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Highlights

- A new method is proposed to assess shoreline change using optical satellite images.
- The method was validated using quasi-simultaneous shoreline measurements
- The validation revealed that satellite-derived shoreline is consistently seaward to the in situ shoreline.
- Consideration of water levels, beach slope and wave run-up is essential to determine confidence bounds of the satellite-derived shoreline.
- The method is shown to be successful and it could be applied to other locations.

Evaluating shoreline identification using optical satellite images

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Abstract

A technique to extract the shoreline location from optical satellite images has been developed and evaluated for the case study site of Progreso, Yucatán, México. A novel method to extract a satellite-derived shoreline (SDS) was developed ensuring the maximum contrast between sea and land. The area under investigation is an 8km length of shoreline that faces north into the Gulf of México.

The SDS was validated using quasi-simultaneous *in situ* shoreline measurements, both adjusted to equal water levels. *In situ* shoreline measurements recorded the instantaneous shorewards extent of the wave run-up when walking along the beach.

The validation of SDS revealed that the SDS is located consistently seawards of the *in situ* shoreline, explained by: a) the water depth that optical satellite image requires to identify a pixel either as sea or land, and b) the shorewards extent of the wave run-up. The overall distance between SDS and *in situ* shoreline is 5.6m on average with a standard deviation of 1.37m (in the horizontal) over 8km of shoreline. Confidence bounds considering the shorewards extent of the wave run-up, inter-tidal

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beach slope variation and tidal uncertainty were computed to assess the accuracy of the SDS.

The SDS has been shown to be capable of detecting shoreline changes of less than 10m and abrupt changes due to storms. The success of our method suggests that it should be applicable to other locations, after adapting the confidence bounds to the beach conditions.

Keywords: coastal monitoring, shoreline, coastal dynamics, remote sensing

1. Introduction

Shorelines are inherently dynamic features that mark the transition between land and sea and are vulnerable to waves, winds, nearshore currents, and human modification. It is estimated that there are more than 347,984km of shoreline in the world and that 60% of the world's population lives within 100km of the sea (Vitousek et al., 1997). Monitoring and managing shorelines is therefore of considerable social and economic importance. Furthermore shoreline erosion and coastal flooding were highlighted among the gravest effects of climate change (IPCC, 1990).

Monitoring the shoreline over appropriate time and spatial scales is challenging because shoreline change assessment involves consideration of the inherent dynamics of the shoreline over a range of temporal scales (Pajak and Leatherman, 2002; Gens, 2010). Although various types of data have been considered for shoreline change studies (Miller and Fletcher, 2003; Kumar and Jayappa, 2009; Chen and Chang, 2009), including maps, *in situ* beach profiling, LIDAR surveys and aerial photography, these techniques are inherently limited in temporal coverage, typically being either too short to identify long term trends or too widely spaced in time to distinguish short term, seasonal changes.

18 Optical satellite imagery, on the other hand, has the potential to combine moder-
19 ate spatial resolution with large spatial coverage and regular, short-timescale repeat
20 measurement. It also has the potential advantage of allowing exploration of shore-
21 line change in remote places with little coastal information. Satellite imagery has
22 developed rapidly over the past few decades in terms of spatial resolution, frequency
23 of passage over the same location and overall availability. For example, over the last
24 20 years, spatial resolution has improved from 10m to 0.4m. An instantaneous visual
25 image that covers a footprint of at least 220km² can now be obtained as often as
26 once every 1 to 8 days.

27 Previous studies have investigated the potential of optical satellite images to study
28 shoreline change (Blodget et al., 1991; Mason et al., 1997; White and El-Asmar, 1999;
29 Aarninkhof, 2003; Foody et al., 2003; Kingston, 2003; Liu and Jezek, 2004; Zakariya
30 et al., 2006; Ekercin, 2007; Dinesh-Kumar et al., 2007; Plant et al., 2007; Chen and
31 Chang, 2009; Wang et al., 2010; Kuleli et al., 2011). However, none of these studies
32 has fully assessed the accuracy of the derived shorelines through comparison with
33 simultaneous and independent *in situ* observations.

34 The research described in this paper has three main objectives. The first is
35 to develop a systematic, objective method to identify the shoreline from optical
36 satellite images. The second is to validate the satellite-derived shoreline against *in*
37 *situ* measurements made as close in time as possible to the satellite image. From
38 this validation, the third aim is to assess bias and confidence bounds for the satellite-
39 derived shoreline locations, considering potential errors in the extraction method and
40 environmental characteristics such as wave set-up and run-up, uncertainty in tide
41 elevation, surge level and variations in beach slope. The overall aim is to provide
42 a clear, quantitative and objective method for extracting shoreline location from
43 satellite images which can be applied to a wide range of beach locations.

44 The next section describes the study area chosen to evaluate satellite derived
45 shorelines (SDS). Section 3 then sets out the newly developed method to extract
46 SDS from satellite images. The results of applying the new method to images from
47 the chosen study area are then described in section 4, which includes an assessment
48 of the accuracy of the new method by estimating quantitative confidence bounds for
49 the computed SDS. Finally the implications of our results are discussed in section 5,
50 looking particularly at what would be needed to apply our method to other locations.

