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Source: Journal of Coastal Research, Number 10062:19-29. 2011.
Published By: Coastal Education and Research Foundation
DOI: 10.2112/SI_62_3
URL: http://www.bioone.org/doi/full/10.2112/SI_62_3

Journal of Coastal Research	SI	62	19–29	West Palm Beach, Florida	Spring 2011

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Integration Potential of INFOMAR Airborne LIDAR Bathymetry with External Onshore LIDAR Data Sets

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ABSTRACT

COVENEY, S. and MONTEYS, X., 2011. Integration potential of INFOMAR airborne LIDAR bathymetry with external onshore LIDAR data sets. *In:* Pe'eri, S. and Long, B. (eds.), *Applied LIDAR Techniques*, Journal of Coastal Research, Special Issue No. 62, 19–29. West Palm Beach (Florida), ISSN 0749-0208.

Light detection and ranging (LIDAR) data are used for a wide array of purposes in the coastal zone. This can result in LIDAR data being collected multiple times in order to meet the specific needs of different agencies. This paper assesses the potential for airborne LIDAR bathymetry (ALB) and topographic LIDAR to be integrated for use in coastal research. Two topographic LIDAR data sets and an ALB data set are examined in three coastal test areas. Consideration of the potential for data integration focuses upon external validation of each data set using global positioning system (GPS) points, comparison of subareas and onshore-offshore cross-sections, horizontal feature matching onshore, and data set datum conversion. Data accuracy and datum integration potential confirm that all three data sets can be integrated onshore to facilitate extended LIDAR coverage and possibly also to minimise survey duplication in the coastal zone. Integration potential offshore is assessed by comparing the littoral component of an onshore topographic LIDAR digital surface model (DSM) data set with ALB data. Water-surface returns in the topographic LIDAR data collected during times of high water are found to constitute a barrier to data integration offshore, but topographic LIDAR data captured at low tide in one of the three coastal test areas suggest an opportunity to minimise duplicate surveying in the coastal zone.

ADDITIONAL INDEX WORDS: *Data integration, bathymetric LIDAR, topographic LIDAR, accuracy.*

INTRODUCTION

Background

The National Centre for Geocomputation at National University of Ireland (NUI) Maynooth in Ireland was commissioned by INFOMAR (INtegrated Mapping FOr the Sustainable Development of Ireland's MArine Resource) in November 2008 to evaluate the potential for the integration of INFOMAR bathymetric aerial light detection and ranging (LIDAR) data with existing onshore aerial LIDAR data from external data providers. Data from INFOMAR airborne LIDAR bathymetry (ALB) are already available for a number of the INFOMAR priority bays. Three of these bays provide spatial overlaps with topographic LIDAR surveys undertaken by the Office of Public Works (OPW) and Ordnance Survey Ireland (OSI). This made it possible to evaluate the potential for LIDAR data integration, and to identify any barriers to integration in three separate test locations (Sligo Bay in County Sligo, Ireland; Galway Bay in County Galway, Ireland; and Tralee Bay in County Kerry, Ireland).

Light Detection and Ranging

Airborne LIDAR systems use radiation pulsed laser (generally green or near-infrared) to capture high-resolution *x-y-z* point-cloud data of the ground or seabed surface. The travel time of the laser pulse is used to determine the range between the LIDAR platform and reflectance sources in the sensor's field of view. These range data are referenced against sensor platform position, which is established using a combination of global positioning systems (GPS) and inertial navigation systems (INS). LIDAR survey data are typically referenced to geographic coordinates and ellipsoidal height and are supplied as a point cloud of *x-y-z* data that can be converted to a digital surface model (DSM) or bare earth digital terrain model (DTM) (Heritage and Large, 2008). ALB operates using a green laser to detect both the water surface and the seafloor, and infrared laser returns are typically used as an additional measurement of the water surface. Bare earth LIDAR DTMs (whether derived from topographic or bathymetric surveys) are produced by processing the raw LIDAR data by reference to first and last reflectance returns

DOI:10.2112/SI_62_3 received and accepted in revision 13 September 2010.

Research presented in this paper was funded by a Strategic Research Cluster grant (07/SRC/I1168) by Science Foundation Ireland under the National Development Plan. The authors gratefully acknowledge this support.

(Fowler *et al.,* 2007; Hall *et al.,* 2005; Lim *et al.,* 2003) or by reference to the waveform of the laser returns (Guenther, 2007; Nayegandhi *et al.,* 2006; Wagner *et al.,* 2008).

INFOMAR LIDAR

The INFOMAR programme is an Irish government initiative that is managed by the Geological Survey of Ireland and the Irish Marine Institute. The aim of the INFOMAR programme is to create a range of integrated mapping products of the physical, chemical, and biological features of the seabed in the nearshore area. INFOMAR uses a variety of acoustic, seismic, and optical methods to collect bathymetric data. Acoustic methods are favoured for deeper water, and ALB is used (in addition to shallow-water acoustic surveys) in shallower coastal waters where acoustic surveys are more difficult to implement. Water-column turbidity places a limit on the effective penetrative depth for ALB below this depth in Irish waters. Generally speaking, the west coast of Ireland is characterised by clearer water than the east, so INFOMAR bathymetric surveys have to date focused on INFOMAR priority bays (Figure 1) on the west coast (INFOMAR, 2007).

The INFOMAR ALB data were obtained and used within the INFOMAR project and for delivery to the United Kingdom Hydrographic Office (UKHO, 2009) for updating their Irish nautical charts. The LIDAR data were acquired from heights between 350 and 650 m at ground speeds between 140 and 175 knots, using the LADS MKII. Surveys were conducted in main-line sounding mode at a line spacing of 100 m across a swath width of 240 m, providing up to 200% coverage in each survey. Bathymetric returns were acquired with an Nd : YAG green laser on a stabilised platform. Bathymetric returns were achieved up to maximum depths of about 25 m. Real-time positioning was provided by Fugro wide area differential GPS (WADGPS). The ground system (GS) allows for subsequent calculation of postprocessed kinematic GPS positions (L1/L2 carrier phase) from the local base station. The OPW data were collected by an external contractor using the Optech ALTM 3100EA aerial terrestrial LIDAR system. Data were captured at a mean altitude of 500 m at 2 × 2 m spacings. The OSI collected their own data in-house (OSI data) using a topographic LIDAR system. Their system employs a Leica ALS50 LIDAR scanner mounted in a Piper Astec fixed-wing aircraft. Data were captured from an altitude of 500 m at 2 × 2 m spacings (OSI, 2009).

