1 Application of Structure-from-Motion photogrammetry 2 in laboratory flumes

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6 **Abstract**

7 Structure-from-motion (SfM) photogrammetry has become widely used
8 for topographic data collection in field and laboratory studies. However,
9 the relative performance of SfM against other methods of topographic mea-
10 surement in a laboratory flume environment has not been systematically
11 evaluated, and there is a general lack of guidelines for SfM application in
12 flume settings. As the use of SfM in laboratory flume settings becomes more
13 widespread, it is increasingly critical to develop an understanding of how to
14 acquire and process SfM data for a given flume size and sediment charac-
15 teristics. In this study, we: (1) compare the resolution and accuracy of SfM
16 topographic measurements to terrestrial laser scanning (TLS) measurements
17 in laboratory flumes of varying physical dimensions containing sediments
18 of varying grain sizes; (2) explore the effects of different image acquisition
19 protocols and data processing methods on the resolution and accuracy of

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20 topographic data derived from SfM techniques; and (3) provide general guid-
21 ance for image acquisition and processing for SfM applications in laboratory
22 flumes. To investigate the effects of flume size, sediment size, and photo
23 overlap on the density and accuracy of SfM data, we collected topographic
24 data using both TLS and SfM in five flumes with widths ranging from 0.22
25 to 6.71 m, lengths ranging from 9.14 to 30.48 m, and median sediment sizes
26 ranging from 0.2 to 31 mm. Acquisition time, image overlap, point den-
27 sity, elevation data, and computed roughness parameters were compared to
28 evaluate the performance of SfM against TLS. We also collected images of
29 a pan of gravel where we varied the distance and angle between the camera
30 and sediment in order to explore how photo acquisition affects the ability to
31 capture grain-scale microtopographic features in SfM-derived point clouds.
32 A variety of image combinations and SfM software package settings were
33 also investigated to determine optimal processing techniques. Results from
34 this study suggest that SfM provides topographic data of similar accuracy to
35 TLS, at higher resolution and lower cost. We found that about 100 pixels per
36 grain are required to resolve grain-scale topography. We suggest protocols
37 for image acquisition and SfM software settings to achieve best results when
38 using SfM in laboratory settings. In general, convergent imagery, taken from

39 a higher angle, with at least several overlapping images for each desired point
40 in the flume will result in an acceptable point cloud.

41 *Keywords:*

42 Structure-from-Motion (SfM), terrestrial laser scanning (TLS), laboratory
43 flume methods, close-range photogrammetry, topographic modeling

44 **1. Introduction**

45 High-resolution topographic data collected during mobile-bed flume ex-
46 periments has led to important advances in our scientific understanding of
47 fundamental processes in river morphodynamics. For example, differenc-
48 ing successive topographic datasets can be used to quantify the formation
49 and migration of alternate bars (Lisle et al., 1993; Lanzoni, 2000a,b; Ven-
50 ditti et al., 2012), the translation and dispersion of sediment pulses (Sklar
51 et al., 2009; Humphries et al., 2012; Nelson et al., 2015), the formation and
52 migration of meanders (Braudrick et al., 2009; van Dijk et al., 2012), and
53 patterns of bedrock erosion (Johnson and Whipple, 2007; Finnegan et al.,
54 2007). High-resolution topographic data can also provide important infor-
55 mation about streambed structure (Aberle and Nikora, 2006), bed roughness,
56 (Qin and Ng, 2012), and bed surface grain size (Butler et al., 2001; Nelson
57 et al., 2010).

58 It generally is impractical to acquire dense topographic data manually
59 using instruments such as point gages (Gilbert and Murphy, 1914; Brush
60 and Wolman, 1960; Schumm and Khan, 1972). Thus, many modern flumes
61 are outfitted with computer-controlled, mechanized instrumentation carts
62 mounted with laser profilers (Marion et al., 2003; Aberle and Nikora, 2006;
63 Nelson et al., 2009, 2010; Kim et al., 2015) and ultrasonic sensors (Kuhnle,
64 1993; Venditti et al., 2015). Cart-based measurement systems can be pro-
65 hibitively expensive because such systems are generally highly customized
66 and require high precision instrumentation to maintain accurate position-
67 ing during data collection. Terrestrial laser scanning (TLS), while primarily
68 used in field-based applications (Brasington et al., 2012), has been used in
69 some flume settings for comparative studies (Peter Heng et al., 2010; Smith
70 and Vericat, 2014). TLS systems can, however, be extremely expensive and
71 challenging to set up and use.

72 Digital photogrammetry provides an alternative to TLS or cart-based
73 systems. Traditional close-range digital photogrammetry generally employs
74 the use of multiple cameras to create 3D models of real space. These meth-
75 ods require either the precise location and angle of the camera position or
76 the location of multiple ground control points in each image captured. Tra-

ditional photogrammetry has been successfully used in both the field (e.g.,
Lane et al., 1993; Marzoff and Poesen, 2009) and laboratory (e.g., Chandler
et al., 2001; Brasington and Smart, 2003; Stojic et al., 1998; Lane et al.,
2001; Bertin et al., 2015). However, the use of these techniques appears to
be limited due to the time required to set up such a system and the degree of
expertise necessary for accurate reconstruction of a 3D surface (Smith et al.,
2015).

An emerging photogrammetric technique that is gaining momentum in
the geosciences is Structure-from-Motion (SfM). The concept behind SfM
was introduced in the late 1970s (Ullman, 1979), but has risen to popularity
among non-photogrammetrists following the work of Snavely et al. (2006).
Structure-from-Motion uses multi-view computer vision methods that detect
and match features between images to estimate the three-dimensional struc-
ture and camera locations and angles simultaneously (Lowe, 2004). There are
a number of free software options for SfM processing (e.g., Bundler (Snavely
et al., 2006), VisualSFM (Wu et al., 2011; Wu, 2013), and Autodesk ReMake
(Autodesk, 2016)) as well as proprietary software (e.g., Arc3D (Tingdahl
and Van Gool, 2011) and Agisoft PhotoScan (Agisoft, 2016a)). Compared
with other close-range remote sensing techniques such as TLS and more tra-

ditional photogrammetry, SfM is relatively low-cost and straightforward to process.

SfM techniques have already been used and tested in a wide array of field applications (e.g., Westoby et al., 2012; Fonstad et al., 2013; Micheletti et al., 2015), but few studies have used SfM in a laboratory setting (Marra et al., 2014; Kasprak et al., 2015; Ramos et al., 2015; Wang et al., 2016). This technology is becoming increasingly popular, but to our knowledge there have been no studies explicitly evaluating the relative performance of SfM against other methods of topographic measurement in a laboratory flume environment (but see Nouwakpo et al. (2014)), and there is a general lack of guidelines for SfM application in flume settings. This is especially problematic because experiments may be conducted in flumes spanning a wide range of physical scales (i.e., widths ranging from a few centimeters to several meters) using sediment ranging from silts or fine sands to large cobbles, and it is not clear how SfM data collection protocols and processing methods should change with flume scale, experimental grain size, or level of detail desired. These issues are all of great interest to experimentalists and therefore the objectives of this study were to: (1) compare the resolution and accuracy of SfM topographic measurements to TLS measurements in laboratory

115 flume experiments of varying scale and grain sizes; (2) explore the effects
116 of different image acquisition protocols and data processing methods on the
117 resolution and accuracy of topographic data derived from SfM techniques;
118 and (3) provide general guidance for image acquisition and processing for
119 SfM applications in laboratory flumes.

