REVIEW OF MULTIBEAM SONAR SURVEYS
WHEELER REEF NORTH, SAN CLEMENTE, CALIFORNIA
TO EVALUATE ACCURACY AND PRECISION OF
REEF FOOTPRINT DETERMINATIONS
AND CHANGES BETWEEN 2008 AND 2009 SURVEYS

Prepared for:

CALIFORNIA COAST COMMISSION

c/o Dr. Stephen Schroeter

45 Fremont Street, Suite 2000

San Francisco, CA 94105-2219

Prepared by:

Mark R. Legg, PhD, PG#6463, RGP#948

LEGG GEOPHYSICAL, Inc.

16541 Gothard Street, Suite 107

Huntington Beach, CA 92647-4472

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Review of Multibeam Sonar Surveys, Wheeler Reef North, San Clemente, California
To Evaluate Accuracy and Precision of Reef Footprint Determinations
And Changes Between 2008 and 2008 Surveys

Introduction

Legg Geophysical was contracted to assist the California Coastal Commission to implement a technical oversight and independent monitoring program for the San Onofre Nuclear Generating Station marine resource mitigation project at the Wheeler North artificial reef near San Clemente, California (Fig. 1). Legg Geophysical was tasked to review the reports and data from two multibeam sonar surveys designed to assess the compliance of Wheeler North Reef with regard to reef footprint immediately following construction in 2008 ("as-built") and one year after completion (2009). In particular, this project involves determination of the accuracy and precision in determining the footprint for both surveys and to determine the magnitude of any observed differences in the reef footprint between the two surveys. The evaluation is based upon raw data obtained from Coastal Environments (CE) and the reports submitted at the completion of the post-construction survey "*Final Construction Report for Wheeler North Reef at San Clemente, California, Vol. I and II*", on November 4, 2008 (revised Dec. 12, 2008) and the one year following survey "*Hydrographic Survey, Wheeler North Reef, Offshore San Clemente, California, Report and Charts*", Fugro Pelagos Inc. Document No: FP-6289-003-RPT-01-00, on November 3, 2009.

Accuracy and Precision in Determining the Footprint of the Wheeler North Reef

The two primary objectives of this review are to determine the accuracy and precision in reef footprint definition and magnitude of difference between the two surveys.

Navigation

Both surveys used differential global positioning satellite (DGPS) for navigation that provide sub-meter positioning accuracy (<1-m or within about 3 feet). For the 2008 survey, the GPS antenna was mounted directly above the multibeam sonar sensors. For the 2009 survey, the navigation data were corrected for offsets of the GPS antenna from the multibeam sonar sensors. Both surveys used inertial motion sensors (Inertial Measurement Unit or IMU) to provide corrections for roll, pitch, and yaw of the boat and sonar systems so that the geographic position and water depth of each sonar ping/beam on the seafloor would be accurately determined.

Multibeam Sonar Calibration and Processing

Calibration of the multibeam sonar systems was performed with a Patch Test before each survey, for both 2008 and 2009 investigations (Fig. 2). The calibration provides a "cleaner" and more accurate image of the seafloor than the un-calibrated data. Because the sonar systems record travel times of sonic pings through the water, it is also necessary to measure the sonic velocity in the water column. Both surveys used sonic velocity profiling systems for this purpose with measurements taken several times during the survey; the 2009 survey measured the sonic velocity profile several times each day.

