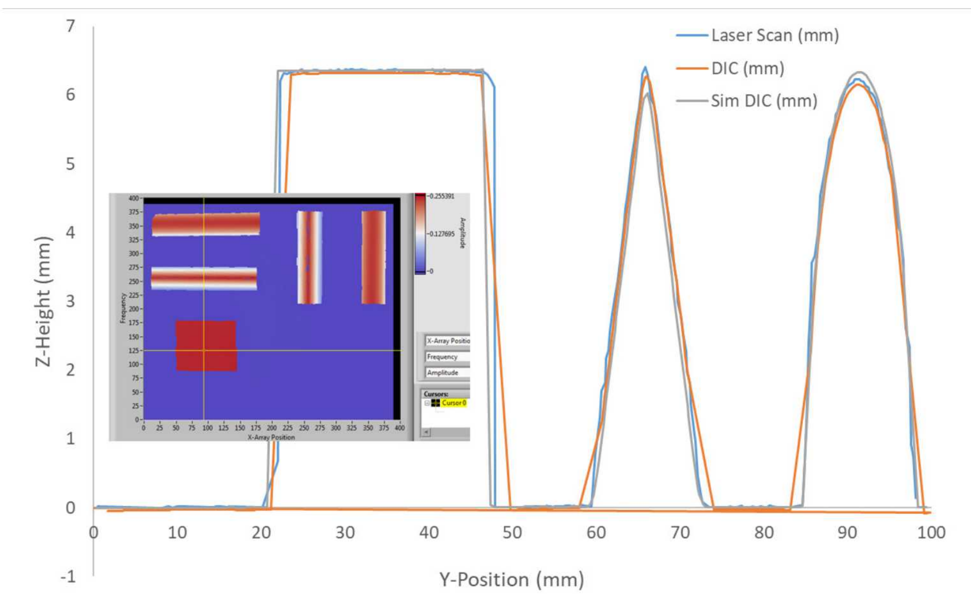


Figure 8. Extracted vertical line cut from the CMM, 35-mm DIC and 35-mm simulated DIC.

Comparison Ideas

Before we can compare two sets of full-field data, we need to register or align the two sets of data and transform them into a common coordinate system. This section outlines (1) a proposed method for defining a common coordinate system for DIC data (which simultaneously registers or aligns the data), (2) a proposed method for registering a set of DIC data and the laser scan data, and (3) a proposed method to interpolate data onto a common grid, and (4) a proposed method for comparing two sets of registered field data.

Obtaining a Common Coordinate System for Two Sets of DIC Data

The first step required for comparison of two sets of field data is to define a coordinate transform to bring all the data into a common coordinate system. For example purposes, we analyzed data from System 1 (35-mm) and System 2 (16-mm), both correlated with Vic3D, as our two sets of field-data. For the actual DIC Challenge, the different sets of field data will not only come from the two DIC systems, but also from different participants with different DIC software packages.

For our current exemplar problem, we used the “Multi-system” approach in Vic3D to get an exact match between System 1 (35-mm) and System 2 (16-mm) to a subpixel level. When we move to comparing field data from different DIC software packages, we propose using 2D correlation to obtain the subpixel matches between the reference image of System 1 and the reference image of System 2; then the two cross-correlation matches will give all needed pixel locations to a subpixel level.

After getting the exact subpixel locations between all 4 cameras, three points were chosen at known integer pixel locations in the reference image of System 1. The three points are labeled the origin, x-axis and top as shown in Figure 9. The idealized global coordinates listed in Table 3 were obtained by finding DIC pixel locations in X, and Y positions as near as possible to these integer “ideal” Global Coordinates X, Y, and Z. Also shown in Table 3 are the subpixel locations in the four cameras. For System 1, the Xs1 (X sensor 1) and Ys1 coordinates are integer pixel locations. The System 1 Xs2 (X sensor 2) and Ys2 are not integer locations because they are cross-correlation locations matched via DIC. The System 2 coordinates are also not integer pixel locations because they are the exact match for the integer pixel locations of System 1 matched via DIC. To determine the coordinate transform needed, the 3 locations listed for each system are triangulated to obtain the X, Y, and Z position of the 3 points (in any arbitrary coordinate system). These are then fit to the ideal “Global Coordinates” and a transform is calculated.