51 **2. Regional setting**

52 The chosen study area is located at Progreso, Yucatán, covering approximately
53 8km of shoreline (Figure 1, Table 2). Most of the Yucatán shoreline has erosion
54 problems and is sparsely populated. Due to its location, between the Gulf of México
55 and the Caribbean Sea, the wave climate incident on Yucatán is fetch-limited but
56 also experiences hurricanes every year. The continental shelf is wide and shallow with
57 slopes of order 1:1000. Unfortunately the closest wave buoy (no. 42001) is 200km
58 offshore from Progreso at a depth of 3,365m. The wide continental shelf means that
59 the observed wave height in deep waters ($0.5 < H_s < 2\text{m}$) is significantly different from
60 shallow water ($< 0.4\text{m}$). The approaching waves into Progreso are locally generated
61 by the wind with no presence of swell. Wave periods are small ($T < 4\text{s}$) and measured
62 wave heights (H_s) typically smaller than 30cm at 5m depth (Mariño-Tapia, 2010).

63 The tide is diurnal, with a form factor (F) larger than 3, indicating that the
64 diurnal constituents are more important than the semidiurnal constituents (Pugh,
65 2004). The tidal range is microtidal with a maximum range of 0.9m. This tidal range
66 is large enough to significantly change the shoreline location. For example, the 0.9m
67 range would produce a horizontal excursion larger than 15m on a 1:20 beach slope.

68 Progreso has a lack of reliable tidal measurements, so measurements were carried out
69 in the current project to compare with existing tidal predictions.

70 The eastern-most segments of the studied shoreline do not have coastal vegetation
71 and their inter-tidal beach width is the narrowest, ranging between 25m and 52m.
72 In addition, the east segments have houses very close to the shore on the top of
73 the dunes. The mean grain size of the beach sand suggests an alongshore gradient.
74 Overall the largest grain size (0.28 to 0.84mm) is towards the east and the finest
75 sand (0.22 to 0.26mm) towards the west. The eastern section also shows a gradient
76 of sand with fine sand (0.28mm) in segment 6. The alongshore gradient of the grain
77 size is in agreement with a predominantly westwards alongshore transport, and with
78 the direction of typical incoming winds from the NE.

79 There is one large man-made structure. Progreso pier extends offshore for 6km,
80 with a shore-parallel breakwater at its seaward end of approximately 2km length
81 (Figure 1). The first 2km of the pier has arches, partially allowing for sediment
82 transport, and the last 4km are solid. There is also a second pier that is 285m long,
83 approximately 110m west of Progreso pier. Although both piers are not completely
84 solid structures their presence is likely to cause a decrease in the alongshore transport
85 rate leading to updrift accretion and downdrift erosion.

86 Shoreline orientation also provides an indication of physical processes modifying
87 the beach. Shoreline orientation was measured using as reference the overall shoreline
88 orientation, that runs from the West to East line. Negative values are clockwise and
89 vice versa. Segment 4 has a slightly negative shoreline orientation (-2°) at the eastern
90 side of the longest pier and much larger (27°) positive orientation at the western
91 side of the pier. That is contrary to the expected shoreline shape with a westward
92 alongshore transport. This suggests that Progreso pier has a significant effect on the
93 local hydrodynamics and beach morphodynamics.

94 The impact of hurricanes in the region is a constant threat. There are on average
95 10 hurricane events in the Atlantic basin per year, from which two events have
96 intensities of at least hurricane category 3, holding winds higher than 178kmh^{-1}
97 (NHC, 2010). Hurricanes Isidore (in 2002) and Gilbert (in 1988) directly impacted
98 Yucatán (approximately 45km east from Progreso) producing considerable damage.
99 Hurricane Isidore reached its peak intensity in Yucatán, with measured winds of
100 129kmh^{-1} and atmospheric pressure of 934mb (NHC, 2002). The properties located
101 next to the beach were totally destroyed. Isidore changed the beach morphology,
102 opening inlets connecting the coastal lagoon with the sea and so far, no recovery of
103 the beach has been detected.

104 3. Methods

105 3.1. Preliminary analysis of the optical satellite images

106 Two cloud-free multispectral images (SPOT) from July 12th 2010 and September
107 9th 2008, both 10m pixel size and a pre-processing level 2A¹, were obtained for the
108 current study. Table 1 details the electromagnetic range covered by the spectral
109 bands of the SPOT satellite.

110 Spectral bands from SPOT images cover most of the visible light and short wave
111 infrared wavelengths (Table 1). Each surface on Earth has its unique response at
112 each wavelength (Parker and Wolff, 1965), so the use of different spectral bands
113 allows identification of specific features on the ground, such as the sea and the land.

114 In the first step in the analysis, the images were geometrically corrected to en-
115 sure positional accuracy within the pixel size. Once the images were geometrically

¹Images with a pre-processing level 2A are rectified to match a standard map projection (UTM WGS84), without using ground control points.

116 corrected, the new method was developed and applied to extract SDS.

117 *3.1.1. Geometric correction of satellite images*

118 The geometric correction was performed using 45 *in situ* Ground Control Points
119 (GCP). The chosen GCP were street intersections that were located all over the
120 image, and the correction used a linear model involving translation of coordinates.
121 The resulting root mean square error between the corrected image and the GCP was
122 smaller than half the pixel size, as White and El-Asmar (1999) suggests. Detailed
123 visual inspection was carried out ensuring that both images match the GCP.