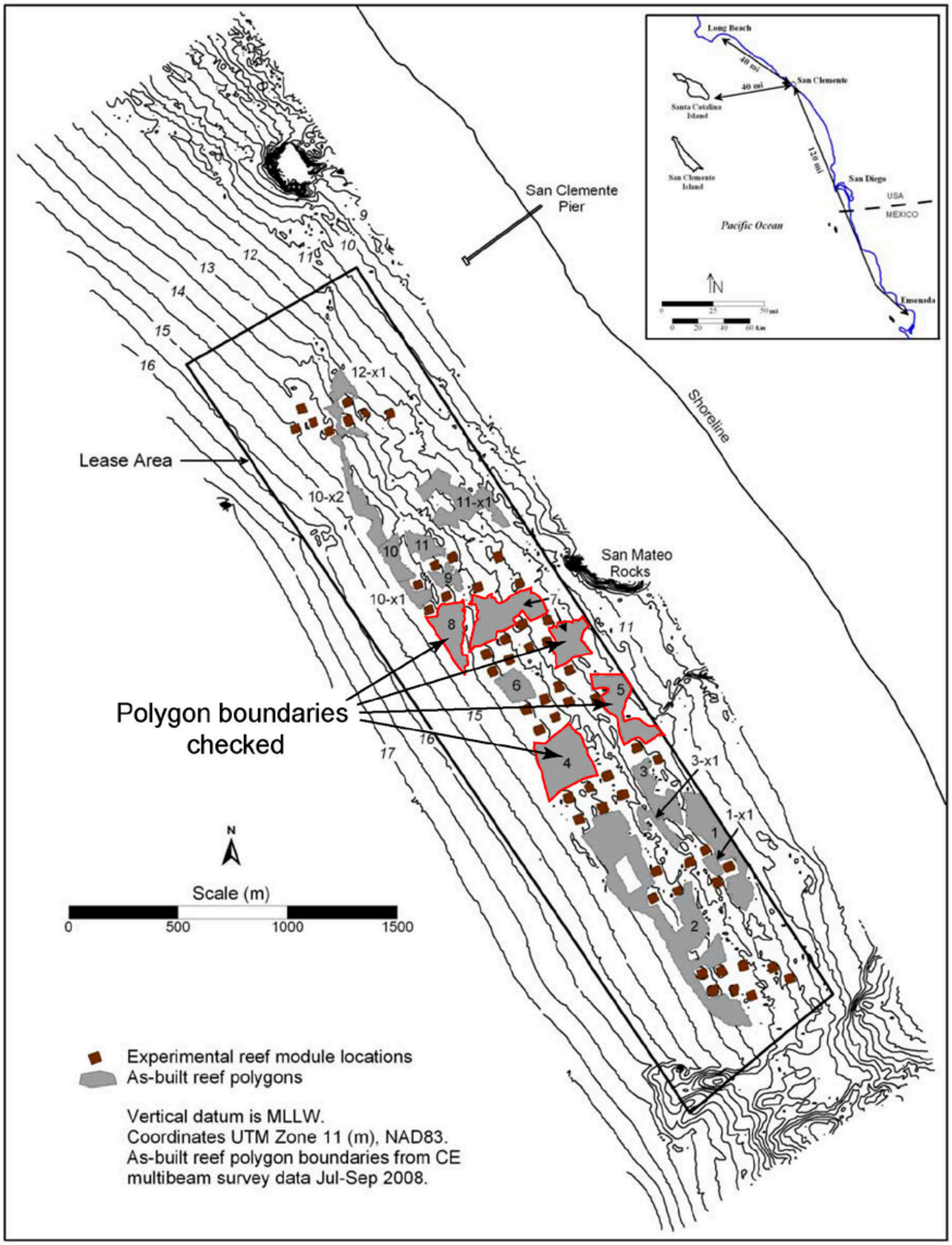
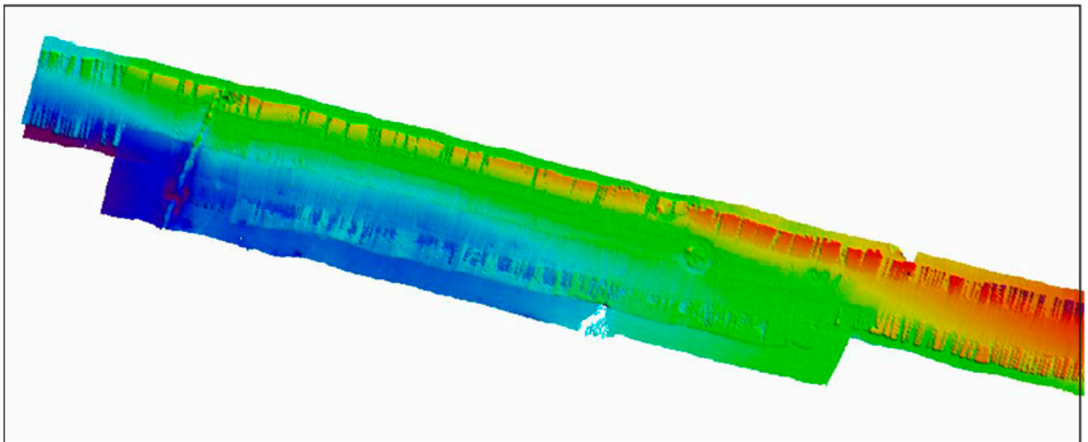


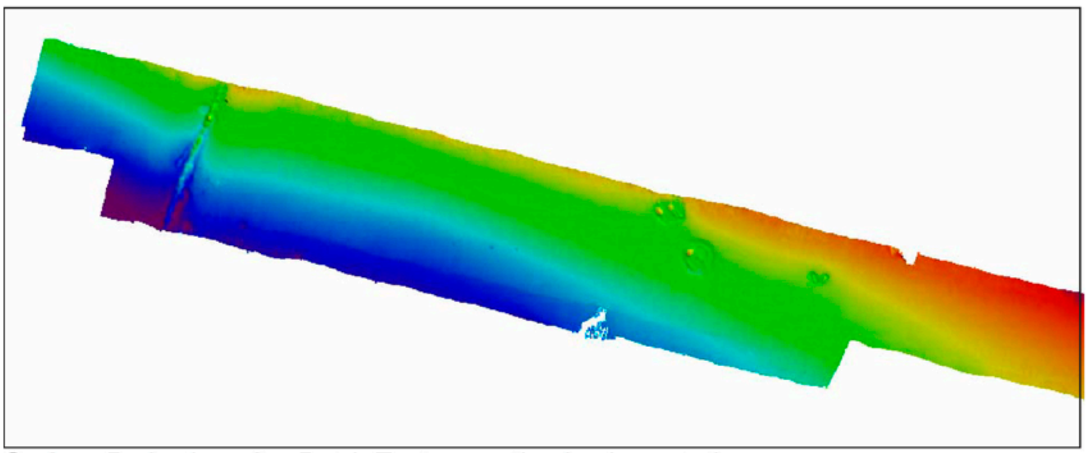
Figure 1. WNR polygons and project location site (Coastal Environments 2008 survey report).

PATCH TEST #1 (JD302) REPORT

Three survey lines are acquired; two coincident in reciprocal directions, and one line at ~60 meter offset (see figure). Patch data were processed in CARIS HIPS calibration mode.



Surface projection prior to Patch Test correction implementation



Surface Projection after Patch Test correction implementation

Survey Lines

Line name	Heading	Speed	Line position
1PATCH-246-001	193	5kts	Centerline
1PATCH-246-002	103	5kts	Centerline
1PATCH-245-003	103	5kts	Offset 60m

Figure 2. Patch test report from the 2009 multibeam sonar survey.