The X, Y and Z locations after best fit for System 1 and System 2 are also shown in Table 3. The results are not identical to the Global Coordinates X, Y and Z because the integer pixel locations, which must be used for System 1, are not at exact integer X, Y and Z locations. Z has a better fit because three points can always be brought to a plane. The chosen idealized global coordinates are not exactly at the pixel triangulated positions – but are very close. This approach was chosen to avoid the question as to which data is the “standard” used to define the coordinates. This approach is open for discussion.

Table 4 shows the coordinate transform matrix used for the data in this report. This transforms the DIC data from the camera coordinates to the Global Coordinates for System 1 and System 2. These matrices will be different for every system and every calibration done and a fit and transform will be required for all results. It is therefore proposed that all submitted results provide the X, Y and Z triangulated positions in the coordinate system of the submitted challenge data. We will then fit to the global coordinates as shown here and create a transformation matrix for each DIC result sent in for analysis.

Note: This idea could also be used for doing rigid-body motion removal by providing the X, Y and Z position at each translation step of these three points.

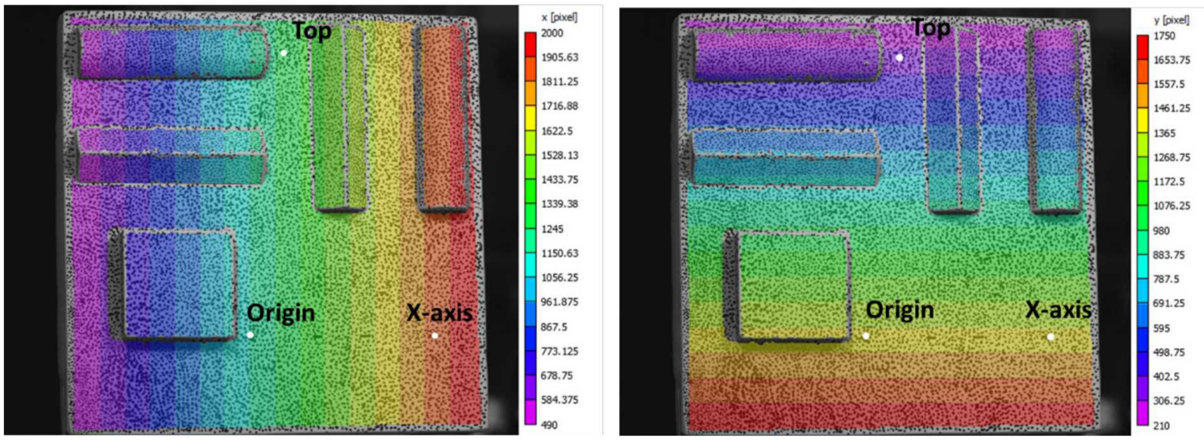


Figure 9. Locations of the three points to fit for transformation to analysis coordinate system (35-mm system).

Table 3. Pixel locations, global coordinates and coordinate fits.

	System 1 35-mm				System 2 16-mm				Global Coordinates			System 1 Fit			System 2 Fit		
Point Location	Xs1 [pix]	Ys1 [pix]	Xs2 [pix]	Ys2 [pix]	Xs1 [pix]	Ys1 [pix]	Xs2 [pix]	Ys2 [pix]	X [mm]	Y [mm]	Z [mm]	X [mm]	Y [mm]	Z [mm]	X [mm]	Y [mm]	Z [mm]
Origin	1164	1409	1150.901	1392.114	1092.909	1395.507	1193.652	1354.671	0	0	0	0.168159	-0.03816	0	0.168764	-0.03765	0
X	1855	1403	1843.909	1395.129	1738.654	1382.73	1859.497	1370.702	45	0	0	44.8353	-0.01943	-1.14E-13	44.8329	-0.0156	0
Top	1306	312	1345.901	294.1977	1312.953	317.6764	1267.083	268.0739	11	70	0	10.9966	70.0576	-1.14E-13	10.9983	70.0532	0

Table 4. Coordinate transform (Rotation and Translation) matrix.