120 **2. Methods**

121 For this study, we took advantage of several ongoing flume experiments
122 being conducted at Colorado State University’s Engineering Research Center.
123 The flumes used in these experiments have widths varying from 0.22 m to
124 6.71 m and lengths from 9.14 m to 30.48 m, and the sediment used in the
125 experiments has median grain sizes ranging from 0.20 mm to 31 mm. For
126 each flume, we collected topographic data with two TLS systems, as well as a
127 series of photographs taken at multiple locations with different camera angles
128 that were later used to generate topographic data with SfM. This allowed
129 us to quantitatively compare 3D point clouds generated from each method,
130 and we can explore how the different image acquisition techniques affect
131 topographic data for different flume scales and grain sizes, as well as how
132 SfM processing techniques affect point cloud characteristics. Additionally

133 images were acquired for sediment in a circular pan from a variety of distances
134 and camera angles, for which a qualitative analysis allowed us to assess the
135 requirements necessary to acquire grain-scale topography.

136 *2.1. Flume descriptions*

137 We collected data in five flumes (summarized in Table 1 and shown in
138 Figs. 1a-e), which for this study we refer to with numbers 1 to 5, where the
139 smallest channel is Flume 1 and the largest is Flume 5. We also collected
140 imagery for a pan filled with gravel (Fig. 1f). The grain size distributions of
141 the sediment mixture in each flume and the pan are shown in Fig. 2.

142 Flume 1 is a narrow (0.22 m wide), 9.14 m long, rectangular channel that
143 is deeper than it is wide (depth = 0.38 m), with a sediment D_{50} of 1.5 mm.
144 This flume has sinusoidal width variations in the downstream direction, and
145 was used in the experiments described in Nelson et al. (2015). At the time of
146 this study, the sediment bed in this flume exhibited riffle-pool topography,
147 with locally high bed elevations in wide sections of the channel (riffles) and
148 locally low elevations in narrow sections (pools).

149 Flume 2 is 1.22 m wide and 9.14 m long. It was being used to study pro-
150 cesses in steep, coarse-grained rivers, and therefore had the coarsest sediment
151 of any of the flumes in this study with a D_{50} of 31 mm.

152 Flume 3 is 1.22 m wide and 18.29 m long, with a surface sediment D_{50} of
153 4.1 mm. This flume was being used to investigate alternate bar dynamics,
154 and at the time of data acquisition this flume had approximately 1.5 alternate
155 bar sequences and noticeable bed surface sorting (e.g., Nelson et al., 2010).

156 Flume 4 is a wide rectangular basin (4.88 m wide by 15.24 m long) that
157 was being used to study flow and erosion around navigation locks. The sedi-
158 ment in this flume was a relatively well sorted (geometric standard deviation
159 $\sigma_g = 1.67$) gravel ($D_{50} = 6.2$ mm).

160 Flume 5 is a large rectangular basin (6.71 m wide by 30.48 m long) filled
161 with very well sorted ($\sigma_g = 1.37$) sand with $D_{50} = 0.2$ mm. This basin
162 was being used to perform experiments on braided channels in high sediment
163 supply environments (Ettema et al., 2016), and at the time of data acquisi-
164 tion for this study the bed exhibited many shallow (~ 1 cm depth) braided
165 channels.

166 The pan is a circular container (0.39 m diameter) filled with a bi-modal
167 mixture of very fine to coarse gravel. This container was not being used
168 for any other experimentation and is only used in this study to examine the
169 effect of camera distance/angle from the sediment surface. No TLS data were
170 collected for the pan because the level of detail of interest is finer than the

171 accuracy of TLS equipment available to us.

172 2.2. Data acquisition

173 2.2.1. TLS

174 Two TLS systems were used to collect topographic data. The first was
175 a Leica ScanStation HDS3000, which is a time-of-flight style scanner with
176 a stated accuracy of ± 6 mm at a distance of 50 m (Leica, 2016). This
177 scanner computes distances using the speed of light by measuring the time
178 from short pulses of light sent from the scanner until a reflection of the pulse
179 is monitored (Paschotta, 2008). The second scanner was a Faro Focus3D
180 S 120, which is a phase-shift scanner with a stated accuracy of ± 2 mm
181 at a distance of 25 m (Faro, 2011). This scanner sends light with a known
182 sinusoidal power modulation and measures distances by comparing this mod-
183 ulation with the phase of the power modulation that is reflected back to the
184 scanner (Paschotta, 2008). In both cases, scanner accuracy should be better
185 at closer ranges, to a point, since the range of accuracy cannot be any smaller
186 than the laser point itself. Each flume was scanned by both scanners from
187 three separate stations, one at the upstream end, one at the downstream end
188 and one near the middle of the flume. Each scan contained a minimum of
189 five reflective spheres that were used to align and position the three scans for

190 a single flume. For two flumes the TLS stations were located with the instru-
191 ment tripod on a cart that moves above the flume bed, and for the others
192 the stations were located with the tripod at the bed level of the flume. The
193 distance from the instrument to the flume bed depended on the dimensions
194 of the flume and whether the station was on the flume cart or at the bed
195 level. Scanner height above the bed varied from approximately 1.5 to 4 m,
196 resulting in overall distances generally less than those given for the stated
197 accuracy by the manufacturers. The maximum downward angle of view for
198 each of the scanners is 45° and 27.5° , resulting in ranges from the scanner
199 to the closest scanned points of 2.1 to 5.7 m for the Leica and 1.7 to 4.5
200 m for the the Faro. Point density using any TLS is highly dependent on
201 the parameters defined by the user at the time of acquisition as well as the
202 number of stations; here, we set the resolution of the TLS data acquisition so
203 that measurements had a vertical and horizontal spacing of approximately 1
204 cm at a distance of 10 m from the instrument. Both Leica ScanStation and
205 Faro Focus3D data were processed using the manufacturer’s software, Leica
206 Geosystems Cyclone and Faro SCENE, respectively.

207 2.2.2. Photographs for SfM

208 Images were acquired using a Canon EOS Rebel T3i camera with a Canon
209 EF-S 24 mm prime lens. This is a consumer grade DSLR camera capable of
210 capturing images with 18.0 megapixel resolution. We acquired all images in
211 both RAW and JPG formats (RAW file sizes are generally 3-4 times larger
212 than their JPG counterparts), and we performed SfM processing with both
213 file types to investigate the effects of digital image compression. The spacing
214 of photograph locations and the angle of each photograph depended on the
215 dimensions of the flume (Fig. 3a). First, a set of photographs was taken
216 along the flume centerline. These camera positions were at an oblique angle
217 ($\sim 45^\circ$ below horizontal) positioned toward the flume bed pointing in both
218 the upstream and downstream direction. These locations were evenly spaced
219 along the longitudinal axis of the flume. The spacing was determined by the
220 camera height above the bed relative to the flume width (e.g., Flume 1 is
221 very deep relative to its width and therefore had finer spacing than some of
222 the larger flumes (Table 2)). Photographs were also taken from the left and
223 right edges of each flume, and these camera positions were also oriented at
224 a vertically oblique angle ($\sim 45^\circ$) looking down toward the flume bed. For
225 the larger flumes (Flumes 4 and 5) camera azimuth angles were set to 0° (di-

226 rectly upstream), 45° , 90° (directly across the flume), 135° , and 180° (directly
227 downstream). For the smaller flumes (Flumes 1, 2, and 3) the side camera
228 angles included 45° , 90° (directly across the flume), and 135° . These camera
229 positions were uniformly spaced along the longitudinal axis at approximately
230 the same locations as were collected for the upstream/downstream images.