Both surveys also acquired multibeam sonar bathymetry swaths with significant overlap to provide redundant data coverage for additional quality control insuring accurate sounding positions for digital elevation models (DEM) bathymetry and backscatter mapping. Post-processing of the multibeam sonar data used weighted averaging of the redundant soundings to provide Digital Terrain Models (DTM) for the final sonar images and XYZ (DEM) files. The weighting schemes provided more weighting to ping/beam footprints closer to each grid point.

The multibeam sonar data provide two different types of seafloor information: bathymetry (depth to seafloor) and backscatter (reflected signal strength). Bathymetry data are used to produce the DEM and seafloor color bathymetry and shaded relief images (Fig. 3). Bathymetry maps also can be presented showing contours of the water depth (Fig. 1). Backscatter data are used to provide images of the seafloor reflectivity, similar to side-scan sonar images (Fig. 4). Hard substrate produces higher reflection signal strength than sand or mud. A rough seafloor scatters the energy creating many shadows, whereas a smooth seafloor provides a more uniform reflectivity. The images from individual survey swaths are tiled together forming a mosaic of the entire survey area, and subsets of the data can be produced for individual areas of interest.

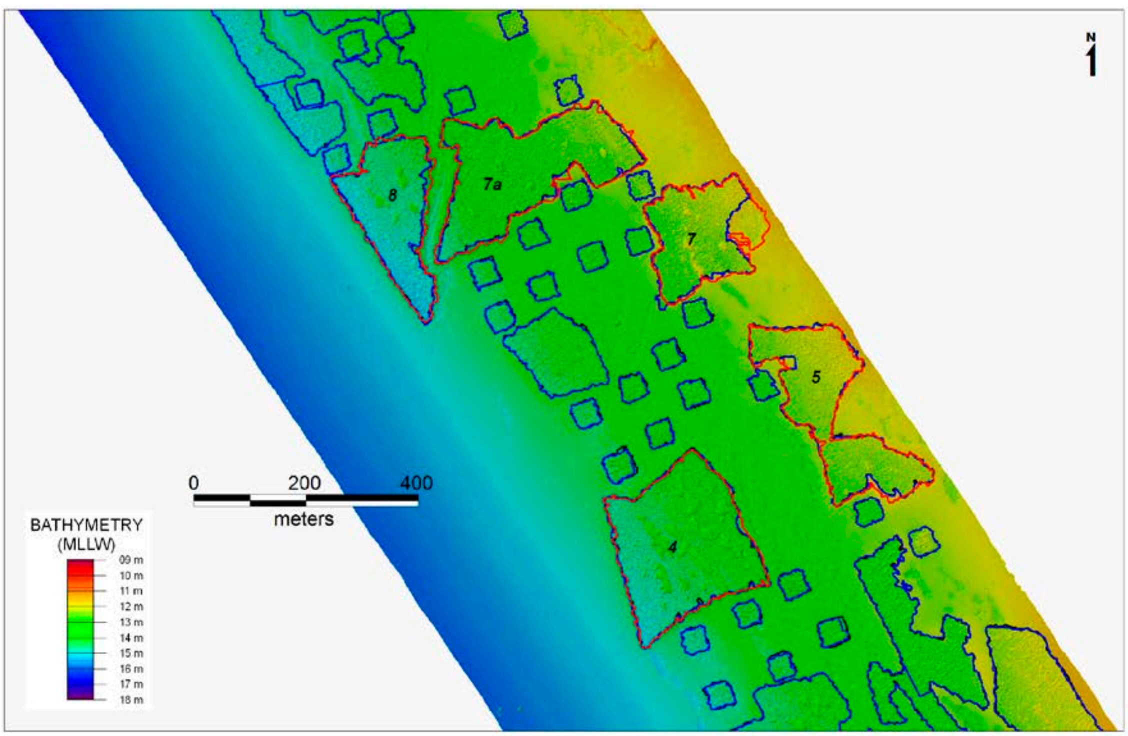


Figure 3. Shaded relief bathymetry showing polygons evaluated for this review. Red outlines are polygon boundaries determined from the 2008 survey backscatter data. Black boundaries are from the 2009 survey backscatter data; blue boundaries are from the 2009 survey bathymetry data.

The reef polygons are areas of rough seafloor with a hard substrate. Consequently, the bathymetry and backscatter images show irregular features in the reef polygons whereas intervening channels with smooth sand produce more uniform reflectivity and water depths. The 2008 survey relied mostly on the backscatter images to define the polygon boundaries. The 2009 survey defined polygon boundaries based on both reflectivity and bathymetry images. Due to differences in the multibeam sonar systems and processing used, the 2009 survey data appear to have sharper and better defined polygon boundaries than the 2008 survey data. Note that the 2008 survey shows high reflection strength as bright areas, whereas the 2009 survey data show high reflection signal strength as dark areas (Figs. 5 & 6). The edges of the reef footprint polygons were traced and digitized from geo-referenced images (geotiff), and area computed from these polygon boundaries. A similar method was used for selected areas (check polygons) in the present analysis.