System 1 35-mm Transform				System 2 16-mm Transform			
0.99917	0.002924	0.040622	27.1137	0.998135	-0.00034	0.061037	18.4342
0.001878	0.99305	-0.11768	-49.0985	-0.01246	0.977778	0.209274	77.7759
-0.04068	0.117655	0.992221	614.207	-0.05975	-0.20965	0.97595	257.103
0	0	0	1	0	0	0	1

Obtaining a common coordinate system for DIC data and laser scan data

To register data from the laser scan to the DIC, we must develop a different method than the one proposed in the previous section, since we cannot use cross-correlation of the speckle pattern for the laser scan data. As previously mentioned, we are currently pursuing the use of iterative closest point algorithms to align the laser scan data with the DIC data. Preliminary results indicate that the Iterative Closest Point (ICP) algorithm does not do a good job of registering this data set. We suspect this is because of the simple geometry of the part. This was studied by numerically transforming a sample set of data (with a known transform), and then using the ICP algorithm to fit and transform the data back. There was a residual misalignment of 25 µm after fitting. The results suggest that the DIC Challenge plate may lack sufficient “shape complexity” for the ICP algorithm. Other approaches to solving this problem are welcome.

Interpolation of field data onto a common grid

Once the coordinates for any two sets of full-field data are transformed into the same global coordinate system, the next step before the data can then be compared is to interpolate the data onto a common grid of coordinate locations. For example, to compare results from System B to System A (e.g. Z, U, V, and W), the data for System B must be interpolated to the exact X, Y position of System A. The data is now at the same location in space (X and Y) and the data can be subtracted. This involves a 2D linear interpolation between System A and System B due to small misalignments of the pixel data. If the DIC data is reported on a 1-pixel step size, only a small interpolation error between the data points will result when comparing two sets of DIC data. While higher order interpolations could be done, a inear interpolation was done for these results. Suggestions on the best method to do this interpolation are welcome.

For the laser scan data, If a common coordinate system can be determined, there are more than 2× the number of data points relative to the DIC results with a 1-pixel step size. This should allow interpolation to be done in a similar manner to the DIC results shown here.

Methods to compare full-field data sets between different systems: Example results

As an example, comparison between the results from System 1 (35-mm) and System 2 (16-mm) are shown here. It is hoped the same ideas can be used to compare between different DIC system results. The obvious problem here arises as to what the “baseline” system should be. For this example, the baseline is System 1.

The first check was to compare the X, Y and Z positions between the two systems (Figure 10). For X and Y, I only show the main area (although all ROIs had similar results). Machine precision differences remain after interpolation of the data between the systems. This indicates that the interpolation routines are working correctly and the coordinate transform is good. The Z measurement has some residual differences because the surface is not a true plane. The differences could arise because of differences in the Z-measurement of the two DIC systems, or a coordinate system misalignment. My assumption is this is a difference in measurement between the two systems because to is not a tilted plane error.