231 The most common parameterization used to characterize the overlap of
232 images in a series or between lines is the percent overlap, particularly for
233 aerial imagery. However, because of the multiple camera angles used in this
234 study the overlap percentage between images is highly variable and difficult
235 to interpret. We therefore used the of number of images in which any point
236 is present as a metric to describe the image overlap. This number of overlap-
237 ping images can easily be quantified spatially, as opposed to the percentage
238 overlap. For aerial imagery Agisoft (2016b) suggests 80% forward overlap of
239 images in a single flight line and 60% side overlap for adjacent flight lines.
240 This corresponds to a maximum of 15 overlapping images when the camera
241 orientation for all images is straight down. In our study, many locations were
242 captured by more than 15 overlapping images because we took photographs
243 from oblique angles.

244 Different combinations of the entire set of photographs were employed on

245 Flumes 3 and 5 to test the effect of image orientation, number of images,
246 and image overlap on SfM point cloud density and quality. The combina-
247 tions included all images (All images) for both JPG and RAW, only images
248 taken from the middle positions looking upstream and downstream (US-DS
249 images), only images taken from the side of the flume (LB-RB images), only
250 diagonal images taken from the side of the flume (LB-RB angled images; i.e.,
251 45° and 135° images only), only images taken from the middle of the flume
252 with 45° and 135° images from the side of the flume (no cross-flume images),
253 all images from every second position, all images from every third position,
254 and all images from every fourth position (Fig. 3b).

255 Photographs for the pan were collected using the same camera and lens
256 as for the flumes. The pan filled with sediment was placed on a rotating
257 turntable and the camera was positioned at six different distances (approx-
258 imately 0.5, 0.75, 1, 1.5, 2, and 3 m) from the center of the pan to the camera
259 sensor for two angles (30° and 60°) above horizontal (Fig. 3c). Images of
260 the turntable were taken at 10° intervals, resulting in 36 images for each
261 distance at each camera angle (Fig. 3d). Seven markers were placed on the
262 turntable around the pan to aid in both image alignment and point cloud
263 scaling/referencing.

264 2.3. SfM point cloud creation

265 Three-dimensional point clouds were created from each set of images us-
266 ing two different SfM software options: Agisoft PhotoScan Professional ver-
267 sion 1.2.3 (Agisoft, 2016a) and VisualSFM version 0.5 (Wu et al., 2011; Wu,
268 2013). Photoscan is widely used proprietary software that allows the user to
269 select the level of alignment accuracy and dense cloud quality. VisualSFM
270 (VSFM) is freely available from <http://ccwu.me/vsfm/> and implements a
271 scale invariant feature transform (SIFT) (Lowe, 2004) and mutli-core bundle
272 adjustment (Wu et al., 2011) to recreate a three-dimensional scene from the
273 two-dimensional images (Wu, 2013). The software also has the ability to in-
274 tegrate the Clustering Views for Multi-view Stereo/Patch-based Multi-view
275 Stereo version 2 (CMVS/PMVS2) tool developed by Furukawa and Ponce
276 (2010) to create a denser point cloud.

277 Comparisons between SfM and TLS elevation datasets used SfM point
278 clouds generated from all of the images acquired in each flume. The SfM
279 datasets generated in PhotoScan used a photographic alignment accuracy
280 set to “highest” (out of the options “lowest”, “low”, “medium”, “high”, and
281 “highest”) and a dense cloud quality set to “medium” (out of the options
282 “lowest”, “low”, “medium”, “high”, and “ultra high”). Although PhotoScan

283 has the ability to specify targets or ground control points to aid in image
284 matching, no targets were specified for the objective of testing these different
285 settings. Although some process settings can be specified by the user in
286 VSFM, only default settings were used for this study.

287 In order to explore the effect of the user-controlled settings in PhotoScan
288 on the final point cloud density and quality, we processed the photos taken
289 of Flume 3 in a variety of ways and compared the results. We varied the
290 alignment accuracy setting from “lowest” to “medium” to “highest” and we
291 varied the dense cloud quality setting from “lowest” to “medium” to “ultra
292 high”. Additionally, we tested the effect of selecting targets in the software
293 processing for three of the image combinations: all images, US-DS images,
294 and LB-RB images. Printable targets were obtained through PhotoScan
295 software. For Flumes 2 and 3 targets had previously been taped to the inside
296 of the flume walls at a spacing of approximately 0.5 m in the downstream
297 direction. For Flumes 1, 4, and 5, targets were spread out at the edges of
298 the imaged area, either in or around the flumes.

299 Point clouds for the pan experiment were generated in PhotoScan using
300 the “highest” alignment accuracy setting and the “ultra high” dense cloud
301 quality setting.

302 2.4. Point cloud scaling and alignment

303 The free, open-source software CloudCompare (Girardeau-Montaut, 2011)
304 was used to align and scale the SfM point clouds, and to align the Faro point
305 clouds to the Leica point clouds. This process began by importing all the
306 clouds for a given flume. Three readily identifiable points in common be-
307 tween each cloud (e.g., flume wall corners) were selected to initially align the
308 reference cloud to the Leica base cloud. These point clouds were all clipped
309 to a rectangular box that eliminated points outside the flume, yet kept the
310 walls. The iterative closest point (ICP, see Besl and McKay, 1992) algorithm
311 was then used to finely register the two point clouds together by using a ran-
312 dom sampling limit of 100,000 points and was reduced to a root mean square
313 (RMS) difference between the point clouds of 1.0×10^{-5} m. The point clouds
314 were then clipped such that walls and structures in the flume were removed.

315 The pan point clouds were aligned using measured arbitrary coordinates
316 in the scene. Seven markers were placed around the pan and the coordinates
317 of each of those targets were used in all the photosets to scale and align each
318 point cloud in PhotoScan. The point clouds were clipped to a circular area
319 such that the rotating turntable and pan edges were removed.

320 2.5. Point cloud processing

321 In order to quantitatively compare the TLS and SfM methods, point cloud
322 post-processing consisted of calculating statistics related to model elevations,
323 two surface roughness metrics, and computation of the spatial differences
324 between each point cloud. The first surface roughness calculation was a
325 single value for rugosity, which was measured for the entire final, clipped
326 point cloud for each flume. Rugosity is defined as the 3D surface area of
327 a region divided by the planimetric, or 2D, surface area of the same region
328 (Brasington et al., 2012). A triangulated irregular network (TIN) was created
329 from each point cloud in ArcGIS and the ‘Surface Volume’ function in the
330 3D Analyst toolbox calculated the necessary areas. The second approach
331 of estimating surface roughness was to use a spatially variable roughness
332 index-elevation. This measure of roughness is computed as the standard
333 deviation of residual topography across a moving window for a specified
334 number of cells (e.g., Cavalli et al., 2008; Prosdocimi et al., 2015). For this
335 calculation the point cloud data were first gridded onto a raster with 1 cm
336 cells. Residual elevations were computed by differencing each cell’s value
337 in a 5×5 cell window with the mean value of those same 25 cells. The
338 roughness index-elevation of the cell in the center of the window is defined as

339 the standard deviation of those elevation residuals (see Cavalli et al., 2008,
340 for more details). Ideally both the raster cell size and computation window
341 size would vary according to point density, grain size, feature size, and noise
342 (Prosdocimi et al., 2015). However, because we are mainly interested in
343 the differences between methods, we used the same cell and window size
344 for all five flumes and all four methods of point cloud creation. Roughness
345 values may not be comparable between flumes because the number of grains
346 present in the 5×5 cell window will depend on the grain-size distribution
347 of the sediment in each flume.