124 *3.2. New method for extracting SDS from optical satellite images*

125 For shoreline change studies, it is necessary to identify the shoreline as a line
126 that runs between pixels grouped as either sea or land. To achieve this, two major
127 processes were required. First, a series of steps were followed to obtain a vector that
128 represents the shoreline within the accuracy of the pixel size. Second, the location
129 of the resulting vector has to be adjusted to a standard water level, correcting for
130 the tidal level, meteorological conditions, wave height and inter-tidal beach slope,
131 for the conditions when the satellite passed over Progreso.

132 *3.2.1. Identification of sea and land*

133 To identify pixels as sea and land different techniques were reviewed (filters, clas-
134 sification, visual interpretation), as well as the parameters (spectral band(s), conver-
135 gence threshold and subsamples of the image) to use in the classification technique.
136 Following the assessment of a number of options, the chosen technique was an unsu-
137 pervised classification (ISODATA), executed in ERDAS software. The unsupervised
138 classification has been used in previous research, for example by Foody et al. (2005),
139 and allows the clearest definition of the sea and the land. The basic premise in the

140 unsupervised classification is that the pixels within a group should have intensities
141 with a similar spectral pattern. Conversely, intensities from a different group should
142 be relatively well separated (Lillesand et al., 2008). In our case, we require the inten-
143 sity values from the sea to have very similar spectral patterns and to have contrasting
144 intensity values from those from the land.

145 Figure 2 (a) shows the cross-shore profile of pixel intensities along a representative
146 cross-shore line from the analysed image. These intensity values reveal a clear drop
147 in intensity values from land to sea for all the spectral bands. The intensities over
148 the sea are relatively homogeneous.

149 Each spectral band and combinations of bands were assessed to find the optimum
150 method for separating sea and land. As figure 2 (a) shows, the green band has
151 relatively small differences in intensities from sea to land and their use resulted
152 in some misclassification. The seawards drop in intensity is largest at the longer
153 wavelengths (NIR and SWIR) and the optimum method was found to involve solely
154 the NIR spectral band, with a convergence threshold for the objective classification
155 of 95%. No advantage was found when using subsamples or masks to focus on the
156 area being classified so these were not used in the final method.

157 Figure 2 (b) shows the intensities of all the pixels in the image grouped as sea
158 and land using the longer wavelengths (NIR and SWIR). The red points represent
159 land and the blue points sea, based on an unsupervised classification using the NIR
160 band. Intensities of pixels over the sea are the smallest (<96) in the NIR, whilst the
161 sea intensities in the SWIR spectral band range between 25 and 190.

162 Visual verification of the geographic location of pixels in the overlap region, with
163 similar intensities for the sea and the land was undertaken to ensure the correct
164 identification of pixels as sea or land, and it was found that their spatial locations
165 were far from the shoreline. These pixels correspond to streets and vegetation, which

166 have both high and low intensities, as do the land and the sea. Therefore, although
167 misclassification of these pixels could occur, their geographic location is far from the
168 boundary between sea and land.

169 Figure 3 shows the extract of a classified image. The pixels in the sea region
170 are identified as homogeneous and are well separated group from the pixels in the
171 land region. It is important to emphasize that despite the fact that this region has
172 very shallow water features, such as a coastal lagoon and inlets, the classification
173 separates both groups well.

174 3.2.2. *Vectorisation of the classified image*

175 Vectorisation has the aim of obtaining a vector that represents the pixel boundary
176 of the identified sea and land. The raster to vector conversion was executed in
177 ArcMap software using standard conversion tools. The output is a stepped raw
178 vector that goes along all the boundaries of the pixels in between the two groups
179 in the analysed image (Figure 3). The vector has a pair of coordinates at each
180 transition (Figure 4). Straight sections of the stepped raw vector do not have a pair
181 of coordinates until a transition in the shore occurs.

182 3.2.3. *Smoothing*

183 The central locations of the pixels vary from image to image, so comparison be-
184 tween different stepped vectors would result in high frequency "noise". It is therefore
185 prudent to smooth the stepped vectors to remove most of this noise.

186 The smoothing method chosen uses as input the stepped raw vector, locating the
187 shoreline as the midpoint of each step. In straight sections without transitions, a
188 pair of coordinates was added at 50m intervals (Figure 4). These coordinates were
189 then smoothed over a fixed alongshore distance.

190 In order to assess the effect of the smoothing, the smoothed shoreline was com-
191 pared with the *in situ* shoreline described below in section 3.3. Figure 5 shows the
192 comparison of four different alongshore smoothing distances. The smoothed SDS at
193 alongshore distances of 10m and 20m retain a jagged shape showing abrupt changes in
194 the cross-shore ranging between -10 and -1m, whereas smoothed SDS with a distance
195 of 50 and 60m range between -10 and -4m, reducing the variation in the cross-shore
196 by almost half the magnitude. The negative value indicates that the SDS is seaward
197 of the *in situ* shoreline (see section 4.1).