Aims of this Study

Coastal LIDAR data are collected by three separate agencies in Ireland. The different focus of each agency has resulted in different spatial coverages and relatively few overlaps. Each agency plans to extend its surveying in the future, which could potentially result in survey duplication. Successful integration of these data sets would enhance the utility of these data sets for research, planning, and management in the coastal zone and might reduce the requirement for multiple surveys in the future. The individual requirements of each of these agencies have led to differences in data capture methods, coordinate reference systems used, spatial resolutions favoured, and the level of postprocessing applied in each case. These issues can discourage data users from exploring the potential for data integration.

The primary aim of this paper is to explore the potential for the integration of LIDAR data captured for different purposes in the coastal zone. The integration potential of three LIDAR data sets is considered in three coastal areas where they overlap. Data integration is important for two principal reasons. First, the successful integration of ALB, topographic LIDAR DSM data, and bare earth topographic LIDAR DTM data may in many cases extend the availability of LIDAR data for coastal research. Second, successful data integration might minimise the requirement for survey duplication, helping to reduce survey costs.

METHODOLOGY

Site Selection

LIDAR is currently being collected by three agencies in Ireland. INFOMAR ALB data extend inland to the 10 m contour, OPW coastal LIDAR DSM data straddle the coastline (and extend into the littoral zone), and the OSI bare earth LIDAR DTM data focus explicitly on the terrestrial domain. INFOMAR (bathymetric) LIDAR data have now been captured for INFOMAR priority bays (Figure 1a) on the SW, W, NW, and N coastlines. The OPW LIDAR data set provides extensive coverage on the E and S coasts, and is now beginning to extend W as well (Figure 1b). OSI LIDAR to date include substantial coverage of urban areas in addition to extensive inland coverage (Figure 1c).

Integration Test Areas

Integration of the INFOMAR LIDAR data with the OPW and OSI LIDAR data sets necessitates the selection of locations where these LIDAR coverages overlap. Three locations were selected: Sligo Bay, Galway Bay, and Tralee Bay (Figure 2). The spatial overlap in these areas amounts to: Sligo 2 km^2, Galway 4.25 km^2, Tralee 3.75 km^2. Each site represents an independent case study of the potential for data integration. The combined results from all three test areas allow more general conclusions to be drawn.

Potential Barriers to Data Integration

Three potential barriers to integration are considered here. The first issue relates to the accuracy of each of the LIDAR data sets. The accuracy statistics that are provided by the data suppliers (Table 1) suggest that this is unlikely to be an issue. However, the elevation error statistics that are typically supplied with LIDAR data typically provide a global measure of error within a given percentile of the entire data set based upon ground truth in flat open areas (Flood, 2004). Therefore, local errors can be significantly larger than these global measures would suggest (Cobby, Mason, and Davenport, 2001; Palamara *et al.,* 2007; Rosso, Ustin, and Hastings, 2006).

The second question pertains to the degree to which datum transformation error might affect integration potential. Aerial LIDAR data are typically referenced against geograph-

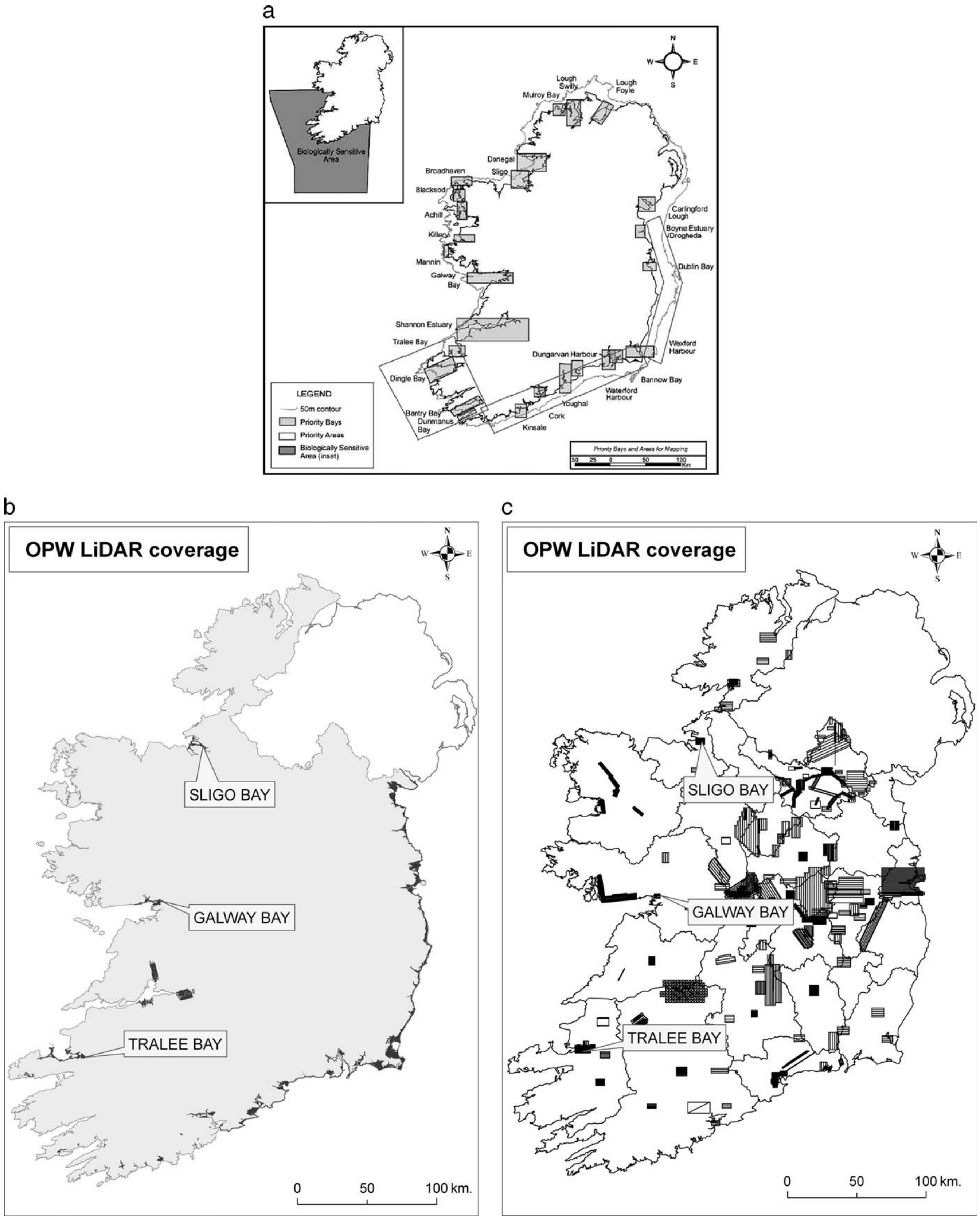

Figure 1. Overlap areas for (a) INFOMAR, (b) OPW, and (c) OSI LIDAR data sets.