348 Point cloud differencing was computed using the Multiscale Model to
349 Model Cloud Comparison (M3C2) algorithm (Lague et al., 2013). This dif-
350 ferencing method is available in CloudCompare and requires the user to de-
351 fine several parameters. The general concept behind M3C2 is to compute
352 cloud-to-cloud distances using a local normal direction rather than only the
353 vertical direction. The normal direction is computed from the points within
354 a sphere around a given point, defined by the so-called “normals diameter”.
355 Once the normal direction is computed, the algorithm creates a cylinder ori-
356 ented along the normal vector, with a diameter (the “projection diameter”)
357 specified by the user. The intersection of each point cloud with this cylinder

358 defines two subsets, which are projected on to the axes of the cylinder and
359 used to compute a distribution of normal distances between the two clouds
360 at that location. More details on the M3C2 algorithm are provided by Lague
361 et al. (2013).

362 For the purpose of our study we chose to always specify the point cloud
363 with fewer points as the reference cloud, and also chose to use the entire
364 reference point cloud to be the core points for which M3C2 differences were
365 computed. A sensitivity analysis on the mean, median and standard de-
366 viation of the M3C2 differences for Flume 3 were relatively insensitive to
367 adjusting the normal and projection diameters. We ultimately chose to use
368 normal and projection diameters of 5 cm and 1 cm, respectively, for all of
369 the flumes. Lague et al. (2013) suggest that these values should vary relative
370 to local point cloud roughness, however for simplicity and consistency we
371 elected to use the same values for all flumes and point clouds. Unlike many
372 previous SfM validation studies which compared SfM models to other models
373 by first converting one or both point clouds to rasters (Smith et al., 2015),
374 the M3C2 algorithm allowed us to compare point clouds directly. M3C2
375 differences were computed for all point cloud combinations.

376 Considering the accuracy of the TLS units and the fine level of detail in

the imagery and subsequent SfM point clouds for the sediment in the pan experiment, no TLS data were collected. Instead, the different SfM point clouds were qualitatively evaluated against one another to determine whether individual grains were discernible and at what distance the differences between individual grains was smoothed over.

3. Results

3.1. TLS and SfM comparisons

3.1.1. Point density and image overlap

The horizontal spacing between photographs was varied between flumes due to their varied sizes (Table 2), which resulted in substantial photo overlap across most of the flume for all flumes (Figs. 4a–8a). Larger flumes contain areas with greatest image overlap and the greatest overlap generally occurs near the center of the flume just downstream from the middle. For each flume the point count and point density vary over an order of magnitude (Table 2). In every case the Leica model contains the fewest number of points. The TLS models nearly always have lower point counts than the SfM models, with the exception of Flume 5, where the Faro model contains more points than the VSfM model. Spatial distributions of the point density results for

the TLS models in each flume illustrate a strong dependency on the location of the TLS scanner (Figs. 4b–8b), where overlapping scans had one or more orders of magnitude more points than areas that were only included in a single scan. The point density map of the VSFM model of Flume 5 shows large gaps where no point data exists (Fig. 8b).

3.1.2. *Bed elevations and roughness metrics*

Elevation values for each method are generally similar for each flume (Figs. 4c–8c); however, the range of elevation values for the VSFM model in Flume 4 is greater than the other clouds (Table 3). Both rugosity and the roughness index-elevation calculations were derived from elevation values (Table 3). Rugosity is greatest for Flume 2 where the D_{50} is 31.0 mm, and in Flume 4 the rugosity for the VSFM model is nearly four times that of the other models. The maps of the roughness for each flume illustrate both form and grain roughness features such as alternate bar edges in Flume 3 and individual grains in Flume 2 (Figs. 4d–8d). For each flume both rugosity and roughness index-elevation values are generally greatest for the VSFM models.

412 3.1.3. M3C2 differences

413 Differences computed using the M3C2 algorithm show that for most of the
414 flumes 98% of the computed differences lie within 2 cm of each method (Fig.
415 9), with the exception of Flume 2 and some comparisons in Flume 5. Figs.
416 S1 through S5 in the Supplemental Information show the spatial distribution
417 of M3C2 differences for all model comparisons. Root mean square (RMS)
418 values for the M3C2 differences are consistently at or under 1 cm for all
419 flumes except Flume 2. Comparisons between the two TLS models generally
420 have the smallest range of M3C2 distance encompassing the middle 98%,
421 with the exception of Flume 2. Comparisons between all of the models in
422 Flume 3 are the most consistent with RMS values varying between 2-3 mm.

423 3.2. Image combinations

424 The spatial patterns of image overlap for the different photo acquisition
425 protocols for Flume 3 are shown in Fig. 10. The smallest number of over-
426 lapping images for any area is four, which occurs for the image combination
427 including only angled images taken from the side (LB-RB angled images).
428 The greatest number of overlapping images, 51, occurs when all images are
429 used. Despite the different amount of overlap between image combinations,
430 there was little difference in the number of points in each point cloud for

431 Flume 3 (Table 4). The combination using only images taken from the mid-
432 dle of the flume pointing in the upstream and downstream directions (US-DS
433 images) was not able to align in PhotoScan without the selection of targets.
434 Alignment was unable to be performed, with or without targets specified,
435 for image combinations using images acquired from every third and every
436 fourth position. Computed M3C2 distances between each of the image com-
437 binations and select combinations with and without targets specified against
438 the Leica model show relatively little difference (Fig. 11 and supplemental
439 Fig. S6). Median and RMS values for these M3C2 differences show almost
440 no variation between image combinations (Table 4).

441 Image overlap maps computed from different image combinations for
442 Flume 5 are shown in Fig. 12. The maximum number of overlapping images
443 for any point is 96 and occurs when all the images are used. The minimum
444 is one, occurring for the LB-RB angled images. There is greater range in
445 the point counts for different image combinations of Flume 5, with models
446 created from RAW images, US-DS images, and every third position hav-
447 ing about half the point count as the other image combinations (Table 5).
448 Alignment was unable to be performed, with or without targets specified,
449 for the image combination using images acquired from every fourth position.

450 There is greater range in the M3C2 distances from the Leica model for point
451 clouds of Flume 5 than Flume 3 (Fig. 13). The spatial distribution of these
452 M3C2 distances are shown in supplemental Fig. S7. Median values for RAW
453 images and every third position and RMS values for RAW images, RB-LB
454 angled images, and every third position are greater than the other image
455 combinations.