198 The smoothed SDS at 50m has been preferred because it removes shorter varia-
199 tions, captures well the shoreline shape and has the narrowest cross-shore variation.
200 The chosen smoothed distance was found to be adequate for a location such as Pro-
201 greso, where the shoreline orientation is mainly straight and does not show large,
202 short-wavelength oscillations. The few oscillations in shoreline orientation (for ex-
203 ample in segments 3 and 4) are well registered by the SDS (Figures 4 and 5).

204 3.2.4. *Water level considerations*

205 The instantaneous shoreline location measured by a satellite depends on tidal
206 level and on wave run-up produced by the waves approaching the beach. To estimate
207 their influence on the horizontal shoreline position, it is also necessary to know the
208 intertidal beach slope.

209 Because local measurements at Progreso showed inconsistencies, new water level
210 measurements were collected using a data logger RBR model TWR-2050, recording
211 total pressure every 10 mins between July 12th and August 4th 2010. Beach profiles
212 were also surveyed on July 13th 2010 for each beach segment. The SDS was adjusted
213 to a predetermined common tidal datum, in this case the local BMI (mean lower low
214 water level, the acronym in Spanish is Bajamar Media Inferior).

215 Satellite images cover a large area simultaneously, thus, the whole extracted shore-
216 line has the same tidal level. However, the instantaneous shoreline location varies in
217 the alongshore due to the wave run-up and set-up variation. The vertical wave run-
218 up in Progreso is typically between 0.2 and 0.4m height. On a beach with a slope
219 of 6° , that magnitude will cause a cross-shore excursion of between 2m and 4m.
220 The alongshore smoothing will also reduce the influence of run-up, tending to the
221 smaller set-up values but dependent on the long-crestedness of the incident waves.
222 For Progreso, the influence of waves is therefore considerably smaller than the pixel
223 size. However, when comparing point locations of different smoothed shorelines, the
224 magnitude could become significant, making it a potentially important limitation
225 for shoreline change estimates. On shorelines with larger incident waves, it could
226 become a dominant factor, as discussed below in section 4.2.2.

227 3.3. Validation of the Satellite Derived Shoreline and ancillary data

228 The SDS was validated by comparing the SDS from July 12th with *in situ* shore-
229 line measurements from the same day, with only five hours difference. The *in situ*
230 shoreline measurements were adjusted to the tidal level when the satellite passed
231 over Progreso (see section below). This inter-comparison is an excellent opportunity
232 to examine the accuracy of the shoreline identification and so it has been used to
233 define confidence bounds on the SDS.

234 The main difference between the SDS and the *in situ* shoreline measurements is
235 the time span that occurred during *in situ* shoreline measurements. Both types of
236 data registered the shoreward and the seaward extent of the wave run-up. However
237 while the satellite captured an instantaneous picture of the shore, the *in situ* shoreline
238 measurements captured a similar time-dependant feature when walking along the
239 shore.

240 3.3.1. *In situ* shoreline measurements

241 Because Progreso has such a small wave height ($<0.3\text{m}$) it was possible to fol-
242 low the instantaneous wave run-up and run-down. Measurements were carried out
243 on July 12th using a Leica Differential Global Positioning System (DGPS) in Post-
244 Processing Kinematic (PPK) mode, recording positions every second. Each mea-
245 surement is spaced approximately one and a half metres alongshore. An alongshore
246 distance of 8km was covered encompassing all the beach segments (Figure 1) and
247 took two hours to complete.

248 The measurements were projected using a Universal Transverse Mercator (UTM)
249 projection, zone 16 N, with the geoid of reference WGS84. A planar projection
250 adjusts effectively in flat places like Yucatán. The height measured during the *in*
251 *situ* shoreline survey was verified with water levels measured in 2010 (see section
252 3.2.4) and tidal predictions. In this way it was possible to detect whether any other
253 factors could be involved in the shoreline location apart from the tides (e.g. surges).

254 3.4. *Adjustment of the SDS and in situ shoreline measurement prior its inter-comparison*

255 Adjustment of *in situ* shoreline measurements ensures that the inter-comparison
256 between SDS and *in situ* match on tidal levels. The first location surveyed (segment
257 8) showed a higher tidal level than the last location surveyed (segment 1). The ap-
258 proximate decrease in the tidal level was of approximately 40cm height. In contrast,
259 the SDS has the same tidal level at all points in the alongshore.

260 The adjustment was done using the inter-tidal beach slope and the difference in
261 the predicted tidal level between the *in situ* measurements and the image. The ad-
262 justment to equal tidal levels was carried out under the assumption of a homogeneous
263 inter-tidal beach slope for each beach segment. Because each beach segment was de-
264 termined based on geomorphological characteristics, this assumption seemed to be

adequate. However, it is recognised that local differences may occur particularly at the transitions between beach segments. For example the horizontal excursion of 20cm difference in the water level on a beach slope of 3° is 3.8m, whereas in a shallower beach of 1° will have a horizontal excursion larger than 10m. The largest difference in beach slopes in the study area occurs from segment 1 to 2, segment 3 to 4 and segment 4 to 5 (Table 1). Given these examples, the expected order of magnitude of discontinuity in the shoreline location to occur in the transitions between segments would be as large as 1.5m from segment 1 to 2, of 1m from segment 3 to 4 and 0.6m from segment 4 to 5.

