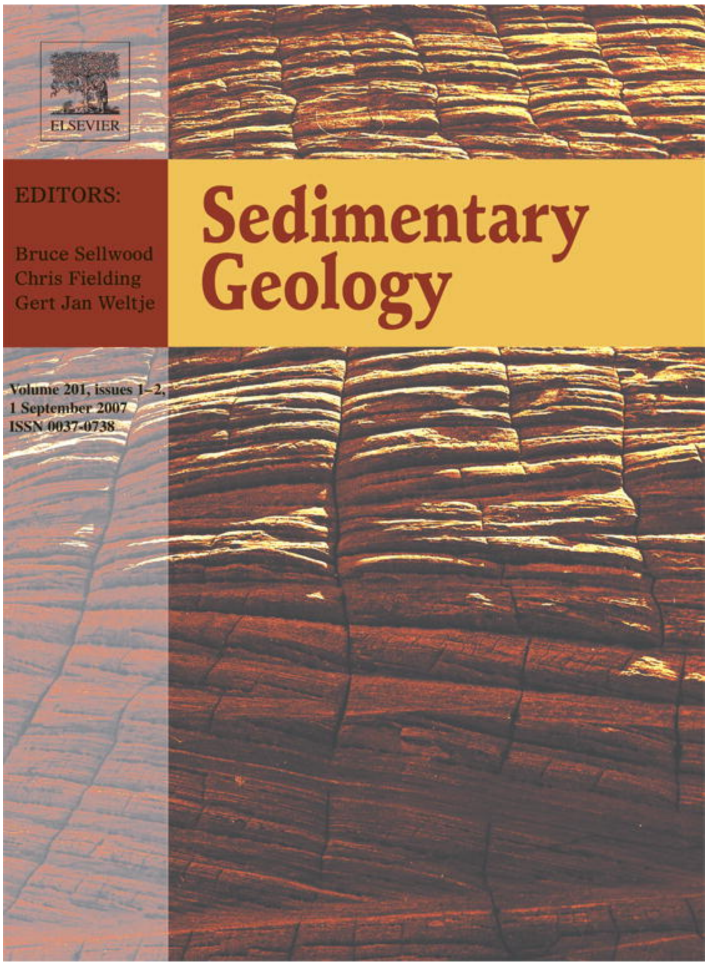
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Field test comparison of an autocorrelation technique for determining grain size using a digital 'beachball' camera versus traditional methods

Patrick L. Barnard [a,*], David M. Rubin [a], Jodi Harney [a], Neomi Mustain [b]

[a] United States Geological Survey, Coastal and Marine Geology Team, Pacific Science Center, 400 Natural Bridges Drive, Santa Cruz, CA 95060, United States
[b] Department of Earth and Planetary Sciences, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95060, United States

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Abstract

This extensive field test of an autocorrelation technique for determining grain size from digital images was conducted using a digital bed-sediment camera, or 'beachball' camera. Using 205 sediment samples and >1200 images from a variety of beaches on the west coast of the US, grain size ranging from sand to granules was measured from field samples using both the autocorrelation technique developed by Rubin [Rubin, D.M., 2004. A simple autocorrelation algorithm for determining grain size from digital images of sediment. Journal of Sedimentary Research, 74(1): 160–165.] and traditional methods (i.e. settling tube analysis, sieving, and point counts). To test the accuracy of the digital-image grain size algorithm, we compared results with manual point counts of an extensive image data set in the Santa Barbara littoral cell. Grain sizes calculated using the autocorrelation algorithm were highly correlated with the point counts of the same images ($r^2 = 0.93$; $n = 79$) and had an error of only 1%. Comparisons of calculated grain sizes and grain sizes measured from grab samples demonstrated that the autocorrelation technique works well on high-energy dissipative beaches with well-sorted sediment such as in the Pacific Northwest ($r^2 \geq 0.92$; $n = 115$). On less dissipative, more poorly sorted beaches such as Ocean Beach in San Francisco, results were not as good ($r^2 \geq 0.70$; $n = 67$; within 3% accuracy). Because the algorithm works well compared with point counts of the same image, the poorer correlation with grab samples must be a result of actual spatial and vertical variability of sediment in the field; closer agreement between grain size in the images and grain size of grab samples can be achieved by increasing the sampling volume of the images (taking more images, distributed over a volume comparable to that of a grab sample). In all field tests the autocorrelation method was able to predict the mean and median grain size with ~96% accuracy, which is more than adequate for the majority of sedimentological applications, especially considering that the autocorrelation technique is estimated to be at least 100 times faster than traditional methods.
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Keywords: Grain size; Digital image; Beach; Bed sediment

1. Introduction

Grain size analysis has traditionally been a long and arduous task, utilizing either mechanical sieving (Krumbein and Pettijohn, 1938), settling tube (Gibbs,

* Corresponding author.
E-mail address: pbarnard@usgs.gov (P.L. Barnard).

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Fig. 1. Location of the three field sites for grain size analysis.

1972), or laser diffraction (Agrawal et al., 1991). Butler et al. (2001) used an algorithm to determine the size of individual grains, but not entire images, and his work was limited to coarse-grained fluvial systems. Automated grain size determination has been developed successfully using airborne digital imagery in fluvial systems (Carbonneau, 2005; Carbonneau et al., 2005; Verdu et al., 2005), but the measurable grain size is limited by the image resolution, typically >3 cm, and therefore this technique is not applicable to sandy coasts. The development of the autocorrelation technique by Rubin (2004) and accompanying bed-sediment camera (Chezar and Rubin, 2004; Rubin et al., 2006a,b) has increased the speed of grain size analysis for sandy environments by perhaps 100 times for large sample sets ($\sim n \geq 50$), but an extensive test of the accuracy of the

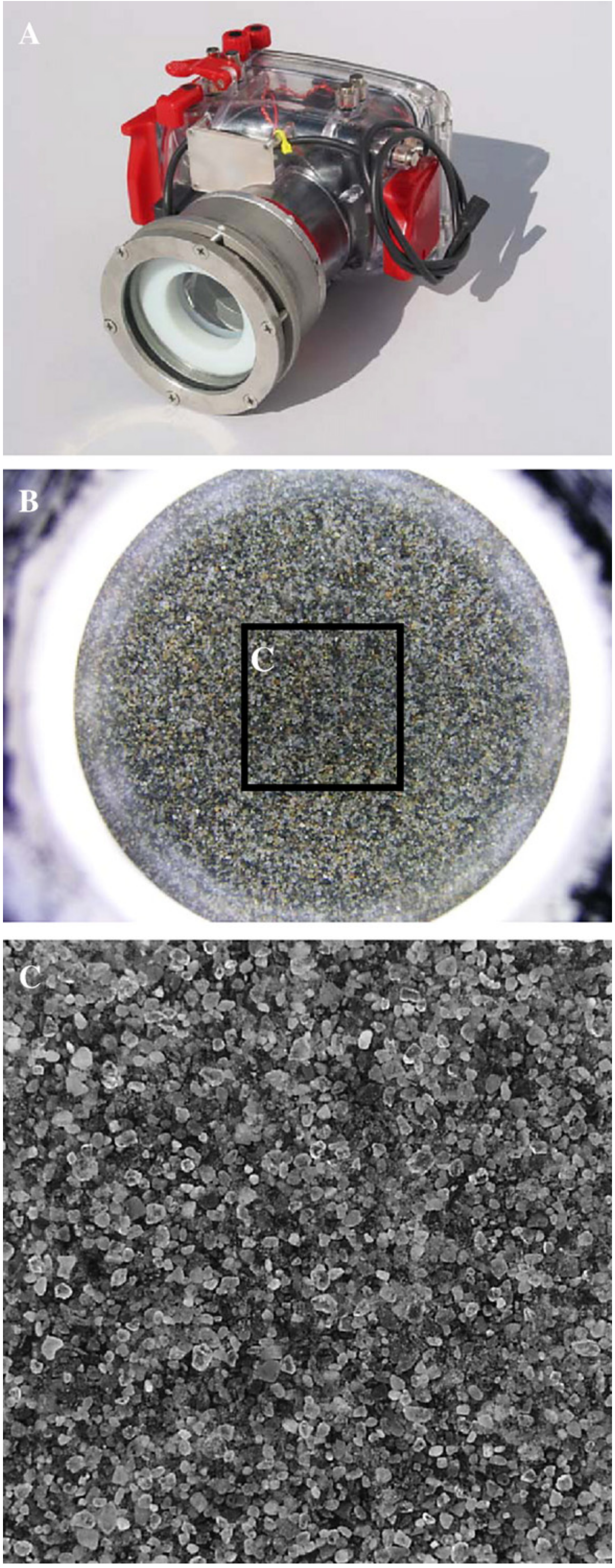

Fig. 2. A) The digital bed-sediment camera, or 'beachball,' with waterproof housing. B) A raw jpeg image prior to processing. The image is 5 cm across. C) The image converted to a grey scale TIF format, cropped, and ready for analysis. The median grain size of this sample (Ocean Beach #L2ST1S3) is 0.250 mm as determined by the autocorrelation technique and 0.247 mm as determined by the settling tube.

results for a variety of field areas has not been completed previously. This paper compares the results of median and mean grain sizes on a variety of West Coast beaches using extensive field testing of the hand held eyeball camera (a.k.a. 'beachball') compared to traditional methods. The potential problem of spatial variance (i.e. difference between image captured and grain size of a grab sample) is also discussed, as is the potential error introduced by improper image calibration techniques, image quality, and sampling volume.