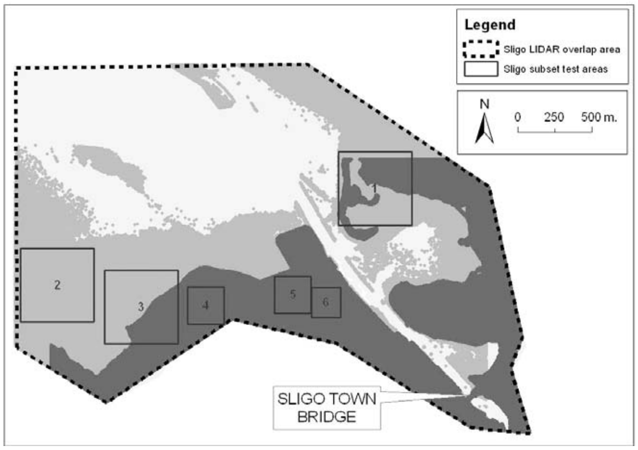

Figure 2. Subset areas selected for Sligo subset area LIDAR elevation comparative tests. Colour code for differentiation of data sets: dark grey (OSI), mid-grey (OPW), light grey (INFOMAR).

ic coordinates and ellipsoid. The INFOMAR and OPW data were supplied relative to ETRF89 (European variant of WGS84) coordinates and ellipsoid height. The OSI data were supplied relative to Irish map datum (Irish Transverse Mercator [ITM] Projection horizontal coordinates and Malin Head [Malin] vertical datum), so the possibility that some errors might have been introduced by the OSI datum converter during transformation had to be considered. The OSI datum converter was used to transform the other two data sets in order to standardise the transformation used.

The third potential barrier to integration relates to potential mismatches arising from water-column representation in the LIDAR acquired by topographic LIDAR survey. The OPW data were collected using topographic LIDAR survey, so we also examine the possibility that water-column presence in the OPW data caused a mismatch with the INFOMAR LIDAR bathymetry.

Validation of LIDAR Accuracy

Elevation error was externally validated in all three data sets in each of the three LIDAR overlap areas using high-accuracy FastStatic GPS ground validation data. Errors highlighted by validation can be expected to represent contributions from absolute LIDAR data error, coordinate/datum transformation error, and errors introduced during interpolation of the LIDAR point data.

Validation surveys were conducted in flat open paved areas in the onshore component of the LIDAR overlap areas in Sligo, Galway, and Tralee (presented in the Results section). It should be noted at this point that the assessment of integration potential focuses primarily on the problem of elevation error. Horizontal error is not generally a problem in published LIDAR data, but ground feature matching was carried out in each overlap area in order to verify this. The locations of a minimum of three spatially dispersed static components of the built environment (bridge features, road intersections, and corners of paved areas) were identified in each of the three study sites.

LIDAR accuracy statistics supplied with all three LIDAR data sets are outlined in Table 1. Each of these LIDAR data sets was externally validated in each of the three overlap test areas using postprocessed FastStatic GPS survey data in order to quantify gross elevation error (the sum of LIDAR data error, datum transformation error, and validation interpolation error) after LIDAR data integration.

External validation of all three LIDAR data sources was carried out for each overlap area using FastStatic dual-frequency GPS data collected specifically for this study. This provided certainty regarding the accuracy of the GPS data that were used to quantify LIDAR elevation error. Two additional integration tests were applied to provide additional reference results. These included subarea elevation comparison tests and cross-section elevation comparison tests.

RESULTS

As explained in the previous section, the LIDAR data were supplied in a variety of coordinate formats, but all were captured relative to ETRF89 geographic coordinates and ellipsoid. These were standardised to ITM/Malin for the integration tests. Spatial reference system standardisation, external validation of LIDAR elevation accuracy, comparison of LIDAR elevation accuracy, and visualisation checks were carried out for each site in turn.

The INFOMAR and OPW data were transformed to ITM/Malin using Grid Inquest, and the OPW bathymetric depth values were reclassified to positive floating point values to match with the depth classification used in the INFOMAR data. All standardised data were subsequently exported to a single Microsoft Access database. Source-specific ITM/Malin LIDAR data tables were externally validated with high-accuracy postprocessed FastStatic GPS survey data. The results of each validation were used to assess integration performance.

Test Area One: Sligo Bay

Sligo External Validation

Sixty GPS measurement points were collected over open paved areas. The 50 most accurate GPS points (*i.e.,* those that

Table 1. *Basic specifications of data sets used in this study, including quoted elevation error.*

Supplier	Horizontal Coordinates	Vertical Reference	Vertical Accuracy
OPW	ETRF89 & ITM	GRS80 Spheroid	±0.15 m
OSI	ITM metres	Malin metres	0.25 m
INFOMAR	ETRF89, LAT, ITM	GRS80 Malin metres	±0.28 m topo & bathy

Table 2. *Results of elevation validation of OSI, OPW, and INFOMAR LIDAR data for Sligo.*

	OSI Sligo	OPW Sligo	INFOMAR Sligo
Point count	50	50	50
90% elevation error (m)	±0.08	±0.39	±0.21
Max negative error (m)	−0.18	−0.48	−0.41
Max positive error (m)	0.20	1.17	0.37
Mean error (m)	−0.01	0.07	0.08
Standard deviation (m)	0.07	0.27	0.13

were not affected by overhanging vegetation or the proximity of walls and other features of the built environment) were used for validation. A Trimble R8 dual-frequency GPS receiver was used in FastStatic mode on 8 to 20 min residence times based on satellite availability. The maximum elevation error (relative to ellipsoid) highlighted by postprocessing among the best 50 GPS points used for external validation of the Sligo LIDAR data was 1 cm, confirming the suitability of the GPS data for the validation of LIDAR elevation error.