4. Results

4.1. Validation of Satellite-Derived Shoreline

4.1.1. Inter-comparison of the SDS and *in situ* shoreline measurements in July 12th in 2010

The difference between the *in situ* shoreline measurements and the SDS using the new method was calculated for data gathered on 12th July 2010. The comparison was based on measurements at every 10m over 8km of shoreline.

The results show that the SDS is consistently seawards of the *in situ* shoreline (Figures 6, 7). On average over the 8km length of shoreline, the SDS is -5.6m from the *in situ* shoreline, a value which is smaller than the pixel size (10m) (Figure 6, Table 3).

Figure 7 also shows that eighty percent of the values are at a distance of one standard deviation from the average (-6.9m and -4m), indicating a consistent seaward displacement of the SDS, though differences as large as the pixel size can occur at a few point locations (0.2%). Table 3 shows the separate mean differences between the

289 SDS and *in situ* for each beach segment. The magnitudes are in agreement with the
290 overall magnitude and direction of the displacement. The mean of segment 4 is the
291 only one that exhibits a larger displacement, which is probably due to the abrupt
292 change in shoreline orientation.

293 The rapid variations about the mean displacement between the SDS and the *in*
294 *situ* shoreline measurements are associated with fluctuations in the cross-shore extent
295 of the wave run-up. The standard deviation of the DGPS height recorded during the
296 *in situ* shoreline measurements ranges between 0.13m and 0.38m, which also corre-
297 sponds to the observed wave run-up in the region on the day of the measurements,
298 which was between 0.2m and 0.4m height. The associated horizontal excursion for
299 beach slopes between 3° and 6° , as measured in Progreso, is between 1.7m and 3.2m.
300 That magnitude is approximately twice the horizontal standard deviation (Table 3),
301 suggesting that the standard deviation is a good estimator of confidence bounds for
302 the SDS.

303 4.2. SDS confidence bounds

304 The shoreline position captured by the satellite is instantaneous, but if different
305 shorelines captured over a period of time are to be used to assess shoreline change,
306 each SDS requires well defined confidence bounds. The current study enables us to
307 make a tentative quantitative assessment of the factors that cause deviation of the
308 SDS from the *in situ* shoreline and the uncertainty arising from adjusting shoreline
309 position to a standard water level datum. This section summarises the uncertainties
310 that arise from image rectification, beach slope variations, wave run-up and set-up,
311 the offset due to absorption of light by sea water, tide levels and surge levels.

312 4.2.1. Image rectification

313 The influence of image rectification is relatively simply to quantify. In the present
314 case, use of 45 GCPs resulted in a standard deviation in the location of the pixels of
315 less than 3m for our rectified images (see section 3.1.1). This value is less than half
316 the pixel size but is comparable with other sources of uncertainty.

317 4.2.2. Beach slope

318 Many of the factors involved in interpreting SDS require converting a vertical
319 estimate of sea level variation into an associated horizontal variation using the beach
320 slope. These factors include wave run-up, the minimum depth for identification of
321 sea water, tide and surge levels. In the current study, beach slopes were measured
322 in each of the eight beach segments and showed reasonable consistency across all
323 segments (Table 2), the largest slope being in segment 4 and the smallest in segment
324 1. Nevertheless as discussed in section 3.3.2, uncertainty in the beach slope will
325 result in an error in the SDS, particularly at the boundaries between the segments.
326 The largest estimated error occurs at the boundary between segments 1 and 2 with
327 a value of up to 1.5m for a vertical tidal correction of 0.2m. Whilst this value is
328 typically smaller than other uncertainties identified below, it does highlight the need
329 for accurate intertidal beach slopes when applying the method, with the greatest
330 sensitivity associated with the smallest beach slopes.

331 4.2.3. Wave run-up

332 As mentioned in the previous section, the magnitude of the cross-shore excursion
333 of the wave run-up is a potentially important factor. The small standard deviation
334 between the SDS and *in situ* shoreline in our study (1.37m) is consistent with the
335 small incident wave heights and measured beach slopes on the Progreso shoreline and
336 is likely to be unimportant when comparing SDS from different times. This factor

will of course become more important during larger wave events such as storms or hurricanes but it is unlikely that suitable satellite images would be available at such times. Nevertheless on beaches which experience larger incident waves, particularly swell, and with shallow beach slopes, the influence of wave run-up could be dominant.

4.2.4. Seaward displacement of the SDS

Error bounds on the observed seaward displacement of the SDS relative to the *in situ* shoreline are more difficult to quantify with confidence. The results described in section 4.1 show a mean seaward displacement over the 8km studied of 5.57m and it is encouraging that the values in the eight segments are well within one standard deviation of the overall mean, suggesting a degree of stability in this displacement for different beach slopes and wave exposure. The one exception is segment 4, but the presence of the pier and the rapid change of shoreline orientation in this segment probably accounts for the larger seaward displacement in this segment. However, the explanation of this displacement in terms of light absorption by sea water suggests that it might vary depending on water quality. At Progreso, the presence of fine sand means that turbidity is generally rather higher than might be expected from the small wave heights. The green and the red spectral bands do show evidence of these plumes of sediment in the nearshore water. The fact that the NIR band does not pick up these plumes suggests that their influence is minimal at the longer wavelengths, but conditions of higher turbidity, perhaps during slightly higher wave conditions, could increase the seaward displacement. The magnitude of any such effect is not known and needs further research.