Three principal study sites were chosen for the analysis at field sites that are part of current US Geological Survey coastal research projects (Fig. 1). Ocean Beach is a 7-km long, high-energy beach at the mouth of San Francisco Bay, with median grain size ~0.29 mm and localized coarse gravel lags (Barnard and Hanes, 2005) (web site: http://walrus.wr.usgs.gov/coastal_processes/). The Columbia River littoral cell extends more than 145 km from Tillamook Head, Oregon, to Point Grenville, Washington, and represents the end-member high energy, dissipative beach. Median grain size averages 0.20 mm in a range of 0.12 to 0.71 mm (Ruggiero et al., 2005). The third site is the Santa Barbara littoral cell, which extends 150 km from Pt. Conception to Pt. Mugu, and includes a broad spectrum of beach settings (e.g. cliff backed, hard structures, coastal plain) and grain sizes (i.e. cobbles to fine sand).

2. Purpose

The purpose of this study was to test the use of spatial autocorrelation to quantify grain size in digital images of sand on beaches. This study has two components: (1) to investigate how well the algorithm works at measuring the size of grains in an image of the beach surface, and (2) to evaluate how many images are needed to be representative of the bed in a particular location. Vertical stratification is addressed by comparing surface images with grab samples analyzed by sieving and settling tube analysis, the algorithm is tested by comparison with point counts of grains in the same image, and the spatial variability is addressed by comparing the grain size determined from images at nearby locations (few tens of cm).

3. Methods

This study utilized an Olympus five-megapixel Camedia C-5050 Zoom Digital camera in a waterproof housing, collectively known as the 'beachball' (Fig. 2). In super macro mode there are 2000 pixels across the image with an effective resolution of 40 pixels

Table 1
Field grab samples analyzed for this study

Site	Total # beachball Samples	Beachball sample In field	# of settling Tube samples	# of sieved Samples-median	# of sieved Samples-mean
Ocean Beach, CA	67	Yes	67	0	0
Columbia River littoral cell	115	No	0	47	115
Santa Barbara littoral cell	23	Yes	23	0	0
Totals	205		90	47	115

per mm. The sediment bed is evenly illuminated using an LCD light ring mounted inside the camera housing. Three to five field images are typically taken at each sample site, with the autocorrelation results averaged. For more detailed information on the hardware used and the autocorrelation technique see Chezar and Rubin (2004), Rubin (2004), and Rubin et al. (2005; 2006a,b).

In May 2004, 67 grab samples were collected along 18 profile lines spaced over the full extent of Ocean Beach for settling tube analysis in the lab. At the same time, three images were taken with the beachball camera of the sediment surface at each of the grab sample locations, for a total of 201 images. Sample locations included swash, forebeach, berm crest, back beach, and dune toe. After the settling tube analysis was completed, archived settling tube samples were also imaged using the beachball camera in an attempt to test the effects of vertical and horizontal spatial variation in the field.

Between 2001 and 2004, 115 mid-beach samples were collected from 45 alongshore-spaced profiles within the Columbia River littoral cell. Sediment statistics were generated in the lab using traditional sieving techniques. Five images of each of the archived samples were later taken with the beachball camera for a total of 575 images for comparison with the sieving technique.

In 2006 and 2007, 23 grab samples were taken at various locations within the Santa Barbara littoral cell for settling tube analysis, and 3 images captured at each site. A summary of the field samples analyzed for this entire study is listed in Table 1. In addition, 79 images were manually point counted (i.e. 100 individual grains were measured in pixels, converted to mm, and then averaged to determine the mean grain size of the image) for comparison with the autocorrelation results. Lastly, 414 total images from nine, 1 m^2 sites were captured to document the spatial variation of surface samples from representative sample sites and assess the image sampling volume required for the desired level of precision.

The autocorrelation technique is a two-step process. First, acceptable calibration curves are established using a representative bulk sample from the study site that covers all the anticipated grain sizes sieved to quarter-phi intervals. At least three calibration images are taken of each size class with the digital camera, an autocorrelation is performed on the images, and resulting calibration curves are plotted (Fig. 3). A MATLAB® Script for autocorrelation is shown in the Appendix. Overlapping or closely-spaced curves from different size classes are combined with adjacent classes or removed until a final set of distinct calibration curves and associated matrix is established. The calibration images should be taken under conditions that are similar to the field samples (i.e. wet and/or dry depending on typical field conditions) for most accurate results. In this study, a unique set of calibration curves was constructed for each site. While constructing a calibration curve for each new study site may not be essential, it may slightly increase the accuracy of the results by calibrating for the differing optical properties of the site specific mineralogy that may skew the autocorrelation results. Alternatively, calibration curves can be determined using point counts of sieved sediment. This insures that the grain size attributed to a sieved size fraction is accurate; grain size retained on a sieve can be smaller than the nominal sieve size if sieving is incomplete. The second step is to perform an autocorrelation of the field sample images and perform a 'best fit' with the calibration matrix (Rubin, 2004). See Appendix for the MATLAB® script used to generate the mean and median grain size results presented in this paper.

4. Results

The field test results of beachball performance compared to traditional methods are summarized in Fig. 4. Although different sampling techniques were used at the various study sites, in all cases the autocorrelation technique was able to predict the grain size of a sample set with excellent accuracy, with median and mean percent error values 0.6% and 6.2%, respectively, based on 203 samples. Upon removing up to four outlier samples, r^2 increased dramatically to ~0.8 for both median and mean grain size (Fig. 4C–D). These different results are not entirely due to differences in grain size analysis techniques; differences also arise because photographs of a small area of the bed and grab samples of a larger volume of sediment contain different populations of grains, as discussed later.

4.1. Ocean Beach

Despite accurately predicting the grain sizes of the sample set, the correlation of variance for all the Ocean Beach field samples for the median and mean is 0.14 and 0.23, respectively. Initial analysis of these poor values indicates that up to 10 images (out of 201 total) from four sample locations were the cause of the divergence. Removal of the 10 outliers caused the r^2 values to increase to 0.70 and 0.76 for median and mean grain size (Fig. 5A–B).