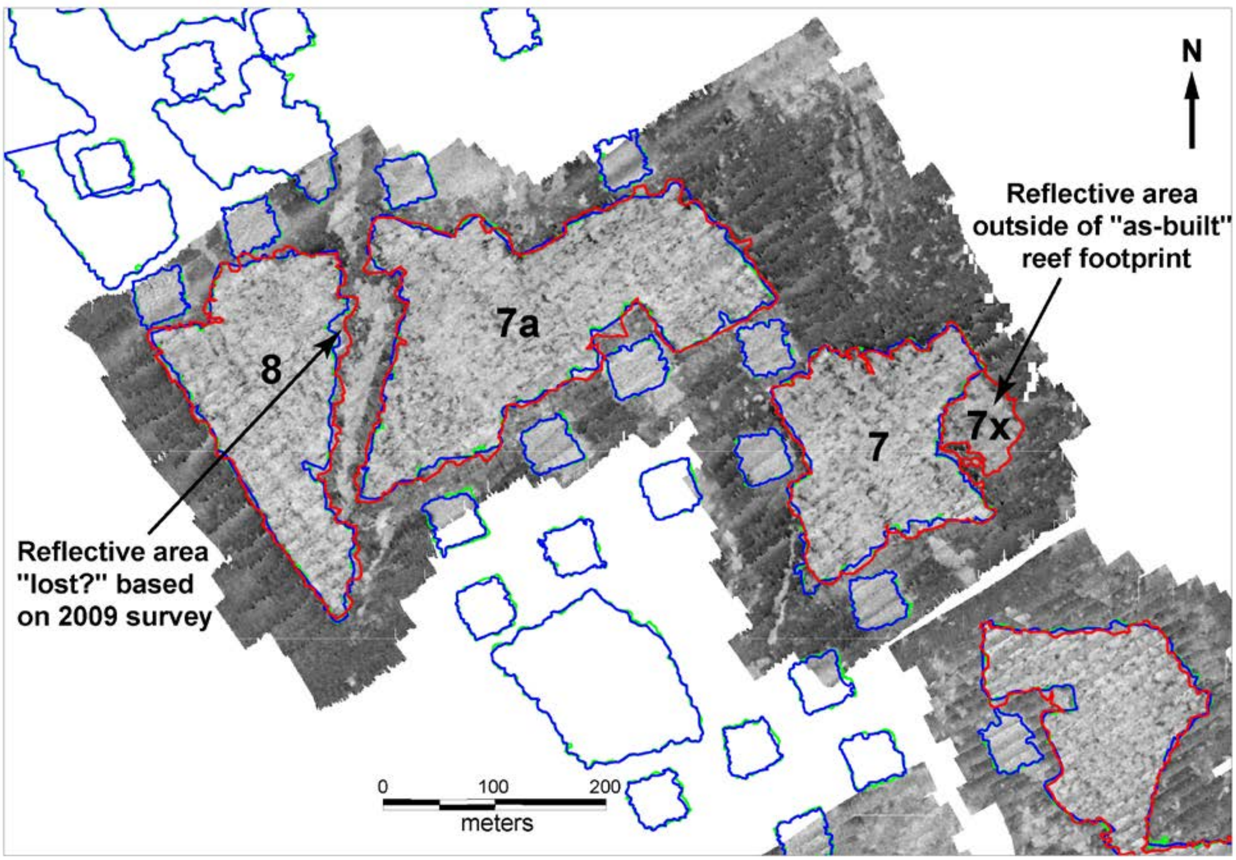


Figure 4a. Georeferenced backscatter images from the 2008 survey of selected polygons reviewed. Red outline is reef footprint boundary interpreted for this review. Blue outline is footprint boundary interpreted from 2009 survey bathymetry; green outline is footprint boundary interpreted from 2009 survey backscatter.