456 Although PhotoScan has the option of automatically detecting targets in
457 the input images, we have not had luck with that feature. The placement
458 of targets required the manual selection of the markers in each image in
459 PhotoScan. For each photoset this took approximately 30 min.

460 3.3. *PhotoScan settings*

461 Calculated M3C2 distances between models of Flume 3 using the differ-
462 ent qualitative settings for PhotoScan’s processing of both image alignment
463 accuracy and dense point cloud quality against the Leica model are sum-
464 marized in Fig. 11, with the spatial distribution of these distances shown
465 in supplemental Fig. S8. These results show a slight decrease in central
466 98% of M3C2 distances as the accuracy and quality settings are increased.
467 However, the median and RMS values for the M3C2 distances between the
468 SfM clouds and the Leica TLS cloud show very little variation between Pho-

469 toScan settings (Table 6). The primary differences between settings are in
 470 the point count for each model and the processing time, which for a typical
 471 desktop computer is roughly on the order of minutes for lowest quality, hours
 472 for medium quality and days for ultra high quality. The dense cloud quality
 473 setting has a much larger effect on point density than image alignment ac-
 474 curacy, where total point counts between dense cloud qualities of “Lowest”,
 475 “Medium”, and “Ultra High” vary by over an order of magnitude each (Table
 476 6). Therefore, the “quality” setting in creating dense clouds is analogous to
 477 density.

478 3.4. Camera distance and angle

479 A summary of point counts for the point clouds generated in the pan
 480 experiment is shown in Table 7. The difference in point count is much more
 481 pronounced between the different distances than between the two different
 482 angles. There is a general power-law decay in model point count with in-
 483 creased distance between the camera and subject (exponent of approximately
 484 -2.15). Although the point clouds generated from 30° imagery tended to have
 485 a higher point count than those generated from 60° imagery the differences
 486 are minor. Figs. 14 and 15 show selected cross-section profiles of the created
 487 point clouds through the center of the circular pan (an animation showing

cross-section profiles for every 1° of rotation is available with the supplemental material). Both the clouds from 30° images and 60° images show a “smoothing” with increased distance between the camera and the surface. For the models made from the closest imagery the interstices between individual grains are relatively clear. As the camera distance increases the difference between the “lows” separating grains and the “highs” at grain apexes are reduced, especially for the smaller grains (e.g., those at the right of the plots in Fig. 15).

4. Discussion

4.1. TLS and SfM Comparisons

The image count for each flume is mostly a function of flume dimensions and the camera height above the flume bed. In general the maximum image overlap increases with increasing flume size. Flumes 2 and 5 each have a concentration of high image overlap slightly downstream from the middle of the flume, which can be explained by the slope of the flume bed, i.e., camera positions looking in the downstream direction are able to see a greater area of the flume bed because the bed is sloping away from the camera’s viewpoint. Flume 3 also appears to have an area of high image overlap

506 slightly downstream from the middle, however, it should be noted that the
507 data shown in Fig. 7 are clipped and do not represent the total area of
508 the flume. The suggestion of Agisoft (2016b) for 80% forward overlap of
509 images in a single flight line and 60% side overlap for adjacent flight lines
510 corresponds to a maximum image overlap count of 15, generally well below
511 what we achieved with our image overlap.

512 Processing time for both the TLS and SfM methods are highly dependent
513 on the size of the dataset, computer power, and the user familiarity with the
514 software. We did not include processing time for each method as we used
515 multiple computers, each with different processors and available RAM. Raw
516 data acquisition time was generally lower for the SfM imagery than the TLS
517 scans, with the single exception of the Faro in Flume 5. To obtain data of
518 similar point densities with manual measurements would take an extremely
519 long time. Even more modern, conventional methods of measuring flume
520 topography could potentially be very time consuming. Lane et al. (2001)
521 reported an acquisition time of 8 h to obtain data necessary to create a
522 DEM with 0.5 mm resolution on a $0.25\text{ m} \times 0.25\text{ m}$ area, using a laser sensor
523 on a motorized cart. The SfM imagery for each of the smaller flumes was
524 collected in less than an hour and produced point clouds with multiple points

525 per mm² (Table 2). By adjusting the software settings the point density has
526 the potential to increase dramatically (Table 6). In the pan experiment
527 imagery for each photoset required mere minutes to collect and resulted in a
528 coverage area nearly twice that used by Lane et al. (2001) and at a minimum
529 of several points per mm².

530 The point counts and spatial point densities of the topographic mod-
531 els show a high dependence on the method used to collect the data. The
532 lower point count and density associated with the TLS models is due largely
533 to both the limited number of scanning positions and the settings of each
534 scanner. Had more scans been performed from additional stations or scanner
535 resolution increased the point counts would have been higher, but at the cost
536 of additional acquisition and processing time. Lower point density in areas
537 of less image overlap would seem logical, however it came as a surprise that
538 PhotoScan models show a spatially consistent point density for each flume.
539 The VSFM models, on the other hand, show spatial point density distribu-
540 tions with generally lower values near the flume walls. The average point
541 densities between the two SfM models are comparable to one another with
542 the exception of Flume 5, where PhotoScan produces a model with twice the
543 density of VSFM. Based on the spatial distribution of points in the VSFM

544 model we suspect that the software had a difficult time with the apparent
545 lack of texture and color of the fine sand surface. PhotoScan, however, con-
546 tinued to produce a spatially consistent point cloud, even in areas with little
547 texture. Given the proprietary nature of the algorithms in PhotoScan, it
548 is difficult to know for certain the reason it produces more consistent point
549 densities.

550 In general the elevation values and ranges for the different methods are
551 comparable to one another. The VSFM model for Flume 4, however, has an
552 elevation range two to three times larger than the other models (Table 2).
553 This high elevation variability is obvious in the elevation map and propagates
554 to produce higher ranges in roughness (Fig. 7). With the similarity in grain
555 sizes between Flumes 3 and 4, this wider range of elevations in the VSFM
556 model for Flume 4 can likely be attributed to two factors. First, as a result
557 of the greater flume width/height the camera positions for Flume 4 were
558 located a greater distance from the bed than the camera positions for Flume
559 3. Smith and Vericat (2015) report from more than 15 validation studies
560 that the root mean square error of SfM models increases linearly with the
561 range of imagery from the subject. However, the range scales reported there
562 cover three orders of magnitude, which is much more variation than what

we have between Flumes 3 and 4. Still, the closer camera angles for Flume 3 are more likely to produce more consistent feature matches of individual grains in the images, while single grain features may be difficult to match in Flume 4. Second, the wider range of elevations in the VSFM model of Flume 4 may be due to a relative lack of image texture. Flume 3 had both a wider range of grain sizes as well as grains of different colors, while the grains in Flume 4 were of more uniform size and color. This may have produced difficulty in feature detection and matching that was exacerbated by the dark color of the sediment and relatively low lighting. It is curious, however, that such elevation variability was produced in the VSFM model but not the PhotoScan model. Again, without knowledge of PhotoScan algorithms it is difficult to interpret the different results from the two SfM software packages. A lack of image texture also likely contributed to the elevation variability in the VSFM model of Flume 5 (Fig. 8).