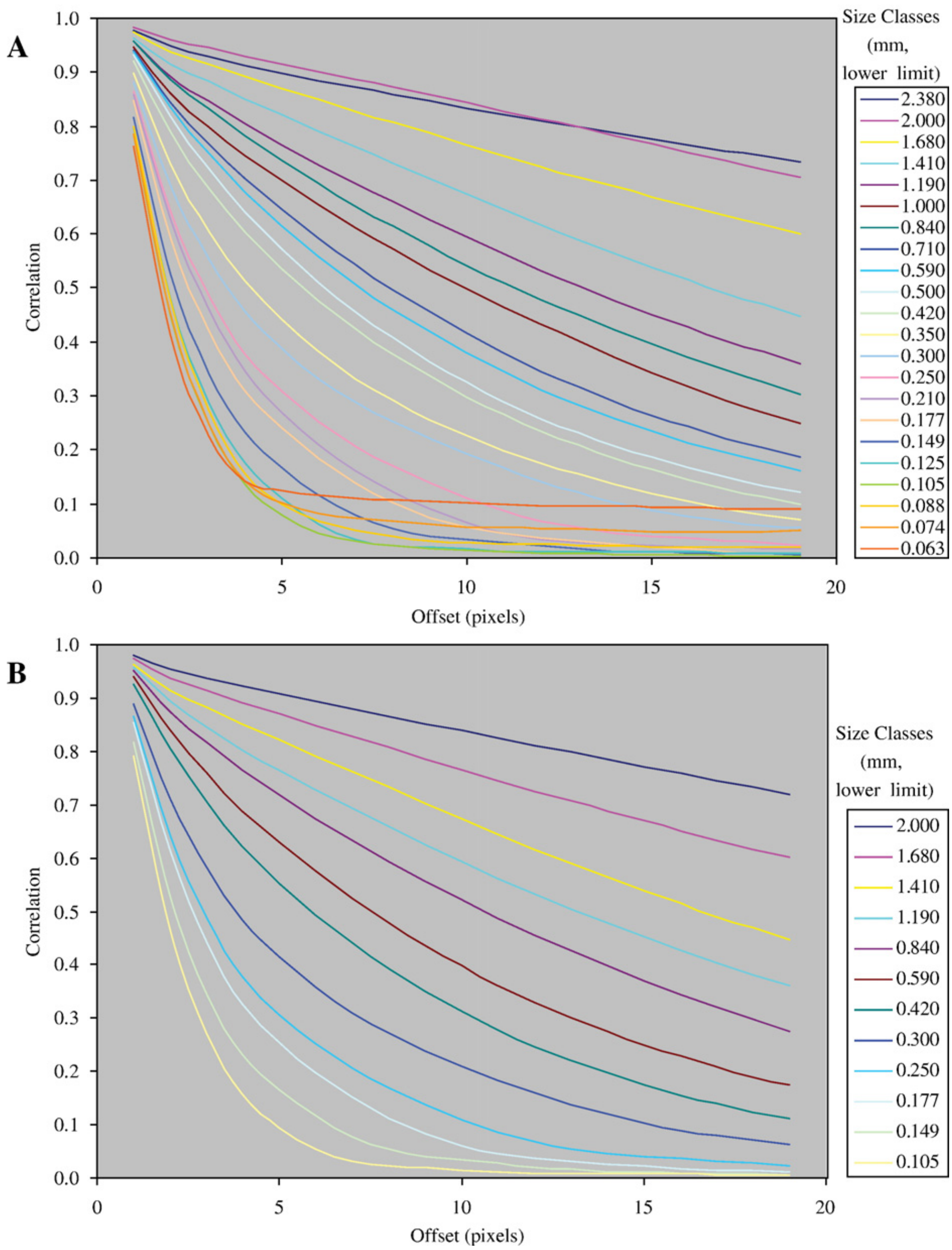

Fig. 3. An example set of calibration curves from the Ocean Beach study. A) Raw calibration curves with 22 size classes. B) Final set of 12 size classes created by cutting and combining size classes from raw curves to make class boundaries distinct.

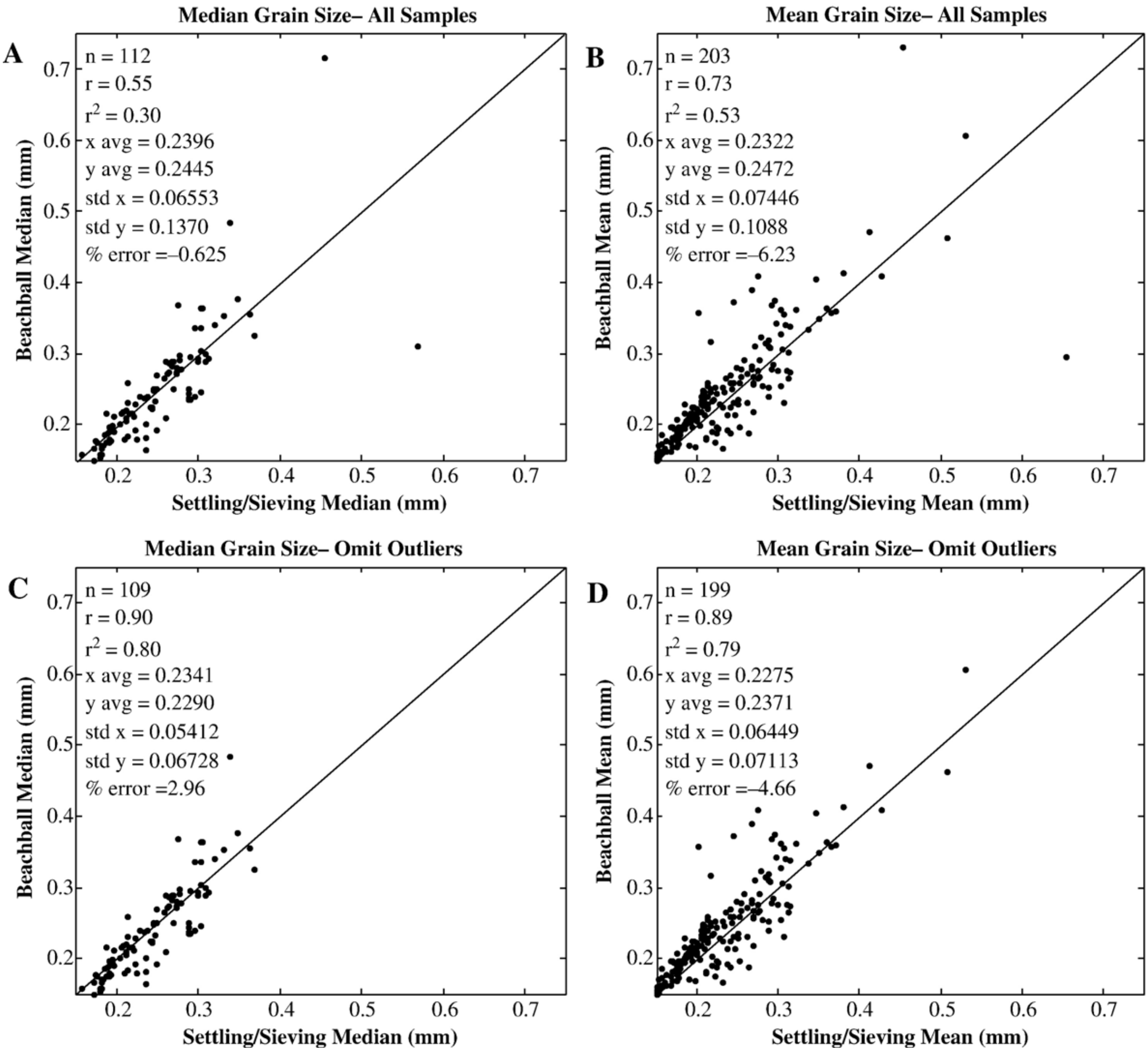

Fig. 4. Plots of all the samples analyzed in this study using both the autocorrelation technique and a traditional method to measure median and mean grain size. The 1:1 correlation line is plotted for reference. A) All field samples, median grain size, B) All field samples-mean grain size, C) All field samples, median grain size, omitting three outliers, and D) All field samples, mean grain size, omitting four outliers.

When the autocorrelation was performed on the archived settling tube samples the correlation improved for the mean values ($r^2=0.84$) and was relatively unchanged for the median values ($r^2=0.67$) (Fig. 5C–D). In all cases the predicted median and mean grain size values were quite accurate. Swash samples show the highest correlation with r^2 values ranging from 0.74 to 0.80 (Fig. 6).

4.2. Columbia River littoral cell

The beachball samples show excellent correlation with the sieving results, with r^2 values for mean and median of 0.96 ($n=115$) and 0.92 ($n=47$), respectively (Fig. 7). Predictions of median and mean grain size are also excellent, with an overall % error of less than 8%. However, there is an apparent systematic overestimation for the mean grain size estimates using the autocorrelation technique.