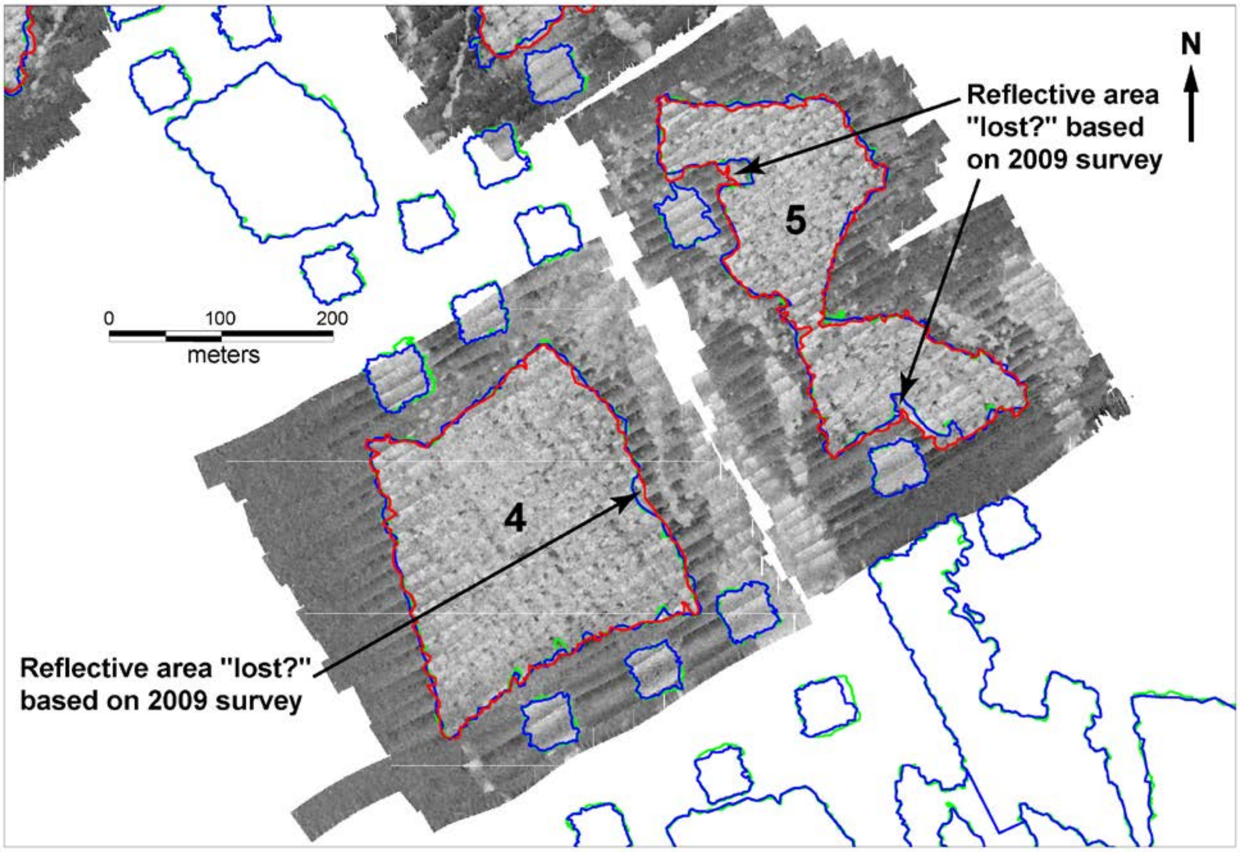


Figure 4b. Georeferenced backscatter images from the 2008 survey of selected polygons reviewed. Red outline is reef footprint boundary interpreted for this review. Blue outline is footprint boundary interpreted from 2009 survey bathymetry; green outline is footprint boundary interpreted from 2009 survey backscatter.

To estimate the accuracy and precision of the polygon boundary determinations, Legg Geophysical used backscatter image data from the 2008 survey (as-built) for a subset of the reef polygons (#4, #5, #7, #7a, #8; Fig. 4) to trace and digitize the boundaries in a Geographic Information System (GIS; MapInfo vers. 6.5). The images are geographic projections using the Universal Transverse Mercator projection (UTM) for zone 11 with the 1984 World Geodetic System (WGS84) horizontal datum. The georeferenced polygon boundaries were compared directly to the digitized polygon boundaries produced by CE (Fugro) in the 2009 survey data report imported as overlays into the GIS at Legg Geophysical. The 2009 georeferenced bathymetry and backscatter images were also loaded into the GIS as underlays to verify location accuracy; polygon boundaries were directly compared between the two surveys and the 2008 survey polygon boundaries digitized by Legg Geophysical (Figs 5 & 6). The reef polygon areas were computed using the GIS tools to compare footprint acreage estimates between the two surveys and the various estimates of the polygon boundaries (Table 1; 2008 as-built estimates, 2008 Legg Geophysical check polygon boundaries, 2009 bathymetry and 2009 backscatter boundary estimates from the CE/Fugro report). The 2009 bathymetry and backscatter acreage estimates provide a measure of the uncertainty in boundary definition for a given survey year.

Table 1. Comparison of Wheeler North Reef Polygon Footprint Areas (acres).

Polygon	ID	As-Built*	2008_Legg	2009_CE1**	2009_CE2**	Ratio_Lg08	Ratio_CE1**	Ratio_CE2**
1	1	13.83		13.485	13.313		0.975	0.963
2	2	38.88*		37.751	37.481		0.971	0.964
3	3	6.61		6.185	6.054		0.936	0.916
4	4	14.05	13.942	13.995	13.918	0.992	0.996	0.991
5	5	9.48	9.732	9.598	9.588	1.027	1.012	1.011
6	6	4.24*		4.288	4.322		1.011	1.019
7	7	19.03	19.694	18.927	18.796	1.035	0.995	0.988
8	8	7.64	8.060	7.500	7.428	1.055	0.982	0.972
9	9	2.52		2.623	2.633		1.041	1.045
10	10	3.89		3.884	3.841		0.998	0.987
11	11	3.48		3.688	3.680		1.060	1.057
12	1-x1	1.35		1.344	1.304		0.996	0.966
13	3-x1	2.85		2.922	2.876		1.025	1.009
14	10-x1	2.12		2.176	2.142		1.026	1.010
15	10-x2	5.54		5.466	5.436		0.987	0.981
16	11-x1	11.19		11.220	11.463		1.003	1.024
17	12-x1	5.32		5.410	5.394		1.017	1.014
Totals		**152.02**		**150.462**	**149.669**		**0.990**	**0.985**
Data		backsctr	backsctr	bathy	backsctr	backsctr	bathy	backsctr

Ratios are between the 2009 survey area estimates and the "As-Built" area estimates. Data types used for footprint boundary estimates include backscatter (backsctr) and bathymetry (bathy). Polygon 7 includes both 7 (east) and 7a (west); the reflective area outside the original design polygon (7x, Fig. 4a) is excluded from the table. *Polygons 2 and 6 footprint areas were estimated using gray-scale bathymetry images. *Coastal Environments (2008a and 2002b). *Final Construction Report for Wheeler North Reef at San Clemente, California, Vol. I and II*", on November 4, 2008 (revised Dec. 12, 2008). **Fugro Pelagos Inc (November 3, 2009). *Hydrographic Survey, Wheeler North Reef, Offshore San Clemente, California, Report and Charts*. Document No: FP-6289-003-RPT-01-00,