4.2.5. Tide level

Another potentially significant contributor to error bounds for SDS is uncertainty in the instantaneous water level. Instantaneous water level is required in order to

adjust SDS to a standard level before they are compared, so uncertainty in instantaneous level contributes directly to confidence bounds when comparing different SDS.

There are no reliable continuous measurements of water level at Progreso. Tidal level must therefore be based on tide predictions. Our own water level measurements over a three week period, described in section 3.2.4, show that the range of the predicted tide underestimates the real tidal range by 5%. However, the microtides at Progreso (maximum range 0.9m) make this error unimportant when adjusting water levels for tidal differences, changing the horizontal location of the satellite typically by less than 1m.

4.2.6. Surges

Potentially much more important for shoreline location is the possible influence of surges in changing the water level. Some evidence of the influence of surges at Progreso was gained in an earlier comparison between SDS and *in situ* shoreline measured in September 2008 (García-Rubio et al., 2009). In 2008, the satellite image was obtained for 20th September whilst the *in situ* measurements were carried out on 9th September, during a period when Hurricane Ike was crossing the Gulf of México. Its nearest approach was approximately 500km away but the water levels measured during the *in situ* survey by the DGPS system showed the presence of a positive surge of around 30cm at the start of the measurements, reducing almost to zero by the end of the survey. This progressive reduction of surge level added to the falling tide, resulting in a much larger drop of water level (Figure 8). This drop was also in good quantitative agreement with an observed trend in the cross-shore difference between the SDS and the *in situ* shoreline, with a difference of around 2m based on the falling tide alone. Over a typical beach slope of around 3° a surge

387 of 30cm would produce a horizontal displacement of the shoreline of around 5.7m.
388 The frequency and magnitude of surges along the coast at Progreso is not known,
389 but these observations suggest that their effect can be comparable with the tidal
390 excursion. The conclusion proposed by García-Rubio et al. (2009) was that images
391 obtained when a hurricane was in the vicinity should be avoided if possible.

392 4.2.7. Overall confidence bounds

393 The balance of each of the factors discussed in this section will depend on the
394 conditions at any given location, but for Progreso, the primary factors contributing
395 to error bounds on the SDS are found to be the image rectification, the wave run-up
396 and a much smaller effect of uncertainty in the tidal level. Based on the observations
397 from 2010, the combined influence of these factors gives an overall standard deviation
398 of approximately 5m when averaged over several kilometres of shoreline, which is
399 smaller than the pixel size of 10m. As pointed out, however, there remains some
400 unquantified uncertainty about the variability of the seaward offset of the SDS from
401 the true shoreline and the influence of surges even when no hurricane is obviously
402 nearby.

403 4.3. Shoreline change measured using SDS and *in situ* shoreline measurements

404 Shoreline change assessed over a two year-period (2008-2010) using *in situ* shore-
405 line measurements is within the same range as the change measured using SDS
406 (Figure 9). Segment 4 shows a change of 33m and an abrupt change in shoreline
407 orientation. The estimated shoreline change is within the estimated shoreline change
408 using SDS, showing the capabilities of the SDS to identify shoreline change at shore-
409 lines with an abrupt change in shoreline orientation.

410 Shoreline change smaller than 5m was detected using *in situ* shoreline measure-
411 ments but were not detected by SDSs (e.g. segments 2, 7 and 8), showing that

412 shoreline change assessment using SDSs cannot detect changes that occur below half
413 the magnitude of the pixel size. Nevertheless SDSs can provide a very good estima-
414 tion of the overall shoreline change. This is particularly valuable for those locations
415 with no *in situ* shoreline measurements or few measurements of the shoreline position.

416 The measured *in situ* shoreline change is closer to the upper bound (landward)
417 of the SDS confidence limits than the lower bound (seaward). This is likely to be
418 due to an uncertainty in the water levels of the *in situ* shoreline measurements from
419 2008, and not to the capability of the SDS to detect shoreline change. However, the
420 shoreline change assessed using *in situ* shoreline measurements remains within the
421 defined range of shoreline change using SDS.

422 This comparison confirms that the use of SDS provides another resource to explore
423 shoreline change covering large geographical scales ($>1\text{km}$ and $<40\text{km}$) and that its
424 future application to assess longer periods of time is possible. This is the subject of
425 future research.

426 5. Discussion

427 Systematic shoreline identification using optical satellite images has proved to be
428 possible using the new method. The new method is based on the inherent physical
429 properties of sea and land, which make the reflected energy from the NIR wavelengths
430 have higher and lower intensities over the land and sea respectively. Estimation of
431 the water levels (tide, wave run-up), beach slope, and the use of a common vertical
432 tidal datum allowed high accuracy to be achieved in the shoreline identification.

433 The inter-comparisons between SDS and *in situ* shoreline measurements allowed
434 validation of SDS and a better understanding of the factors involved in shoreline
435 identification. Although there are a number of research projects that have previously
436 used optical satellite images for shoreline identification (Blodget et al., 1991; White

437 and El-Asmar, 1999; Mason et al., 1997; Aarninkhof, 2003; Liu and Jezek, 2004;
438 Zakariya et al., 2006; Ekercin, 2007; Dinesh-Kumar et al., 2007; Chen and Chang,
439 2009; Wang et al., 2010; Kuleli et al., 2011; Foody et al., 2003), no validation has
440 been carried out using quasi-simultaneous *in situ* shoreline measurements. Therefore
441 these inter-comparisons are a first indication of the differences between a shoreline
442 identified by optical satellite images in relation to *in situ* shoreline measurements.