4.3. Santa Barbara littoral cell

The comparison of manual point counting versus the autocorrelation technique based on 79 images shows excellent correlation with r^2 values for mean grain size of 0.93 (Fig. 8). In addition, a best fit line

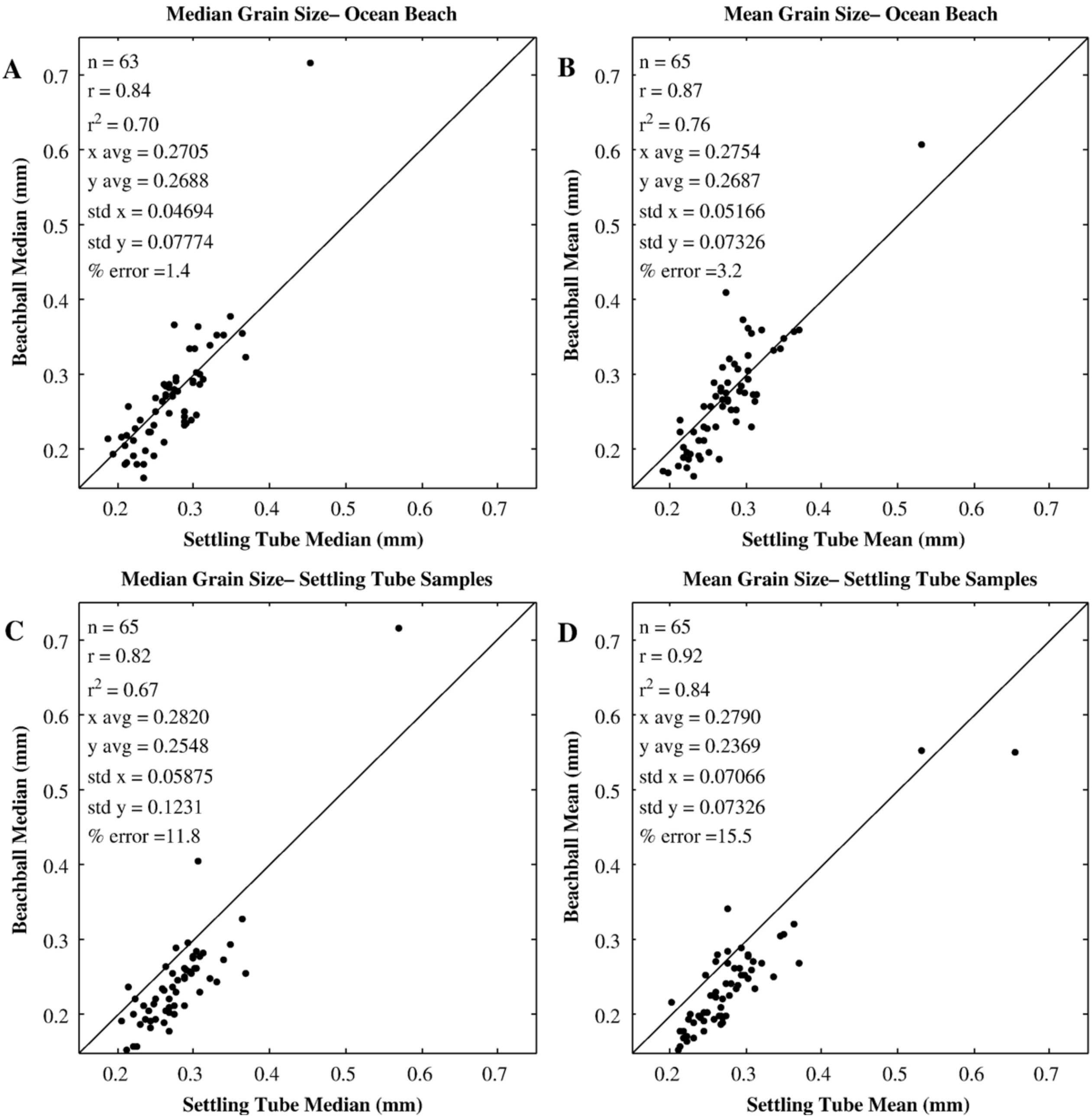

Fig. 5. Plot of the Ocean Beach sample results using the autocorrelation technique and settling tube. The 1:1 correlation line is plotted for reference. A) Median grain size, omitting outliers from four sample sites (10 images out of 201 total), B) Mean grain size, omitting outliers from two sample sites. C) Comparison of digital beachball images of archived settling tube samples with settling tube results, median grain size. D) Comparison of digital beachball images of archived settling tube samples with settling tube results, mean grain size.

through the data displays only a slight systematic offset. Intense sampling in the nine, 1-m^2 areas shows that grain size can vary by a factor of two or more in a small area, and that for most areas at least 7–10 images should be taken to be confident that accuracy to within 10% of the "true" mean is achieved at each sample station (Fig. 9).

5. Discussion

The field experiments in the Santa Barbara littoral cell demonstrate the accuracy of the technique and also the importance of increasing the image sampling volume for an accurate measurement of the true grain size. Despite the variation of grain sizes

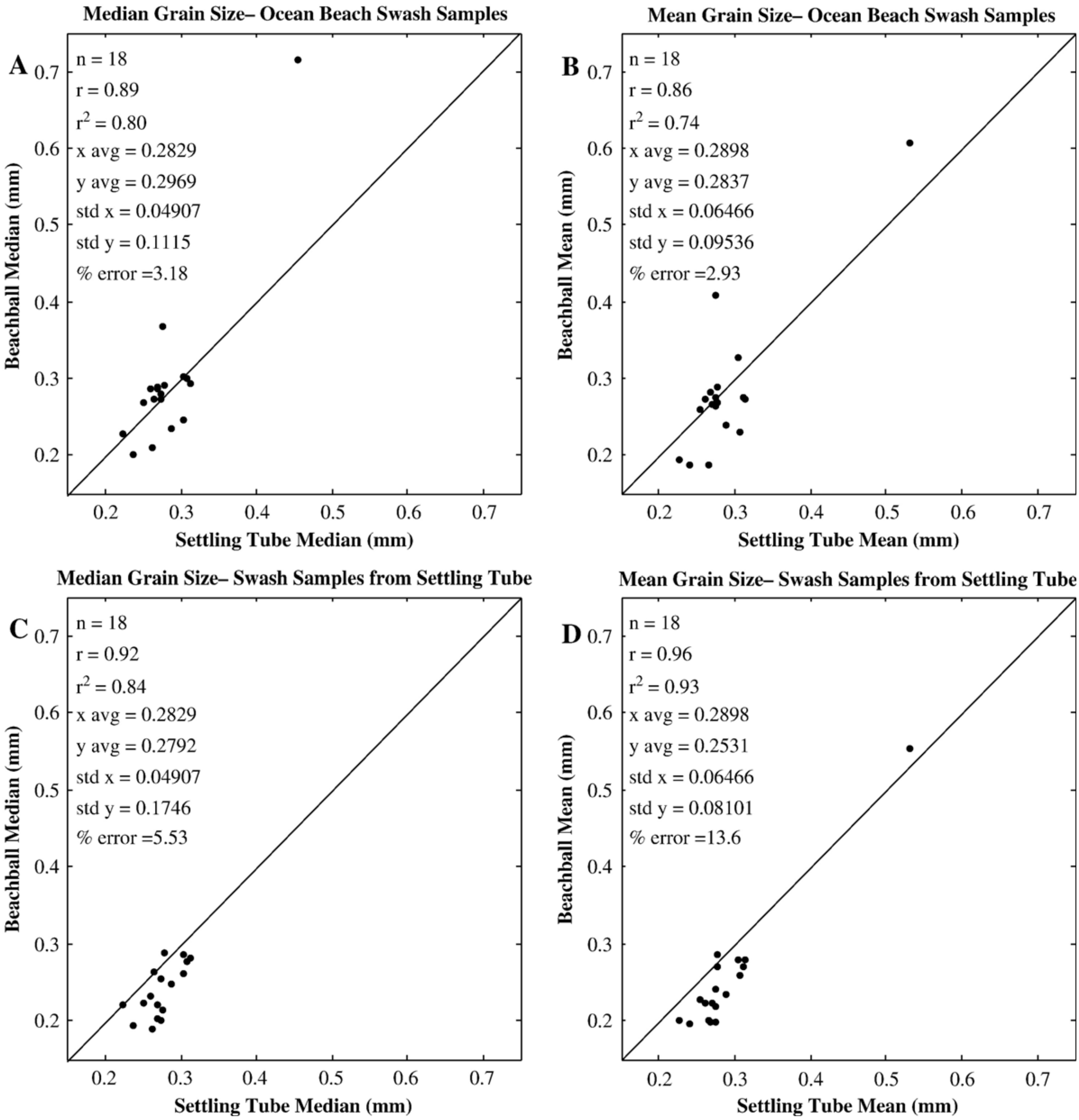

Fig. 6. Plot of the Ocean Beach swash sample results using the autocorrelation technique and settling tube for A) Median grain size, and B) Mean grain size. Comparison of digital beachball images of archived settling tube swash samples with settling tube results for C) Median grain size and D) Mean grain size. The 1:1 correlation line is plotted for reference.