Results of Comparisons

1. The 2009 polygon boundaries from both bathymetry and backscatter estimates generally lie within the 2008 check polygon boundaries from this review (Legg Geophysical boundary estimates (Figs. 3-6), showing that the overall geographic positions of the two surveys are consistent. In general, the Legg Geophysical polygon boundaries are smoother and represent a somewhat simplified estimate of the reef polygon boundaries that should bracket the other estimates.
2. The 2009 polygon boundaries for the bathymetry and backscatter estimates differ by less than about 2 percent, in general, although the backscatter images (Figs. 5-6) appear to provide better definition of the reef footprint edges.
3. The maximum deviation of boundaries for the 2009 backscatter and bathymetry estimates is about 5-m to 6-m, but most edges are within 1-m to 2-m of each other.
4. Comparisons of both bathymetric and backscatter estimates of reef area in 2009 to

backscatter estimates in 2008 are very similar, indicating a reduction in footprint area between 1% to 1.5%, respectively.

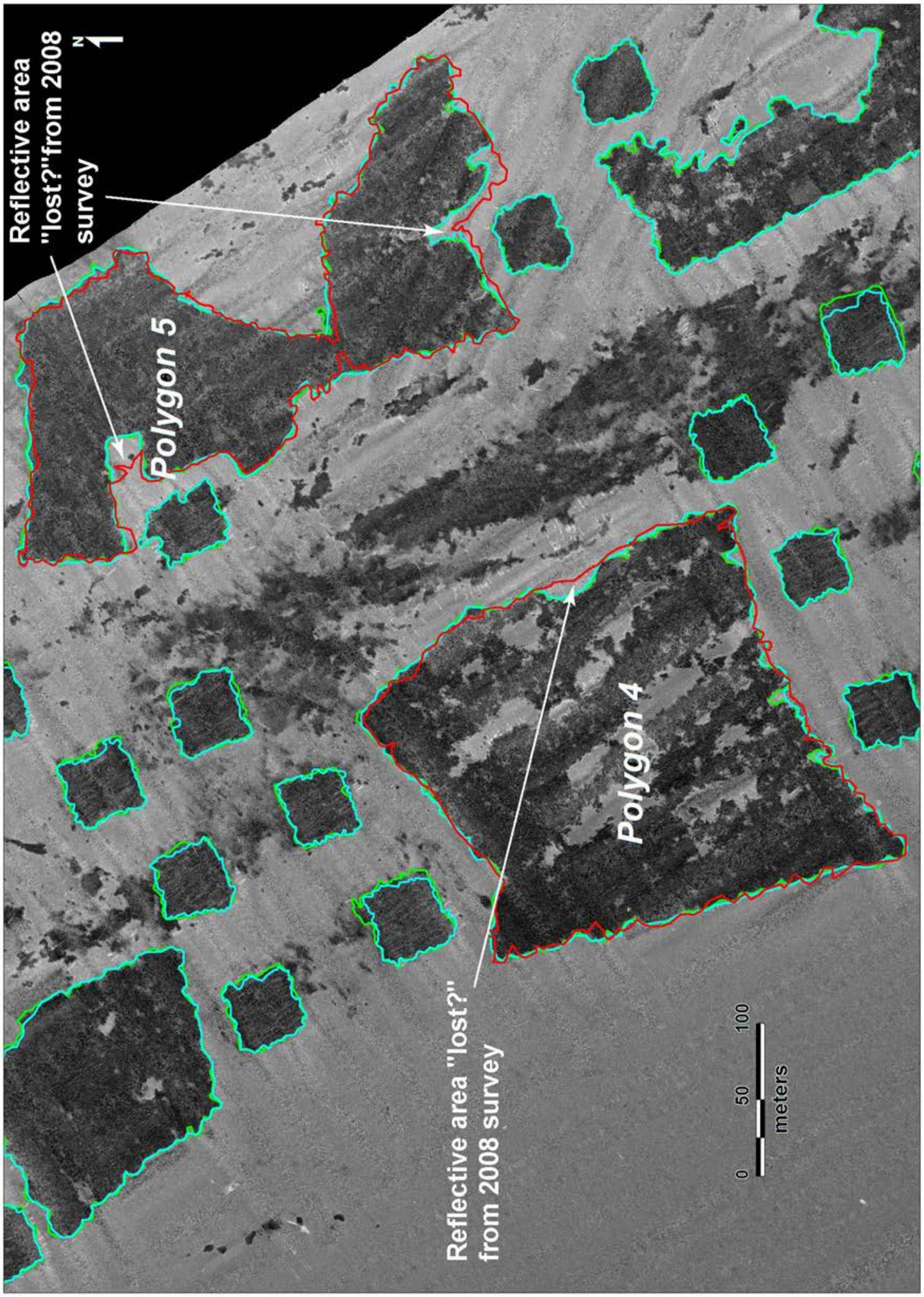


Figure 5. Georeferenced backscatter images from the 2009 survey of selected polygons reviewed (southern area). Red outline is reef footprint boundary interpreted from the 2008 survey. Blue outline is footprint boundary interpreted from 2009 survey bathymetry; green outline is footprint boundary interpreted from 2009 survey backscatter.