Similar to the elevation results, rugosity and roughness index-elevation calculations are comparable for each model. Smaller grain sizes and topographic relief (e.g., Flume 5) result in much lower roughness parameters than larger grain sizes (e.g., Flume 2) and more significant relative topographic relief (e.g., Flume 1) (Table 3). As mentioned previously, the “noise” in some

582 of the elevation values can propagate to create variability in the roughness
583 metrics. It should be remembered that we used the same moving window
584 and cell size for roughness index-elevation calculations regardless of grain
585 size. For most of the flumes both elevation and roughness calculation are
586 comparable between the TLS and SfM models despite large differences in
587 point densities.

588 The M3C2 distances show a high degree of variability across flumes, and
589 among models (Fig. 9). The widest range of M3C2 distances occurs for the
590 models of Flume 2, and this is primarily due to “shadows” in the TLS models,
591 resulting in limited coverage between grains. In contrast the SfM approaches
592 were more capable of creating detailed topography between grains due to
593 the hundreds more locations from which photos were taken, as compared to
594 the three instrument points used in the TLS data acquisition. An additional
595 source of discrepancy could stem from error in the computed normal direc-
596 tions in the M3C2 algorithm, which would result in greater M3C2 distances
597 between point clouds. It has also been pointed out that rough surfaces re-
598 sult in increased error effects (Prosdocimi et al., 2015). Computed distances
599 between models mostly fall within ± 2 cm for Flumes 1, 4 and 5, and more
600 than 98% of the measured distances are within ± 1 cm for Flume 3. M3C2

601 distances for Flume 2 reach upwards of 7 cm as a result of the higher rough-
602 ness. In most cases the distances between the two TLS models is the lowest,
603 and the distances between the TLS and SfM models fall within the reported
604 error range of the TLS instruments.

605 The spatial distribution of M3C2 distances does not appear to show any
606 patterns except for in Flume 1 where there is obvious nonlinear longitudinal
607 deformation in the SfM models (Fig. 16). Because of the deep and narrow
608 dimensions of Flume 1 the differences in camera angles are minute and result
609 in more-or-less parallel imagery. James and Robson (2012) note that SfM
610 analyses generally rely on angles that are convergent rather than parallel,
611 and parallel imagery in other close-range photogrammetry applications has
612 been shown to result in lens model errors propagating and expounding in
613 the 3D model to produce a “dome” effect (e.g., Wackrow and Chandler,
614 2008, 2011). Interestingly, the direction of deformation of the PhotoScan and
615 VSFM models are reversed from one another, highlighting another apparent
616 difference in algorithms. It should be noted, however, that the measured
617 magnitude of the doming effect in the SfM Models for Flume 1 is approximate
618 to the range of accurate measurements for the TLS machines (Leica, 2016;
619 Faro, 2011). The other flumes had sufficient convergence of images to avoid

noticeable nonlinear deformation, demonstrating the importance of including convergent imagery during acquisition.

4.2. Image Combination and PhotoScan Setting Comparisons

Understandably the number of overlapping images depends on both the number of camera positions and camera orientation (Figs. 10 and 12). The fact that the US-DS image combination for Flume 3 contains nearly the same number of images as the every third position combination (Table 4) yet has image overlap 4-6 times higher (Fig. 10) illustrates the importance of image orientation on achieving overlap. Similarly, the fact that the US-DS images were able to be aligned for Flume 3 while every third position could not be aligned further implies the importance of overlap rather than number of images alone. For Flume 3 the corresponding point counts for the models produced from different image combinations somewhat follow the image count, but the differences are minor. For Flume 5 the point counts do not seem to follow any pattern. The fact that upstream and downstream oriented images taken from a position in the center of flume can only be aligned if targets are used is likely due to the extreme angle (180°) between the two orientations. The measured M3C2 differences of each image combination model against the Leica model for Flume 3 show very little deviation, suggesting that as

639 long as PhotoScan is able to align images and create a 3D model the quality
640 of point cloud is largely independent from both the number of images as well
641 as the amount of image overlap (Fig. 11). We did not find any significant
642 difference in using RAW imagery versus JPG files. However, in cases of over-
643 or under-exposure and high lighting contrast, RAW images may have an ad-
644 vantage because their ability to retain more detailed color depth. Similarly,
645 the selection of targets did not result in a significant change in M3C2 dis-
646 tances, however, the selection of targets is sometimes necessary for camera
647 alignment to be successful, as seen in the case of the US-DS images. Target
648 identification also provides a convenient method for scaling and aligning a
649 point cloud, as would be necessary for a field application.

650 The primary difference between the variations in PhotoScan settings is
651 the processing time required and the point count of the consequent model
652 (Table 6), and even then only for the setting of dense construction quality.
653 While the lowest alignment accuracy setting and the lowest dense quality
654 setting produce a wider central 98% of M3C2 differences, it is still only on the
655 order of millimeters and within the range of variability of the measurements
656 themselves (Fig. 11). However, the model created using the lowest accuracy
657 alignment shows a range of M3C2 differences 5-6 cm greater than the models

658 created using other PhotoScan settings. Considering this, the selection of
659 PhotoScan settings should be guided by particular applications and point
660 cloud uses. For example, a dense quality set to “lowest” should probably
661 only be used for qualitative assessment.

662 *4.3. Camera Distances and Angles*

663 In the results from our pan experiment, the differences are minute be-
664 tween the point clouds produced using SfM from images taken at different
665 angles below horizontal and different distances between the camera and sed-
666 iment surface (Figs. 14 and 15). In general the elevation differences in the
667 cross-section profiles are no more than a millimeter or so. The major excep-
668 tion is in the interstices between some of the grains, where the closer camera
669 locations show lower elevations (i.e., more pronounced differences between
670 grains). In most cases the 0.5 and 0.75 m distance clouds fall very closely
671 to one another, capturing the interstices between the fine particles, and the
672 2 and 3 m clouds fall closely to one another, smoothing over the interstices
673 between the fine particles. Due to the higher angle and consequent ability
674 to capture deep interstitial space between grains the 60° imagery seems to
675 capture this void more readily and at greater distances than the 30° im-
676 agery. The 1 m imagery represents an apparent transition between photo

sets whose point clouds resolve the spaces between 2 mm particles and those that smooth over fine grain-scale detail. The Canon EOS Rebel T3i that was used to capture imagery has a megapixel (MP) count of 18 and with the 24 mm lens each image has approximately 2400 pixels across the pan diameter (0.385 m), resulting in a pixel spacing of equivalent to 6 pixels/mm with the camera located 1 m from the center of the pan. Because the imagery was taken from an oblique angle finer pixel spacing occurs closer to the camera (and conversely, coarser spacing farther). An unobstructed 2 mm grain (the smallest in the pan and assumed to be completely visible as a circle) would then occupy about 113 pixels (assuming the cross-sectional area of the grain is about 3.14 mm^2), given the 6 pixels/mm (36 pixels/mm^2) resolution at 1 m camera distance. From a camera distance of 1.5 m the average approximate pixels to 2 mm grain ratio decreases to 49. These findings suggest that SfM may be used to capture grain scale topography for particles occupying about 100 pixels, so the camera sensor resolution, lens focal length, and smallest resolvable grain-scale desired can be used to determine the distance.