443 The validation revealed that the extracted SDS at Progreso has a bias from *in*
444 *situ* shoreline measurements of -5.6m. This bias is probably related to the optical
445 requirements of the NIR spectral band to detect a pixel as sea. This is in agreement
446 with the research of Lafon et al. (2002) where the NIR significantly decreases inten-
447 sity values with depth and with White and El-Asmar (1999) who used NIR to study
448 shoreline change. Other factors such as depth variation, suspended particles in the
449 water column, and probably the presence of small ripples on the sea surface would
450 also affect the required minimum water depth for a pixel to be identified as sea.
451 The change in intensity values due to the previously mentioned factors has not been
452 fully explored in this research. However, the range of water depth estimated in this
453 research is within the order of magnitude (0.5m) that Lafon et al. (2002(a)) deter-
454 mined when deriving bathymetry from optical satellite images at the Banc d’Arguin
455 in France.

456 Tidal levels should be as precise as possible. The results of this research also show
457 that uncertainties in water levels degrade the accuracy of shoreline location, even at
458 locations with microtidal conditions. The implication of this is that satellite images
459 alone cannot provide precise shoreline identification. The lack of water level and
460 beach slope estimations for Progreso limits the accuracy of shoreline identification
461 and hence shoreline change studies. Estimation of water levels and inter-tidal beach
462 slope is essential for the further application of our method to other locations.

463 The inter-comparisons showed that the deviation of SDS relates to the cross-
464 shore extent of the wave run-up. Wave run-up has not previously been considered
465 in shoreline change studies using satellite optical images. Its acknowledgement can
466 help to develop better evaluation of shoreline estimations. Wave run-up has been
467 shown to be a major factor in limiting the accuracy of the SDS. At Progreso, this
468 factor was one of the largest contributors to the confidence bounds on the SDS but
469 was still well below the pixel size due to the low incident wave conditions.

470 When analysing large geographical areas the magnitude and the variation in the
471 alongshore of the wave run-up could lead to large confidence bounds and therefore
472 decrease our capability to detect the shoreline. Alongshore smoothing would average
473 out most of the cross-shore extent of the wave run-up but would still leave the effect
474 of wave set-up. Thus estimation of the wave set-up and wave run-up is required when
475 assessing shoreline change and cannot be neglected when assessing the accuracy of
476 SDS.

477 For other sites with large incident waves and low beach slopes, the wave run-up
478 variations will be much larger and could severely limit the accuracy of the SDS. Wave
479 run-up has been shown to be a major factor in limiting the accuracy of the SDS, but
480 has not previously been considered in shoreline change studies using satellite optical
481 images.

482 This factor could in principle be alleviated to some extent by alongshore averaging
483 of the shoreline but its effectiveness would depend on the long-crestedness of the
484 incident waves, itself variable, and wave set-up (a negligible factor at Progreso)
485 would also contribute uncertainty. At Progreso, this factor was one of the largest
486 contributors to the confidence bounds on the SDS but was still well below the pixel
487 size due to the low incident wave conditions.

488 The application of SDS to explore shoreline change on different types of beaches

489 requires a definition of confidence intervals. Confidence intervals can be based on *in*
490 *situ* shoreline measurements or on accurate estimations of the shoreward extent of the
491 wave run-up and the beach slope. Because these factors vary at different locations,
492 the confidence bounds will increase for some beach types, reaching a magnitude
493 at which shoreline change detection would not be possible in extreme cases. For
494 example, beaches with large run-up and tidal range, without good measurements
495 of incident wave height, and beaches with large uncertainty of actual water levels,
496 either because tide predictions are poor or because of potentially large surge levels,
497 would not be suitable for our new method.

498 A more serious factor for Progreso, and potentially for other sites, is the possible
499 change in the mean water level due to a surge. The *in situ* measurements at Progreso
500 in 2008 reveal a surge with a maximum height of 0.3m, diminishing over the time
501 of the survey but displacing the shoreline by up to 6.5m. This value is larger than
502 the uncertainty due to wave run-up and comparable with the effect of the tides. At
503 Progreso, this surge was undoubtedly associated with the passage of Hurricane Ike a
504 minimum of 500km away, and surges of this magnitude may not occur at times when
505 there is no hurricane in the vicinity. However, in the absence of continuous water
506 level measurements, this remains conjecture.

507 Combining the uncertainties for Progreso, based on the observed variability of
508 the seaward displacement and assuming no surge for the 2010 observations, gives an
509 estimated standard deviation for the SDS of about half the pixel size. However, it
510 is interesting to note that most of the factors contributing to the standard deviation
511 would not be reduced for an image with a smaller pixel size. The primary benefit of a
512 smaller pixel size is likely to be the alongshore scale of features which can be observed,
513 but for the larger scale features which generally contribute most to shoreline change,
514 the pixel size of 10m is probably adequate.