illustrated in Fig. 9, manual point counting in Fig. 8 shows that the autocorrelation technique is 99% accurate in measuring the mean grain size of the captured image. However, due to the potential local variation in grain size, converging on the true mean and median grain size of the surficial beach can only be achieved through increasing the image sampling volume to a level based on the acceptable error. In the example shown in Fig. 9, for beaches with significant local variation ~10 samples may be required to achieve a confidence level that your sampling station is well represented to within 10% of the true mean. However, increasing the number of images per sample station only increases the sampling and analysis by ~10 s/sample. Additional grab samples for traditional grain size analysis would increase the

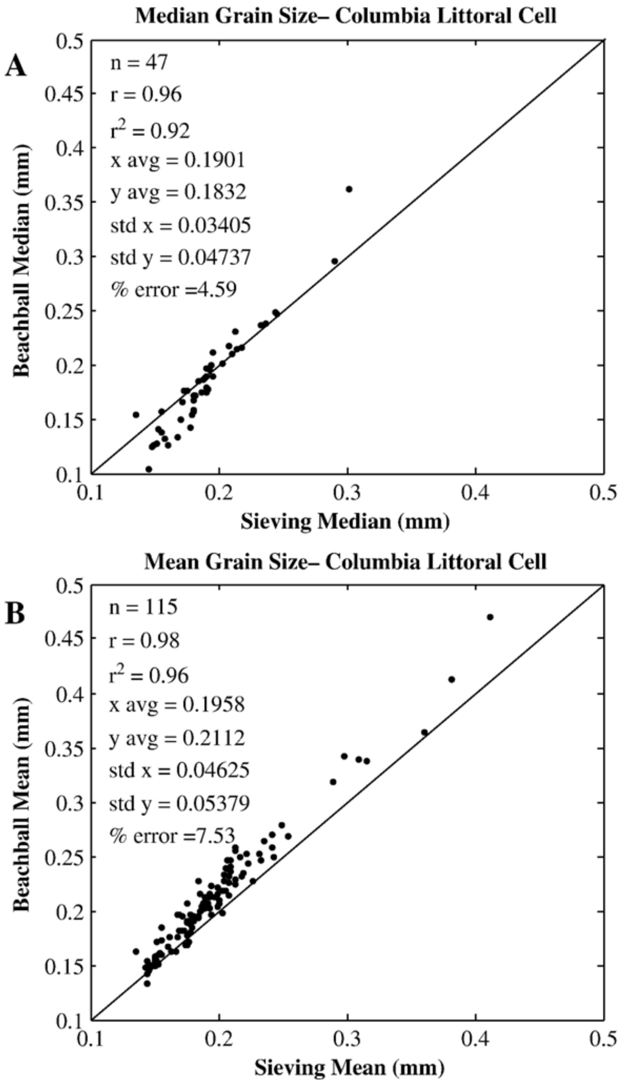

Fig. 7. Plot of the Columbia River littoral cell grain size results using the autocorrelation technique and sieving: A) Median grain size, B) Mean Grain size. The 1:1 correlation line is plotted for reference.

time spent by up to several orders of magnitude per sample.

Overall the performance of the beachball camera with the autocorrelation technique has proven to be an efficient and accurate method, with 203 samples tested using both the beachball camera and traditional methods, yielding ~80% correlation and 96% accuracy through a range of study sites. The four major outliers in 203 samples (or 10 out of >800 images) were from Ocean Beach, and were a result of geological spatial variation. In other words, what was sampled for settling tube analysis was not what was captured by the camera on the sediment bed. Fig. 10A shows an instance whereby a single anomalous grain yielded results with poor correlation. When this sample location was compared with the archived settling tube sediment, the correlation was much better (Fig. 5C–D). Other samples that yielded poor results with the beachball camera, and hence discarded, were samples with large air bubbles, poor image exposures (e.g. too dark), and grains out of focus (Fig. 10B–D). Such samples should not be used for grain size analysis. It is important to emphasize that quality control is essential. The images in question would have normally been excluded initially as would be the case if no lab analyses are available. Further, to minimize the impact of a single image with a single large grain, it is essential to increase the sampling frequency in these coastal settings to converge on the "true" median and mean (see Fig. 9).

At Ocean Beach the swash samples returned excellent correlation of variance: 0.80 and 0.74 for median and mean, respectively. The active swash zone is traditionally better sorted (Blackley and Heathershaw, 1982; Li and Komar, 1992), with little to no wind effects to create an armored surface as in the back beach (Carter, 1976; Isla, 1993). Therefore, analyzing the swash samples results in a better agreement between a surficial sample (i.e. beachball image) and a grab sample that penetrates several centimeters. The true test of the camera's accuracy at Ocean Beach was comparing settling tube results with digital images of the settling tube samples (Fig. 5C–D). In this case the correlation of variance for median grain size was 0.67, as opposed to 0.14 for the unedited beach surface samples. Further, manual point counting for Santa Barbara samples (Fig. 8) illustrates the accuracy of the autocorrelation technique, with an error of only ~1% and correlation of variance well over 90%.

It is well known that the settling velocity of particles is not only a function of grain size diameter, but also shape (i.e. sphericity) and density, and therefore sieving results and settling tube results may not be identical (Jones and Cameron, 1976). At Ocean Beach, the settling tube results consistently overestimate the grain size, which could be due to the abundance of heavy minerals, roundness of grains, or scarcity of clay mineralogy at this field site. However, the goal here is to show that the results are acceptably accurate and consistent whether the autocorrelation technique is used or a traditional technique. No attempt has been made in this analysis to correct for the precise settling velocity of the particles in question.

The Columbia River littoral cell data set shows excellent correlation throughout, with no outliers and r^2

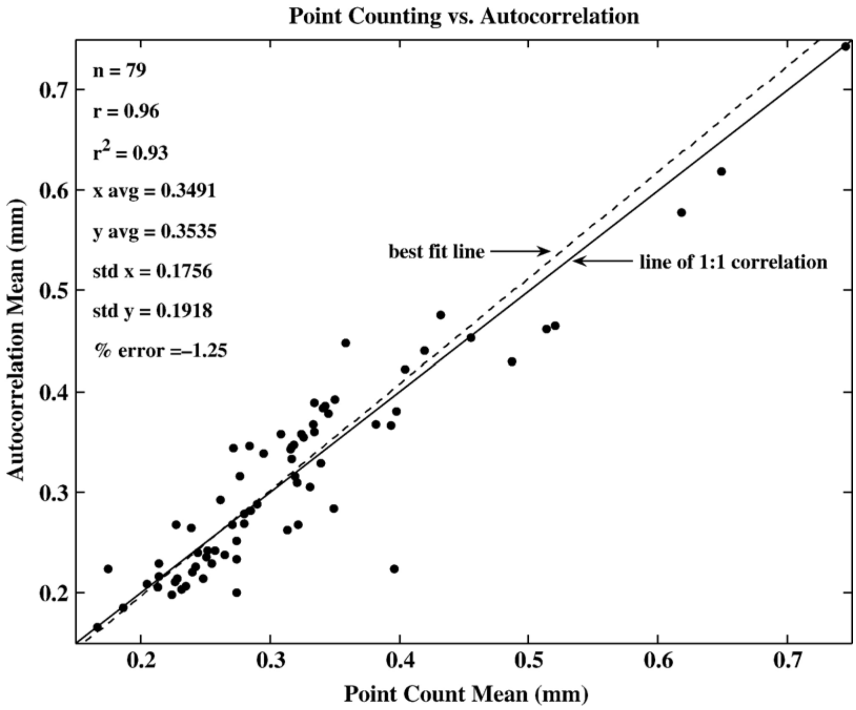

Fig. 8. Plot of point count results of mean grain size versus autocorrelation for 79 images from the Santa Barbara littoral cell.

values exceeding 0.90 for both median and mean grain size. However, although the correlation is excellent for the Columbia River littoral cell, there is a systematic offset in the mean grain size calculations by the beachball camera of approximately +7.5%. This minor overestimation could be a result of improper sieving for calibration curves, such as inadequate sieving time to get all the finer sediments through the sieves, or overfilled sieves blocking finer sediment from getting through the sieves. However, once calibrated with sieved samples, a systematic offset could be rectified by applying a correction factor to the samples (e.g. in this case 7.5%) to produce more accurate results for this data set and future analyses using the same set of calibration curves if a higher level of accuracy is desired.