4.4. Guidelines & Recommendations for SfM in Flumes

Our results suggest that SfM can produce topographic point clouds in flumes with quality comparable to TLS and much greater point density, with

696 less acquisition time and at much lower overall cost. However, SfM may not
697 perform as optimally for deep and narrow flumes, such as Flume 1, where it
698 is difficult to obtain images from sufficiently convergent angles to completely
699 alleviate lens distortion issues. Also, SfM requires image texture to define
700 features and in cases of very small grains with camera positions a significant
701 distance from the flume bed, as in Flume 5, some SfM algorithms may have
702 difficulty in defining and matching features. Sediment of nearly all the same
703 size and color under low light, as in the case of Flume 4, can also produce
704 poor feature detection and matching. In these cases we would recommend
705 additional ground control points on the flume surface and/or supplementary
706 light sources to potentially increase image texture. However, care should be
707 taken to ensure light sources are outside the field of view of the imagery and
708 the camera flash should not be used (Agisoft, 2016b).

709 For image acquisition, we simply recommend that images are taken at a
710 number of positions and angles that provide sufficient coverage of the flume
711 bed. Agisoft's (2016b) recommendations of overlap of 80% in the downstream
712 and 60% in the cross-stream directions result in an image overlap count of
713 15 and this seems like a reasonable goal. Insufficient overlap, which seemed
714 to be the case when we skipped every third or fourth position in Flume 3,

715 can make photo alignment impossible or significantly reduce the quality of
716 the resultant model. If the differences between camera angles are too great it
717 may be necessary to specify targets for the camera alignment. In our image
718 combinations for both Flumes 3 and 5 the upstream and downstream facing
719 camera angles from the center of the flume provided an acceptable output
720 model with the fewest number of images. In general we found no significant
721 difference in RAW imagery verses JPG, but for situations of under- or over-
722 exposure we expect that RAW images may produce more satisfactory results.

723 PhotoScan consistently produced more satisfactory results than Visu-
724 alSFM, particularly for point density. When selecting PhotoScan settings we
725 recommend the default settings in version 1.2.3.2016 with the photo align-
726 ment accuracy set to “highest” and the dense cloud quality set to “medium”.
727 For cases where very high point density is required it may be necessary to
728 increase the dense cloud quality, however it should be noted this significantly
729 increases the processing time.

730 The camera distance from the subject will depend greatly on the detail
731 required as well as the sensor resolution and focal length. If sub-grain scale
732 topography is required, we suggest positioning the camera a distance from
733 the flume bed such that 100 pixels per grain is achieved. In our experiment

734 the imagery captured from a steeper angle above the horizontal seemed to
735 result in a point cloud that characterized the interstices between grains more
736 clearly, especially at farther distances. However, for cases of very poorly
737 sorted sediment, for which there is little to no interstitial space, the angle of
738 the camera would likely have less of an effect.

739 5. Conclusions

740 The lack of previous work involving Structure-from-Motion photogram-
741 metry methodology in laboratory flumes has led us to conduct a series of
742 experiments to explore how flume size, sediment size, photo acquisition, and
743 software processing affects the density and accuracy point clouds derived
744 using SfM photogrammetry. TLS and photographs were collected for five
745 laboratory flumes, for which the resulting topographic models were com-
746 pared, and photographs were collected at varying angles and distances from
747 a pan of sediment to assess the ability to accurately characterize grain scale
748 topography.

749 Both PhotoScan and VisualSFM tended to have comparable elevation
750 accuracy, but PhotoScan generally produced more uniformly high point den-
751 sity than VisualSFM, and VisualSFM produced noisier topographic data for

752 flumes of large size, low relief, and uniform grain size. Comparisons between
753 different combinations of images show that the number of images, camera
754 orientation, and number of overlapping images have little bearing on the
755 character of the resultant point cloud model, either in total point count or
756 in M3C2 distance from the Leica TLS model. Process settings in the Photo-
757 Scan software also showed to have negligible effect on the distance from the
758 Leica TLS model. However, the dense quality setting did have a significant
759 effect on the total point count in the resultant model and the processing time.
760 The pan experiment showed that fine-scale detail decreased with increased
761 distance between the camera and the subject. Point count was shown to
762 decrease with distance as a power function to the -2.15. Imagery taken at
763 a steeper angle also produced more defined boundaries between grains. We
764 suggest that the finest grain-scale topography likely to be resolvable using
765 SfM photogrammetry methods will correspond to grains occupying about
766 100 pixels in the digital imagery.

767 These results ultimately indicate that SfM photogrammetry provides a
768 viable alternative to other topographic measurement techniques, with the
769 ability to provide higher resolution datasets of comparable quality, at a frac-
770 tion of the cost and time. Additionally, the SfM photogrammetry software

771 proved to be more intuitive and present less of a learning curve than TLS
772 processing software. Given these considerations we expect SfM photogram-
773 metry to continue gaining popularity in flume experiments, as well as other
774 physical sciences.

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784 **Appendix A. Supplementary Data**

785 Supplementary data associated with this article can be found in the online
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Table 1: Dimensions of the flumes used to compare TLS and SfM as well as their grain size distribution medians (D_{50}) and geometric standard deviations (σ_g). These dimensions do not correspond to the dimensions used in the point cloud comparisons.

Flume	Total width (m)	Total length (m)	Approx. depth (m)	D_{50} (mm)	σ_g (mm)
1	0.22	9.14	0.38	1.5	2.74
2	1.22	9.14	0.58	31.0	4.33
3	1.22	18.29	0.66	4.1	2.00
4	4.88	15.24	1.20	6.2	1.67
5	6.71	30.48	0.78	0.2	1.37

Table 2: Point cloud sizes and times associated with acquisition for each method in each flume.

Flume	Image count	Approx. longitudinal image spacing (cm)	Cloud	Data acquisition time (hr)	Point count	Avg. point density (points per cm ²)
1	388	20	Leica	1.8	119,105	9.3
			Faro	1.0	485,116	37.8
			PhotoScan	0.8	7,220,309	562.2
			VSFM		6,340,931	493.8
2	218	50	Leica	3.0	1,229,703	12.3
			Faro	1.0	4,021,050	40.5
			PhotoScan	0.7	14,767,625	148.6
			VSFM		14,919,139	150.1
3	266	60	Leica	2.5	619,293	3.3
			Faro	1.0	2,030,260	10.7
			PhotoScan	0.7	14,368,454	75.7
			VSFM		14,452,316	76.2
4	248	80	Leica	3.0	1,174,194	3.6
			Faro	1.0	2,598,663	8.0
			PhotoScan	0.8	6,313,620	19.4
			VSFM		8,603,440	26.5
5	429	100	Leica	2.8	3,076,640	1.7
			Faro	1.0	10,659,966	5.8
			PhotoScan	1.1	18,006,588	9.8
			VSFM		8,910,358	4.8

Table 3: Point cloud elevation and roughness values for each method in each flume.