Validation was carried out in ArcGIS/ArcInfo using Geostatistical Analyst. Ordinary kriging continuous prediction surfaces were generated for the OSI, OPW, and INFOMAR LIDAR data in the Sligo overlap area. The difference between GPS elevation and LIDAR elevation values at each of 50 locations was assessed for each of the LIDAR data sets tested. Summary statistics for the OSI LIDAR DSM, the OPW LIDAR DEM, and the INFOMAR LIDAR DEM validations are outlined in Table 2.

The LIDAR elevation errors that were observed were close to the error statistics provided by the data suppliers. The distribution of elevation errors above and below 0 m Malin (highlighted by all mean errors coming very close to zero) confirmed that standardisation of all three LIDAR data sets to Malin datum (by the data suppliers in the case of the OSI data, and by the principal author in the case of the OPW and the INFOMAR data) was handled appropriately by Grid Inquest. Further tests were applied to confirm this, but external validation suggests that LIDAR integration worked satisfactorily in the case for Sligo.

Sligo Subset Area Elevation Comparison

Six subset areas were selected within the Sligo LIDAR overlap area (Figure 2) to determine if systematic differences could be detected among the INFOMAR bathymetric data, the OPW DSM data, and the OSI bare earth DTM data. Elevation statistics (particularly mean elevation values) were evaluated in the six overlap areas used for the comparative tests (Table 3). The primary purpose of this test was to determine if systematic elevation differences could be detected in wider areas than could be detected using the GPS points. The spatial dispersion of the subset areas also provided a mechanism for assessment of the spatial distribution of error.

Three 500 × 500 m and three 250 × 250 m subset areas were selected. The 500 × 500 m areas focused on the comparison of the OPW and the INFOMAR data in the littoral zone, but it included one comparison with OSI data also (Table 3). The 250 × 250 m subsets focused on comparison of all three data sets (Table 3). Large open areas were chosen to maximise the size of the comparison areas and to avoid the potential complicating influence of urban structures or forest cover during cross comparison. As noted previously, the OSI LIDAR data are made available as bare earth DTM data. However, the OPW and INFOMAR data were not processed to such a high degree, so urban and forested areas were avoided when selecting the comparison areas. Mean elevation statistics for each data set were compared in each subset area to see if any systematic elevation differences could be noted between the three LIDAR data sets tested.

Mean elevation values for each data set in each subset area were comfortably within the elevation accuracy ranges quoted by each data supplier. Only one comparison test failed the test (subset area 3) due to variations in LIDAR point sampling resolution within the INFOMAR data in this location. The onshore component of the INFOMAR DEM data in this subset area was approximately double the mean point sampling density offshore, biasing the mean elevation value toward the onshore elevation values. Therefore, the transformation of the OPW and INFOMAR LIDAR from ETRF80/GRS80 to ITM/Malin appeared to have caused no detectable problems.

Sligo Visual Verification Test

The three LIDAR data sets were integrated in Microsoft Access (which was used to handle the 1.5 gigabyte integrated file size in ArcGIS), and the integrated data were visualised in ArcGIS to provide an additional visual confirmation of integration performance. The results of this final visual confirmation test were positive (Figure 3). Clear definition of the coastline (A), demarcation of dockland warehousing (B), housing within Sligo town (C), the elevated coastal road north of Sligo town (D), the offshore channel bund (E), and Sligo bridge all suggest successful integration.

It should be noted that a critical component of successful integration of the offshore OPW and INFOMAR data in the

Table 3. *Comparison of mean elevation statistics in each of the six Sligo subset areas.*

Subset	Subset Size (m)	OPW Mean Elevation (m)	INFOMAR Mean Elevation (m)	OSI Mean Elevation (m)
1	500 × 500	2.2	2.22	*Incomplete overlap*
2	500 × 500	−0.33	−0.28	*Incomplete overlap*
3	500 × 500	−2.87	−4.73	*Incomplete overlap*
4	250 × 250	−11.84	−11.67	−11.84
5	250 × 250	−5.14	−5.35	−5.44
6	250 × 250	−3.67	−3.74	−3.71

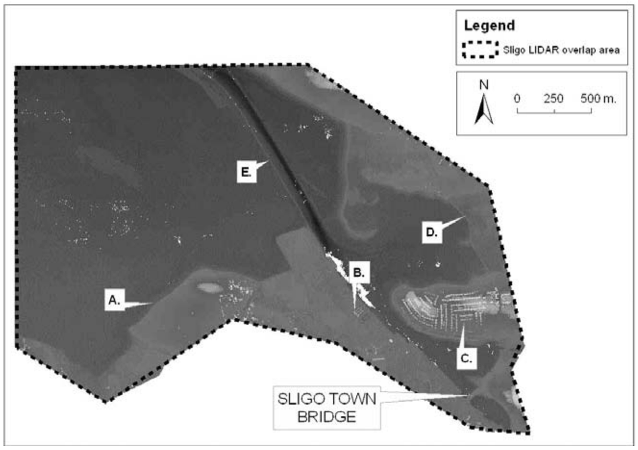

Figure 3. Visualisation of combined OSI, OPW, and INFOMAR LIDAR data for Sligo integrated onto ITM coordinates and Malin datum.

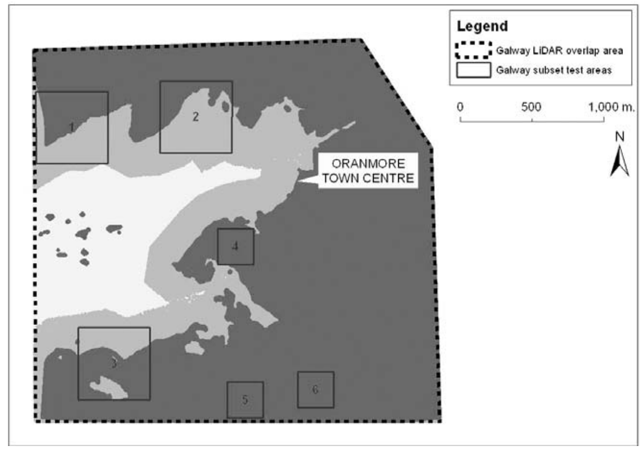

Figure 4. Subset areas selected for Galway subset area LIDAR elevation comparative tests. Colour code for differentiation of data sets: dark grey (OSI), mid-grey (OPW), light grey (INFOMAR).