The greater correlation for the Columbia River littoral cell in comparison to Ocean Beach is due to a series of factors: grain size, sorting, sampling volume, and sampling technique. Grain size in the Columbia River littoral cell is finer and better sorted under the prevailing dissipative conditions. This results in more grains per image and less grain size variation, producing more accurate results. Five images were taken for each sample in the Columbia River littoral cell as opposed to only three at Ocean Beach, giving more statistically significant results. Finally, the analysis for the Columbia River littoral cell was conducted on archived sieve samples, rather than field surface samples as at Ocean Beach. At Ocean Beach, and as was demonstrated in Santa Barbara (Fig. 9), a series of samples from a very small area can yield vastly different results, and therefore a grab sample and an image taken nearby do not necessarily sample the same population of grains.

The grain size range of application of the method is primarily a function of the camera resolution and field of view. The camera used in this study is designed for sandy beaches. At 5 megapixels, the measurable grain size range is from very fine sand (~0.0625 mm) to gravel (~2.5 mm). At finer grains sizes (i.e. silt), the grain size approaches the pixel size, and therefore autocorrelation becomes increasingly unreliable. At coarser grain sizes, given the field of view of the camera (5 cm by 5 cm), only several grain sizes may be in view, decreasing the statistical significance of the results.

The grain size and sorting characteristics of a given study site must be taken into account when designing a sampling strategy, as well as the level of accuracy desired. In general, for a given sample station, finer sediment and/or better sorting require fewer images per site to converge on the true mean or median grain size. Coarser sediment results in fewer grains per image

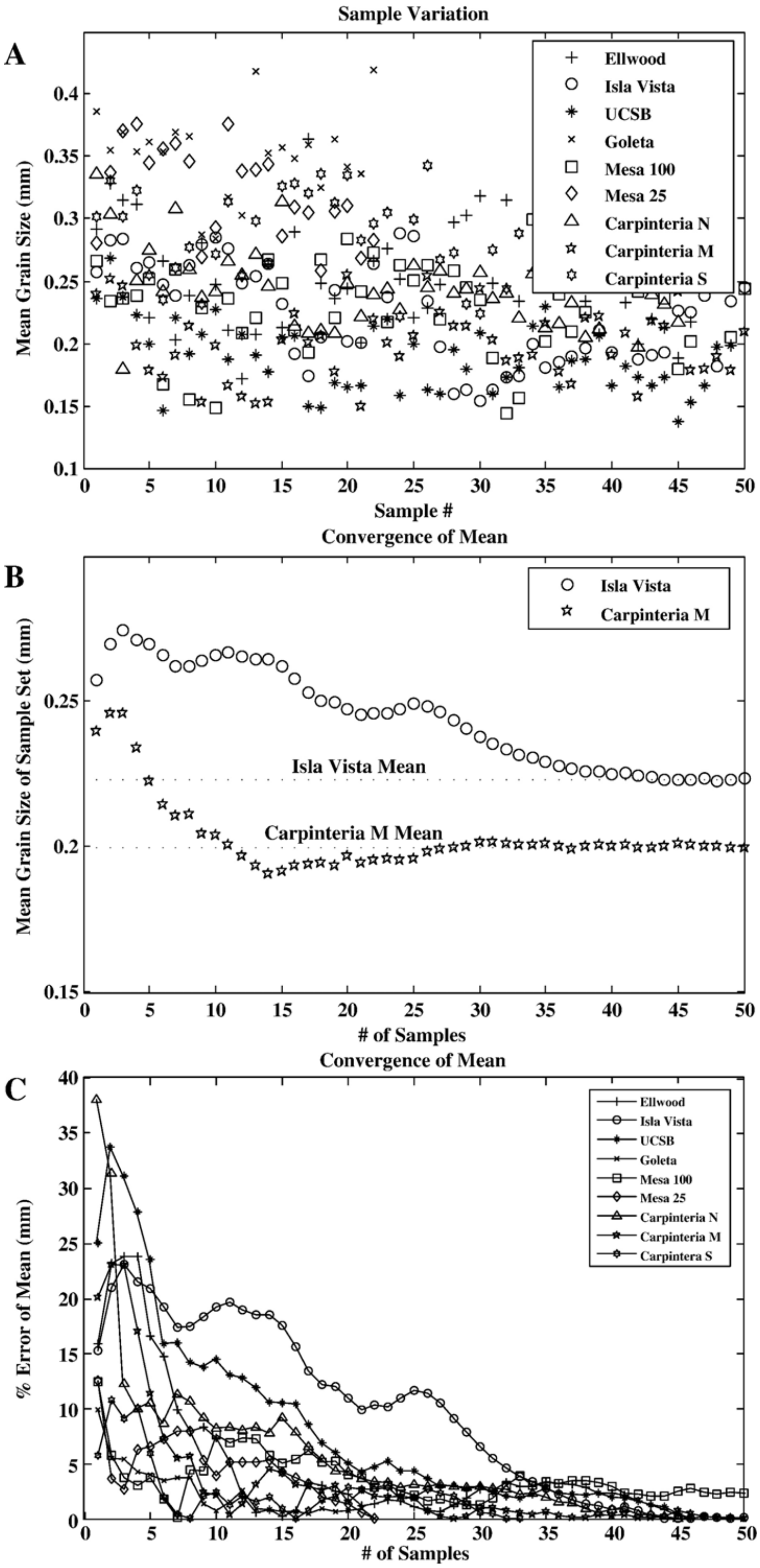

Fig. 9. The effects of spatial variation and sampling frequency-examples from the Santa Barbara littoral cell. A) Sample variation from nine field sites each sampling a 1 m^2 area. Only up to the first 50 samples from each site are plotted. B) Examples from two of the study sites showing the convergence of the mean with increased sampling frequency and the dependence of calculated mean grain size on the initial samples. C) Convergence of the mean using per cent error from each of the nine test sites.