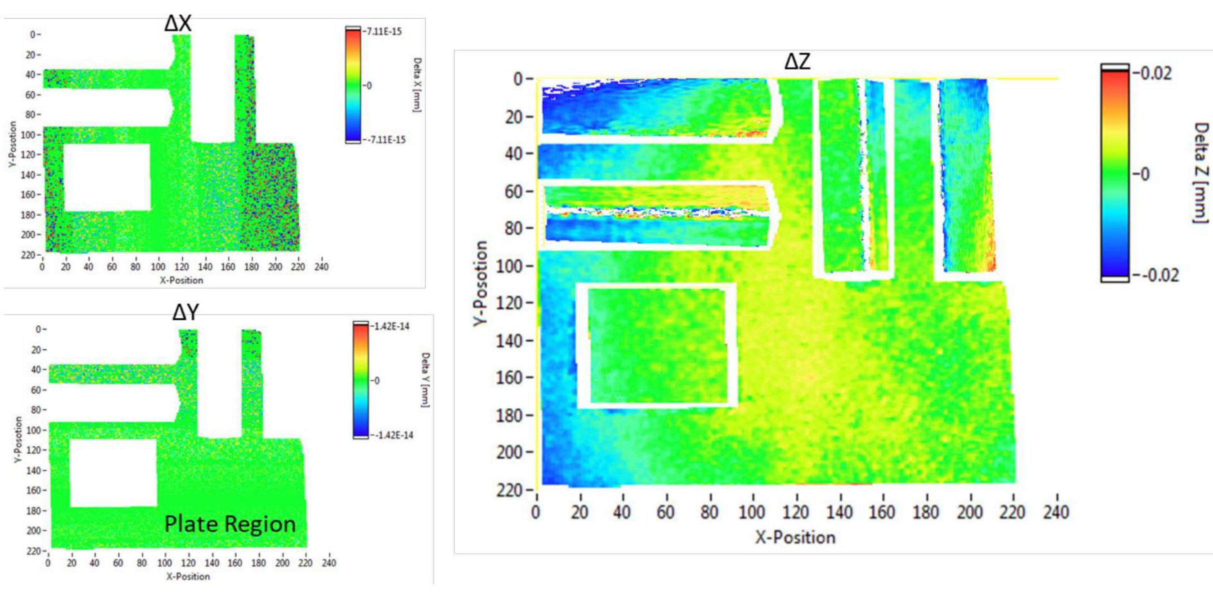


Figure 10. X, Y and Z comparison between System 1 and System 2. X and Y are machine precision. Z shows some differences.

Displacements (U, V and W) were also compared at three different step locations. The delta plots shown in Figure 11 to Figure 13 are the simple subtraction of System 2 from System 1 (after interpolation). The bias error listed under the color scale indicates an offset mean value calculated for the large plate region of the sample (see Figure 10).

