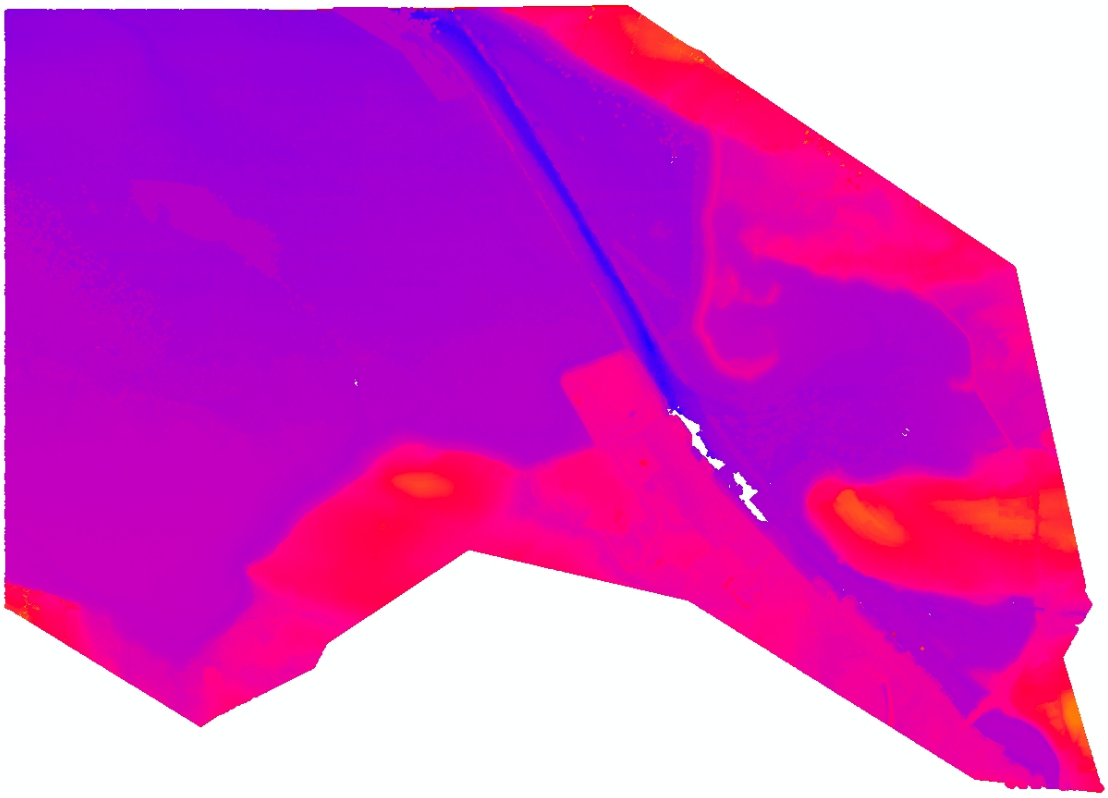
Integration of INFOMAR Bathymetric LiDAR with external onshore LiDAR datasets



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Executive Summary

This study was carried out by the National Centre for Geocomputation at NUI Maynooth. The NCG is a resource for those interested in any aspect of the capture, storage, integration, management, retrieval, display, analysis or modelling of spatial data. Research at the NCG is diverse, but much of its work focuses on Algorithm development, Geosensor integration, Geovisualisation and Location Based Services. Research under the Geosensors banner includes LiDAR research, which includes LiDAR acquisition, processing and error quantification.

The primary aim of this study is to test onshore-to-offshore and offshore-to-onshore integration potential between INFOMAR bathymetric LiDAR data and onshore aerial LiDAR supplied by the Office of Public Works and Ordnance Survey Ireland. Three potential barriers to integration are examined and quantified (namely absolute LiDAR error, datum transformation error, and water-column segregation issues). Investigations focus on the potential for LiDAR integration in:

- Sligo bay
- Oranmore bay (within Galway bay)
- Blennerville bay (within Tralee bay)

Successful LiDAR integration is achieved between all three aerial LIDAR datasets in each of three LiDAR overlap areas in both the onshore-to-offshore and the offshore-to-onshore integration tests. LiDAR elevation errors highlighted by external validation with post-processed FastStatic GPS were all within the ranges outlined by data suppliers. Close parity of the error ranges detected in the three candidate integration datasets also suggested that no systematic errors were introduced during any of the datum transformations applied for the onshore-to-offshore or the offshore-to-onshore integration tests.

Subset area comparison tests applied in the Sligo, Galway and Tralee LiDAR overlap areas further confirmed that no systematic differences were evident between the three LiDAR datasets tested in the onshore-to-offshore and the offshore-to-onshore integration tests. The combination of the validation results and the subset area comparison tests indicated that integration from onshore-to-offshore and from offshore-to-onshore integration were not subject to any substantial difficulties.

Offshore elevation mismatches were noted between the OPW and the INFOMAR LiDAR data in within the Galway and Tralee LiDAR overlap areas. These mismatches appear to have been due to the presence of water-surface returns in the OPW topographic LiDAR survey data. Offshore elevation mismatches were not noted in the Sligo test area, suggesting that full integration is possible in the Littoral zone if the OPW topographic data have been captured at low water.

These results suggest that there may be potential opportunities to reduce future INFOMAR bathymetric surveys in areas where OPW data have been captured at low water. It is even more likely however that existing INFOMAR data may have potential re-use value to other agencies or individuals that are interested in aerial LiDAR mapping in the Irish coastal zone. The representation of the offshore sub-surface in the INFOMAR data, and the relative ease with which it can be integrated with onshore LiDAR suggests that it offers additional potential outside of its defined use within INFOMAR. Furthermore, the accuracies that were highlighted within the onshore component of the INFOMAR bathymetric LiDAR suggest that DSM-processed onshore INFOMAR bathymetric LiDAR data may offer scope for integration with onshore mapping-grade LiDAR in rural areas. The INFOMAR data also undoubtedly presents valuable opportunities for geospatial research in Ireland.

1 Introduction

1.1 Background

The National Centre for Geocomputation at NUI Maynooth were commissioned by INFOMAR in November 2008 to evaluate the potential for the integration of INFOMAR bathymetric aerial LiDAR (Light Detection and Ranging) data with existing onshore aerial LiDAR data from external data providers. INFOMAR bathymetric aerial LiDAR is already available for a number of the INFOMAR priority bays. Three of these bays provide spatial overlaps with onshore 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 integration, and to identify any barriers to integration in three separate test locations.

The following LiDAR overlap areas were examined:

- Sligo Bay – specifically Sligo harbour, which is located within Sligo Bay (figure 2.4).
- Galway bay – specifically Oranmore Bay, which is located within Galway bay and lies approximately 10km east of Galway city (figure 2.5).
- Tralee bay – specifically the environs of Blennerville located approximately 3km west of Tralee town in county Kerry (figure 2.6).

1.2 Light Detection and Ranging

Light Detection and Ranging (LiDAR) uses laser pulse emissions and returns to measure the distance between a LiDAR platform and a backscatter source. LiDAR pulse systems use short-wavelength electromagnetic radiation (generally visible spectrum, but near-infrared and ultraviolet are sometimes used also) to capture high-resolution x,y,z point-cloud data of the ground or seabed surface (and the objects that reside on this surface). LiDAR ranging uses distance over time calculations to determine the range between the LiDAR platform and reflectance sources on the surface. These range data are referenced against sensor platform position, which is established using a combination of Global Navigation Satellite Systems (GNSS) and

Inertial Navigation Systems (INS) data. Data issuing from these systems are generally referenced against geographic coordinates and ellipsoid height in as x,y,z Digital Elevation Model (DSM) data or as processed Digital Surface Model (DSM) data. Topographic (i.e. onshore) LiDAR survey systems generally use a single laser source operating in the visible range of the electromagnetic spectrum. Bathymetric LiDAR acquisition systems (see section 1.3) use infrared and visible light to (respectively) identify the top and the bottom of a water column. LiDAR DSMs (whether derived from topographic of bathymetric surveys) are produced by processing the raw LiDAR data by reference to first and last reflectance returns (Lim *et al.,* 2003, Hall *et al.,* 2005) or by reference to the waveform of the laser returns (Nayegandhi et al., 2006, Wagner et al., 2008). DSM data are generally provided as a regular grid of x,y,z points. LiDAR DEMs will more often be provided as raw x,y,z points which are not statistically filtered or regularised onto an x,y,z point framework.

1.3 INFOMAR LiDAR

INFOMAR uses a variety of acoustic, seismic and optical methods to capture bathymetric data. Acoustic methods are favoured for deeper water, and bathymetric LiDAR is used (in addition to shallow-water acoustic surveys) in waters shallower than about 15metres. Water column turbidity places a limit on the effective penetrative depth for bathymetric LiDAR, so it is better suited to coastal areas where turbidity is not a significant issue. Generally speaking, the west coast is characterised by clearer water than the east, so INFOMAR bathymetric surveys have to date focused on INFOMAR priority bays (figure 2.1) on the west coast.

Bathymetric LiDAR operates in a slightly different way to terrestrial LiDAR surveying. The principal difference between topographic and bathymetric LiDAR acquisition systems is the use of a single wavelength laser for terrestrial and two laser wavelengths for bathymetric surveying. Bathymetric LiDAR uses infrared to define the top of the water column and a green laser to penetrate the water column. Bathymetric LiDAR also uses slower laser pulse rate intervals than topographic LIDAR surveys in order to accommodate longer / higher energy laser pulses to penetrate the water column (Source: Fugro-Pelagos. http://www.fugro-pelagos.com/lidar/tech/lidar_bathy.html).

1.4 The National Centre for Geocomputation

This study was carried out by Dr. Seamus Coveney at the National Centre for Geocomputation (NCG) at NUI Maynooth. Research at the NCG is diverse, but much of its work focuses on Algorithm development, Geosensor integration, Geovisualisation and Location Based Services. Research under the Geosensors banner includes LiDAR research, which includes LiDAR acquisition, processing and error quantification.

1.5 Aims of this study

INFOMAR has invested significant energy, expense and time in capturing high quality bathymetric data around the Irish coast. These data extend inland up to the 10-metre contour in order to overlap with onshore topographic datasets. External agencies have been capturing aerial topographical LiDAR for the purpose of mapping the terrestrial component of the coastal zone. These coverages are quite extensive. OPW coastal LiDAR now covers large portions of the east and south coasts, and smaller sections of the west coast have been surveyed also (figure 2.2). Critically, the OPW data is characterised by some overlap into the Littoral zone, so the successful integration of the INFOMAR and OPW LiDAR offers opportunities for INFOMAR to potentially reduce some of its requirements for bathymetric LIDAR surveying in the future. However, this depends on a number of issues (tidal conditions and LiDAR penetration of the water column). These questions are examined in detail in section 4. Integration of offshore and onshore LiDAR may also be of interest to OPW. The onshore component of INFOMAR bathymetric surveys might potentially meet some of its requirements for future onshore coastal flood risk assessment. The use of INFOMAR data onshore is likely to be more straightforward. However, since the INFOMAR, OPW and OSi datasets are surveyed relative to different horizontal and vertical reference systems, and since transformation between these is subject to the introduction of error from a number of sources (see section X.X) the efficiency with which these datasets can be integrated has yet to be comprehensively tested. The potential for integration of INFOMAR LiDAR with all the other LiDAR datasets that are available for Ireland is the primary aim of this research project.

Ordnance Survey Ireland high-accuracy onshore LiDAR DSM data are available for coastal and non-coastal urban areas and large non-urban areas inland (figure 2.3). The OSi data do not extend into the Littoral zone, but the data are processed to a very high degree of accuracy, so they are primarily used in this study as an accuracy reference dataset (in conjunction with extensive accuracy validation surveys carried out for this project). However, the scope for integration for integration with OSi LiDAR is also assessed. The OSi LiDAR data are included in the onshore-to-offshore data integration tests, and to evaluate the potential for the INFOMAR and OPW LiDAR data to be integrated with the highest-accuracy onshore LiDAR that are available for Ireland. The onshore-to-offshore integration is introduced before the offshore-to-onshore in this report. However, this is done purely for readability purposes. The assessment of LiDAR accuracy was conducted in hard-standing and paved areas onshore, so the issue of onshore-to-offshore integration is dealt with first.

The primary aims of this study are:

- To perform an onshore-to-offshore integration in a terrestrial coordinate and datum framework and an offshore-to-onshore integration in a geographic coordinate / ellipsoid framework in order to determine the potential for the INFOMAR bathymetric LiDAR data to be used in conjunction with existing high-accuracy mapping-grade terrestrial LiDAR.
- To assess the degree to which absolute LiDAR error, datum transformation error, and water-column segregation constitute barriers to integration.
- To generate integrated LIDAR datasets referenced against ITM coordinates / Malin datum and ETRF89 / GRS80 ellipsoid frameworks.

2 Site selection

2.1 Irish LiDAR coverage

As outlined in section one, aerial LiDAR is currently being captured by three agencies in Ireland. INFOMAR bathymetric LiDAR extends inland to the 10-metre contour, OPW coastal LiDAR straddles the coastline (and extends into the Littoral zone) and the OSi data focuses explicitly on the terrestrial domain. INFOMAR (bathymetric) LiDAR data have now been captured for INFOMAR priority bays (figure 2.1) on the southwest, west, northwest and north coastlines. The OPW LiDAR dataset provides extensive coverage on the east and south coasts, and is now beginning to extend west also (figure 2.2). OSi LiDAR to date includes substantial coverage of urban areas in addition to extensive inland coverage (figure 2.3).

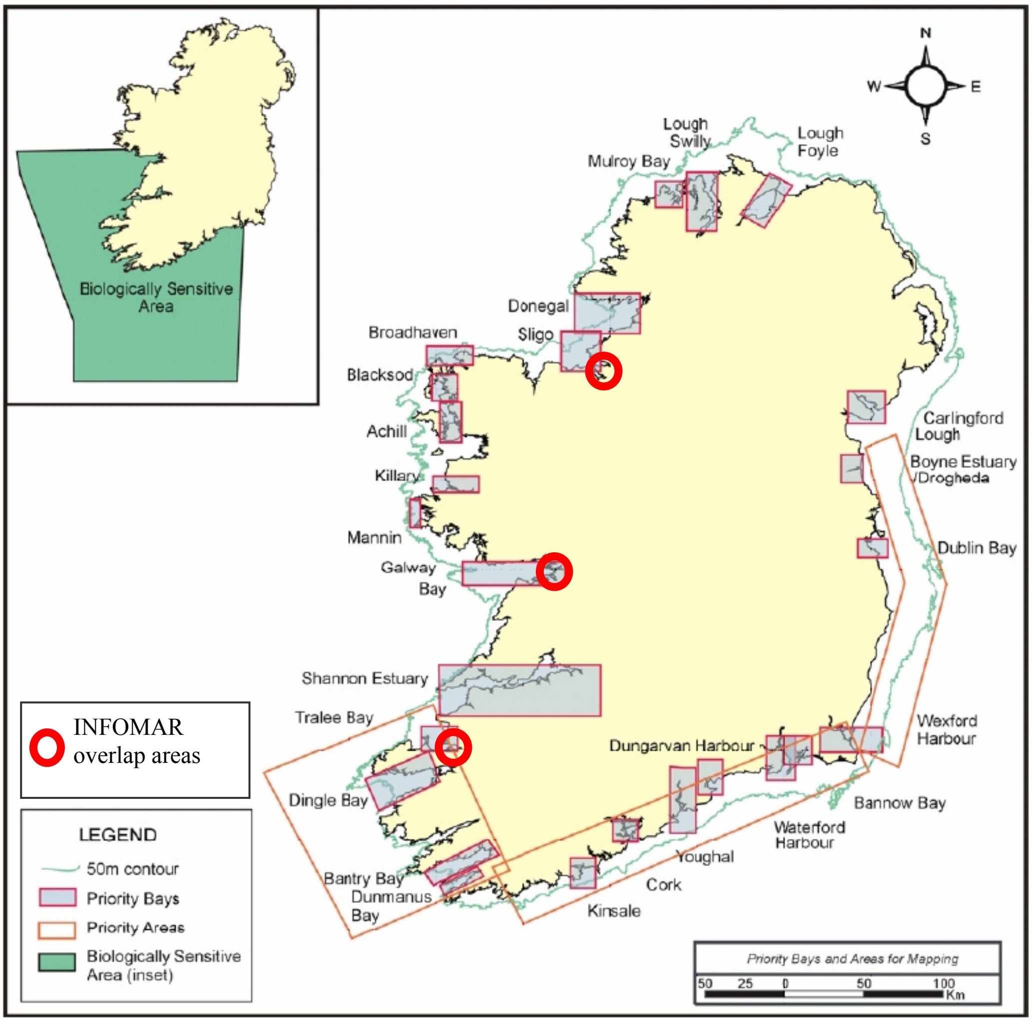


Figure 2.1: INFOMAR Priority Bays, Priority Areas and Biologically Sensitive Area. INFOMAR LiDAR overlap areas are highlighted with red circle symbols. *Map Source: Fergal McGrath, INFOMAR.*

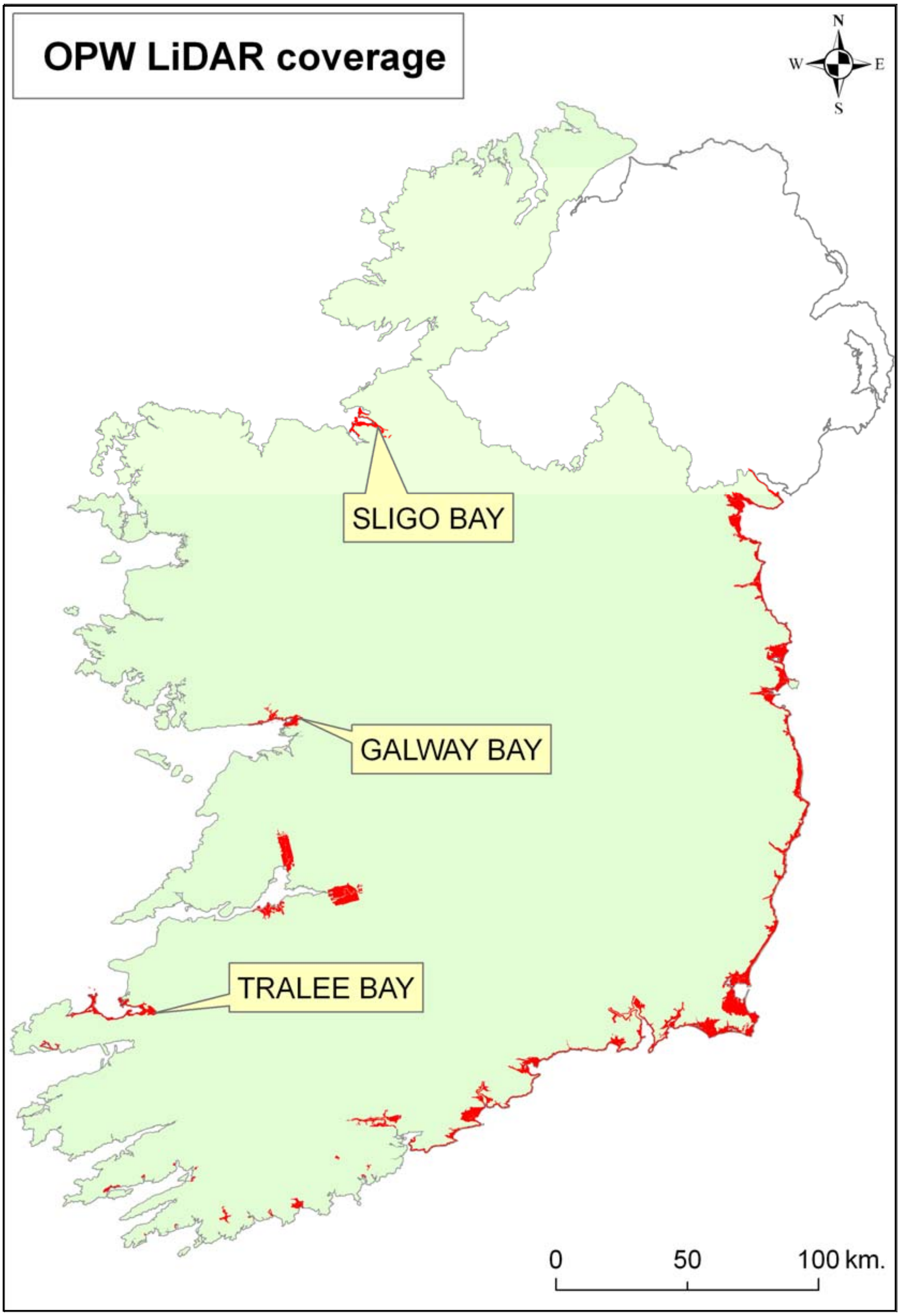


Figure 2.2: OPW LiDAR data flown (up to summer 2009), highlighting the availability of LiDAR for the west coast from which the chosen overlap areas (Tralee Bay, Galway Bay and Sligo Bay) were selected. *Data Source: Jim Casey OPW (LiDAR coverage areas) and OSi (background mapping).*