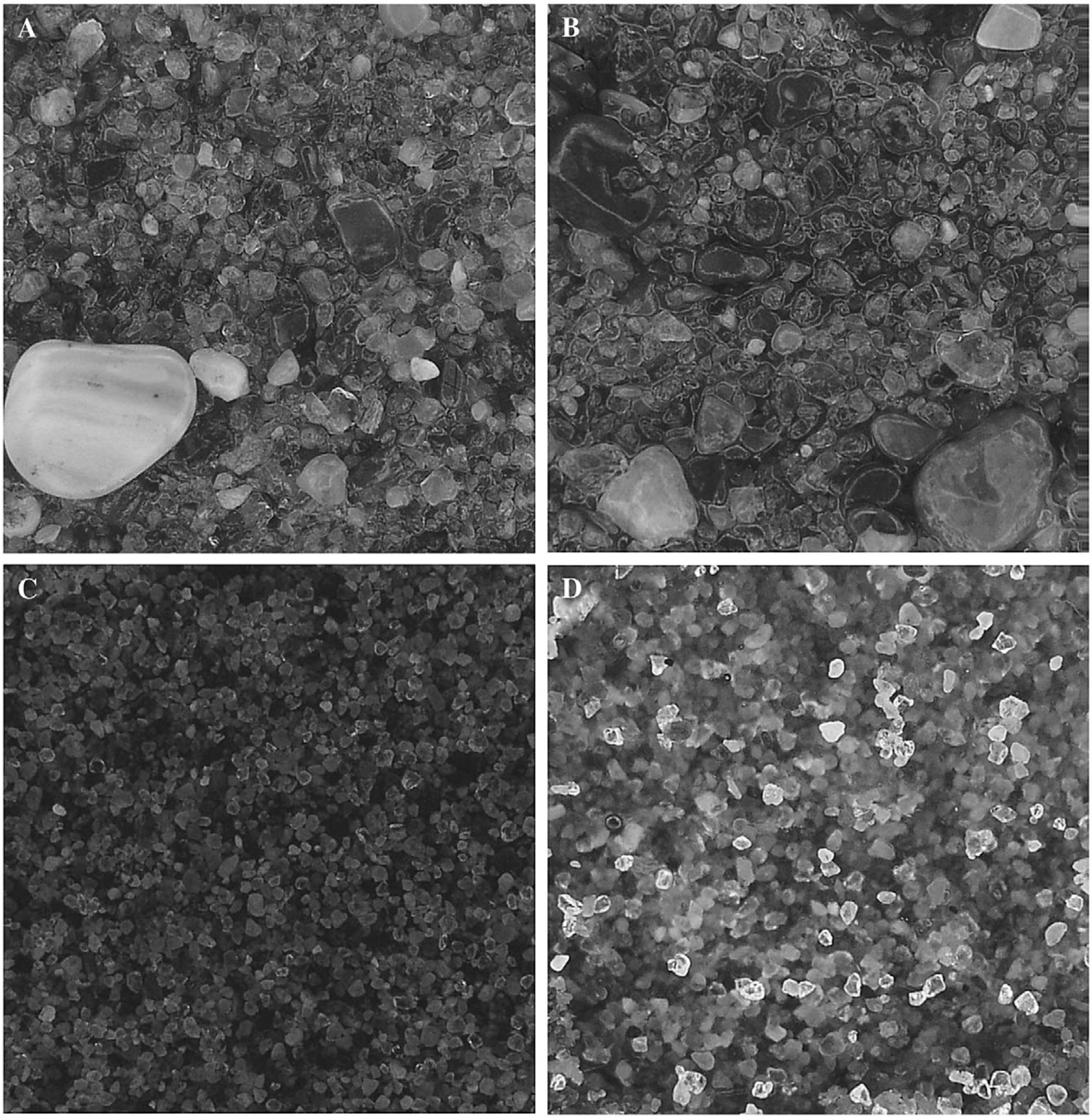

Fig. 10. Photos of samples that yield poor correlation. A) Coarse lag, median from settling tube = 0.2916 mm, eyeball = 1.4150 mm (0.2560 mm using settling tube archive), mean settling tube = 0.2939 mm, eyeball = 0.9150 mm (0.2400 mm using settling tube archive). Other examples of images of poor quality that should be discarded prior to standard analysis include: B) air bubbles, C) dark image, and D) out of focus.

which means less statistical significance. In poorly sorted sediments, a single large grain in an image can skew the results and therefore more images per site are recommended.

The method of field sampling with the beachball camera should be determined by the scientific objective. If the surface grain size is desired, then using the beachball in the field is ideal. This method would be preferable if the size of the grains interacting with the flow is desired, be it wind or water. Rubin et al. (2006a,b) used differences between grain size at the surface and grain size 1 cm below the surface to document eolian winnowing of the bed. If the 'average' grain size of the active beach is desired, then perhaps a more typical grab sample should be extracted, mixed, a splitter used to avoid grains segregating by the mixing (shearing) process, and then captured with the beachball camera.

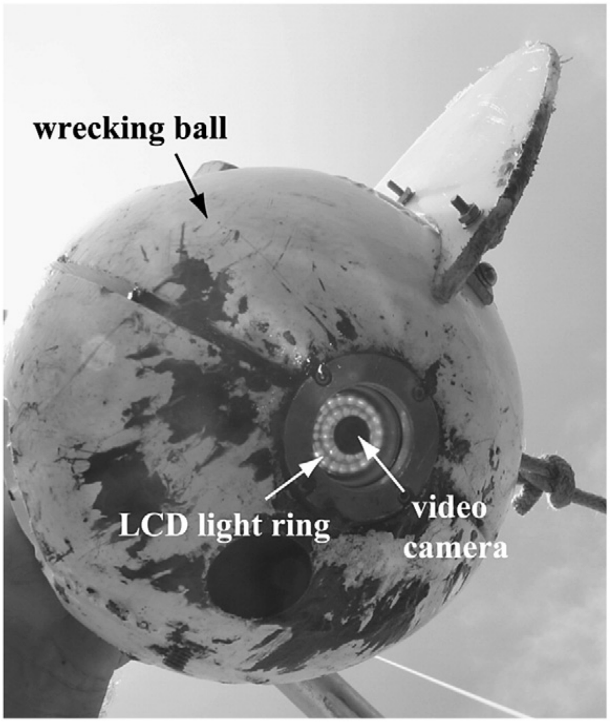

Fig. 11. View of the bottom of the 'flying eyeball,' a bed-sediment camera designed for underwater use.

The beachball camera is an especially powerful and efficient tool for sampling study sites periodically. For instance, ongoing research at Ocean Beach, CA, requires quarterly sampling to analyze the seasonal relationship between wave energy and beach grain size. Having already established a set of calibration curves for this study site, subsequent surveys and data analysis can be performed extremely rapidly. With an All-Terrain Vehicle, the entire 7-km long beach can be sampled with the beachball camera in just several hours, recording over 200 images at ~70 sampling stations. With the images downloaded, grain size statistics can be determined with only several more hours of processing. Thus, in a single day, over 200 samples can be 'collected' and processed. Traditional grain size analysis of 200 samples would take many weeks.

The autocorrelation technique described in this paper was initially developed for underwater use using the same fundamental concepts as the beachball camera. For this purpose, Chezar and Rubin (2004) developed the 'flying eyeball,' an underwater microscope camera designed to rapidly record images of the seabed. This design features a video camera inserted into a wrecking ball (Fig. 11). The camera is raised and lowered to the seabed using a boat winch, and the video feed is viewed live and recorded digitally on the boat. Rubin et al. (2006a,b) has used this technique extensively in the Grand Canyon, where over 20,000 images of the Colorado River bed have been recorded. In the Santa Barbara littoral cell, Mustain et al. (2007) used this technique, in concert with the beachball to characterize the grain size of the entire 150-km long littoral cell onshore and offshore. In this study, over a period of just several weeks, over 2000 images of the bed were collected on the beach and in water depths ranging from 5 to 20 m to rapidly assess compatibility between beach grain size and potential nearshore borrow sites for beach nourishment.

6. Conclusions

An extensive field test of Rubin's (2004) autocorrelation technique shows that median and mean grain size can be determined with >96% accuracy using a digital camera and associated autocorrelation when compared to traditional methods such as mechanical sieving and settling tube analysis. This autocorrelation technique works even better when compared with point counts of the same image; the poorer correlation with grab samples must be a result of spatial and vertical variability of sediment in the field. Such differences due to natural variability in grain size, sorting, color, and image calibration, must be considered and addressed when using this technique. Grain size determined from digital images is particularly suited to measuring grain size of surficial grains that interact with the flow. When properly automated for large numbers of samples, the autocorrelation technique is roughly 2 orders of magnitude faster than traditional grain size analysis, saving time and money, without sacrificing accuracy in measuring average grain size; the technique may not be as accurate in measuring the fine and coarse tails of a size distribution.

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Appendix A

MATLAB® Script for determining autocorrelation. Note, for automated operation, images are run as a batch, with this script implemented for all images contained in a folder. Results are compiled in a single file.

```
%AutoC20
data=double(imread(FileName)); % read image and store as data
[ImageHeight, ImageWidth]=size(data);
MaxOffset=20;
ImageWidthToProcess=ImageWidth−MaxOffset;
for i=1:MaxOffset;
data1=data(1:ImageHeight,1:ImageWidthToProcess);
data2=data(1:ImageHeight,1+i:ImageWidthToProcess+i);
correlation=corrcoef(data1,data2);
autoc1(i)=correlation(1,2);
offset(i)=i;
end
% report result as vector
SampleAutoC=autoc1';
SampleAutoC,FileName
```

MATLAB® Script for determining grain size mean, median and distribution. Used in conjunction with autocorrelation script above:

```
% SizeDist.m
% THIS SCRIPT WRITES OUT YOUR RESULTS, NEED YOUR MATRIX AND INTERVAL MIDPOINTS
% requires AutoC.m, FilesToRun.txt
% this script loads data image, runs autocorrelation, calculates size dist and mean, and
% writes results to two files: median.txt and mean.txt
% m=20 offsets, n=# size classes (14)
%clear, home % comment out when Batching
%FileName='L18SwashS3.tif' % comment out when Batching
%AutoC20 % comment out when Batching
%This is your correlation matrix, lt to rt=increasing grain size intervals, top to bottom=offsets 1–20
%Ocean Beach Correlation Matrix, 14 size classes, 20 offsets
CalibData=[
```