Sligo LIDAR overlap area was the fact that OPW data were surveyed during conditions of low water. This was not the case for Galway and Tralee, where high-tide conditions introduced problems for integration offshore.

Test Area Two: Galway Bay

Galway Transformation

The same sources of LIDAR data were used in Galway as were used in Sligo, so the same transformation, data management, and external validation schemes were applied to the Galway LIDAR data.

Galway External Validation

Similar to Sligo, the best 50 GPS validation points were used. The maximum elevation error (relative to ellipsoid) highlighted by postprocessing among the 50 GPS points used for external validation was 1.5 cm. Once again, the GPS validation points were transformed to Malin datum format in Grid Inquest before validation was carried out in ArcGIS/ArcInfo using Geostatistical Analyst. Summary statistics for the OSI LIDAR DSM and the OPW and INFOMAR LIDAR DEM validations are outlined in Table 4.

Table 4. *Results of elevation validation of OPW, INFOMAR, and OSI LIDAR data for Galway.*

	OSI Galway	OPW Galway	INFOMAR Galway
Point count	50	50	50
90% elevation error (m)	±0.11	±0.14	±0.25
Max negative error (m)	−0.15	−1.06*	−0.51
Max positive error (m)	0.15	0.30	0.21
Mean error (m)	−0.02	−0.002	−0.12
Standard deviation (m)	0.07	0.19	0.19

* The maximum negative error highlighted in OPW data represents a single outlier.

The 90% error ranges, mean elevation statistics, and standard deviations of the elevation errors noted in all three LIDAR data sets indicate that no systematic differences existed between the three data sets, based on the use of onshore GPS points.

Galway Subset Area Elevation Comparison

Similar to the previous subset area tests, three 500 × 500 m and three 250 × 250 m subset areas were evaluated (Figure 4). The same selection criteria were applied as was the case for the Sligo test. Mean elevation values for each data set in each 250 × 250 m subset area were strikingly similar and were comfortably within the elevation accuracy ranges quoted by each data supplier. Subset area six (250 × 250 m) performed least well, though entirely satisfactorily, which may have reflected the small number of INFOMAR LIDAR points in this subset area (3123) in relation to the OSI data in subset area six (15,625) and the OPW data points in subset area six (99,114) (Table 5).

The INFOMAR bathymetric data and the OPW DSM data in the 500 × 500 m subset areas did not match up as well, however. Mean elevation differences of 1.29 m in subset area 1, 0.4 m in subset area 2, and 0.33 m were noted between the OPW and INFOMAR LIDAR elevation values in subset area 3. This could not be wholly attributed to the number of sample points in each case. Visual examination of the integrated LIDAR data set for Galway (Figure 5) indicated substantial differences between both data sets in terms of mean elevation offshore.

Galway Visual Verification

An integrated OSI, OPW, INFOMAR data coverage image was created in ArcGIS to provide visual confirmation of integration performance (Figure 5). The clarity with which relatively subtle features were highlighted in the integrated

Table 5. *Comparison of mean elevation statistics in the six Galway subset areas.*

Subset	Subset Size (m)	OPW Elevation (m)	INFOMAR Mean Elevation (m)	OSI Mean Elevation (m)
1	500 × 500	−5.54	−4.25	*Incomplete overlap*
2	500 × 500	−1.43	−1.03	*Incomplete overlap*
3	500 × 500	−2.89	−2.56	*Incomplete overlap*
4	250 × 250	−3.05	−3.07	−3.12
5	250 × 250	−5.98	−5.98	−5.87
6	250 × 250	−17.27	−17.68	−17.25

data set indicates successful integration onshore. An eroded sea-defence wall (A), the regional road between Oranmore and Galway (B and C), and Oranmore Bridge (D) are all clearly defined. These features were identifiable in all three LIDAR data sets. Their clear delineation in the integrated dataset suggests successful transformation of the OPW and INFOMAR data from geographic ETRF89/GRS80 format to ITM/Malin format. However, the offshore elevation mismatches (E) that were noted in the subset area tests are clearly evident in Figure 5. The mismatch suggests a uniform water surface in the OPW data.

Galway Offshore Comparison

Six cross-sections were applied to the offshore OPW and INFOMAR data. The relationship of the six cross-sections to the Galway LIDAR data is provided in Figure 6. Cross-sections were aligned to northings or eastings to provide spatial ordering for cross comparison of the OPW and INFOMAR plots (Figure 7).

The OPW and INFOMAR LIDAR points falling within 1 m of each cross-section were plotted (Figure 7) to assess whether sea-surface LIDAR returns were present in the data.

The elevation values in the littoral component of the OPW DSM data corresponded closely with 0 m elevation in all cases. Variation around zero was noted in cross-sections three and four (possibly due to the presence of swell in this area during data acquisition). However, in general, the OPW LIDAR returns corresponded so closely with a consistent (and relatively even) surface that it appeared to be coincident with the top of the water column. Therefore, it seems that the littoral zone topographic LIDAR DSM data would only be suitable for integration with the ALB data if the topographic LIDAR surveys have been conducted at low water. This appears to have been the case for the Sligo OPW LIDAR data.

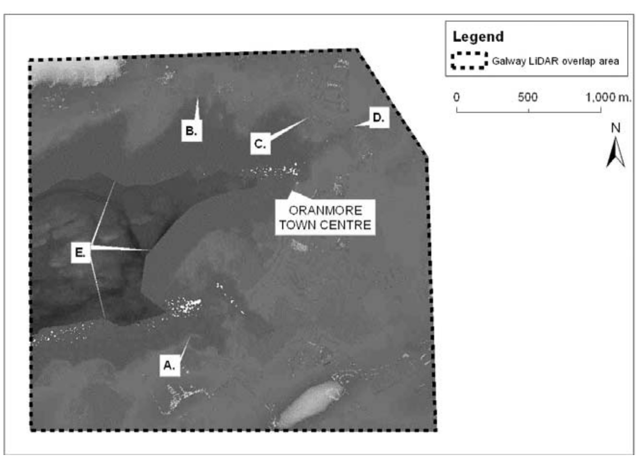

Figure 5. Visualisation of combined OSI, OPW, and INFOMAR LIDAR data for Galway integrated onto ITM coordinates and Malin datum.