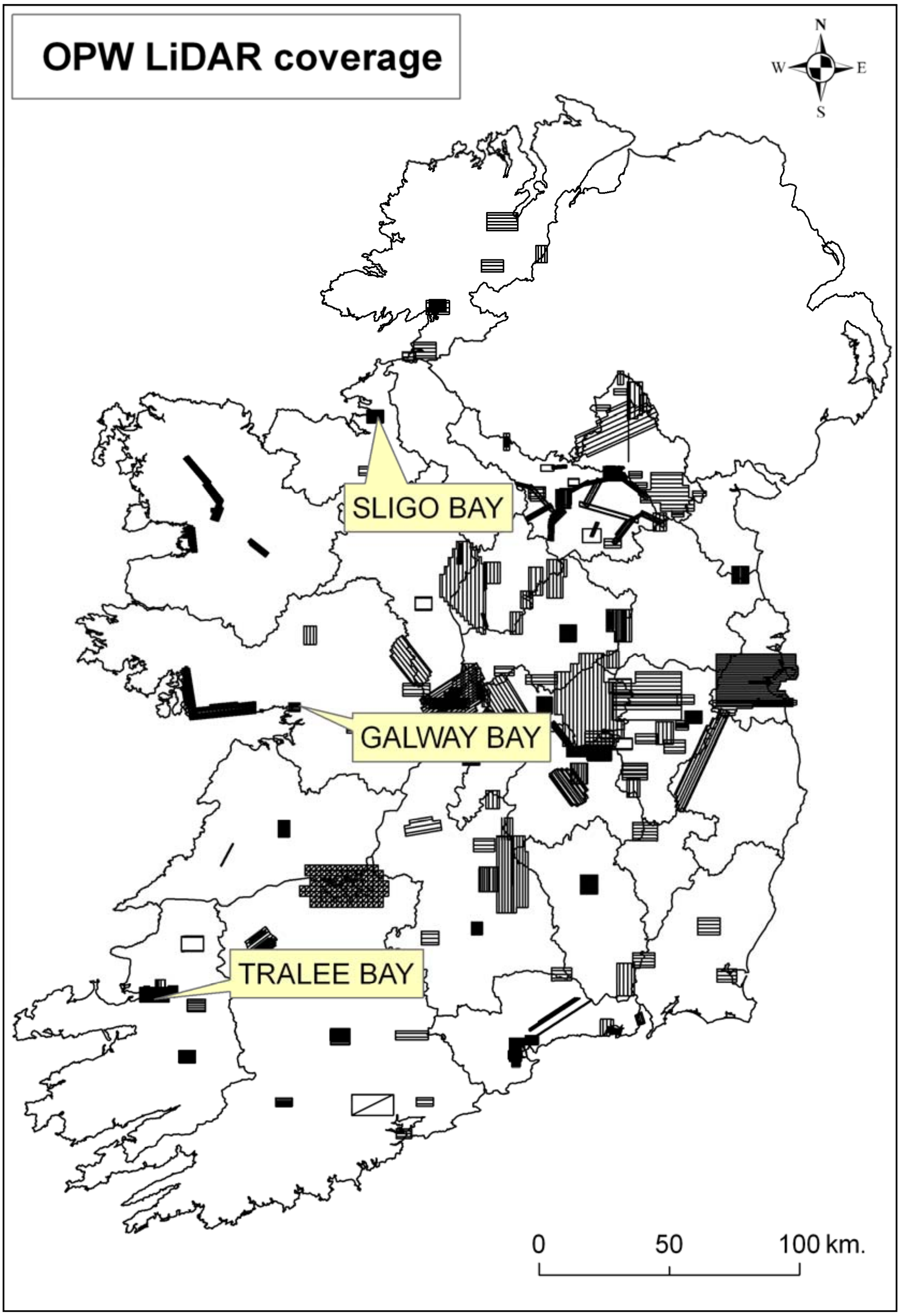


Figure 2.3: OSi LiDAR data flown (up to summer 2009), highlighting the availability of LiDAR for the west coast from which the chosen overlap areas (Tralee Bay, Galway Bay and Sligo Bay) were selected. *Data Source: Stephen Curran Ordnance Survey Ireland.*

2.2 Potential overlap integration test areas

Integration of the INFOMAR LiDAR data with the OPW and OSi LiDAR datasets necessitated the selection of locations where these LiDAR coverages overlapped spatially. It was possible to select three overlap areas on the west coast. These locations were: Sligo bay (figure 2.4), Galway bay (figure 2.5) and Tralee bay (figure 2.6). The spatial overlap in these areas amounted to:

- Sligo – c. 200 Ha.
- Galway – c. 425 Ha.
- Tralee – c. 375 Ha.

The geographical spread of the overlap areas offers an important additional advantage. The Kerry, Galway and Sligo overlap sites are well distributed along the west coast. Therefore, each site represents an independent case study of the performance of the integration methods presented, providing validation regarding their potential applicability elsewhere.

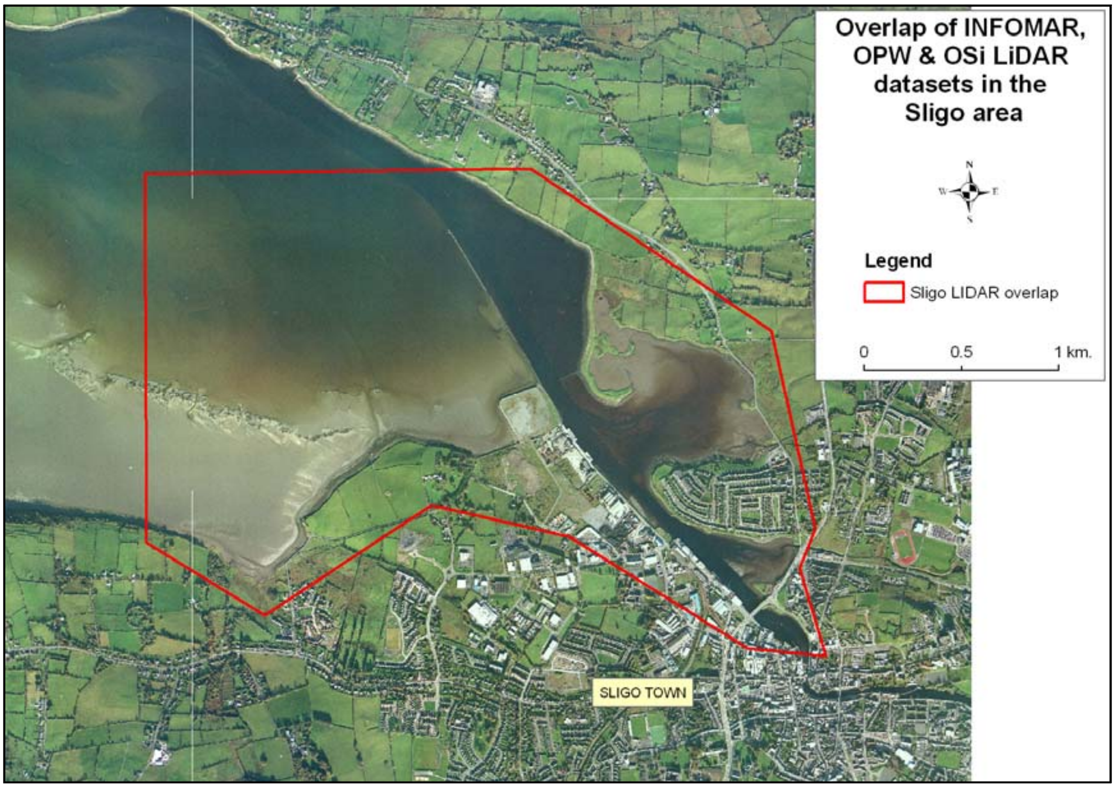


Figure 2.4: Spatial overlap of INFOMAR, OPW and OSi LiDAR coverages in Sligo Bay. *(Orthoimagery courtesy of Stephen Curran, Ordnance Survey Ireland).*

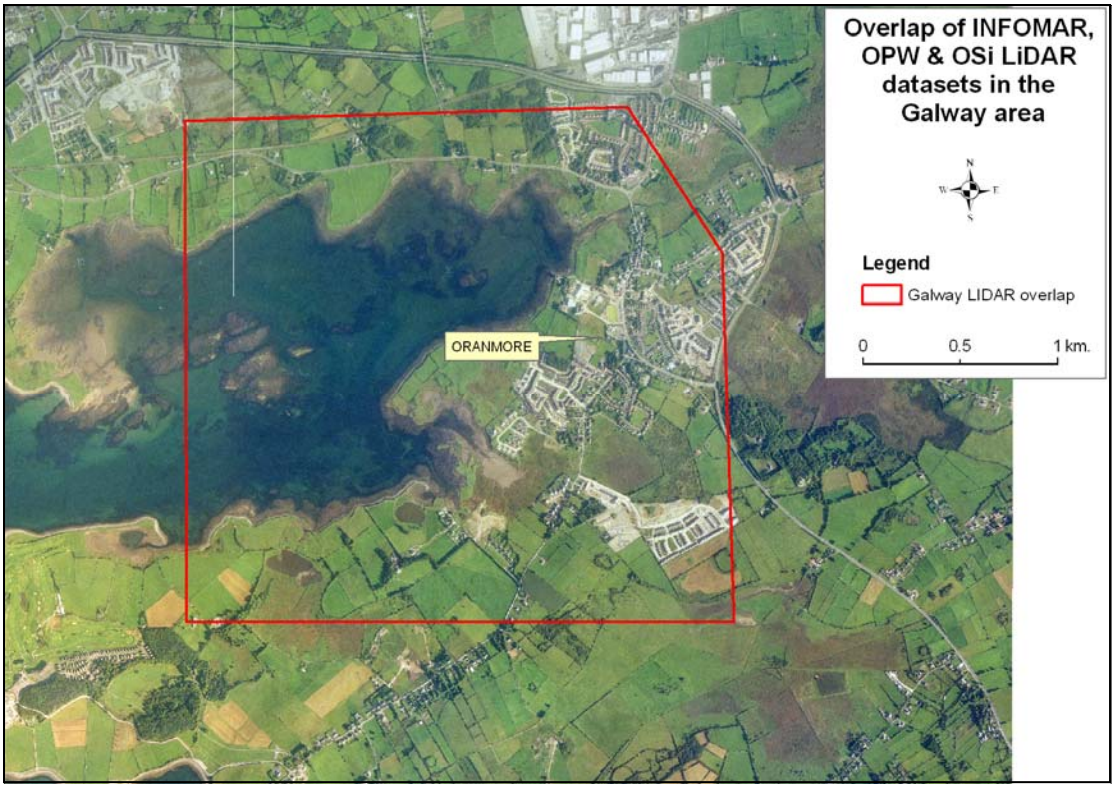


Figure 2.5: Spatial overlap of INFOMAR, OPW and OSi LiDAR coverages in Galway Bay. *(Orthoimagery courtesy of Stephen Curran, Ordnance Survey Ireland).*

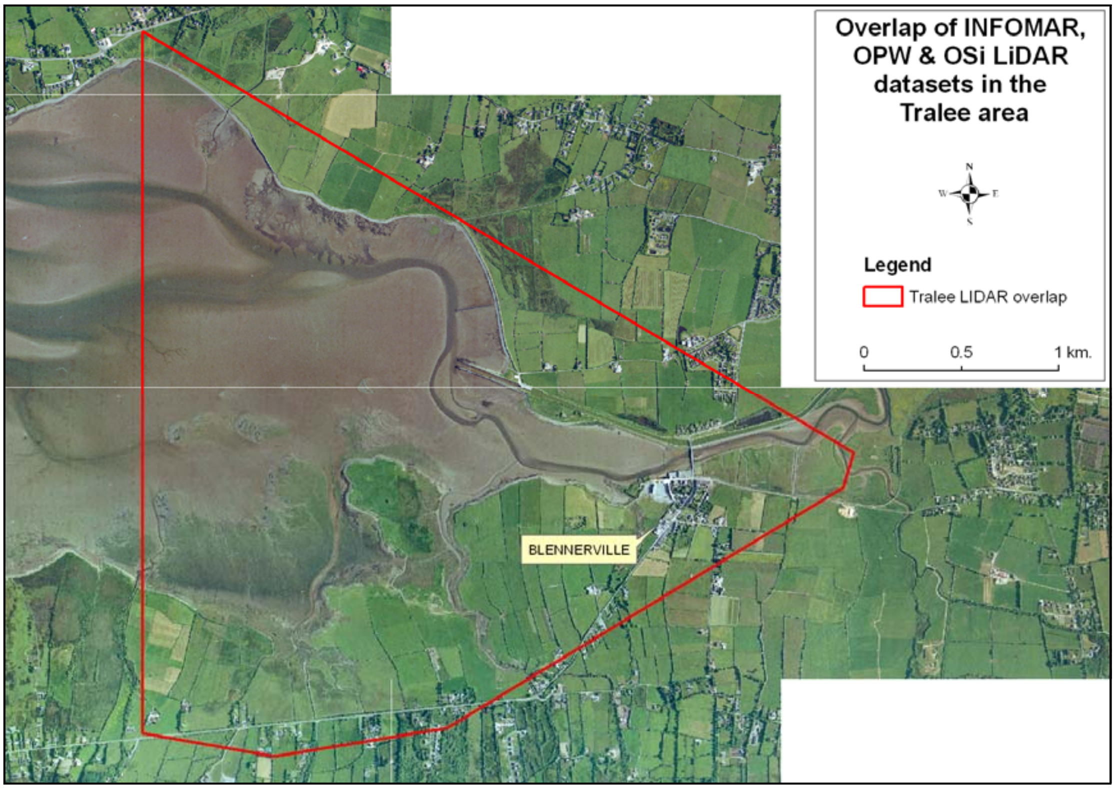


Figure 2.6: Spatial overlap of INFOMAR, OPW and OSi LiDAR coverages in Tralee Bay. *(Orthoimagery courtesy of Stephen Curran, Ordnance Survey Ireland).*

3 Potential barriers to data integration

Three main questions arise when it comes to integrating the INFOMAR LiDAR with the OPW and OSi LIDAR datasets. The first issue relates to the accuracy of each of the LiDAR datasets. The accuracy statistics that are provided by the data suppliers (table 3.1) 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 dataset. Therefore, local errors can be significantly larger than these global measures would suggest (Cobby *et al,* 2001, ASPRS 2004, Rosso *et al.* 2006, Palamara *et al.* 2007). This can represent a problem when different datasets are being integrated into a single coverage. The accuracy of each dataset in each of the three overlap test areas is assessed (see section 4) using post-processed FastStatic GPS survey data to verify the accuracy of each LiDAR dataset in each of the three overlap test areas.

The second question pertains to the degree to which datum transformation error might affect integration potential. Aerial LiDAR are typically captured relative to GPS-defined geographic coordinates and ellipsoid. However, datum transformation can introduce error, so integration potential is assessed on an ETRF89 / GRS80 framework and on a separate ITM / Malin framework to quantify the extent to which transformation errors may interfere with smooth data integration. It should be noted at this point that all of the datasets used in this study were captured relative to GPS coordinates on ETRF89 / GRS80 ellipsoid. The aim of this study is to assess integration performance and to isolate the principal barriers to LiDAR integration in a GIS context. Some of the INFOMAR LiDAR data exist as double datasets; one dataset being supplied relative to ETRF89 / GRS80 ellipsoid and another dataset being supplied relative to LAT. The LAT data are examined here also, but it should be noted that these LAT format aerial LiDAR data were captured relative to ETRF89 / GRS80 ellipsoid, and were transformed to LAT by the data suppliers (personal communication Blom Aerofilms, October, 2009). Therefore, assessments of integration issues associated with the use of INFOMAR LAT LiDAR are not expected to be subject to tidal complications.

The third issue relates to potential mismatches arising from water column representation in the LiDAR acquired by topographic (single-beam) LiDAR survey. The OPW data were captured using topographic LiDAR survey, so the possibility that water column presence in the OPW data caused a mismatch with the INFOMAR LiDAR bathymetry is examined also.

3.1 Validation of LiDAR accuracy

Absolute LiDAR error is quantified in the three LIDAR overlap areas using very high-accuracy FastStatic GPS ground validation data (Appendix 1). These data are used as external validation test data to measure elevation error in (ordinary kriging) interpolations of the INFOMAR, OPW and OSi LiDAR point datasets for Sligo, Galway and Tralee LiDAR overlap test areas. These tests will highlight the sum of errors deriving from:

1. Absolute LiDAR data error
2. Coordinate / datum transformation error
3. Errors introduced during interpolation of the LiDAR point data

This exercise is carried out (see section 4) on the onshore-to-offshore (*on2off*) ITM/Malin integration data and on the ETRF89/GRS80 offshore-to-onshore (*off2on*) integration datasets. It should be noted at this point that all integration focused on the problem of elevation integration. Integrating geographic and projected coordinates is not a problematic issue. Visual ground feature matching was carried out at three dispersed locations in each overlap area to verify horizontal matching between the three LiDAR datasets in each of the three overlap test areas. No problems were detected. As a consequence of this, the term 'LiDAR error' used henceforth in this report refers to elevation error only. It should also be flagged again at this point that the *on2off* integration is dealt with first in this study because the first step in the integration tests involved accuracy validation for each lidar dataset in each of the three overlap areas. The validation surveys were conducted on hard-standing and paved areas in the onshore component of the LiDAR overlaps in Sligo, Galway and Tralee.

3.2 Differing spatial reference systems

The INFOMAR, OPW and OSi LiDAR datasets were all captured and processed to meet the individual requirements of their originator agencies, so each of them uses different spatial reference systems and datum definitions. The *on2off* and the *off2on* integrations require different approaches. Two transformation systems are used here. The *on2off* integration is done using Grid Inquest. The *off2on* integration is carried out using the Vertical Offshore Reference Framework (VORF). A cross-check is also applied (in section 4.2.6) by back transforming to ETRF89/GRS80 from ITM/Malin format in Grid Inquest to see how it matches up with the raw ETRF89/GRS80 INFOMAR and OPW LiDAR data.