Flume	Cloud	Elevation (cm)		Rugosity	Roughness index-elevation (cm)		
		Range	Std. dev.		Range	Median	Std. dev.
1	Leica	9.4	0.8	1.42	0.8	0.1	0.1
	Faro	17.4	1.5	1.61	1.5	0.1	0.2
	PhotoScan	11.8	1.2	1.26	1.2	0.1	0.1
	VSFM	10.7	1.4	1.62	1.3	0.1	0.2
2	Leica	43.3	6.4	4.11	7.3	1.0	0.6
	Faro	52.1	8.3	6.09	7.1	1.1	0.7
	PhotoScan	46.2	7.2	5.73	6.9	1.0	0.7
	VSFM	51.4	6.6	6.77	11.1	1.2	0.7
3	Leica	25.7	4.2	1.19	1.1	0.2	0.1
	Faro	25.6	4.3	1.27	1.3	0.2	0.2
	PhotoScan	25.5	5.1	1.12	1.2	0.2	0.1
	VSFM	26.6	5.0	1.97	1.3	0.2	0.1
4	Leica	4.7	0.7	1.16	0.4	0.1	0.0
	Faro	7.0	0.8	1.15	0.4	0.1	0.0
	PhotoScan	4.2	0.6	1.06	0.4	0.1	0.0
	VSFM	14.6	0.9	4.22	1.4	0.3	0.2
5	Leica	51.5	11.1	1.08	1.6	0.1	0.1
	Faro	52.4	11.2	1.09	3.0	0.1	0.1
	PhotoScan	53.2	12.3	1.14	9.7	0.1	0.1
	VSFM	64.5	9.0	1.78	12.6	0.3	0.4

Table 4: Image combinations comparison for Flume 3.

Image combination	Targets	Image count	Point count	M3C2 distances from Leica (m)	
				Median	RMS
All images (JPG)	no	266	14,368,454	0.001	0.002
All images (RAW)	no	266	14,091,686	0.001	0.002
All images (JPG)	yes	266	14,353,849	0.001	0.002
US-DS images	yes	89	11,307,633	0.000	0.002
RB-LB images	no	177	14,231,567	0.001	0.002
RB-LB images	yes	177	14,263,685	0.001	0.002
RB-LB angled	no	117	12,278,775	0.001	0.002
No cross flume	no	206	12,939,702	0.000	0.002
Every second	no	135	13,862,586	0.001	0.002
Every third	no	90	—	—	—
Every fourth	no	71	—	—	—

Table 5: Image combinations comparison for Flume 5.

Image combination	Targets	Image count	Point count	M3C2 distances from Leica (m)	
				Median	RMS
All images (JPG)	no	429	18,006,588	0.000	0.003
All images (RAW)	no	429	9,199,483	0.004	0.015
All images (JPG)	yes	429	20,163,866	0.000	0.004
US-DS images	yes	94	8,544,152	-0.001	0.004
RB-LB images	no	335	22,732,148	0.000	0.003
RB-LB images	yes	335	24,198,759	0.000	0.003
RB-LB angled	no	134	19,155,313	0.000	0.009
No cross flume	no	362	19,425,883	0.000	0.004
Every second	no	223	14,776,760	0.000	0.004
Every third	no	146	8,597,343	0.006	0.024
Every fourth	no	114	—	—	—

Table 6: Flume 3 point cloud summaries produced using different PhotoScan settings.

Processing times should be taken as “order of magnitude” approximations for a standard desktop computer.

Accuracy	Quality	Point count	M3C2 distances from Leica (m)		Processing time
			Median	RMS	
Lowest	Medium	15,961,002	0.001	0.003	hours
Medium	Medium	14,353,407	0.001	0.002	hours
Highest	Lowest	794,090	0.001	0.003	minutes
Highest	Medium	14,368,454	0.001	0.002	hours
Highest	Ultra High	262,402,248	0.000	0.002	days

Table 7: Point cloud sizes from pan experiment.

Distance (m)	30° imagery		60° imagery	
	Point count	Avg. pt density (pts per cm ²)	Point count	Avg. pt density (pts per mm ²)
0.5	32,824,726	282.0	29,562,203	25390
0.75	15,417,582	132.4	15,200,162	13060
1	7,831,331	67.3	8,127,557	6980
1.5	3,430,310	29.5	3,302,979	2840
2	1,844,637	15.9	1,706,091	1470
3	671,886	5.8	657,6620	570

Figure 1: Photographs showing the setup and grain sizes for (a) Flume 1, (b) Flume 2, (c) Flume 3, (d) Flume 4, (e) Flume 5, and (f) the pan.

Figure 2: Surface grain size distributions present in each flume.

Figure 3: Conceptual illustrations showing (a) the approximate camera angles for flume imagery, (b) the different combinations of images tested for Flumes 3 and 5, (c) the vertical angles for the pan imagery, and (d) the horizontal angles for the pan imagery.

Figure 4: Flume 1 maps showing (a) image overlap count for all images collected for SfM and (b) point density, (c) elevation, and (d) roughness index-elevation for Leica ScanStation, Faro Focus3D, PhotoScan and VisualSFM models.

Figure 5: Flume 2 maps showing (a) image overlap count for all images collected for SfM and (b) point density, (c) elevation, and (d) roughness index-elevation for Leica ScanStation, Faro Focus3D, PhotoScan and VisualSFM models.

Figure 6: Flume 3 maps showing (a) image overlap count for all images collected for SfM and (b) point density, (c) elevation, and (d) roughness index-elevation for Leica ScanStation, Faro Focus3D, PhotoScan and VisualSfM models.

Figure 7: Flume 4 maps showing (a) image overlap count for all images collected for SfM and (b) point density, (c) elevation, and (d) roughness index-elevation for Leica ScanStation, Faro Focus3D, PhotoScan and VisualSfM models.

Figure 8: Flume 5 maps showing (a) image overlap count for all images collected for SfM and (b) point density, (c) elevation, and (d) roughness index-elevation for Leica ScanStation, Faro Focus3D, PhotoScan and VisualSFM models.

Figure 9: Minimum, 1 percentile, median, 99 percentile, and maximum for M3C2 differences between each combination of models for each flume, such that the black line encompasses 98% of the measured M3C2 distances. L = Leica, F = Faro, P = PhotoScan, and V = VisualSFM.

Figure 10: Flume 3 maps showing the count of overlapping images for each of the image combinations. Note that camera positions and directions indicated by the black dots and lines are for illustrative purposes only and do not represent actual image positions and angles.

Figure 11: Minimum, 1 percentile, median, 99 percentile, and maximum for M3C2 differences between SfM models created using different image combinations and PhotoScan settings for Flume 3, such that the black line encompasses 98% of the measured M3C2 distances.

Figure 12: Flume 5 maps showing the count of overlapping images for each of the image combinations. Note that camera positions and directions indicated by the black dots and lines are for illustrative purposes only and do not represent actual image positions and angles.

Figure 13: Minimum, 1 percentile, median, 99 percentile, and maximum for M3C2 differences between SfM models created using different image combinations for Flume 5, such that the black line encompasses 98% of the measured M3C2 distances.

Figure 14: Cross-section profiles at a rotation angle of -70° for the pan experiment. The top left image is from an orthoimage created in PhotoScan showing the line of the cross-section profile. The bottom right circle shows the entire area of interest for the pan with and the line of the cross-section profile. The profiles have a vertical exaggeration of 4.

Figure 15: Cross-section profiles at a rotation angle of 47° for the pan experiment. The top left image is from an orthoimage created in PhotoScan showing the line of the cross-section profile. The bottom right circle shows the entire area of interest for the pan with and the line of the cross-section profile. The profiles have a vertical exaggeration of 4.

Figure 16: Longitudinal M3C2 differences and fitted second-degree polynomials showing nonlinear deformation in the downstream direction of SfM point clouds for Flume 1.