515 6. Conclusion

516 A method has been developed to identify the shoreline from satellite optical
517 images, applying an unsupervised classification, using the NIR spectral band (95%
518 convergence threshold and no mask) to separate the sea and the land. Adjustment
519 of shoreline position considering water levels (tide and wave run-up) and beach slope
520 has been shown to be essential.

521 The SDS identified with satellite optical images is located seawards with a mean
522 cross-shore displacement of -5.6m and a standard deviation of 1.4m over 8km of
523 shoreline. This difference was assessed using quasi-simultaneous *in situ* measure-
524 ments, over a five hour period, both adjusted to equal tidal levels.

525 Confidence bounds for the SDS were defined including the horizontal excursion
526 of the wave run-up, uncertainty on tidal levels and inter-tidal beach slope variability.
527 The defined confidence bounds are within the pixel size and they are shown to be
528 effective to explain the deviation of the SDS from *in situ* shoreline measurements.

529 Estimated shoreline change over a two year period with SDS is within the same
530 magnitude as the estimated shoreline change using *in situ* shoreline measurements.
531 The SDS measurements proved able to detect abrupt changes in the shoreline lo-
532 cation, encouraging the further exploration of the technique to determine shoreline
533 change over longer periods of time and larger extents of shoreline.

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Figure 1: Geographic location of Progreso, Yucatán, México (upper box), and the studied shoreline segments.

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Figure 2: a) Cross-shore spectral profile in intensity values at a point location along the shoreline level. The horizontal axis is spaced by the pixel size (10m). (b) Intensities from the NIR against the SWIR from the pixels identified either as sea and land covering the entire image.

Figure 3: Extract of a classified image in sea (grey) and land (white) using the NIR spectral band. The close-up is the area within the black square.

Figure 4: Smoothed vector (red line) using an alongshore distance of 50m, and stepped raw vector (black line) from the raster to vector conversion. The horizontal axis is the Eastern and the vertical axis is the Northern coordinates, projected using a UTM projection 16 N.

Figure 5: Smoothed SDS using different distances in the alongshore (10 (red), 20 (blue), 50 (black) and 60m (green)).

Figure 6: Difference in the cross-shore (m) between the SDS and *in situ* shoreline measurements (2010) in Progreso, Yucatán. Horizontal axis is the eastern, vertical axis is the northern coordinates in a UTM projection (16 zone North). Segments 1 to 8 are from left to right (dashed lines). Progreso piers are located within segment 4 at 2.238 m eastern.

Figure 7: Histogram of the cross-shore distance between *in situ* shoreline measurements and SDS in 2010. The distribution fits into a normal distribution ($k=0.979$, $c.v.=0.0182$, $n=709$). The dashed lines indicate the values within 1 standard deviation from the average.

Figure 8: Measured height during the *in situ* shoreline measurements against the predicted tide (in relation to the local BMI) in 2008 at Progreso, Yucatán, México. The gradient is -4, the intercept is 0.42 m, and $r^2=0.78$. The black line has a gradient of 1 placed as a reference.

Table 1: Electromagnetic range covered by the spectral bands of SPOT satellite.

Spot satellite	Spectral bands	Pixel size (m)	Spectral resolutions
5	Panchromatic	2.5 or 5	0.48 to 0.71 μm
	Green	10	0.50 to 0.59 μm
	Red	10	0.61 to 0.68 μm
	Near infrared	10	0.78 to 0.89 μm
	Short-wave infrared	10	1.58 to 1.75 μm
4	Monospectral	10	0.61 to 0.68 μm
	Green	20	0.50 to 0.59 μm
	Red	20	0.61 to 0.68 μm
	Near infrared	20	0.78 to 0.89 μm
	Short-wave infrared	20	1.58 to 1.75 μm

Table 2: Beach characteristics of the beach segments from Progreso, the case study area, α is the shoreline orientation using as a reference the West to East line. Positive values are anticlockwise, and negative values are clockwise, β is the beach slope in degrees.

	West				East			
	Seg.1	Seg.2	Seg.3	Seg.4	Seg.5	Seg.6	Seg.7	Seg.8
α ($^{\circ}$)	5	8	18	27 to -2	3.1	3.7	6.8	9.7
β ($^{\circ}$)	3	5	5	9	6	6	5	5
Beach width (m)	80	50	178	15	30	52	25	23
$\bar{X}$ grain size (mm)	0.22	0.26	0.24	0.61	0.34	0.28	0.52	0.84
Coastal vegetation	Yes	Yes	Yes	No	No	No	No	No
Coastal structures	No	No	No	Yes	No	No	No	No
Length (m)	810	810	1,300	310	680	1,185	1,000	2,280

Table 3: Cross-shore difference (m) of the SDS and *in situ* in 2010.

	2010	Mean=-5.57 m, SD=1.37 m						
	Seg. 1	Seg. 2	Seg. 3	Seg. 4	Seg. 5	Seg. 6	Seg. 7	Seg. 8
Mean	-6.6	-5	-4.7	-7.4	-6	-5.6	-5.7	-5.3
Std. dev.	1	0.8	1.6	1.9	1.1	1	0.9	1.4
Range	7.1	3.5	10.3	9.7	4.9	5.6	4	7.5

Figure 9: Shoreline change from September 2008 to July 2010 estimated using *in situ* shoreline measurements and SDS.