3.2.1 Grid Inquest

Grid Inquest allows transformations to be made between WGS84/ETRF89/GRS80 and the National coordinate systems of Britain, Northern Ireland and the Republic of Ireland. (http://www.qgsl.com/?product=gridinquest). The principal advantages of Grid Inquest include its facility to handle three dimensional transformations incorporating the RI (Republic of Ireland) OSGM02 geoid model, and its use as the industry standard software by the Ordnance Survey Great Britain and OSi for performing these conversions. The OSi and OPW LiDAR were mapped to Malin Datum, so this made Grid Inquest the most suitable for datum transformation on the *on2off* data integration tests.

It should be noted that Grid Inquest has potential limitations for the definition of datum offshore. Grid Inquest uses the OSGM02 geoid model to convert from ellipsoid height to orthometric heights. This geoid model is characterised by very small accuracies in the range of ±0.035m (Forsberg et al. 2003). However, Grid Inquest also uses an additional second-order correction to account for small historical artifacts of earlier triangulations of the Irish National Grid (Ordnance Survey Ireland, 1996). Small elevation errors that may derive from this additional correction surface are not readily quantifiable, so these can potentially be problematic when integrating data that have been captured relative to tidal surfaces (mean or Lowest Astronomical tide for example) with data that are referenced against GRS80 ellipsoid or Malin datum. None of the data examined here were captured relative to tidal surfaces. The offshore INFOMAR data that are used in the offshore-to-onshore integration tests in this report were back-transformed from a Lowest Astronomical Tide (LAT) reference system to a GRS80 ellipsoid reference framework. However, this LAT data was derived from origin GRS80 LiDAR survey data that was simply back-transformed to LAT using

VORF. Therefore, the potentially thorny issue of integrating with tidal data did not arise. However, the possibility that elevation errors may have been introduced during transformation from origin ETRF89 / GRS80 to LAT, and during back-transformation from LAT ETRF89 / GRS80 was a very real one, so this issue was carefully considered also (see section 4).

3.2.2 Vertical Offshore Reference Framework (VORF)

VORF provides a suite of mathematical models for transformation between the major surfaces used in the charting of UK and Irish waters (UKHO, 2007, http://www.iho-ohi.net/mtg_docs/com_wg/IHOTC/IHOTC8/UK_VORF.pdf). Transformations include LAT and Ellipsoid, both of which are free from the potential problems that may be prone to occur when Grid Inquest is used for datum transformations on offshore data.

3.3 LiDAR data elevation error

Quoted elevation error for aerial LiDAR typically falls within the range of approximately ±0.2m. This may initially appear to be very small, but these statistics can be misinterpreted by data users. There are a number of reasons for this.

1. The ± error range provided by data suppliers gives a global measure of the magnitude of elevation errors across the entire area of a dataset. As a result of this it would be inappropriate to assume that this accuracy occurs across an entire data coverage (ASPRS, 2004).
2. Guidelines for the quantification of error in LiDAR refer to the application of 'compiled to meet' standards for situations where ground validation is particularly problematic (ASPRS, 2004). Therefore, there may at times be little guarantee regarding the nature or extent of the ground validation that has been carried out.
3. Ground validation is commonly applied in flat and open paved areas where LiDAR acquisition error is easiest to verify. Therefore, quoted error statistics will tend to refer to these optimal test areas. Errors in vegetated areas can be substantially larger than the quoted error range (Cobby *et al.* 2001, Rosso *et al.*

2006, Palamara *et al.* 2007). This is important to consider when dealing with integration of data that predominately represents natural areas

Each of the three LiDAR datasets tested here was captured using different acquisition systems and has been processed to the meet the individual requirements of the agencies for which they were captured. As a consequence of this, each dataset is likely to be characterised by elevation errors that derive from the particularities of the surveys, systems, and methods that were applied in each survey area and by each of the survey contractors. LiDAR accuracy statistics supplied with all three LiDAR datasets are outlined in table 3.1. Each of these LiDAR datasets is externally validated in each of the three overlap test areas using post-processed FastStatic GPS survey data (see section 4) in order to quantify gross elevation error (the sum of LiDAR data error, datum transformation error and validation interpolation error) after LiDAR data integration.

Data supplier	Coverage	XY Coord system	Z reference system	Accuracy Z	Accuracy source
OPW	Tralee	ETRF89 & ITM	GRS80 Spheroid	±0.15m	opw metadata
OPW	Galway	ETRF89 & ITM	GRS80 Spheroid	±0.15m	opw metadata
OPW	Sligo	ETRF89 & ITM	GRS80 Spheroid	±0.15m	opw metadata
OSI	Tralee	ITM metres (integers)	Malin metres (float)	0.25m	osi lidar spec
OSI	Galway	ITM metres (integers)	Malin metres (float)	0.25m	osi lidar spec
OSI	Sligo	ITM metres (integers)	Malin metres (float)	0.25m	osi lidar spec
INFOMAR	Tralee	ETRF89, LAT & ITM (float)	GRS80 Spheroid Malin metres (float)	±0.28m topo & bathy	G.2.5 Tenix 2009
INFOMAR	Galway	ETRF89, LAT & ITM (float)	GRS80 Spheroid Malin metres (float)	±0.28m topo & bathy	G.2.5 Tenix 2009
INFOMAR	Sligo	ETRF89, LAT & UTM (float)	GRS80 Spheroid Malin metres (float)	±0.28m topo ±0.2m bathy	Appendix D BLOM 2008

Table 3.1: Basic specifications of datasets used in this study including quoted elevation error.

3.3.1 LiDAR validation with GPS

External validation of all three LiDAR data sources is carried out for each overlap area (see section 4) using FastStatic dual-frequency GPS data captured for this study. The close proximity of the three LiDAR overlap areas to OSi GPS correction stations meant that GPS post-processing (with OSi RINEX data) could be carried out on short (<10km) baselines. This provided confidence regarding the accuracy of the validation data, and the elevation errors highlighted within each dataset in each overlap area. The issue of GPS validation data accuracy is expanded upon in section 4.2.2, but is highlighted here to demonstrate the suitability of these sites in terms of location.

3.4 LiDAR elevation matching

As noted at the outset three main sources of elevation error (namely absolute data error, datum transformation error and water column mismatch errors) needed to be considered. Absolute error in each of the datasets in each of the LiDAR overlap areas is quantified by external validation with dual-frequency FastStatic GPS data. The GPS data were captured relative to ETRF89/GRS80, and were used in this format for the *off2on* integration tests. The GPS data are transformed (using Grid Inquest) to ITM/Malin for the *on2off* integration tests. Therefore, the *on2off* validation data were characterised by the identical elevation transformation parameters applied to the LiDAR data to which they were applied. Nonetheless, the possibility that errors might have derived from this process was considered and investigated. The possibility for water column mismatches to occur between the OPW and INFOMAR data is investigated using sub-area comparisons and cross-section comparison tests.

4 LiDAR data integration

Separate standardised horizontal and elevation referencing systems are used for both the *on2off* and the *off2on* integration tests. ITM projected coordinates and Malin datum are used for the *on2off* LiDAR integration tests, and ETRF89 geographic coordinates and GRS80 ellipsoid are used for the *off2on* LiDAR integration tests. As was outlined in section 3 (table 3.1) the LiDAR data were supplied in a variety of coordinate formats, but all were captured relative to ETRF89 / GRS80. These had to be standardised to ITM/Malin for both the *on2off* and the *off2on* 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 (starting with *on2off* integration for the Sligo LiDAR integration test area.

4.1 Sligo

4.1.1 Sligo on2off transformation

The OSi data were supplied in ITM/Malin format for Sligo, so it required no transformation. The OPW data for Sligo were supplied referenced to ETRF89 geographic horizontal coordinates, and to GRS80 ellipsoid. These data were transformed to ITM / Malin x,y,z metres using Grid Inquest. The INFOMAR LiDAR data for the Sligo LIDAR overlap area were transformed from ETRF89 / Malin to ITM Malin in Grid Inquest. Elevation values in the INFOMAR bathymetric LiDAR data are classified as positive for depth and as negative values for height above Malin datum, so the all Malin orthometric heights in the OPW and OSi data were multiplied by minus one before data integration. All standardised data were subsequently exported to a single Microsoft Access database. Individual tables were used for each of the OSi, OPW and INFOMAR data coverages, and a single combined data table was used to accommodate all three datasets in an integrated OSi, OPW, and INFOMAR LIDAR coverage referenced against ITM / Malin. The source-specific ITM / Malin LiDAR data tables were externally validated with very high-accuracy post processed FastStatic GPS survey data (see section 4.1.2) and were compared against one another (section 4.1.3) the combined ITM/Malin data table was

4.1.2 Sligo on2off external validation

The ITM / Malin format OSi, OPW and INFOMAR data for Sligo were all externally validated with post processed FastStatic GPS data to assess elevation accuracy (and to test transformation accuracy where it was applied). ASPRS (2004) suggests that a minimum of 25 points are used to validate LiDAR elevation accuracy within unique land cover classes. Sixty external validation points were captured in open paved areas for LiDAR validation. Fifty of these validation points were used. The points that were characterised by the highest post-processing elevation errors (Appendix 1) or that were influenced by overhanging trees or being too close to structures were removed.

A Trimble R8 dual-frequency GPS receiver was used in FastStatic mode on 8 to 20 minute residence times (based on satellite availability) to capture the validation points. The maximum elevation error (relative to ellipsoid) highlighted by post-processing among the 50 GPS points used for external validation was 1centimetre (Appendix 1a), confirming that the GPS data provided a reliable reference dataset for LiDAR validation.

The validation points were transformed to Malin datum format in Grid Inquest before LiDAR validation was carried out. This did not introduce any problems. Grid Inquest transformations will always be identical at a given x,y, point, so the same transformation was applied to the GPS points and their corresponding locations in the LiDAR coverages to which they were applied as validation data. Validation was carried out in ArcGIS / ArcInfo using Geostatistical Analyst. Ordinary kriging prediction surfaces (continuous not raster surfaces) were generated for the OSi, OPW and INFOMAR LiDAR data in the Sligo overlap areas. The difference between GPS elevation and LiDAR elevation values at each of fifty locations was assessed for each of the LiDAR datasets tested. Summary statistics for the OSi LiDAR DSM, the OPW LiDAR DEM and the INFOMAR LiDAR DEM validations are outlined in table 4.1.

OSi LiDAR validation	OPW LiDAR validation	INFOMAR LiDAR validation
Count: 50	Count: 50	Count: 50
90% elevation error: ±0.08	90% elevation error: ±0.39	90% elevation error: ±0.21
Max negative err: -0.18	Max negative err: -0.48	Max negative err: -0.403401
Max positive err: 0.20	Max positive err: 1.17	Max positive err: 0.367691
Mean error: -0.008	Mean error: 0.07	Mean error: 0.08
Std. Dev: 0.07	Std. Dev: 0.267628	Std. Dev: 0.13

Table 4.1: Results of the *on2off* external validation of OSi, OPW and INFOMAR LiDAR data for Sligo

The LiDAR elevation errors noted were all very close to the error statistics provided by the data suppliers. Most important of all, the equal distribution of elevation errors above and below zero metres Malin (highlighted by all mean errors coming very close to zero) confirmed that standardisation of all three LiDAR datasets to Malin datum (by the data suppliers in the case of the OSi data, and by NCG 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 suggested that onshore-to-offshore LIDAR integration worked satisfactorily for Sligo.

It should be highlighted at this point that only the OSi data are processed to DSM format and that the OPW and INFOMAR data are processed to DEM format only. Terrestrial data can be converted to DSM format without the safety issues that attach to bathymetric LiDAR. Bathymetric LiDAR is typically not processed to DSM stage, because this would involve data filtering and resampling which would alter the raw ranging values. The application of these kinds of filters to bathymetric data would alter the depth values in data to an unacceptable extent. Therefore, the magnitude of the elevation errors highlighted in the OPW and INFOMAR LiDAR data (relative to the OSi DSM data) should be viewed in this context.

4.1.3 Sligo on2off subset are elevation comparison

The results of the GPS validation of the Sligo LIDAR datasets indicated that integration of the three datasets onto an ITM / Malin framework was viable using Grid Inquest. However, additional comparative tests were carried out over large sample areas to verify this. Six subset areas were selected within the Sligo LiDAR overlap area (figure 4.1) to determine if any systematic differences could be detected between the OSi, OPW and INFOMAR LiDAR data tested. Elevation statistics (particularly mean elevation) were evaluated in the six overlap areas used for the comparative tests (table 4.2).

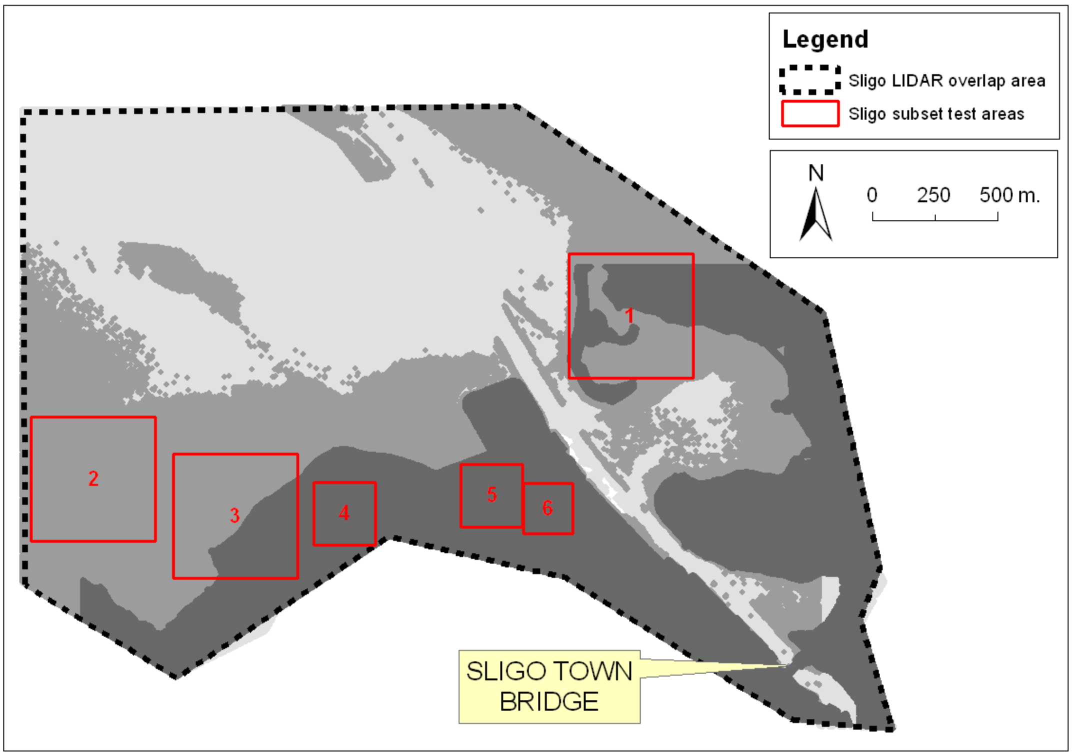


Figure 4.1: Subset areas selected for Sligo subset area LiDAR elevation comparative tests.

Three 500m x 500m and three 250m x 250m subset areas were selected. The 500m x 500m areas focused on the comparison of the OPW and the INFOMAR data in the Littoral zone, but included one comparison with OSi data also (table 4.2). The 250m x 250m subsets focused on comparison of all three datasets (table 4.2). 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 available as DSM data. Buildings and forested areas are filtered out of during DSM generation in order to provide a more accurate model o the terrain surface. The OPW and INFOMAR data are not processed to such a high degree, so urban and forested areas were avoided when selecting comparison areas. Mean elevation statistics for each dataset were compared in each subset area to see if any systematic elevation differences could be noted between the three LiDAR datasets tested.

Sligo subset area 1 (500m x 500m)

OPW data in subset 1	INFOMAR data in subset 1	OSi data in subset 1
Point count: ***327351***	***Point count:*** ***266405***	
Minimum: -13.63	Minimum: -8.74	
Maximum: 0.87	Maximum: 1.81	*INSUFFICIENT OVERLAP*
Mean: -2.20	***Mean: -2.22***	*FOR VALID ANALYSIS*
Std. Dev: 1.97	Std. Dev: 1.69	

Sligo subset area 2 (500m x 500m)

OPW data in subset 2	INFOMAR data in subset 2	OSI data in subset 2
Point count: ***394894***	***Point count:*** ***87805***	
Minimum: -5.66	Minimum: -0.72	
Maximum: 0.47	Maximum: 0.67	*INSUFFICIENT OVERLAP*
Mean: -0.33	***Mean: -0.28***	*FOR VALID ANALYSIS*
Std. Dev: 0.16	Std. Dev: 0.19	

Sligo subset area 3 (500m x 500m)

OPW data in subset 3	INFOMAR data in subset 3	OSi data in subset 3
Point count: ***419428***	***Point count:*** ***129697***	
Minimum: -16.92	Minimum: -12.75	
Maximum: 0.54	Maximum: 0.65	*INSUFFICIENT OVERLAP*
Mean: -2.87	***Mean: -4.73 ****	*FOR VALID ANALYSIS*
Std. Dev: 3.84	Std. Dev: 4.04	
	**** biased by double point density onshore***	

Sligo subset area 4 (250m x 250m)

OPW data in subset 4	INFOMAR data in subset 4	OSi data in subset 4
Point count: ***71110***	***Point count:*** ***20651***	***Point count:*** ***15750***
Minimum: -23.73	Minimum: -17.37	Minimum: -17.58
Maximum: -6.69	Maximum: -6.69	Maximum: -6.71
Mean: -11.84	***Mean: -11.67***	***Mean: -11.84***
Std. Dev: 2.16	Std. Dev: 2.10	Std. Dev: 2.32

Sligo subset area 5 (250m x 250m)

OPW data in subset 5	INFOMAR data in subset 5	OSi data in subset 5
Point count: ***47701***	***Point count:*** ***73010***	***Point count:*** ***15625***
Minimum: -17.18	Minimum: -7.84	Minimum: -10.2
Maximum: -2	Maximum: -0.99	Maximum: -2.24
Mean: -5.14	***Mean: -5.35***	***Mean: -5.44***
Std. Dev: 1.44	Std. Dev: 1.34	Std. Dev: 1.35

Sligo subset area (200m x 200m)

OPW data in subset 6	INFOMAR data in subset 6	OSi data in subset 6
Point count: ***36430***	***Point count:*** ***24440***	***Point count:*** ***10000***
Minimum: -10.89	Minimum: -6.53	Minimum: -5.49
Maximum: -2.08	Maximum: -1.58	Maximum: -2.1
Mean: -3.67	***Mean: -3.74***	***Mean: -3.71***
Std. Dev: 1.03	Std. Dev: 0.76	Std. Dev: 0.71

Table 4.2: Comparison of mean elevation statistics in each of the six Sligo subset areas.

Mean elevation values for each dataset 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) and this was not due to data accuracy or transformation issues. The problem in the case of subset area 3 was due to variations in LIDAR point sampling resolution within the INFOMAR data in this location. As noted previously, the INFOMAR and OPW data are supplied in DEM format (to preserve the original captured data values). This resulted in some variation in the horizontal point sampling density across each of these datasets. The onshore component of the INFOMAR data in this subset area was approximately double the point sampling density offshore. This biased the mean elevation value towards the onshore elevation values.

Mean elevation values for were much closer in all other instances, with no significant systematic elevation differences evident in any of the datasets in any other location. The small differences that were detected were all comfortably within the accuracy ranges quoted by each data supplier. Therefore, the transformation of the OPW and INFOMAR LiDAR from ETRF80/GRS80 to ITM/Malin appears to have caused no detectable issues. These results were in agreement with the results noted in the validation tests. However, one last visual check was applied to the data to verify the results of the other two tests.