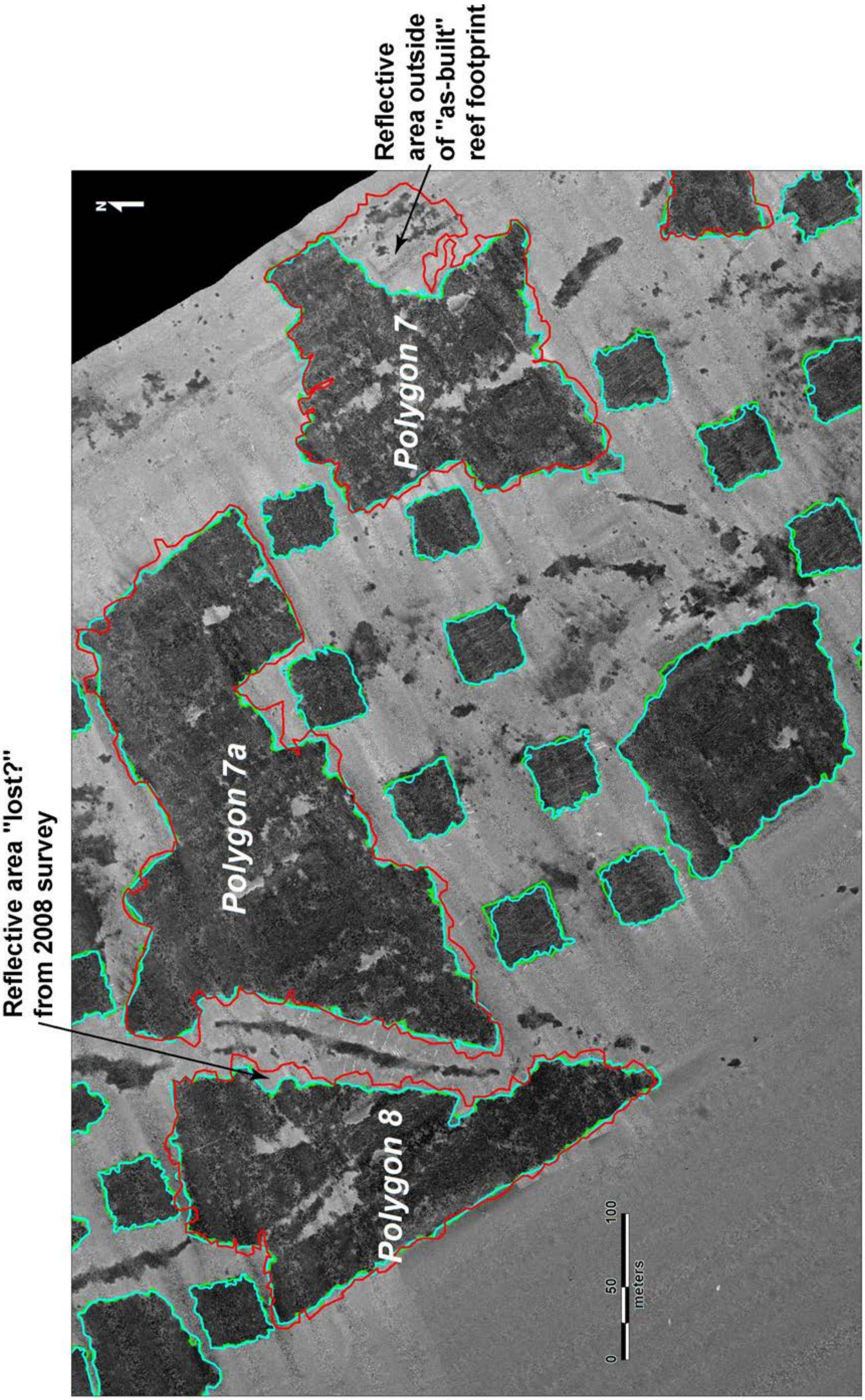


Figure 6. Georeferenced backscatter images from the 2009 survey of selected polygons reviewed (northern area). Red outline is reef footprint boundary interpreted from the 2008 survey. Blue outline is footprint boundary interpreted from 2009 survey bathymetry; green outline is footprint boundary interpreted from 2009 survey backscatter.

5.

4. The Legg Geophysical check polygon boundary estimates generally lie outside the 2009 polygon boundaries and produce larger areas. The most significant difference was for polygon 7 (the eastern part) where the Legg Geophysical estimate includes an area (7x) at the southeast corner that is excluded in both the 2008 CE estimates (as-built) and 2009 survey estimates (Fig. 4a). This area is outside of the design reef footprint for polygon 7 and appears more subdued in the 2009 imagery (Fig. 6) consistent with pre-existing irregular seafloor with possible hard substrate. This area likely represents a pre-existing natural hard substrate area. Table 1 values for polygon 7 have excluded this area outside of the original design polygon. Polygon 8 was estimated to be about 6 percent larger than the 2009 polygon boundaries from the 2008 backscatter image by the Legg Geophysical estimate. Most of this excess area appears to exist along the eastern boundary of the reef footprint along the north-trending channel between polygons 8 and 7a. This may represent a real change in the polygon footprint from 2008 to 2009, or it may only represent uncertainty from the lower resolution backscatter image of the 2008 survey data. The other check polygon areas are only a few percent greater than the 2009 survey estimates.