Test Area Three: Tralee Bay

The OSI data for Tralee were supplied in ITM/Malin format, but the OPW data for Tralee were supplied referenced to ETRF89/GRS80. The OPW data were transformed to ITM/Malin Cartesian *x-y-z* coordinates using Grid Inquest. The INFOMAR LIDAR data for the Tralee LIDAR overlap area were transformed from ETRF89/Malin to ITM Malin in Grid Inquest. All standardised data were subsequently combined in a single Microsoft Access database. The source-specific ITM/Malin LIDAR data tables were externally validated with high-accuracy postprocessed FastStatic GPS survey data and were compared against one another.

Tralee External Validation

The transformation scheme that was applied in Sligo and Galway was applied to the data in the Tralee LIDAR overlap area prior to external validation. Summary statistics for the elevation errors highlighted by external validation with GPS are outlined in Table 6.

Figure 6. Cross-sections used to assess offshore elevation values in OPW data (displayed in relation to Galway LIDAR coverages). Differentiation of data sets: dark grey (OSI), mid-grey (OPW), light grey (INFOMAR).

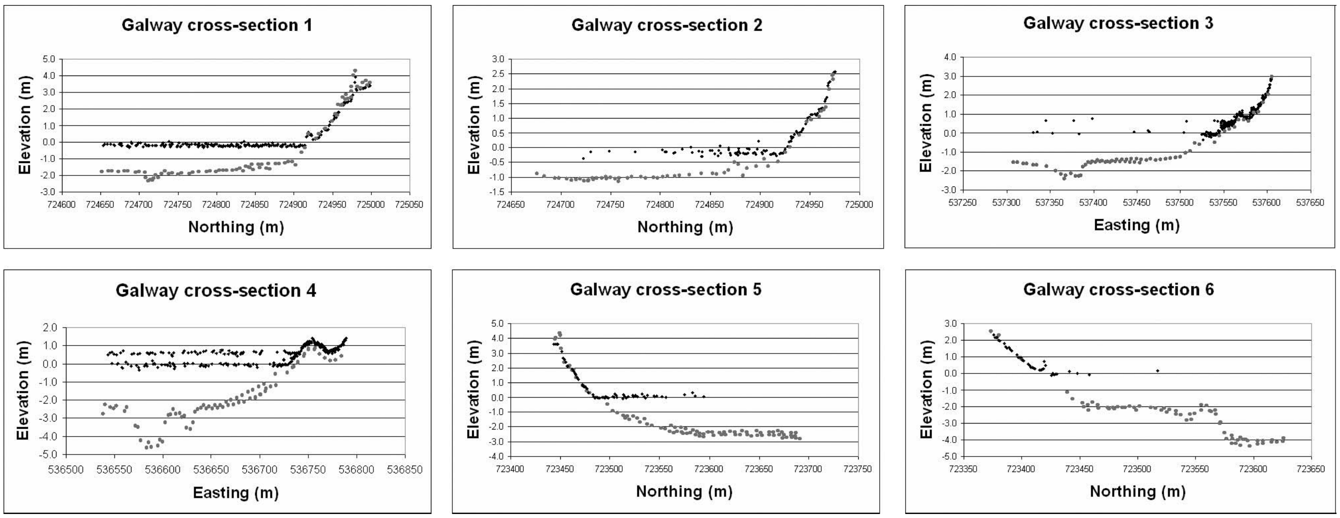

Figure 7. Cross-section comparison of OPW (grey trace) and INFOMAR data (black trace) for Galway (both data sets referenced to Malin Head vertical datum).

Tralee Subset Area Elevation Comparison

Six subset areas were assessed within the Tralee LIDAR overlap area (Figure 8) to determine if any systematic differences could be detected between the three LIDAR data sets tested. Elevation statistics (mean elevation) were evaluated in the six overlap areas used for the comparative tests (Table 7). Similar to the previous subset area tests, three 500 × 500 m and three 250 × 250 m subset areas were selected.

The 500 × 500 m areas focused mainly on the comparison of the OPW and the INFOMAR data in the littoral zone, but subset two did allow comparison of mean elevation values in all three LIDAR data sets (Table 7). The 250 × 250 m subsets focused on comparison of all three data sets (Table 7) onshore. Comparison areas were again selected on the basis of avoiding urban structures or forest cover. Mean elevation values in the 500 × 500 m areas were very similar, and mean elevation values for each data set in each 250 × 250 m subset area were again very similar (Table 7). Visual assessment and cross-sectional elevation statistics were examined to determine if water-surface returns were present in the topographic LIDAR DSM data.

Table 6. *Results of elevation validation of OSI, OPW, and INFOMAR LIDAR data for Tralee.*

	OSI Tralee	OPW Tralee	INFOMAR Tralee
Point count	50	50	50
90% elevation error (m)	±0.38	±0.13	±0.35
Max negative error (m)	−0.51	−0.30	−0.47
Max positive error (m)	0.64	0.27	0.54
Mean error (m)	0.11	−0.01	−0.03
Standard deviation (m)	0.20	0.09	0.26

Tralee Visual Verification

The integrated LIDAR data were rendered in ArcGIS to provide an additional visual comparison (Figure 9). Dendritic drainage patterns (A and B), the canal bunds in Blennerville (C), the definition of the coastline (D), and Blennerville bridge were all clearly defined, confirming that no significant problems resulted from the transformation of OPW and INFOMAR data from ETRF89 ellipsoid to Malin datum. However, elevation mismatches that were not evident in the subset area tests were clearly evident (E) in Figure 9. The appearance of the mismatch areas again suggests a uniform surface coincident with a water surface in the OPW topographic DSM data.