4.1.4 Sligo on2off visual verification test

The three LiDAR datasets were integrated into a single data coverage in Microsoft Access (used because of the large file size and to facilitate data transferability) and the integrated data were subsequently visualised in ArcGIS to provide an additional visual confirmation of integration performance. The results of this final visual confirmation test were positive (figure 4.2). 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 help to clarify integration performance. It should be noted however that processing this data (to remove some of the internal variation associated with ± elevation error in the three origin datasets) would clarify matters considerably. The Combined OPW / INFOMAR data are supplied as adjunct data accompanying this report (in Microsoft Access database format). The data in the database are presented in simple x,y,z format. These data could be easily exported in text format to Caris to remove the 'salt-and-pepper' effect that derives from the local ± elevation error ranges in each of the high-quality origin datasets.

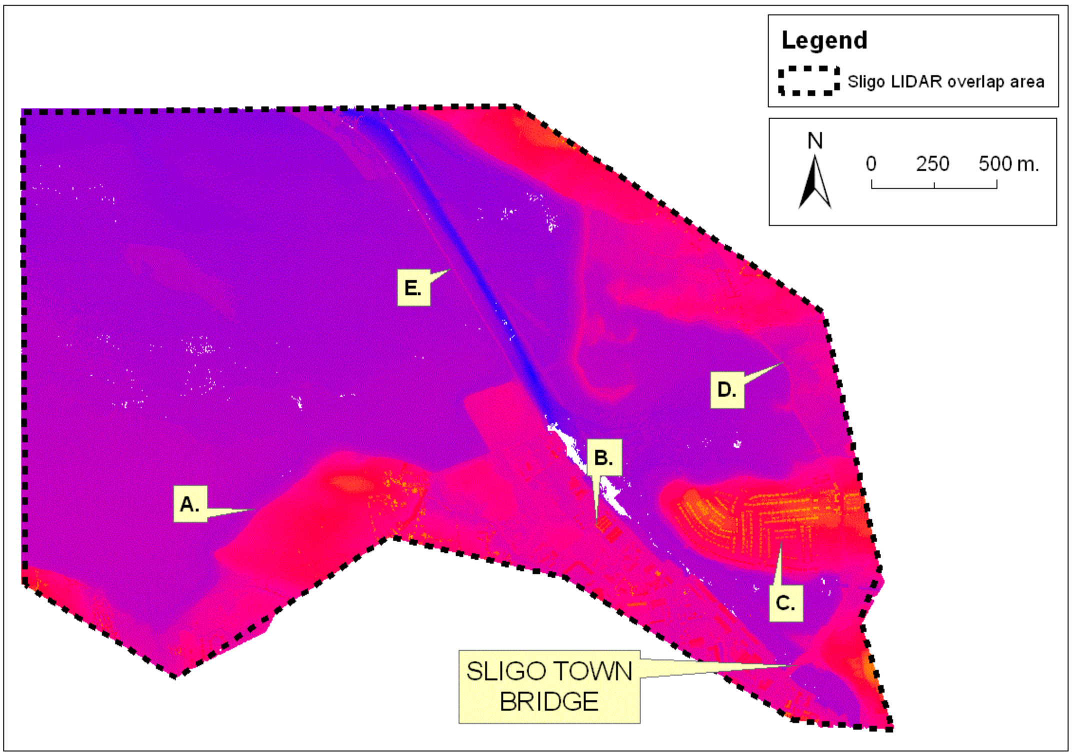


Figure 4.2: Visualisation of combined OSi, OPW and INFOMAR LiDAR data fro Sligo integrated onto ITM coordinates and Malin datum.

It should be noted that a critical component of successful integration of the offshore OPW and INFOMAR data in the Sligo LiDAR overlap area was the fact that OPW data was captured during low-tide conditions. This was not the case for Galway and Tralee, where high tide conditions introduced issues for integration offshore. Offshore-to-onshore integration tests were not applied in the case of Sligo due to the success of the onshore-to-offshore integration. However, additional integration tests were applied to the Galway and Tralee datasets to test for mismatches relatable to water-surface returns in the OPW LiDAR data.

4.2 Galway

4.2.1 Galway on2off transformation

The OSi data were supplied in ITM/Malin format for Galway, so it required no transformation. The OPW data for Galway were supplied referenced to ETRF89 geographic horizontal coordinates, and to GRS80 ellipsoid. These data were transformed to ITM / Malin x,y,z metres using Grid Inquest. The INFOMAR LiDAR data for the Galway LIDAR overlap area were supplied in ITM / Malin format, so no transformation was required in this case. All standardised data were subsequently combined in a single Microsoft Access database (to deal with the large data volume and to facilitate integration for these very large datasets). Individual tables were used for each of the OSi, OPW and INFOMAR data coverages, and a single combined data table was used to accommodate all three datasets in an integrated OSi, OPW, INFOMAR LIDAR coverage referenced against ITM / Malin. The source-specific ITM / Malin LiDAR data tables were externally validated with very high-accuracy post processed FastStatic GPS survey data (see section 4.2.2) and were compared against one another (section 4.2.3) the combined ITM/Malin data table was

4.2.2 Galway on2off external validation

Similar to Sligo, the best fifty GPS validation points were used. The maximum elevation error (relative to ellipsoid) highlighted by post-processing among the 50 GPS points used for external validation was 1.5 centimetres (see Appendix 1b for Galway GPS accuracy statistics), confirming that the GPS data provided a reliable reference dataset for LiDAR validation. Once again, the GPS validation points were transformed to Malin datum format in Grid Inquest before LiDAR validation was undertaken. As noted previously, Grid Inquest transformations will always be identical at a given x,y, point, so the same transformation was applied to the GPS points as was applied to the LiDAR coverages tested. Validation was carried out in ArcGIS / ArcInfo using Geostatistical Analyst, measuring the difference between GPS elevation and LiDAR elevation values at each of fifty locations for each of the LiDAR datasets tested. Summary statistics for the OSi LiDAR DSM, the OPW LiDAR DEM and the INFOMAR LiDAR DEM validations are outlined in table 4.3.

OSi LiDAR validation	OPW LiDAR validation	INFOMAR LiDAR validation
Count: 50	Count: 50	Count: 50
90% elevation error: ±0.11	90% elevation error: ±0.14	90% elevation error: ±0.25
Max negative err: -0.15	Max negative err: -1.06	Max negative err: -0.51295
Max positive err: 0.15	Max positive err: 0.30	Max positive err: 0.208174
Mean: -0.024	Mean: -0.002	Mean: -0.12
Std. Dev: 0.07	Std. Dev: 0.19	Std. Dev: 0.19

Table 4.3: Results of external *on2off* validation of OSi, OPW and INFOMAR LiDAR data for Galway

The 90% error ranges, mean elevation statistics and standard deviations of the elevation errors noted in all three LiDAR datasets indicated that transformation of the OPW and INFOMAR data from ETRF89/GRS80 to ITM/Malin was satisfactorily. The close similarity of the error ranges highlighted by validation (in comparison with the error ranges quoted by each of the data suppliers) further suggested that integration from onshore to offshore using Grid Inquest was free from any substantial difficulties.

4.2.3 Galway on2off subset area elevation comparison

Six subset areas were selected within the Galway LiDAR overlap area (figure 4.3) to see if any systematic differences could be detected between the three LiDAR datasets tested. Elevation statistics (mean elevation) was evaluated in the six overlap areas used for the comparative tests (table 4.4). Similar to the previous subset area tests, three 500m x 500m and three 250m x 250m subset areas were selected.

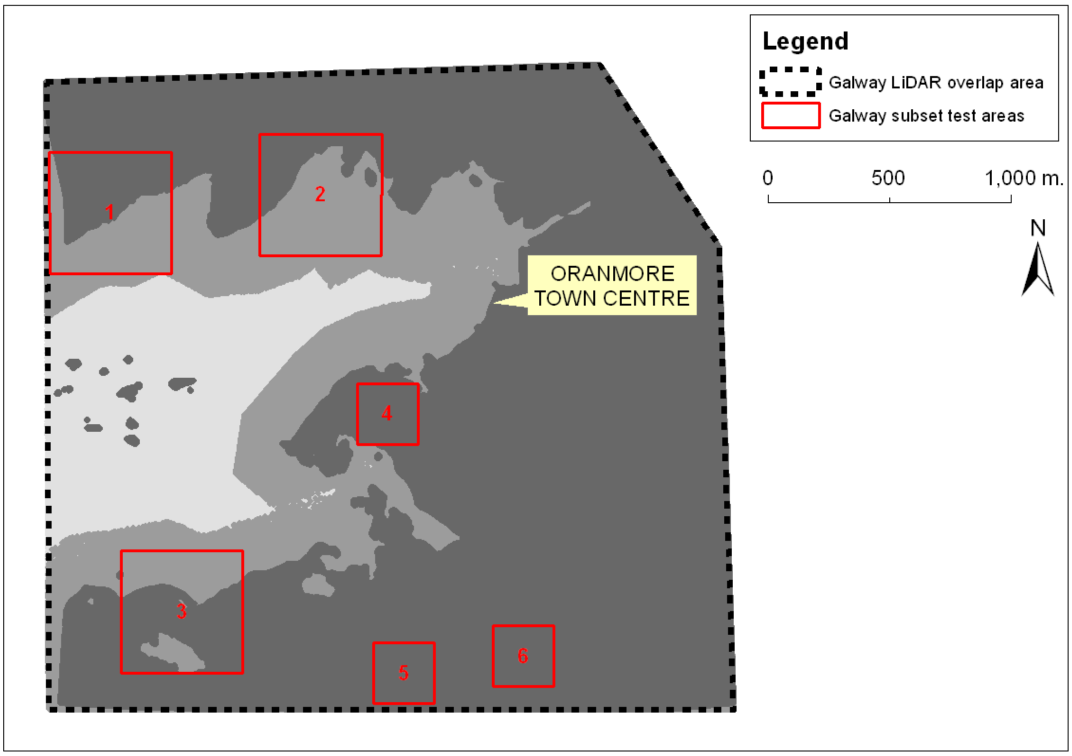


Figure 4.3: Subset areas selected for Galway subset area LiDAR elevation comparative tests.

The 250m x 250m subsets focused on comparison of all three datasets (table 4.4) onshore. The 500m x 500m areas focused on the comparison of the OPW and the INFOMAR data in the Littoral zone only. Comparison areas were selected on the basis of being flat (and for the most part featureless) to avoid the potential complicating influence of urban structures or forest cover during cross-comparison. Mean elevation statistics for each dataset were compared in each subset area to see if any systematic elevation differences could be noted between the three LiDAR datasets tested. Mean elevation values for each dataset in each 250m x 250m subset areas were strikingly similar, and were comfortably within the ± elevation accuracy ranges quoted by each data supplier. This provided backup for the results of the external validation, indicating that transformation of the OPW and INFOMAR LIDAR data from ETRF89/GRS80 to ITM/Malin did not introduce any detectable elevation error into either dataset. Subset area six (250m x 250m) performed least well, though entirely satisfactorily, which may have reflected the small number of INFOMAR lidar points in this subset area six (3123) in relation to the OSI data in subset area six (15625) and the OPW data points (99114) in subset area six (table 4.4).

The OPW and INFOMAR data in the 500m x 500m subset areas did not match up as well however. Mean elevation differences of 1.29m in subset area 1, 0.4m in subset area 2, and 0.33m 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. Assessment of the integrated lidar (figure 4.4) indicated a problem offshore.

Subset area 1 (500m x 500m)

OPW data in subset 1	INFOMAR data in subset 1	OSi data in subset 1
Point count: ***198555***	***Point count:*** ***16292***	
Minimum: -23.01	Minimum: -20.01	
Maximum: 0.58	Maximum: 43.51	*INSUFFICIENT OVERLAP*
Mean: ***-5.54***	***Mean:*** ***-4.25***	*FOR VALID ANALYSIS*
Std. Dev: 5.05	Std. Dev: 4.88	

Subset area 2 (500m x 500m)

OPW data in subset 2	INFOMAR data in subset 2	OSI data in subset 2
Point count: ***155157***	***Point count:*** ***15234***	
Minimum: -19.43	Minimum: -19.74	
Maximum: 0.56	Maximum: 1.66	*INSUFFICIENT OVERLAP*
Mean: ***-1.43***	***Mean:*** ***-1.03***	*FOR VALID ANALYSIS*
Std. Dev: 2.43	Std. Dev: 2.51	

Subset area 3 (500m x 500m)

OPW data in subset 3	INFOMAR data in subset 3	OSi data in subset 3
Point count: ***155618***	***Point count:*** ***17200***	
Minimum: -21.19	Minimum: -20.71	
Maximum: 0.38	Maximum: 3.06	*INSUFFICIENT OVERLAP*
Mean: ***-2.89***	***Mean:*** ***-2.56***	*FOR VALID ANALYSIS*
Std. Dev: 2.38	Std. Dev: 3.09	

Subset area 4 (250m x 250m)

OPW data in subset 4	INFOMAR data in subset 4	OSi data in subset 4
Point count: ***126326***	***Point count:*** ***5633***	***Point count:*** ***15446***
Minimum: -8.58	Minimum: -8.57	Minimum: -5.09
Maximum: -0.45	Maximum: -0.33	Maximum: -0.9
Mean: ***-3.05***	***Mean:*** ***-3.07***	***Mean:*** ***-3.12***
Std. Dev: 0.91	Std. Dev: 0.98	Std. Dev: 0.83

Subset area 5 (250m x 250m)

OPW data in subset 5	INFOMAR data in subset 5	OSi data in subset 5
Point count: ***84883***	***Point count:*** ***3039***	***Point count:*** ***15625***
Minimum: -17.54	Minimum: -17.06	Minimum: -11.56
Maximum: -2.86	Maximum: -2.86	Maximum: -2.9
Mean: ***-5.98***	***Mean:*** ***-5.98***	***Mean:*** ***-5.87***
Std. Dev: 1.78	Std. Dev: 1.79	Std. Dev: 1.49

Subset area 6 (250m x 250m)

OPW data in subset 6	INFOMAR data in subset 6	OSi data in subset 6
Point count: ***99114***	***Point count:*** ***3123***	***Point count:*** ***15625***
Minimum: -26.22	Minimum: -26.25	Minimum: -21.26
Maximum: -5.46	Maximum: -5.59	Maximum: -5.47
Mean: ***-17.27***	***Mean:*** ***-17.68***	***Mean:*** ***-17.25***
Std. Dev: 3.37	Std. Dev: 3.53	Std. Dev: 3.43

Table 4.4: Comparison of mean elevation statistics in the six Galway subset areas.

4.2.4 Galway on2off visual verification test

The three LiDAR datasets were integrated into a single data coverage in Microsoft Access (used because of the large file size and to facilitate data transferability) and the integrated data were subsequently visualised in ArcGIS to provide an additional visual confirmation of integration performance (figure 4.4).

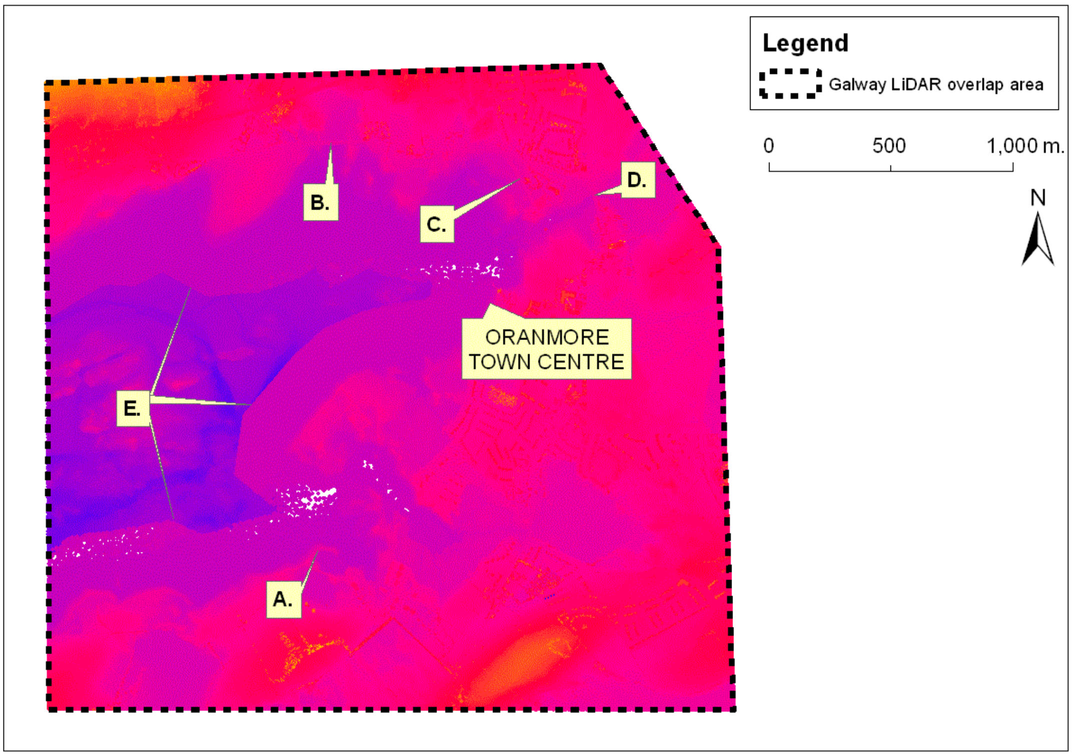


Figure 4.4: Visualisation of combined OSi, OPW and INFOMAR LiDAR data for Galway integrated onto ITM coordinates and Malin datum.

The clarity with which relatively subtle features were highlighted in the combined OSi, OPW, and INFOMAR data provided visual confirmation of integration performance. An eroded sea-defense wall (A), the regional road between Oranmore and Galway (B and C) and Oranmore bridge (D) were all clearly defined. These features were present in all three datasets, and their clear delineation in the integrated dataset confirmed that no significant problems derived from the transformation of OPW and INFOMAR data in ETRF89/GRS80 format to ITM/Malin format. However, additional problems did occur. The offshore elevation mismatches that were noted in the subset area tests were clearly evident in figure 4.4. The appearance of the mismatch areas suggested a uniform surface coincident with a water surface in the OPW data. Further analysis was required to explore this question.

4.2.5 Galway on2off offshore-mismatch analysis

Six cross sections were applied to the offshore OPW and INFOMAR data for Sligo. These were targeted at the problem areas noted in the previous section. The relationship of the six cross-sections to the Sligo LiDAR data are outlined in figure 4.5. Cross-sections were aligned to northings or eastings to provide spatial ordering for cross-comparison of the OPW and INFOMAR data values on each cross-section.

Figure 4.5(a): Cross-sections used to assess offshore elevation values in OPW data (displayed in relation to Tralee LiDAR coverages).