5. The absence of recognizable systematic offset between the 2008 survey polygon boundaries and the 2009 survey polygon boundaries demonstrates that the navigation accuracy is within about 2-m. Accuracy within 1-m range is expected for the DGPS navigation. The other uncertainty arises from the definition of reef footprint edges provided by the bathymetry and backscatter images. The grid increment used for preparation of the bathymetry and backscatter images limits the precision of reef footprint boundary definition – a 1-m grid increment is consistent with the $\pm$1-m DGPS navigation. The 2009 survey used a 0.25-m horizontal grid increment for the DTM model, but output a DEM (XYZ data) at 1.5-m and 5-m grid increments. The finer grid in the DTM model used for the bathymetry and backscatter images in the 2009 survey probably accounts for the better resolution of the reef footprint edges than in the 2008 survey data, although the presence of kelp may also increase the sharpness of the reef images. The interpolation method used to create the DTM from the raw multibeam sonar beam footprint data affects the resolution of seafloor features – averaging soundings from wider areas will smear or smooth sharp edges of seafloor features like small boulders. Both surveys used a distance weighting scheme so that more distant soundings carry less weight in the averaging used to compute the water depth or signal strength at each grid point in the DTM. Another effect limiting resolution of reef footprint boundaries is the uncertainty in defining the actual edge of hard substrate on the reef due to smooth gradations in reflectivity or seafloor slope. This may occur by smearing in the preparation of the DTM discussed above, or by real seafloor smoothing caused by sediment build-up adjacent to the boulders along the reef edges.

6. There appears to be a slight reduction in reef footprint area between 2008 and 2009 (Table 1). The 2009 footprint areas calculated show some area increases and some area decreases, but the total area from the bathymetry and backscatter estimates shows a 1.0 to 1.5 percent decrease. Much of this decrease may result from the sharper definition of the polygon boundaries in the 2009 survey images. However, there appear to be some real "losses" in reef area where sedimentation or other smoothing occurs. For example, the eastern side of polygon 8 shows a significant gap, exceeding 15-m in places, between the 2008 and 2009 boundary estimates (Figs. 4 & 6). Most of these "gaps" exist along the channels between reef polygons. Ground-truth observations by diver or other direct seafloor observations may be needed to determine if these are real losses of reef polygon area and what mechanism may be responsible for these losses.

Summary

The accuracy and precision in determining the footprint of the Wheeler North Reef depends upon the navigation accuracy and smear of the reef polygon boundaries in the processed multibeam sonar bathymetry and backscatter images. The navigation is accurate to within one meter consistent with Differential Geostationary Satellite Positioning (DGPS) used for both the 2008 and 2009 surveys. The precision in determining polygon edges for footprint definition is fixed by the Digital Terrain Model (DTM) grid used for the bathymetry and backscatter images, which is specified as 0.25-m for the 2009 survey; this value was unspecified for the 2008 survey, but appears to be similar or somewhat lower resolution at about 0.5-m to 1.0-m. The accuracy in defining the polygon edges for footprint definition is ultimately fixed by the smearing or smoothing of the color shading in the backscatter and bathymetry images. Comparing polygon boundary interpretations from the 2008 backscatter, 2009 bathymetry and 2009 backscatter images, it appears that the 2008 footprint definition is accurate to about 2-m and the 2009 footprint definition is accurate to about 1-m. Slight changes in polygon acreages were observed between the 2008 estimates and the 2009 estimates. On average, the footprint area, as determined by bathymetric and backscatter estimates made by Fugro and Coastal Environments in 2008 and 2009, declined by less than about one and one-half percent (1.5%). Although much of this reduction appears to be due to better resolution of polygon boundaries in the 2009 survey data, there are some locations where the rugged seafloor relief at reef edges in the 2008 "as-built" images is smoothed in the 2009 survey images. Seafloor ground-truth observations are required to determine what, if any, real smoothing has occurred and by what mechanism(s).

APPENDIX

Table A. "Raw" Data Used for Analysis of Reef Footprint

Item	Survey	Data Type	Filename
1	2008	Backscatter, geotiff	poly4-mosaic-28aug-08.tif; poly4-mosaic-28aug-08.tfw
2	2008	Backscatter. geotiff	poly5-mosaic-28aug-08.tif; poly5-mosaic-28aug-08.tfw
3	2008	Backscatter. geotiff	poly7&8-08sep-08-mosaic.tif; poly7&8-08sep-08-mosaic.tfw
4	2009	Polygon Boundaries, shapefile	6289-003_BackscatterBoundaries.shp; 6289-003_BackscatterBoundaries.sbn; 6289-003_BackscatterBoundaries.sbx; 6289-003_BackscatterBoundaries.shx; 6289-003_BackscatterBoundaries.prj
5	2009	Polygon Boundaries, shapefile	6289-003_BathymetryBoundaries.shp; 6289-003_BathymetryBoundaries.sbn; 6289-003_BathymetryBoundaries.sbx; 6289-003_BathymetryBoundaries.shx; 6289-003_BathymetryBoundaries.prj
6	2009	Backscatter, geotiff	6289-003_01m_Backscatter_Reef.tif; 6289-003_01m_Backscatter_Reef.tfw
7	2009	Bathymetry, geotiff	6289-003_WNR_NBL_Ve1_Az315_An45.tif; 6289-003_WNR_NBL_Ve1_Az315_An45.tfw

References

Coastal Environments (2008a). Final Construction Report for Wheeler North Reef at San Clemente, California, Vol. I. November 4, 2008 (revised Dec. 12, 2008).

Coastal Environments (2002b). Final Construction Report for Wheeler North Reef at San Clemente, California, Vol. II. on November 4, 2008 (revised Dec. 12, 2008).

Fugro Pelagos Inc (November 3, 2009). .Hydrographic Survey, Wheeler North Reef, Offshore San Clemente, California, Report and Charts. Document No: FP-6289-003-RPT-01-00.