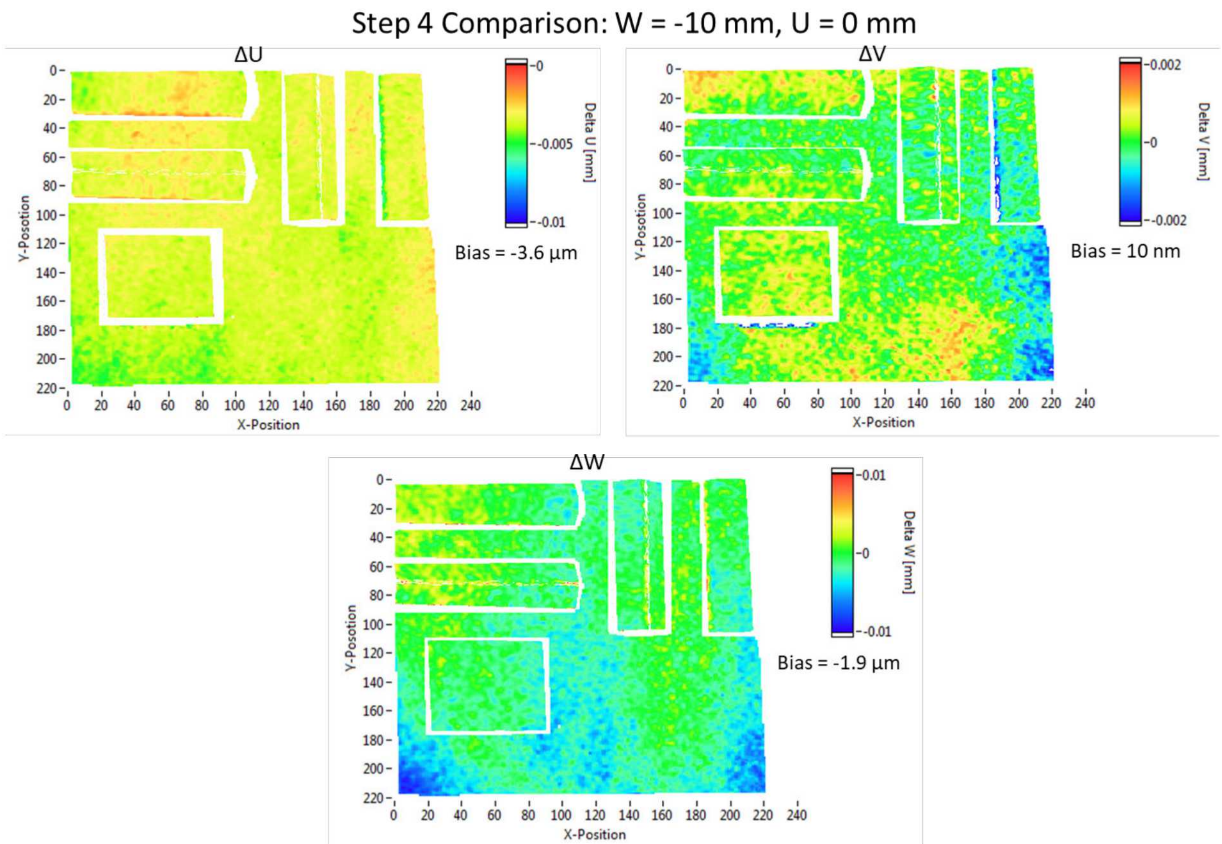


Figure 11. Difference in U, V and W between System 1 and System 2 for Step 4 at W = -10 mm and U = 0 mm. Bias indicates the mean value from the large ROI of the flat base plate.

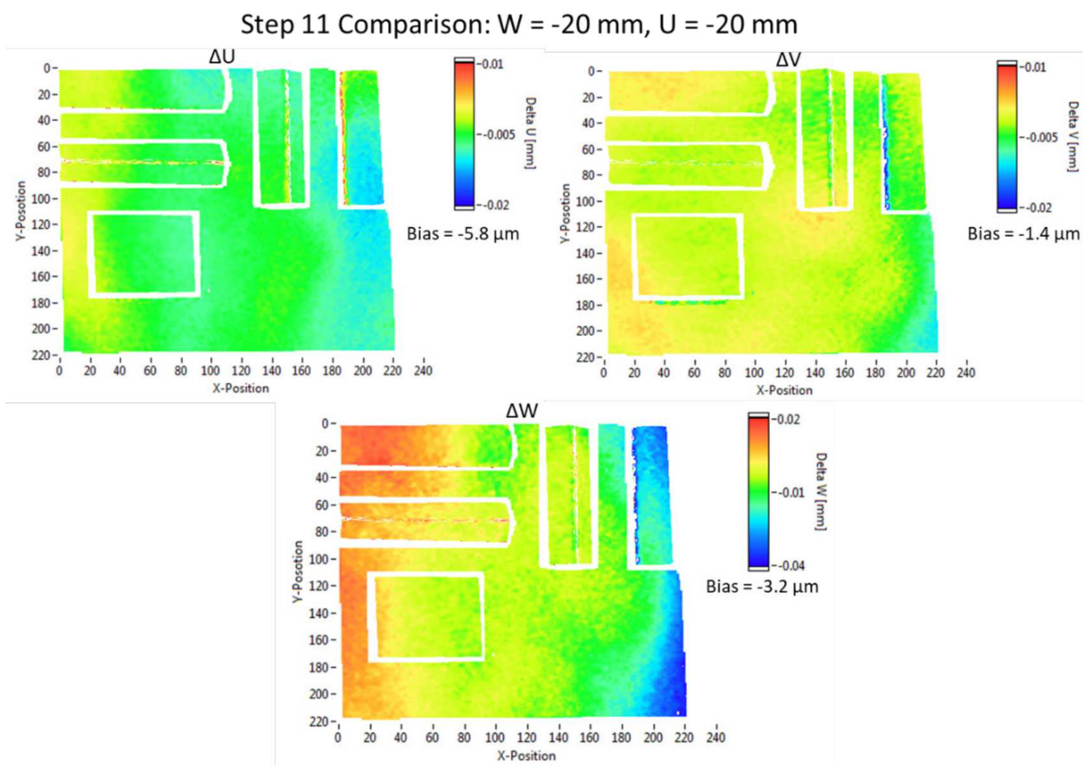


Figure 12. Difference in U, V and W between System 1 and System 2 for Step 11 at W = -20 mm and U = -20 mm. Bias indicates the mean value from the large ROI of the flat base plate.