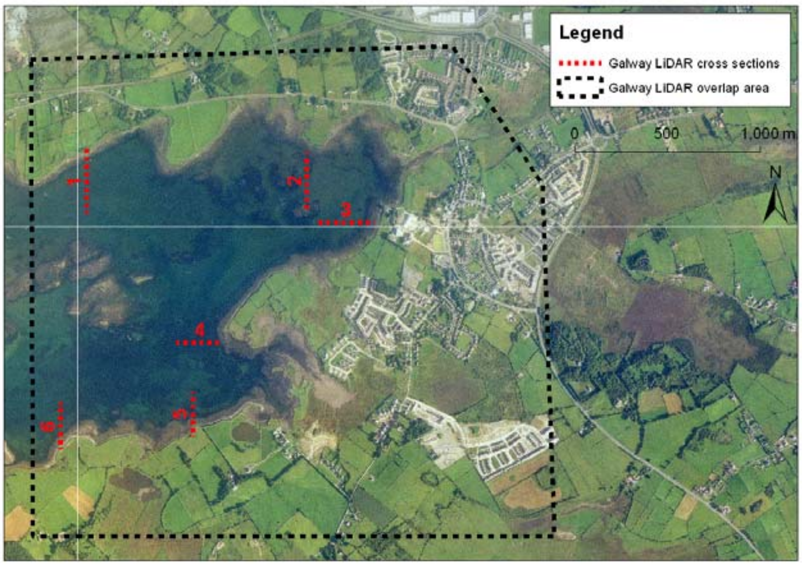
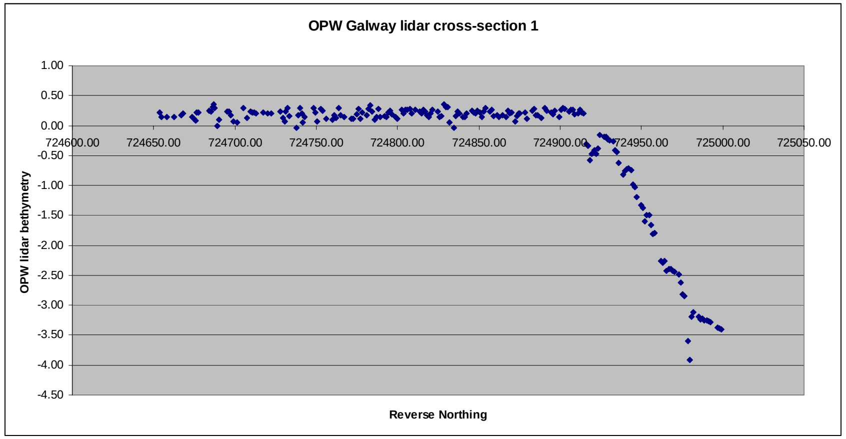


Figure 4.5(b): Cross-sections used to assess offshore elevation values in OPW data (displayed in relation to OSi Orthoimagery.

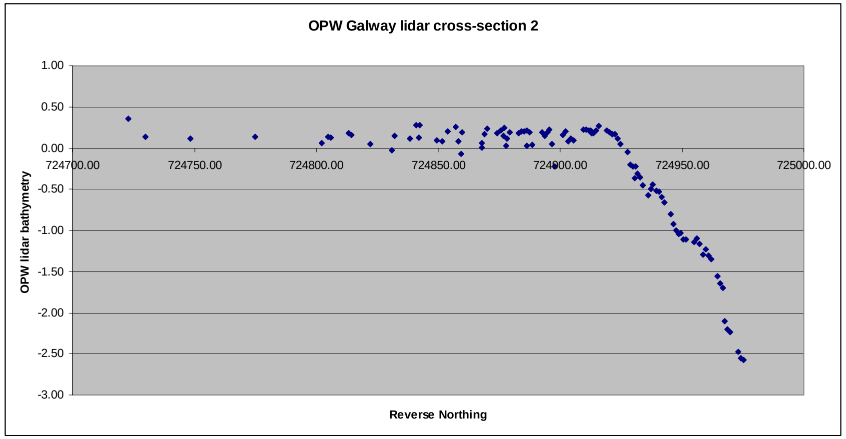
Orthoimage data provided to NCG courtesy of Stephen Curran Ordnance Survey Ireland, 2009.

OPW and INFOMAR LiDAR points falling within 1-metre of each cross-section were graphed to assess whether sea-surface LiDAR returns were present in the data. Bathymetry was graphed against distance along each cross-section for the OPW data and the INFOMAR data that were within the tolerance distance from each cross-section. The results of this analysis are presented in figures 4.6 to 4.11 in the subsequent three pages.

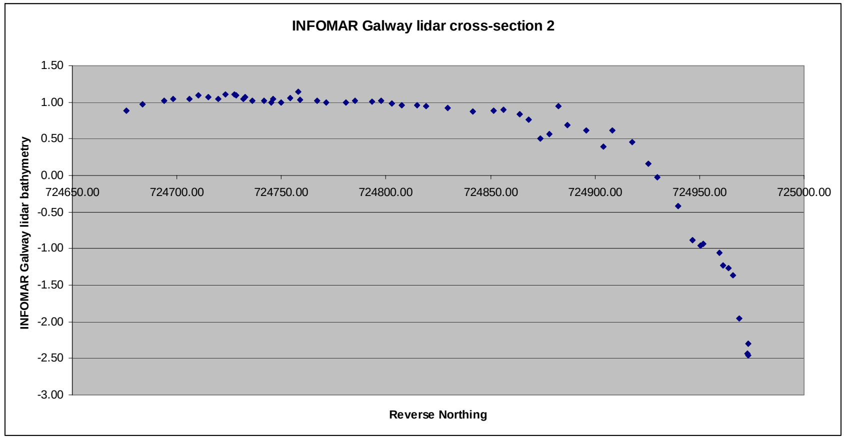


▲ Bathy.

Topo. ▼



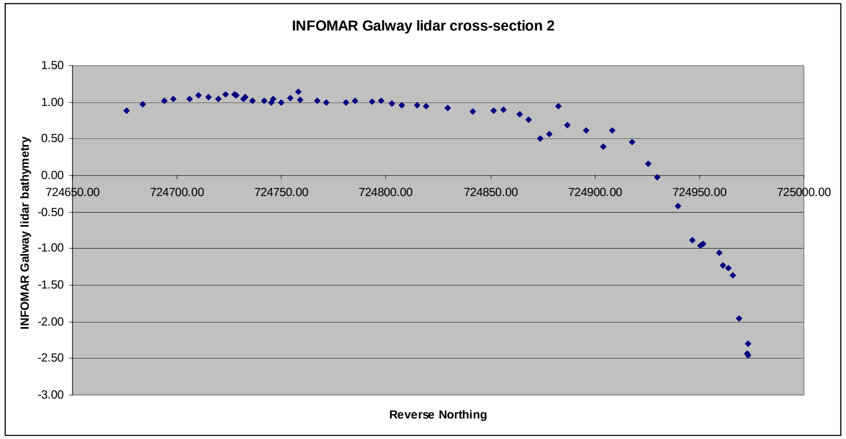
◀ Offshore Onshore ▶



▲ Bathy.

Topo. ▼

◀ Offshore Onshore ▶

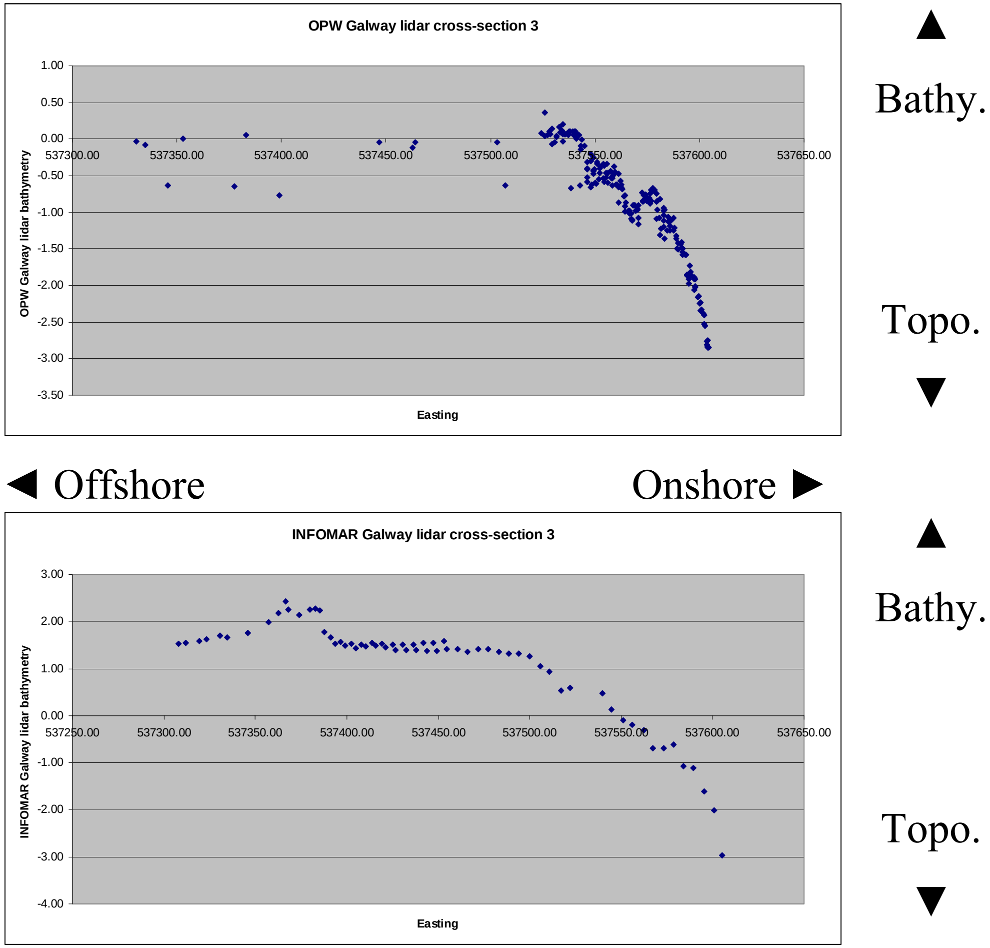


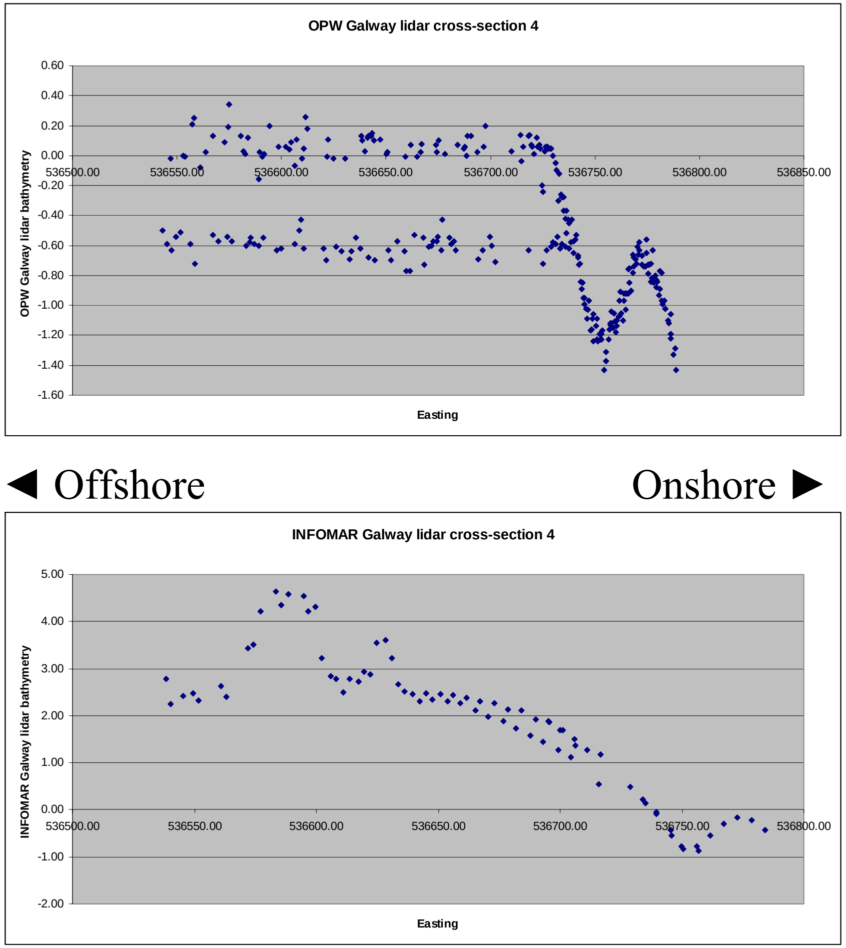
Top – Figure 4.6(a) Cross-section 1 OPW LiDAR

Bottom - Figure 4.6(b) Cross-section 1 INFOMAR LiDAR

Top – Figure 4.7(a) Cross-section 2 OPW LiDAR

Bottom - Figure 4.7(b) Cross-section 2 INFOMAR LiDAR



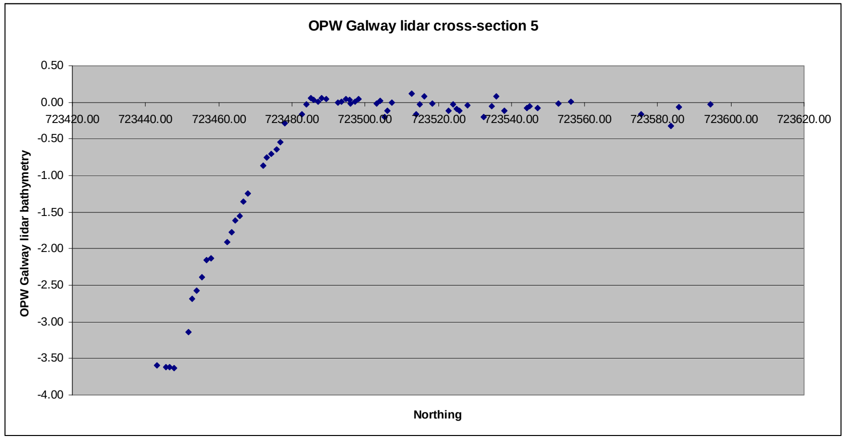


Top – Figure 4.8(a) Cross-section 3 OPW LiDAR

Bottom - Figure 4.8(b) Cross-section 3 INFOMAR LiDAR

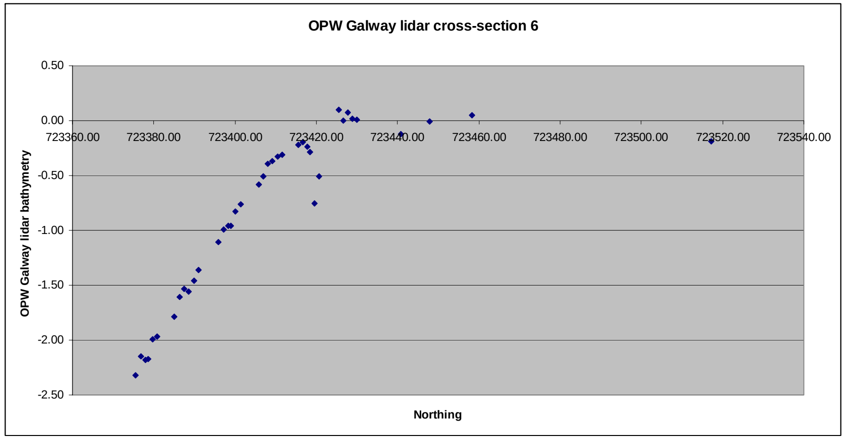
Top – Figure 4.9(a) Cross-section 4 OPW LiDAR

Bottom - Figure 4.9(b) Cross-section 4 INFOMAR LiDAR



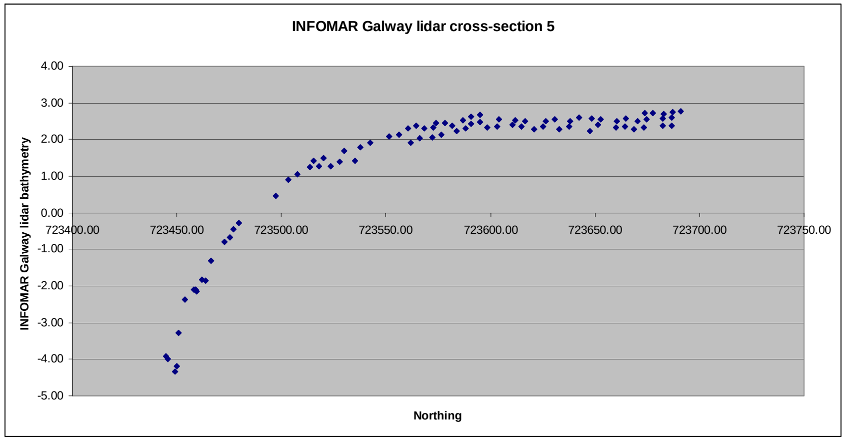
▲ Bathy.

Topo. ▼



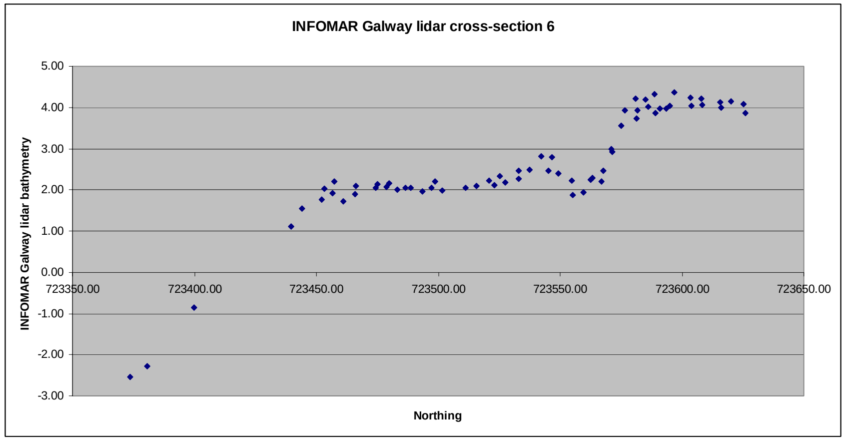
◀ Onshore Offshore ▶

◀ Onshore Offshore ▶



▲ Bathy.

Topo. ▼



Top – Figure 4.10(a) Cross-section 5 OPW LiDAR

Bottom - Figure 4.10(b) Cross-section 5 INFOMAR LiDAR

Top – Figure 4.11(a) Cross-section 6 OPW LiDAR

Bottom - Figure 4.11(b) Cross-section 6 INFOMAR LiDAR

The OPW offshore data corresponded closely with zero metres elevation in all six 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 must have been coincident with the top of the water column. Future OPW surveys may include bathymetric sensing capability, but for the moment it seems that the OPW data should only be considered for integration with the INFOMAR (bathymetric) LiDAR data if the OPW surveys have been conducted at low water. This appears to have been the case for the Sligo OPW LiDAR data.

4.2.6 Galway on2off back-transformation test

A back-transformation test was applied to the data transformed in Grid inquest in order to verify that transformation from ITM/Malin to ETRF/GRS80 matched up with the origin ETRF/GRS80 data. This provided an additional verification of the performance of the transformation, but was undertaken primarily to demonstrate the potential for onshore ITM/Malin datasets to be integrated with ETRF89/GRS80 data by means of transformation with Grid Inquest.

A test area consisting of 65,560 points was transformed and back-transformed from origin ETRF89/GRS80 (in decimal degrees defined to a precision of 12 places of decimal) to ITM/Malin metres and back using Grid Inquest. Origin latitude, longitude and ellipsoid heights were subtracted from their respective back-transformed equivalents. Differences between the original and back-transformed values were zero in all instances. This result suggested that onshore ITM/Malin datasets can be integrated with ETRF89/GRS80 data by means of transformation with Grid Inquest. However, as was noted at the outset, offshore-to-onshore integration is of more relevance to INFOMAR.