0.8077	0.8363	0.8624	0.8756	0.8873	0.9010	0.9198	0.9315	0.9413	0.9490	0.9559	0.9641	0.9703	0.9776
0.5078	0.5802	0.6459	0.6785	0.7131	0.7479	0.7929	0.8221	0.8477	0.8688	0.8884	0.9123	0.9304	0.9469
0.3118	0.4072	0.4938	0.5379	0.5925	0.6390	0.6961	0.7353	0.7733	0.8056	0.8354	0.8741	0.9027	0.9252
0.1855	0.2885	0.3817	0.4333	0.5014	0.5536	0.6149	0.6597	0.7084	0.7484	0.7871	0.8376	0.8746	0.9037
0.1132	0.2111	0.3031	0.3584	0.4352	0.4890	0.5498	0.5969	0.6545	0.6988	0.7457	0.8050	0.8487	0.8843
0.0685	0.1508	0.2380	0.2953	0.3781	0.4319	0.4907	0.5391	0.6047	0.6517	0.7064	0.7730	0.8224	0.8651
0.0459	0.1082	0.1859	0.2433	0.3300	0.3830	0.4383	0.4873	0.5594	0.6078	0.6693	0.7422	0.7964	0.8465
0.0333	0.0797	0.1426	0.1990	0.2881	0.3399	0.3908	0.4400	0.5172	0.5663	0.6339	0.7121	0.7704	0.8279
0.0258	0.0623	0.1068	0.1620	0.2522	0.3020	0.3484	0.3969	0.4783	0.5276	0.6006	0.6831	0.7446	0.8097
0.0203	0.0513	0.0781	0.1310	0.2205	0.2684	0.3103	0.3575	0.4422	0.4911	0.5690	0.6550	0.7189	0.7918
0.0160	0.0438	0.0574	0.1056	0.1919	0.2382	0.2761	0.3218	0.4089	0.4568	0.5389	0.6276	0.6937	0.7743
0.0125	0.0385	0.0441	0.0854	0.1659	0.2110	0.2456	0.2895	0.3782	0.4247	0.5103	0.6010	0.6689	0.7570
0.0101	0.0349	0.0365	0.0707	0.1428	0.1870	0.2186	0.2606	0.3498	0.3950	0.4832	0.5754	0.6445	0.7401
0.0084	0.0319	0.0324	0.0604	0.1227	0.1656	0.1945	0.2346	0.3235	0.3672	0.4573	0.5508	0.6207	0.7237
0.0069	0.0292	0.0301	0.0529	0.1061	0.1464	0.1731	0.2113	0.2991	0.3414	0.4325	0.5272	0.5977	0.7078
0.0059	0.0266	0.0285	0.0468	0.0930	0.1293	0.1539	0.1906	0.2763	0.3172	0.4088	0.5044	0.5752	0.6923
0.0045	0.0243	0.0272	0.0412	0.0829	0.1143	0.1367	0.1719	0.2551	0.2945	0.3862	0.4824	0.5533	0.6773
0.0025	0.0225	0.0262	0.0358	0.0750	0.1017	0.1215	0.1550	0.2354	0.2734	0.3648	0.4613	0.5321	0.6625
0.0011	0.0211	0.0251	0.0306	0.0688	0.0911	0.1081	0.1399	0.2173	0.2536	0.3443	0.4408	0.5114	0.6480
0.0005	0.0197	0.0239	0.0260	0.0635	0.0825	0.0964	0.1266	0.2006	0.2350	0.3250	0.4211	0.4913	0.6339

```
];
% rows are pixel offsets from 1 to 20
% columns are 14 grain sizes classes (x–y where x<=D<y):
% size class boundaries Phi=[3.25 3.00 2.25 2.00 1.75 1.50 1.25 1.00 0.75 0.50 0.25–0.25–0.50–0.75];
% size class boundaries mm=[0.1050 0.1250 0.2100 0.2500 0.3000 0.3500 0.4200 0.5000 0.5900 0.7100 0.8400
1.1900 1.4100 1.6800]
% midpoint of interval (mm):
% 0.1150 0.1675 0.2300 0.2750 0.3250 0.3850 0.4600 0.5450 0.6500 0.7750 1.0150 1.3000 1.5450
%to calculate Phi from mm use MATLAB command y=−log2(x) where x=grain size in mm
ymm=[0.1150 0.1675 0.2300 0.2750 0.3250 0.3850 0.4600 0.5450 0.6500 0.7750 1.0150 1.3000 1.5450];
yPhi=[−log2(ymm)];
% Calculate grain size distribution
MaxOffsetToUse=20;
c1=lsqnonneg(CalibData(1:MaxOffsetToUse, 1:length(yPhi)),SampleAutoC(1:20));
c1=c1/sum(c1);
%comment out 4 lines below when batching
%figure(2)
%plot(1:length(yPhi),c1,‘r.-’),title(‘Sample grain size distribution’),xlabel(‘size class’),ylabel(‘% contribution’)
%title(num2str(FileName))
%pause (0.5)
% Calculate mean grain size
xOnePixel=CalibData(1,1:length(yPhi)); % autocorrelation with 1-pixel offset
xTwoPixel=CalibData(2,1:length(yPhi)); % autocorrelation with 2-pixel offset
xThreePixel=CalibData(3,1:length(yPhi)); % autocorrelation with 3-pixel offset
xFourPixel=CalibData(4,1:length(yPhi)); % autocorrelation with 4-pixel offset
xFivePixel=CalibData(5,1:length(yPhi)); % autocorrelation with 5-pixel offset
Phi(1)=interp1(xOnePixel, yPhi, SampleAutoC(1));
Phi(2)=interp1(xTwoPixel, yPhi, SampleAutoC(2));
Phi(3)=interp1(xThreePixel, yPhi, SampleAutoC(3));
Phi(4)=interp1(xFourPixel, yPhi, SampleAutoC(4));
Phi(5)=interp1(xFivePixel, yPhi, SampleAutoC(5));
SizeInMM=0.5.^Phi
SizeInMM=mean(SizeInMM)
FileName
% Write file name and grain size distribution to txt file (appends!),
% specify type of matrix to analyze results
OutputFID=fopen (‘Mean.txt’,‘at’);%CHANGE NAME HERE OR WILL OVERWRITE!!!
fprintf(OutputFID, FileName);
%fprintf(OutputFID, ‘\t %5.3f’, SizeInMM);
fprintf(OutputFID, ‘\t %5.3f’, SizeInMM, c1(1:length(yPhi)));
fprintf(OutputFID, ‘\n’);
fclose(OutputFID);
% sorting index from cdf
midpoint_mm=ymm’; % make midpoint a vertical vector
cumpct=cumsum(c1); % calculate cumulative percent where c1 is the proportion in each size class
%comment out two lines below when batching
%figure, plot(midpointmm,cumpct,‘r.-’),grid on
%title(‘Cumulative Distribution Function’), xlabel(‘midpoint (mm)’), ylabel(‘percent’), shg
d05=interp1q(cumpct,midpoint_mm,0.05) % interpolates to find the grain size at the 5th percentile
d16=interp1q(cumpct,midpoint_mm,0.16)
d25=interp1q(cumpct,midpoint_mm,0.25)
d50=interp1q(cumpct,midpoint_mm,0.50) % interpolates to find the grain size at the 50th percentile (median)
```

```
d75=interp1q(cumpct,midpoint_mm,0.75)
d84=interp1q(cumpct,midpoint_mm,0.84)
d95=interp1q(cumpct,midpoint_mm,0.95) % interpolates to find the grain size at the 95th percentile
MedianGr=d50 % median and sorting calculated from Folk & Ward (1954) equations
StdGr=((d84−d16)/4)+((d95−d05)/6.6)
%Cumulative Distribution Function output to txt file
OutputFID=fopen ('Median.txt','at');%CHANGE NAME HERE OR WILL OVERWRITE!!!
fprintf(OutputFID, FileName);
fprintf(OutputFID, '\t %5.3f', MedianGr, StdGr, d05, d16, d25, d50, d75, d84, d95);
fprintf(OutputFID, '\n');
fclose(OutputFID);
```

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