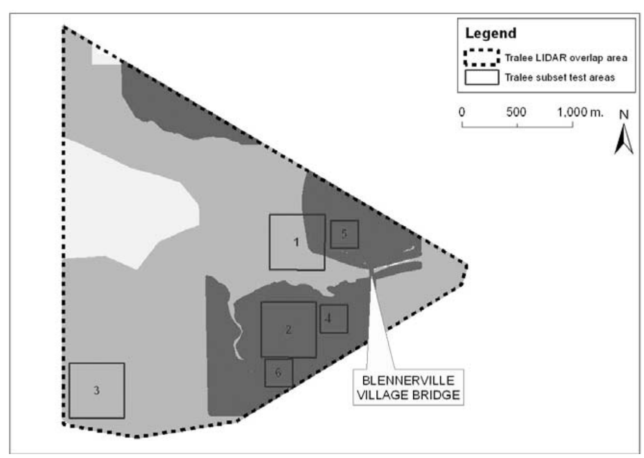

Figure 8. Subset areas selected for Tralee subset area LIDAR elevation comparative tests. Colour code for differentiation of data sets: dark grey (OSI), mid-grey (OPW), light grey (INFOMAR).

Table 7. *Comparison of mean ellipsoidal height statistics in each of the six Tralee subset areas.*

Subset	Subset Statistic	OPW	INFOMAR	OSI
1	Point count	258,070	12,229	Insufficient overlap for valid analysis
	Mean (m)	−2.43	−2.22	
	Std. dev. (m)	1.85	1.51	
2	Point count	454,782	10,694	249,170
	Mean (m)	−7.20	−6.96	−6.94
	Std. dev. (m)	1.29	1.27	1.20
3	Point count	429,172	10,096	No overlap with other LIDAR data sets
	Mean (m)	−5.87	−5.75	
	Std. dev. (m)	3.44	3.41	
4	Point count	130,081	2541	61,064
	Mean (m)	−3.01	−2.89	−2.86
	Std. dev. (m)	1.38	1.37	1.24
5	Point count	64,563	3821	62,786
	Mean (m)	−3.73	−3.49	−3.50
	Std. dev. (m)	0.79	0.88	0.76
6	Point count	108,811	2661	62,750
	Mean (m)	−5.68	−5.44	−5.51
	Std. dev. (m)	0.62	0.63	0.50

Tralee Offshore Comparison

Six cross-sections were applied to the offshore bathymetric data and topographic DSM data for the Tralee LIDAR overlap area (Figure 10). Similar to the case observed in Galway Bay, the OPW data closely correspond with 0 m elevation along all six cross-sections.

There is slight evidence of laser return variation in cross-sections three and four (Figure 11), but in general, the OPW LIDAR returns corresponding with a surface appear to have been coincident with the top of the water column (Figure 11).

DISCUSSION

The availability of aerial LIDAR surveys is expanding, and the use of these data is also increasing in coastal research. However, since LIDAR data are usually collected to meet the specific requirements of the agencies that conduct the surveys, data are often characterised by limited spatial coverage and unique data structures that can limit their integration potential. The primary focus of this paper is to assess the potential for different classes of coastal LIDAR data to be integrated for combined use in coastal research. Three LIDAR data sets were considered. These include: (1) an ALB data set that contains an onshore component, (2) a topographic LIDAR DSM that includes a littoral zone component, and (3) a bare earth onshore topographic LIDAR DEM. The ALB data were captured in a small number of coastal bays for a marine mapping project. The topographic DSM data were collected along erosion-prone coasts for the purpose of coastal management. Bare earth DEM data focused upon coastal and noncoastal urban areas mapped by a national mapping agency. All three data sets were initially referenced against slightly different mapping standards. In

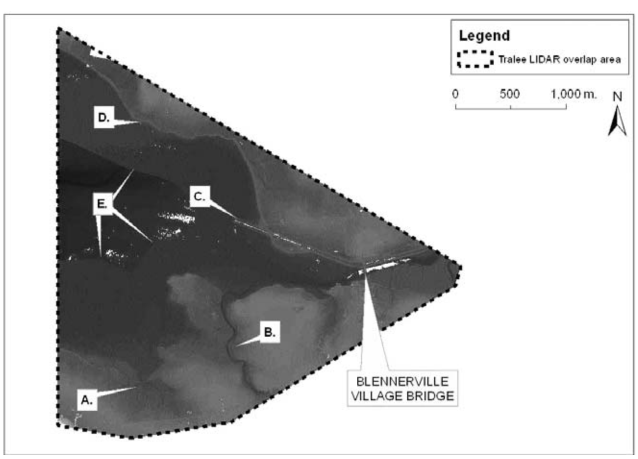

Figure 9. Visualisation of combined OSI, OPW, and INFOMAR LIDAR data for Tralee integrated onto ITM coordinates and Malin datum.

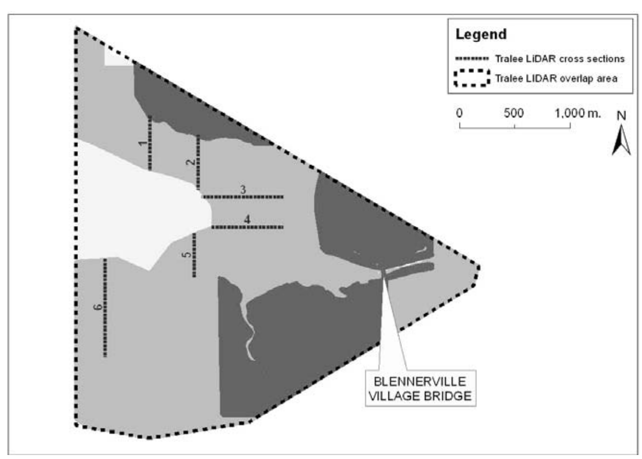

Figure 10. Cross-sections used to assess offshore elevation values in OPW data (displayed in relation to Tralee LIDAR coverages). Differentiation of data sets: dark grey (OSI), mid-grey (OPW), light grey (INFOMAR).