4.2.7 Galway off2on external validation

The height attribute within the INFOMAR and OPW LiDAR coverages for the Galway overlap area was transformed from Lowest Astronomical Tide to GRS80 ellipsoid using VORF. It should be noted at this point that both the OPW and the INFOMAR aerial LiDAR datasets were captured relative to ellipsoid (defined by GPS and Inertial Navigation System onboard the survey aircraft) and GPS ground control. Therefore the offshore-to-onshore LiDAR integration tests that are applied here tested VORF back-transformation performance only. It is important to stress this point. INFOMAR LiDAR data were provided relative to ellipsoid and LAT (personal communication, Blom Aerofilms, October 2009). However, these LAT-format data were derived from transformations of the origin ellipsoid data (using VORF). Therefore, these LAT data were not expected to be subject to tidal complications that typically affect bathymetric data captured relative to tidal surfaces from marine survey platforms. It should be noted that this report focuses upon the integration of onshore and offshore aerial LiDAR only. The very real difficulties that attach to bathymetric data captured from marine platforms do not cause problems for the integration of onshore and offshore aerial LiDAR data, so these issues are not addressed in this report.

Ellipsoid height was used as the elevation input for these interpolations. The OSi data were excluded in this case because this coverage is limited exclusively to onshore. The capacity for the OSi data to be integrated with the onshore component of the OPW and the INFOMAR datasets was demonstrated in sections 4.2.1 to 4.2.4. The OPW and INFOMAR GRS80 LiDAR surface models were subsequently validated with the post-processed FastStatic GPS data captured in the Galway LiDAR overlap area. The results of this external validation were very similar to the results noted in the *on2off* tests. The ± error ranges noted within the GRS80 interpolations were both within the ranges quoted by each data supplier, confirming that back-transformation from VORF LAT to ellipsoid introduced no significant errors (table 4.5). Critically, the close parity of the mean elevation value from the 50 validation points used for both validations suggested that no systematic offset was present either. Additional comparisons were carried out in six different subset areas to confirm these results.

OPW LiDAR validation	INFOMAR LiDAR validation
Count: 50	Count: 50
90% elevation error: ±0.34	90% elevation error: ±0.30
Max negative err: -1.03	Max negative err: -0.29
Max positive err: 1.02	Max positive err: 0.50
Mean: 0.04	Mean: 0.03
Std. Dev: 0.31	Std. Dev: 0.20

Table 4.5: Results of the *off2on* validation of OSi, OPW and INFOMAR LiDAR data for Galway

4.2.8 Galway off2on subset area elevation comparison

The same six subsets were used for the OPW and INFOMAR ellipsoid comparisons as were used in the Malin datum comparisons (section 4.2.3). The results were very similar to these previous tests. Mean OPW and INFOMAR ellipsoid heights were strikingly similar within the three 250m x 250m subset tests areas (table 4.6).

Subset area 1 (500m x 500m)

OPW data in subset 1	INFOMAR data in subset 1
Point count: ***198596***	***Point count:*** ***32592***
Minimum: 56.80	Minimum: 13.75
Maximum: 80.40	Maximum: 77.28
Mean: ***62.93***	***Mean:*** ***61.52***
Standard Deviation: 5.05	Std. Dev: 4.88

Subset area 2 (500m x 500m)

OPW data in subset 2	INFOMAR data in subset 2
Point count: ***155178***	***Point Count:*** ***30462***
Minimum: 56.82	Minimum: 55.62
Maximum: 76.82	Maximum: 77.02
Mean: ***58.81***	***Mean:*** ***58.31***
Standard Deviation: 2.42	Std. Dev: 2.51

Subset area 3 (500m x 500m)

OPW data in subset 3	INFOMAR data in subset 3
Point count: ***155608***	***Point Count:*** ***34404***
Minimum: 56.98	Minimum: 54.20
Maximum: 78.55	Maximum: 77.98
Mean: ***60.25***	***Mean:*** ***59.83***
Standard Deviation: 2.37	Std. Dev: 3.08

Subset area 4 (250m x 250m)

OPW data in subset 4	INFOMAR data in subset 4
Point count: ***126312***	***Point Count:*** ***11266***
Minimum: 57.82	Minimum: 57.60
Maximum: 65.95	Maximum: 65.84
Mean: ***60.42***	***Mean:*** ***60.34***
Standard Deviation: 0.91	Std. Dev: 0.97

Subset area 5 (250m x 250m)

OPW data in subset 5	INFOMAR data in subset 5
Point count: ***84878***	***Point Count:*** ***6084***
Minimum: 60.21	Minimum: 60.14
Maximum: 74.89	Maximum: 74.34
Mean: ***63.34***	***Mean:*** ***63.26***
Standard Deviation: 1.77	Std. Dev: 1.79

Subset area 6 (250m x 250m)

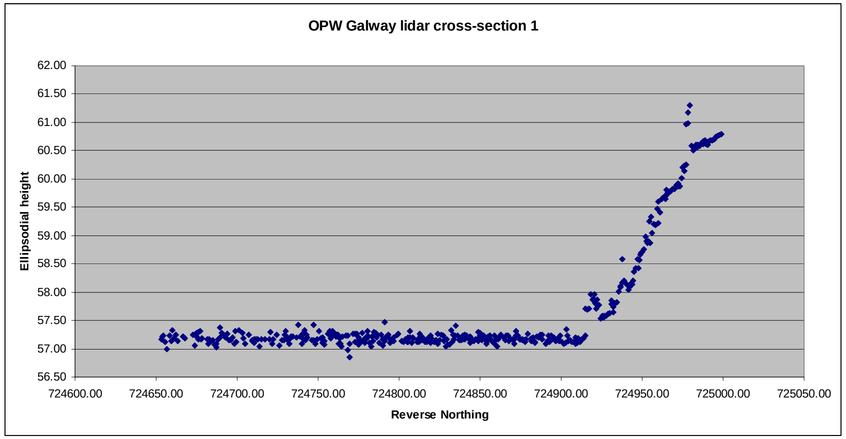
OPW data in subset 6	INFOMAR data in subset 6
Point count: ***99117***	***Point Count:*** ***6226***
Minimum: 62.82	Minimum: 62.87
Maximum: 83.58	Maximum: 83.54
Mean: ***74.63***	***Mean:*** ***74.98***
Standard Deviation: 3.37	Std. Dev: 3.52

Table 4.6: Comparison of mean ellipsoidal height statistics in each of the six Galway subset areas.

This appeared to confirm the viability of LiDAR integration from offshore to onshore based on the use of ellipsoid. However, similar to the datum comparison subset tests carried out in section 4.2.3, the 500m x 500m subset test areas were characterised by slight variations. Mean elevation differences of 1.41m in subset area 1, 0.5m in subset area 2, and 0.42m were noted between the OPW and INFOMAR LiDAR elevation values in subset area 3. These were very similar to results noted in the Malin datum subset comparison tests. Some differences were to be expected, because confidence intervals of approximately 0.12m attached to every point when the data were back-transformed from VORF. More importantly however, the striking similarity of the differences noted between the mean ellipsoidal heights in the 500m x 500m subset test areas (relative to the Galway *on2off* tests) suggested the same cause noted previously (i.e. the representation of the water surface in the OPW data). The same six cross-sections that were used in the ITM/Malin on2off integration tests (figure 4.3) were used once more to verify this supposition.

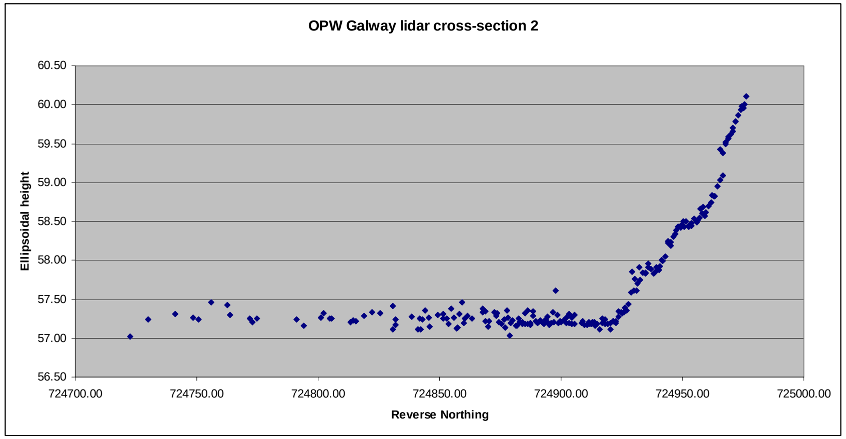
4.2.9 Tralee on2off offshore-mismatch analysis

Similar to the pattern observed previously. The offshore component of the OPW data closely corresponded with an apparent water surface (coincident with an ellipsoidal height of approximately 57.25 metres) in all six cases. There was evidence of laser return variability in cross-sections three and four. As postulated previously, this may have been due to the presence of swell in this area during data acquisition. Bathymetry was graphed against distance along the same six cross-sections that were used in the *on2off* tests (figure 4.3). The results of this analysis are presented in figures 4.12 to 4.17 in the subsequent three pages.



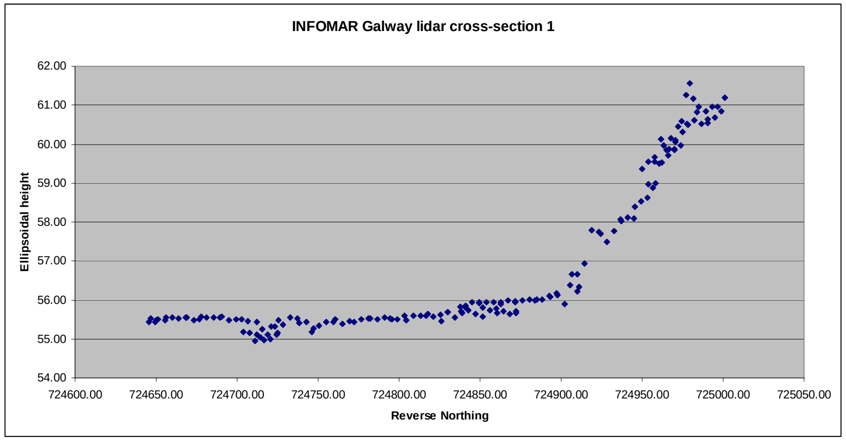
▲ Topo.

Bathy. ▼



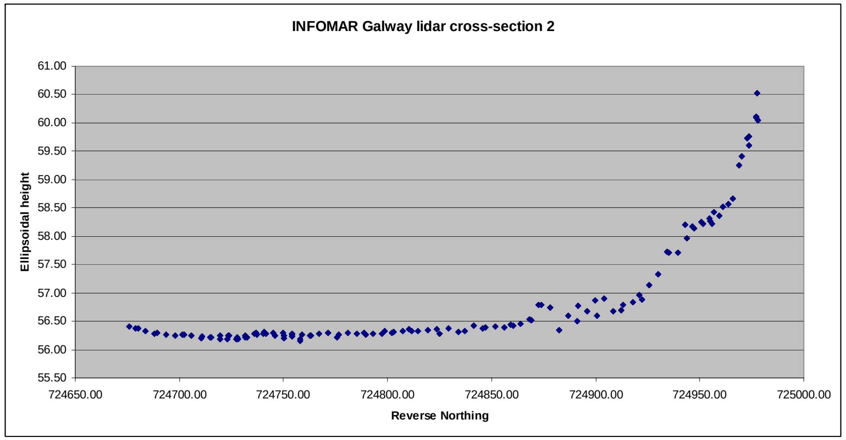
◀ Offshore Onshore ▶

◀ Offshore Onshore ▶



▲ Topo.

Bathy. ▼

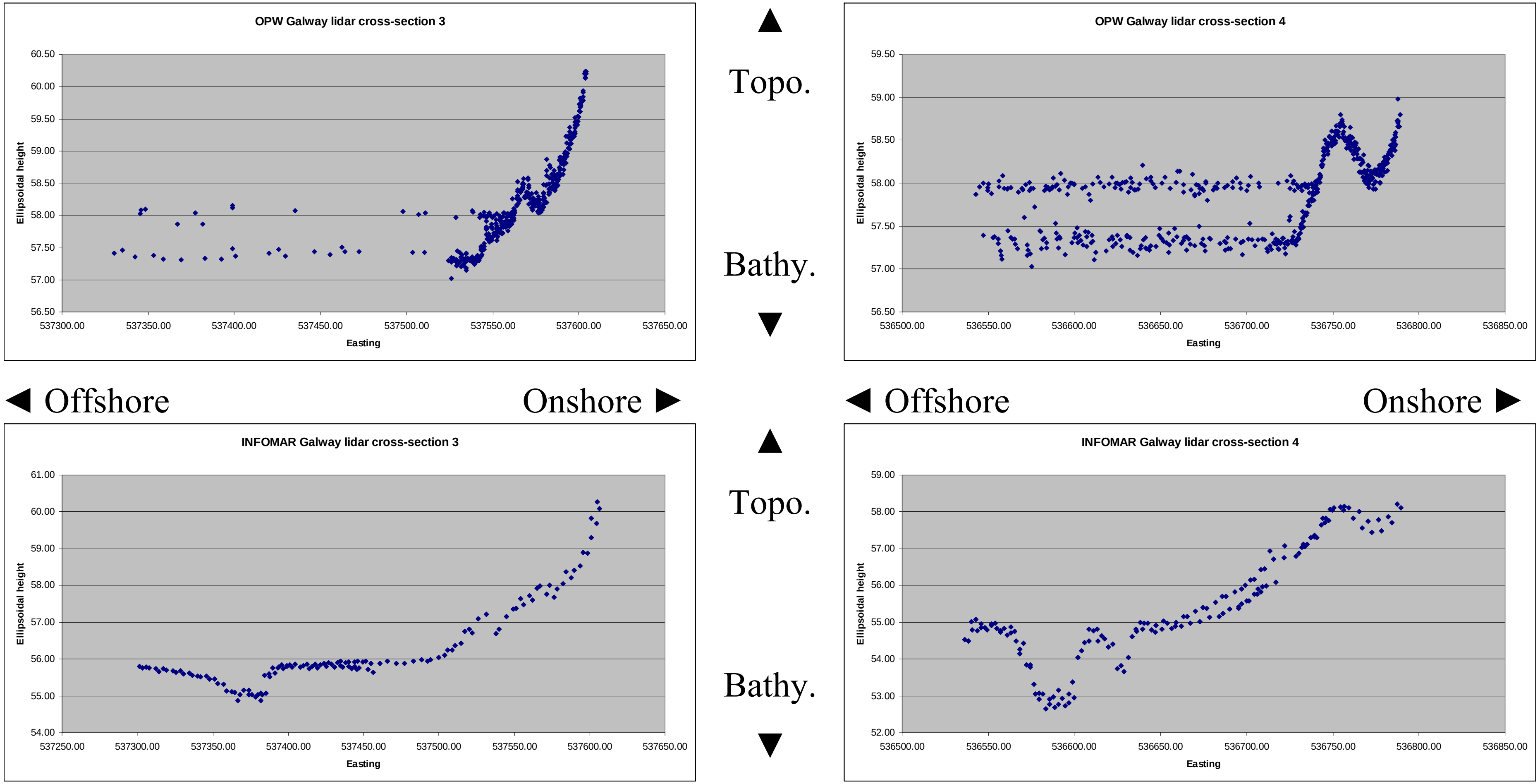


Top – Figure 4.12(a) Cross-section 1 OPW LiDAR

Bottom - Figure 4.12(b) Cross-section 1 INFOMAR LiDAR

Top – Figure 4.13(a) Cross-section 2 OPW LiDAR

Bottom - Figure 4.13(b) Cross-section 2 INFOMAR LiDAR

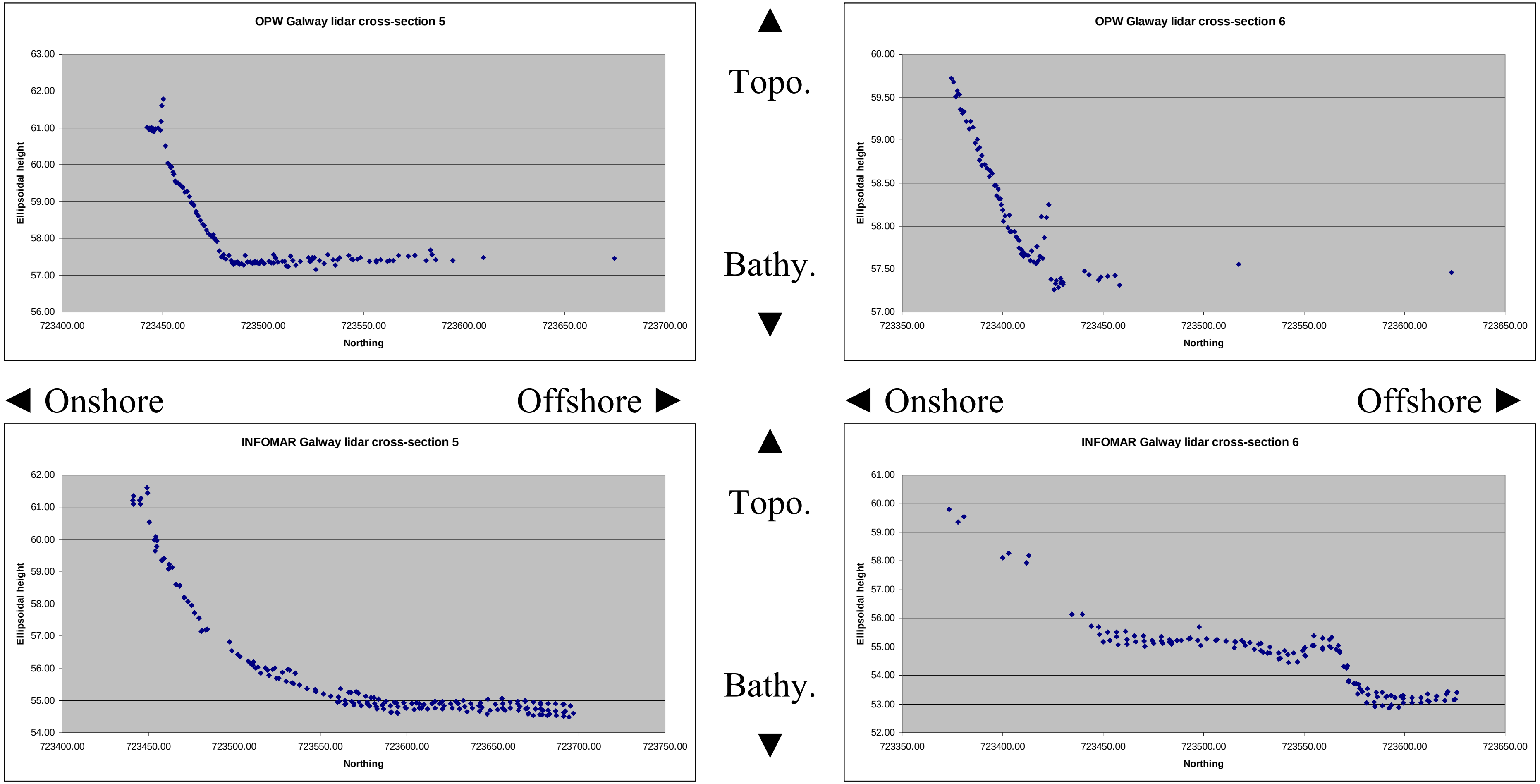


Top – Figure 4.14(a) Cross-section 3 OPW LiDAR

Bottom - Figure 4.14(b) Cross-section 3 INFOMAR LiDAR

Top – Figure 4.15(a) Cross-section 4 OPW LiDAR

Bottom - Figure 4.15(b) Cross-section 4 INFOMAR LiDAR



Top – Figure 4.16(a) Cross-section 5 OPW LiDAR

Bottom - Figure 4.16 (b) Cross-section 5 INFOMAR LiDAR

Top – Figure 4.17(a) Cross-section 6 OPW LiDAR

Bottom - Figure 4.17(b) Cross-section 6 INFOMAR LiDAR

4.3 Tralee

4.3.1 Tralee on2off transformation

The OSi data for Tralee were supplied in ITM/Malin format. The OPW data for Tralee were supplied referenced to ETRF89 / GRS80. These data were transformed to ITM / Malin x,y,z metres using Grid Inquest. The INFOMAR LiDAR data for the Galway 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. Individual tables were used for each of the OSi, OPW and INFOMAR data coverages, and a single combined data table was used to accommodate all three datasets in an integrated OSi, OPW, INFOMAR LIDAR coverage referenced against ITM / Malin. The source-specific ITM / Malin LiDAR data tables were externally validated with very high-accuracy post processed FastStatic GPS survey data (see section 4.3.2) and were compared against one another (section 4.3.3) the combined ITM/Malin data table was

4.3.2 Tralee on2off external validation

Once again the best fifty GPS validation points were used. The maximum elevation error (relative to ellipsoid) highlighted by post-processing among the 50 GPS points used for external validation was 1centimetre (see Appendix 1c for Tralee GPS accuracy statistics) confirming its suitability for LiDAR validation. Validation was carried out in ArcGIS / ArcInfo using Geostatistical Analyst by quantifying the difference between GPS elevation and LiDAR elevation at each of fifty locations for each of the LiDAR datasets tested. Summary statistics for the OSi LiDAR DSM, the OPW LiDAR and INFOMAR LiDAR DEM validations are outlined in table 4.7.