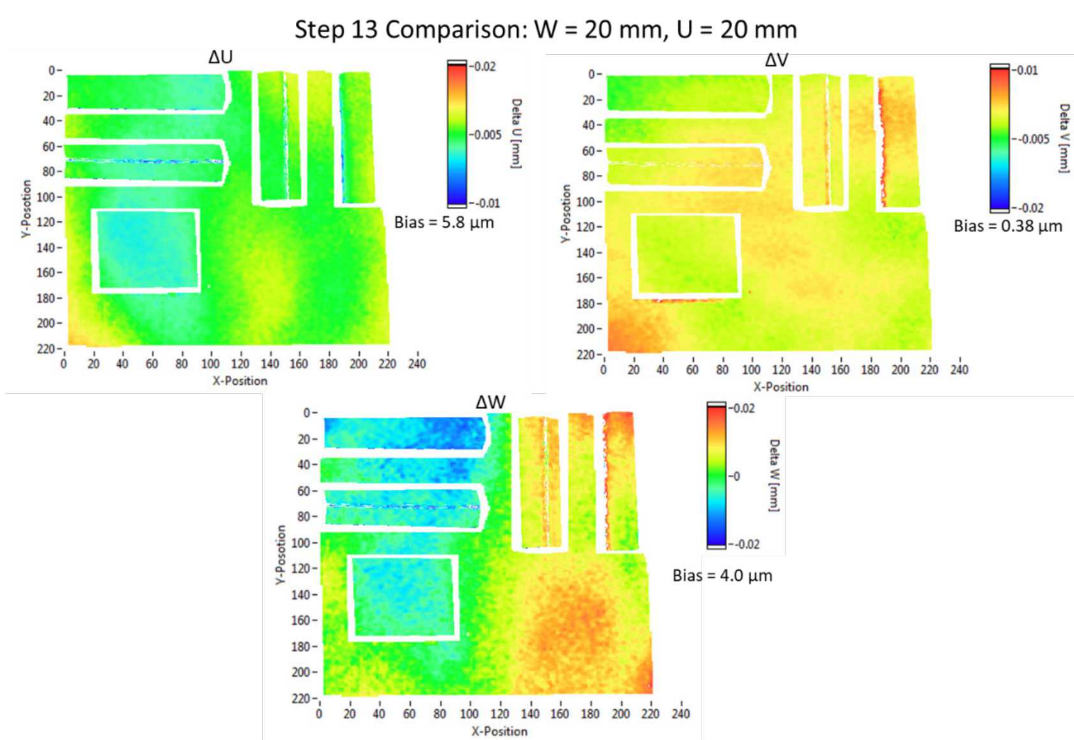


Figure 13. Difference in U, V and W between System 1 and System 2 for Step 13 at W = 20 mm and U = 20 mm. Bias indicates the mean value from the large ROI of the flat base plate.

File Submission Guidelines

Due to the large amount of data, I am suggesting that we submit the data as binary files. MATLAB would be one option for this, where we could provide a MATLAB script that formats and saves the data, to guarantee that all the data is in the correct format. Suggestions for other options are welcome. I believe we need the X, Y and Z positions for the Global Coordinates in one file. We then need X, Y and Z positions in any arbitrary coordinates to be transformed and then compared. For preliminary work I suggest a 2D array in separate files for X, Y and Z. We can start with csv files.

Data is to be reported at the center of the pixel.

Acknowledgements

I would like to thank Paul Farias for help in setting up and conducting these experiments.

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References

1. Balcaen R, Wittevrongel L, Reu PL, Lava P, Debruyne D (2017) Stereo-DIC Calibration and Speckle Image Generator Based on FE Formulations. Exp Mech 57 (5):703-718. doi:10.1007/s11340-017-0259-1