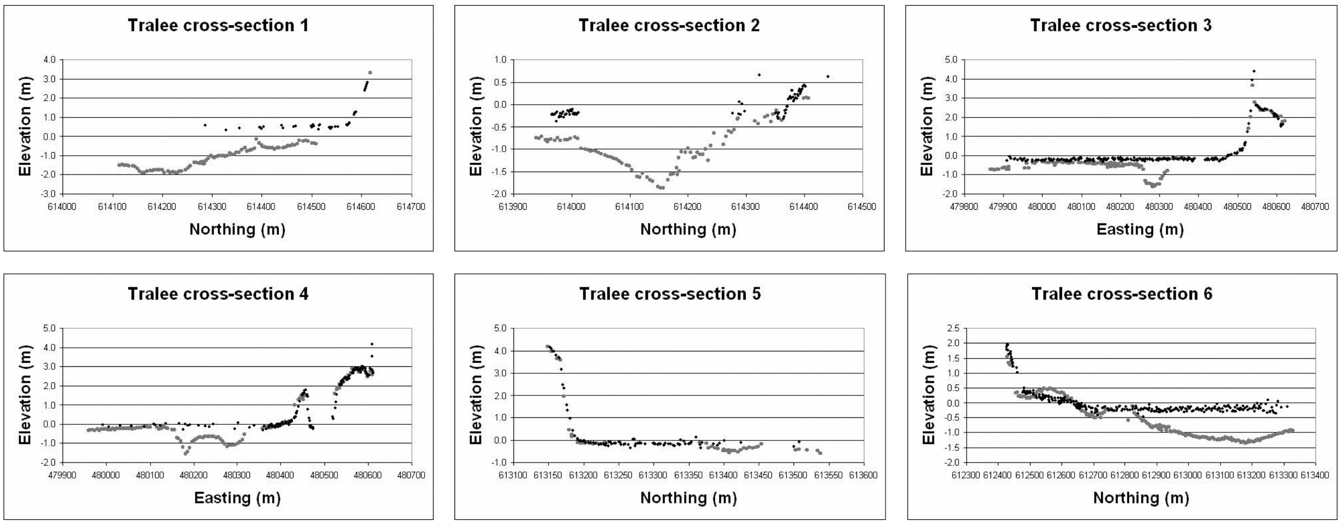

Figure 11. Cross-section comparison of OPW (grey trace) and INFOMAR data (black trace) for Tralee (both data sets referenced to Malin Head vertical datum).

order to be integrated, the data sets were standardised to Irish Transverse Mercator (ITM) Projection horizontal coordinates and Malin Head (Malin) vertical datum using the same transformation software algorithm.

The potential for these data sets to be integrated was evaluated in three separate test areas where the three LIDAR data sets overlapped spatially. Methods applied included external validation of LIDAR error using custom FastStatic GPS surveys, area-based and cross-sectional comparison of elevation values, and assessment of the reliability of datum standardisation methods. Validation of elevation error was carried out according to the ASPRS Guidelines for Vertical Accuracy Reporting for LIDAR (Flood, 2004) to ensure that adequate numbers of accurate validation data points were used.

Validation was carried out in ArcInfo Geostatistical Analyst, using FastStatic GPS data to validate elevation error in kriged elevation surfaces derived from the high-resolution LIDAR points. Elevation errors highlighted in flat open paved areas were close to the error ranges outlined by data suppliers. Ninetieth percentile elevation errors in the bathymetric data were within the quoted ($\pm$0.28 m) range in two of the three test sites, and a 90% error range of $\pm$0.35 m was observed in one test site. Similar outcomes were noted for the other two LIDAR data sets. Ninetieth percentile elevation errors in the topographic LIDAR DSM data were within the quoted ($\pm$0.15 m) range in two of the three test sites, and a 90% error range of $\pm$0.39 m was noted in one test site. Ninetieth percentile elevation errors in the bare earth topographic DEM data were within the quoted ($\pm$0.125 m) range in two of the three test sites, and a 90% error range of $\pm$0.38 m was observed in one test site. These results suggest that onshore data integration could be accomplished in all three test sites. However, it should be noted that elevation errors were measured by reference to flat open paved areas that could be readily identified in each data set. Elevation errors in densely vegetated sections of LIDAR DSM data would typically be expected to be larger than in bare earth DSM data. Therefore, further data processing is necessary to bring an integrated LIDAR data set derived from mixed sources up to bare earth DEM standard.

Subset area comparison tests were applied to determine if systematic elevation differences could be detected over larger mixed land-cover areas than was possible with the GPS validation data. Mean elevation values within common subset areas in each data set were used to search for systematic elevation differences between all three data sets. Mean values in each of the subset areas onshore were similar, further confirming the integration potential of the data sets evaluated in all three test sites. Horizontal accuracy was checked by assessing the relative horizontal positioning of a minimum of three static angular features of the built environment that were detectable in each LIDAR data set. No horizontal errors were observed or detected onshore in any of the three test areas.

Subset area comparison tests were also carried out in the littoral zone. Topographic LIDAR collected by the national mapping agency (OSI) does not extend into the littoral zone. As such, an assessment of the potential for integration in the littoral zone was limited to the INFOMAR bathymetric data and the OPW topographic data only. Mean elevation values in the littoral zone subset comparison areas were very similar in the case of the Sligo test area, while marked differences were noted in the Galway and Tralee test areas. Visualisation of the integrated OPW/INFOMAR data for all three test sites suggested that water-surface returns were the likely cause of the systematic elevation differences noted in the Galway and Tralee areas. For the Sligo littoral zone, topographic data had been captured at low tide. Cross-sections were drawn from offshore to onshore to assess the problems noted in the Galway and Tralee integration visualisations. Comparison of these onshore to offshore cross-sections confirmed that these mismatches were due to the presence of water-surface returns in the topographic OPW LIDAR DSM data.

CONCLUSIONS

Confirmation of the potential for DTM integration onshore suggests that duplication of LIDAR surveys by the three main agencies capturing LIDAR in Ireland may be minimised in the future, possibly freeing up resources to extend LIDAR data coverage more quickly than would otherwise be affordable. The successful onshore integration of the three data sets evaluated also provides a platform for the wider use of integrated LIDAR data sets in planning and research in Ireland, while increasing awareness of the potential for onshore LIDAR integration elsewhere.

When conducting LIDAR surveys in the littoral zone, the results suggest that careful scheduling of surveys is critical. The potential for littoral zone integration that was noted in the Sligo test case suggests that full integration would be viable if topographic DSM data were to be collected at low water. Scheduling topographic surveys to coincide with low water might therefore offer opportunities to reduce future bathymetric survey requirements in areas where topographic DSM data have been captured at low water. However, the potential for existing littoral zone topographic LIDAR data to be used to reduce planned bathymetric surveys would be limited to situations where topographic littoral zone data have been captured at low tide. Recognition of the value of simultaneous acquisition of topographic and ALB will greatly enhance the potential for data integration in the future.

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