OSi LiDAR validation	OPW LiDAR validation	INFOMAR LiDAR validation
Count: 50	Count: 50	Count: 50
90% elevation error: ±0.38	90% elevation error: ±0.13	90% elevation error: ±0.35
Max negative err: -0.51	Max negative err: -0.30	Max negative err: -0.47
Max positive err: 0.64	Max positive err: 0.27	Max positive err: 0.54
Mean: 0.11	Mean: -0.01	Mean: -0.03
Std. Dev: 0.20	Std. Dev: 0.09	Std. Dev: 0.26

Table 4.7: Results of external *on2off* validation of OSi, OPW and INFOMAR LiDAR data for Tralee

4.3.3 Tralee on2off subset area elevation comparison

Six subset areas were selected within the Tralee LiDAR overlap area (figure 4.18) to see if any systematic differences could be detected between the three LiDAR datasets tested. Elevation statistics (mean elevation) was evaluated in the six overlap areas used for the comparative tests (table 4.8). Similar to the previous subset area tests, three 500m x 500m and three 250m x 250m subset areas were selected.

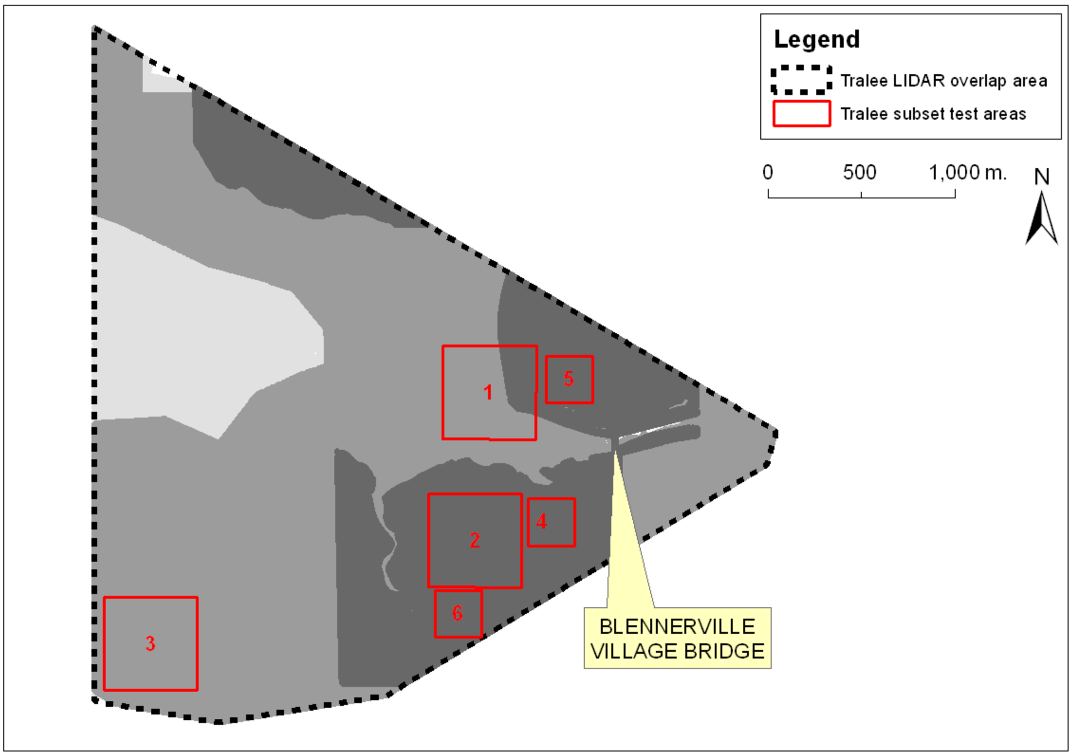


Figure 4.18: Subset areas selected for Tralee subset area LiDAR elevation comparative tests.

The 500m x 500m areas focused mainly on the comparison of the OPW and the INFOMAR data in the Littoral zone, but subset 2 did allow comparison of mean elevation values in all three LiDAR datasets (table 4.8). The 250m x 250m subsets focused on comparison of all three datasets (table 4.8) onshore. Comparison areas were selected on the basis of avoiding the presence or absence of urban structures or forest cover during cross comparison. Mean elevation statistics for each dataset were compared in each subset area to see if any systematic elevation differences could be noted between the three LiDAR datasets tested.

Mean elevation values for each dataset in each 250m x 250m subset areas were strikingly similar, and were comfortably within the ± elevation accuracy ranges quoted by each data supplier. This provided backup for the results of the external validation, indicating that transformation of the OPW and INFOMAR LIDAR data from ETRF89/GRS80 to ITM/Malin did not introduce any detectable elevation error into either dataset. Subset area six (250m x 250m) performed least well, though entirely satisfactorily, which may have reflected the small number of INFOMAR lidar points in this subset area six (3123) in relation to the OSI data in subset area six (15625) and the OPW data points (99114) in subset area six (table X.X).

Subset area 1 (500m x 500m)

OPW data in subset 1		INFOMAR data in subset 1		OSi data in subset 1	
Point count:	***258070***	***Point count:***	***12229***		
Minimum:	-32.6	Minimum:	-17.79	*INSUFFICIENT OVERLAP FOR VALID ANALYSIS*	
Maximum:	0.42	Maximum:	1.28		
Mean: -2.43		***Mean: -2.22***			
Std. Dev:	1.85	Std. Dev:	1.51		

Subset area 2 (500m x 500m)

OPW data in subset 2		INFOMAR data in subset 2		OSI data in subset 2	
Point count:	***454782***	***Point count:***	***10694***	***Point count:***	***249170***
Minimum:	-14.14	Minimum:	-13.27	Minimum:	-9.83
Maximum:	-2.14	Maximum:	-2.28	Maximum:	-2.22
Mean: -7.20		***Mean: -6.96***		***Mean: -6.94***	
Std. Dev:	1.29	Std. Dev:	1.27	Std. Dev:	1.20

Subset area 3 (500m x 500m)

OPW data in subset 3		INFOMAR data in subset 3		OSi data in subset 3	
Point count:	***429172***	***Point count:***	***10096***		
Minimum:	-27.56	Minimum:	-27.25		
Maximum:	-0.24	Maximum:	-0.34	*NO OVERLAP WITH OTHER LIDAR DATASETS*	
Mean: -5.87		***Mean: -5.75***			
Std. Dev:	3.44	Std. Dev:	3.41		

Subset area 4 (250m x 250m)

OPW data in subset 4		INFOMAR data in subset 4		OSi data in subset 4	
Point count:	***130081***	***Point count:***	***2541***	***Point count:***	***61064***
Minimum:	-23.18	Minimum:	-10.42	Minimum:	-6.28
Maximum:	-0.63	Maximum:	-0.67	Maximum:	-0.25
Mean: -3.01		***Mean: -2.89***		***Mean: -2.86***	
Std. Dev:	1.38	Std. Dev:	1.37	Std. Dev:	1.24

Subset area 5 (250m x 250m)

OPW data in subset 5		INFOMAR data in subset 5		OSi data in subset 5	
Point count:	***64563***	***Point count:***	***3821***	***Point count:***	***62786***
Minimum:	-7.95	Minimum:	-6.44	Minimum:	-5.58
Maximum:	-1.58	Maximum:	-1.47	Maximum:	-1.6
Mean: -3.73		***Mean: -3.49***		***Mean: -3.50***	
Std. Dev:	0.79	Std. Dev:	0.88	Std. Dev:	0.76

Subset area 6 (250m x 250m)

OPW data in subset 6		INFOMAR data in subset 6		OSi data in subset 6	
Point count:	***108811***	***Point count:***	***2661***	***Point count:***	***62750***
Minimum:	-10.94	Minimum:	-8.94	Minimum:	-6.74
Maximum:	-3.02	Maximum:	-3.27	Maximum:	-3.03
Mean: -5.68		***Mean: -5.44***		***Mean: -5.51***	
Std. Dev:	0.62	Std. Dev:	0.63	Std. Dev:	0.50

Table 4.8: Comparison of mean ellipsoidal height statistics in each of the six Tralee subset areas.

4.3.4 Tralee on2off visual verification test

The three LiDAR datasets were integrated into a single data coverage in Microsoft Access (used because of the large file size and to facilitate data transferability) and the integrated data were subsequently visualised in ArcGIS to provide an additional visual confirmation of integration performance (figure 4.19).

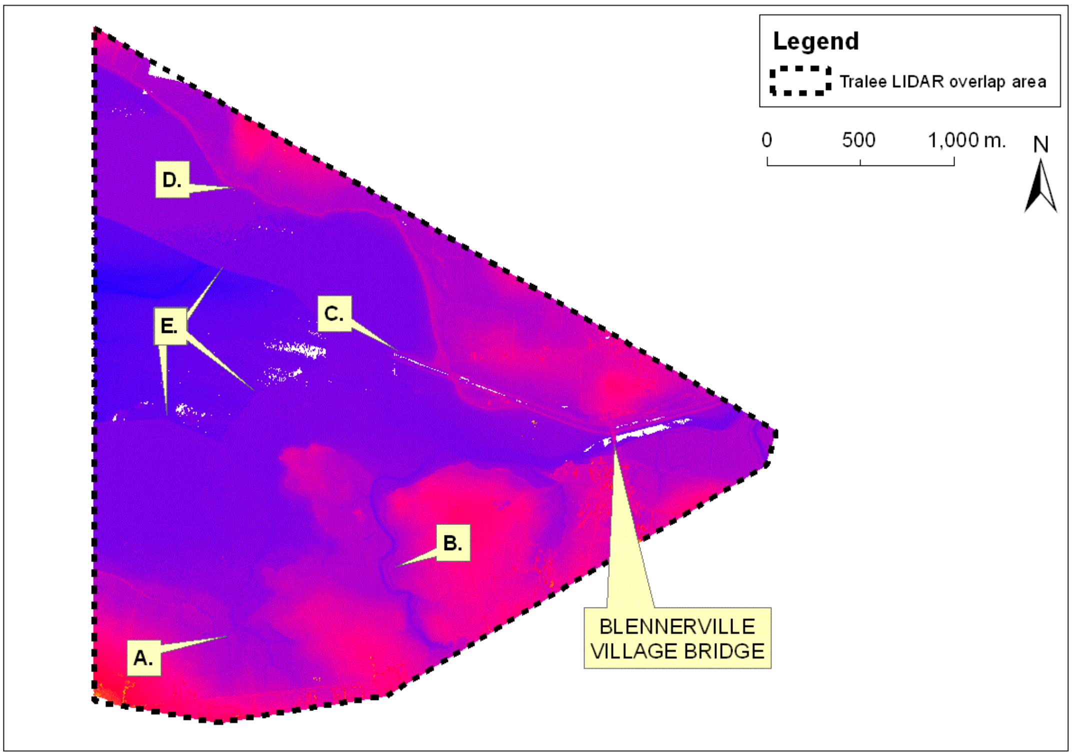


Figure 4.19: Visualisation of combined OSi, OPW and INFOMAR LiDAR data for Tralee integrated onto ITM coordinates and Malin datum.

The clarity with which relatively subtle features were highlighted in the combined OSi, OPW, INFOMAR data provided visual confirmation of integration performance. 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. These features were present in all three datasets, and their clear delineation in the integrated dataset confirmed that no significant problems derived from the transformation of OPW and INFOMAR data in ETRF89/GRS80 format to ITM/Malin format. However, additional problems did occur. The elevation mismatches that were noted in the subset area tests were clearly evident in figure 4.19. The appearance of the mismatch areas suggested a uniform surface coincident with a water surface in the OPW data. Further analysis was required to explore this question.

4.3.5 Tralee on2off offshore mismatch analysis

Similar to the Galway tests, six cross sections were applied to the offshore OPW and INFOMAR data for the Tralee LiDAR overlap area. These were targeted at the problem areas noted in section 4.3.4. The relationship of the six cross-sections to the Sligo LiDAR data coverage are outlined in figure 4.20. Cross-sections were aligned to northings or eastings to provide spatial ordering for cross-comparison of the OPW and INFOMAR data values on each cross-section.

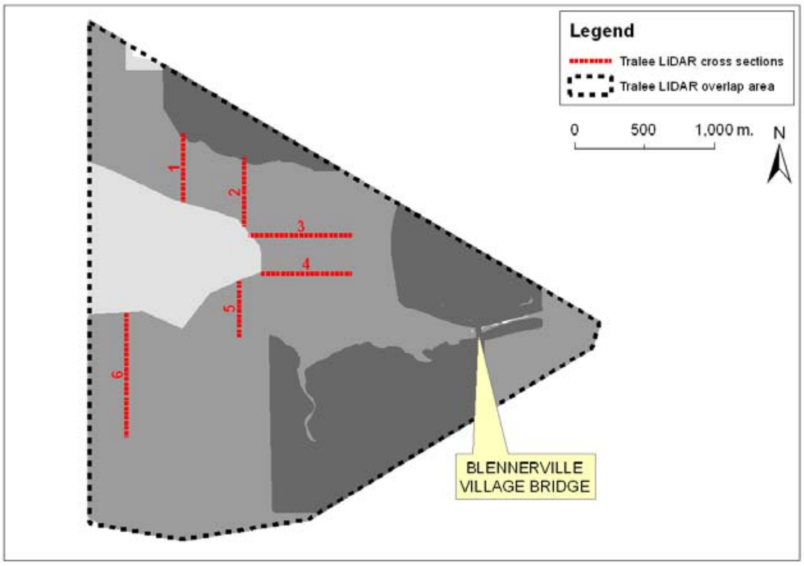


Figure 4.20(a): Cross-sections used to assess offshore elevation values in OPW data (displayed in relation to Tralee LiDAR coverages).

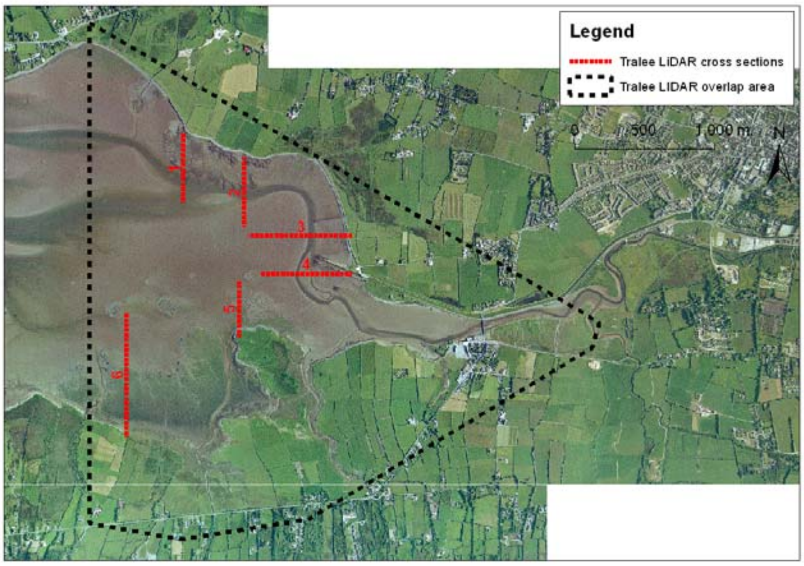
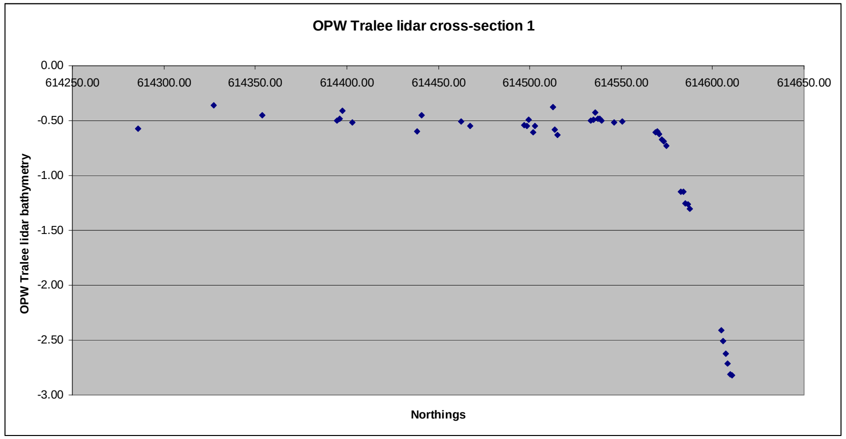


Figure 4.20(b): Cross-sections used to assess offshore elevation values in OPW data (displayed in relation to OSi Orthoimagery.

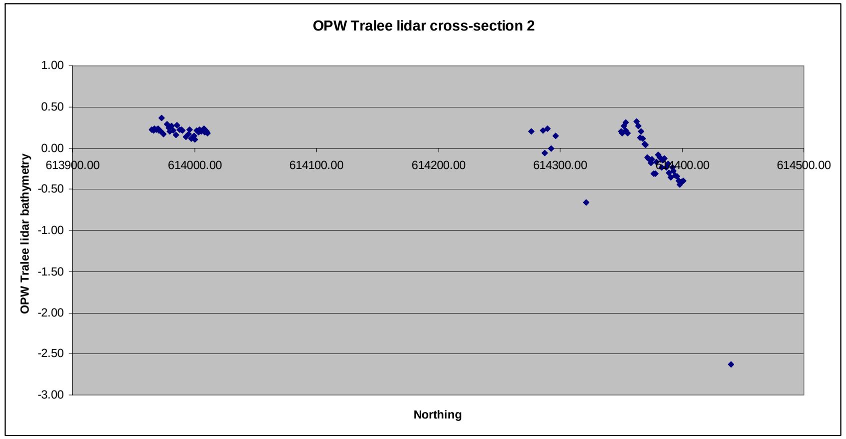
Orthoimage data provided to NCG courtesy of Stephen Curran Ordnance Survey Ireland, 2009.

Similar to the case observed in the Galway LIDAR overlap area, the OPW data closely corresponded with zero metres elevation along all six cross-sections. There was some slight evidence of laser return variation in cross-sections three and four, but in general the OPW LiDAR returns corresponded with a surface appear to have been coincident with the top of the water column (figures 4.21 to 4.26).



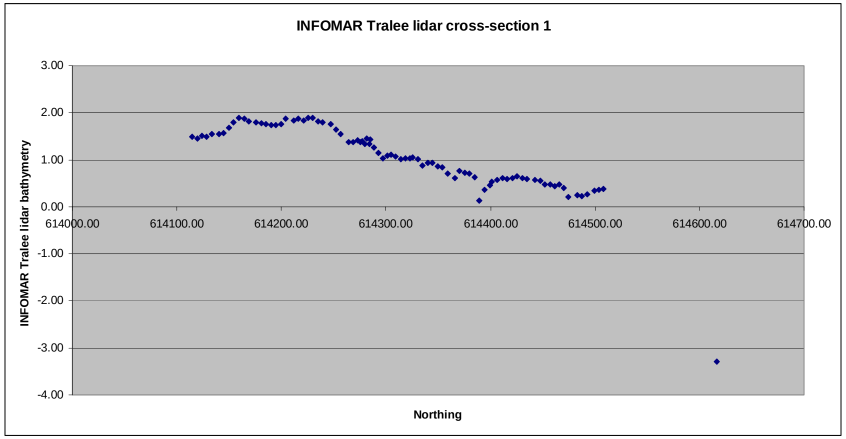
▲ Bathy.

Topo. ▼



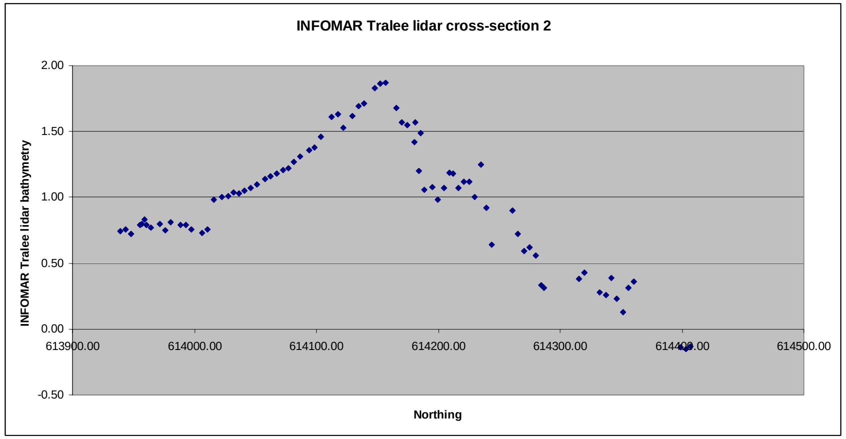
◀ Offshore Onshore ▶

◀ Offshore Onshore ▶



▲ Bathy.

Topo. ▼

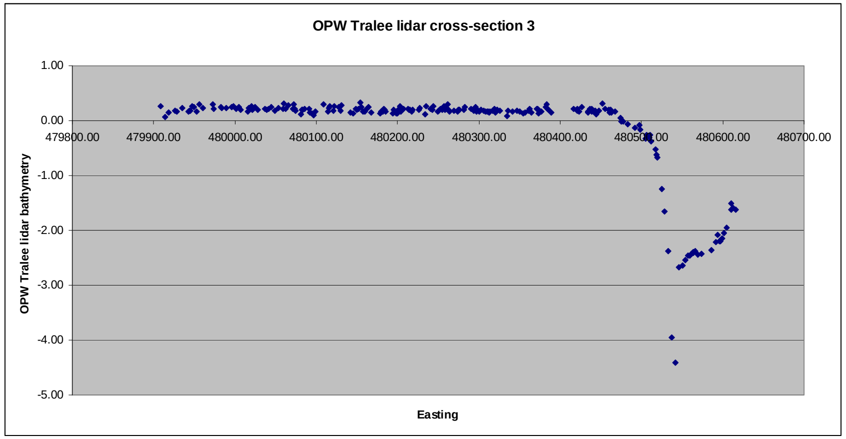


Top – Figure 4.21(a) Cross-section 1 OPW LiDAR

Bottom - Figure 4.21(b) Cross-section 1 INFOMAR LiDAR

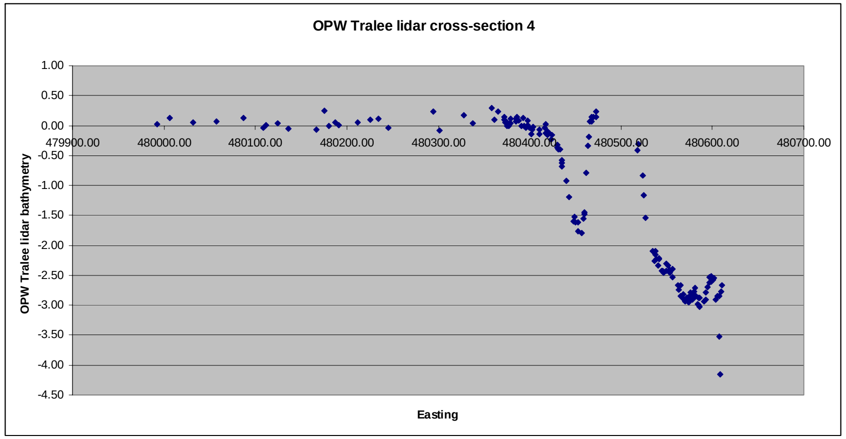
Top – Figure 4.22(a) Cross-section 2 OPW LiDAR

Bottom - Figure 4.22(b) Cross-section 2 INFOMAR LiDAR



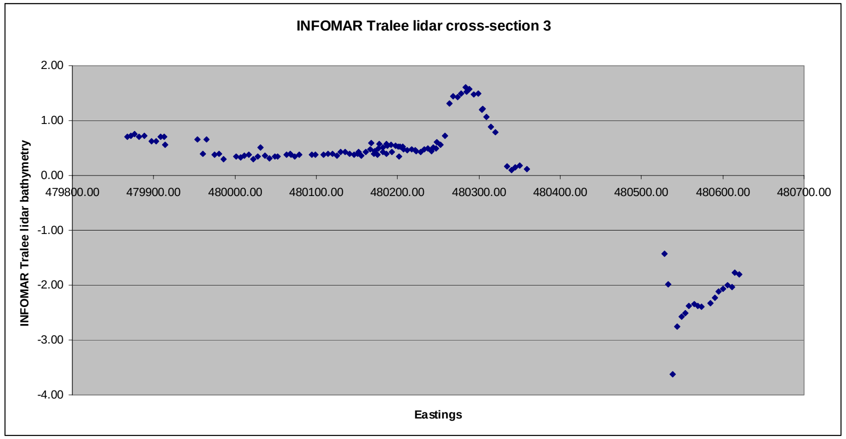
▲ Bathy.

Topo. ▼



◀ Offshore Onshore ▶

◀ Offshore Onshore ▶



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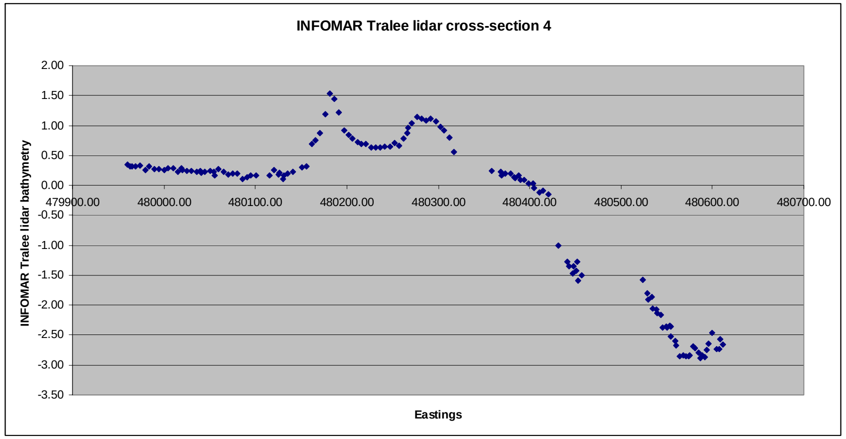
Topo. ▼

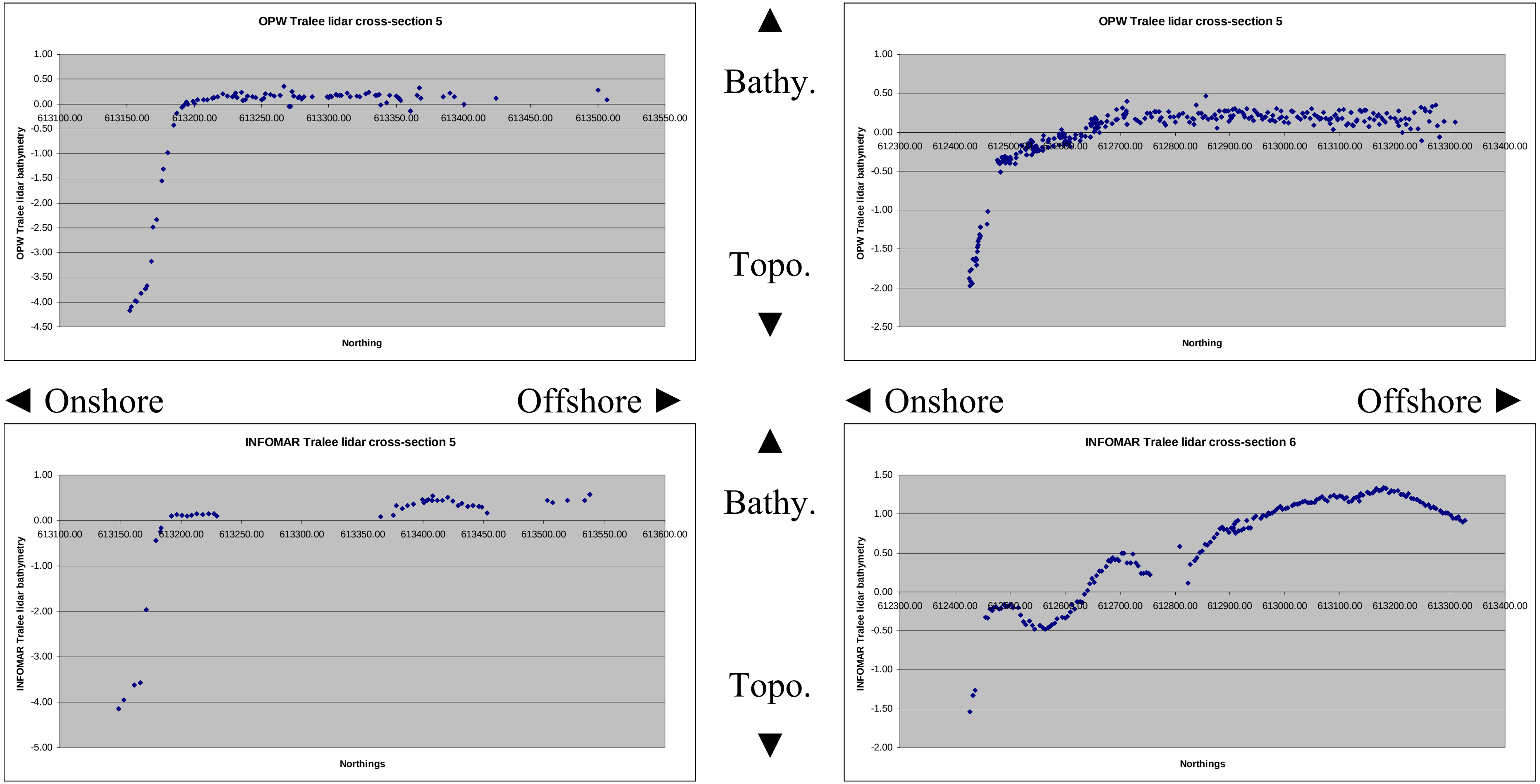


Top – Figure 4.23(a) Cross-section 3 OPW LiDAR

Bottom - Figure 4.23(b) Cross-section 3 INFOMAR LiDAR

Top – Figure 4.24(a) Cross-section 4 OPW LiDAR

Bottom - Figure 4.24(b) Cross-section 4 INFOMAR LiDAR



Top – Figure 4.25(a) Cross-section 5 OPW LiDAR

Bottom - Figure 4.25(b) Cross-section 5 INFOMAR LiDAR

Top – Figure 4.26(a) Cross-section 6 OPW LiDAR

Bottom - Figure 4.26(b) Cross-section 6 INFOMAR LiDAR

The issue of the OPW coinciding with the top of the water column was caused by the survey method used for the capture of the OPW data. The OPW data are characterised by an overlap into the Littoral domain, but the focus of these surveys was on the terrestrial domain. Terrestrial LiDAR surveys use one laser to capture features onshore and to provide a clear definition of the water's edge. Bathymetric LiDAR on the other hand use two lasers; an infrared being used to define the top of the water column and a green being employed to penetrate the water column to define depth to the seafloor. Bathymetric LiDAR also uses slower laser pulse rate interval in order to accommodate longer / higher energy laser pulses to penetrate the water column (Source: Fugro-Pelagos. http://www.fugro-pelagos.com/lidar/tech/lidar_bathy.html). The OPW LiDAR data did not define the depth to seafloor in the Tralee LiDAR overlap area because the OPW data were captured using an onshore aerial laser mapping system. However, it should be noted that the OPW onshore LiDAR surveys may extend meaningfully into the Littoral zone (as was observed in the Sligo LiDAR overlap area) if the LiDAR data have been captured during low water conditions.

4.3.6 Tralee on2off back-transformation test

The back-transformation test that was applied to the Galway data was correct to twelve places of decimal (metres) in each of the 65,560 points tested. Consequently it was deemed unnecessary to repeat the same test for the Tralee test area.

4.3.7 Tralee off2on external validation

The results of this external validation were very similar to the results noted in the *on2off* and in the Galway *off2on* tests. The ± error ranges noted within the GRS80 interpolations were both within the ranges quoted by each data supplier, confirming that back-transformation from VORF LAT to ellipsoid introduced no significant errors (table 4.9). The close parity of the mean elevation value from the 50 validation points used for both validations again suggested that no systematic offset was present either. Additional comparisons were carried out in six different subset areas to confirm these results.

OPW LiDAR validation	INFOMAR LiDAR validation
Count: 50	Count: 50
90% elevation error: ±0.12	90% elevation error: ±0.34
Max negative err: -0.17	Max negative err: -0.56
Max positive err: 0.25	Max positive err: 0.434233
Mean: 0.015	Mean: 0.005
Std. Dev: 0.08	Std. Dev: 0.26

Table 4.9: Results of the *off2on* validation of OSi, OPW and INFOMAR LiDAR data for Tralee

4.3.8 Tralee off2on subset area elevation comparison

The same six subsets were used as were used in the Malin datum comparisons (section 4.2.3) and the results were again very similar to the results noted in the Tralee ITM/Malin LiDAR comparison tests. Mean OPW and INFOMAR ellipsoid heights were again strikingly similar within the three 500m x 500m and 250m x 250m subset tests areas (table 4.10).

Subset area 1 (500m x 500m)

OPW data in subset 1		INFOMAR data in subset 1	
Point count:	***258107***	***Point count:***	***12229***
Minimum:	57.92	Minimum:	57.06
Maximum:	90.94	Maximum:	76.13
Mean: 60.77		***Mean: 60.55***	
Std Dev:	1.84	Std Dev: 1.50	

Subset area 2 (500m x 500m)

OPW data in subset 2		INFOMAR data in subset 2	
Point count:	***454769***	***Point count:***	***10694***
Minimum:	60.48	Minimum:	60.62
Maximum:	72.49	Maximum:	71.62
Mean: 65.55		***Mean: 65.31***	
Std Dev:	1.29	Std Dev: 1.27	

Subset area 3 (500m x 500m)

OPW data in subset 3		INFOMAR data in subset 3	
Point count:	***429151***	***Point count:***	***10096***
Minimum:	58.61	Minimum:	58.71
Maximum:	85.95	Maximum:	85.64
Mean: 64.25		***Mean: 64.13***	
Std Dev:	3.44	Std Dev: 3.41	

Subset area 4 (250m x 250m)

OPW data in subset 4		INFOMAR data in subset 4	
Point count:	***130113***	***Point count:***	***2541***
Minimum:	58.97	Minimum:	59.01
Maximum:	81.52	Maximum:	68.77
Mean: 61.35		***Mean: 61.24***	
Std Dev:	1.38	Std Dev: 1.37	

Subset area 5 (250m x 250m)

OPW data in subset 5		INFOMAR data in subset 5	
Point count:	***64559***	***Point count:***	***3821***
Minimum:	59.91	Minimum:	59.80
Maximum:	66.28	Maximum:	64.77
Mean: 62.06		***Mean: 61.82***	
Std Dev:	0.79	Std Dev:0.87	

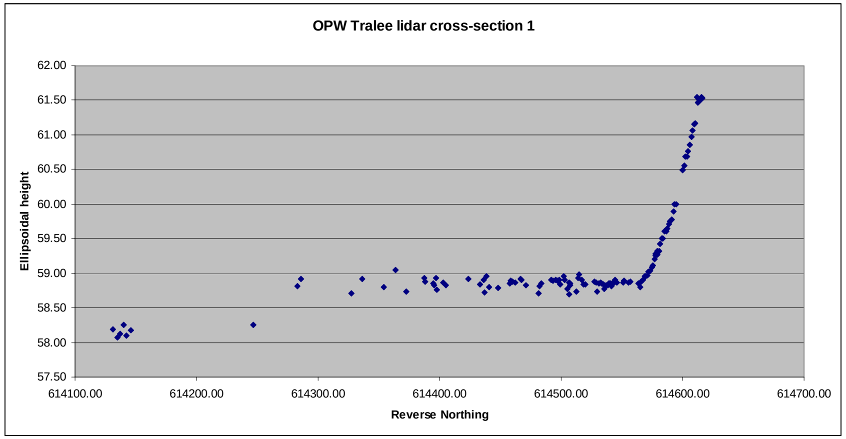
Subset area 6 (250m x 250m)

OPW data in subset 6		INFOMAR data in subset 6	
Point count:	***108802***	***Point count:***	***2661***
Minimum:	61.38	Minimum:	61.63
Maximum:	69.29	Maximum:	67.30
Mean: 64.04		***Mean: 63.80***	
Std Dev:	0.61	Std Dev:0.62	

Table 4.10: Comparison of mean ellipsoidal height statistics in each of the six subset areas.

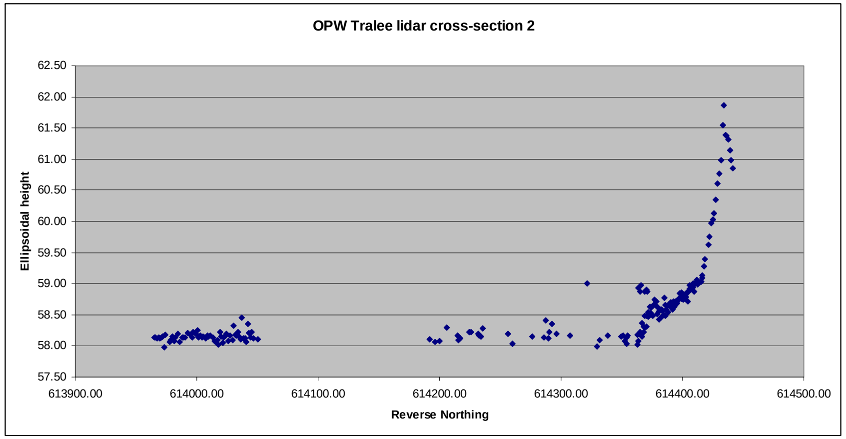
4.3.9 Tralee off2on offshore-mismatch analysis

The same six cross-sections that were used in the ITM/Malin on2off integration tests (section 4.3.5) were used once more to determine if the small differences could be attributed I part tot eh presence of a water surface in the OPW data. The same patterns noted in section 4.3.5 were again noted in the off2on LiDAR integration tests (figures 4.27 to 4.32).



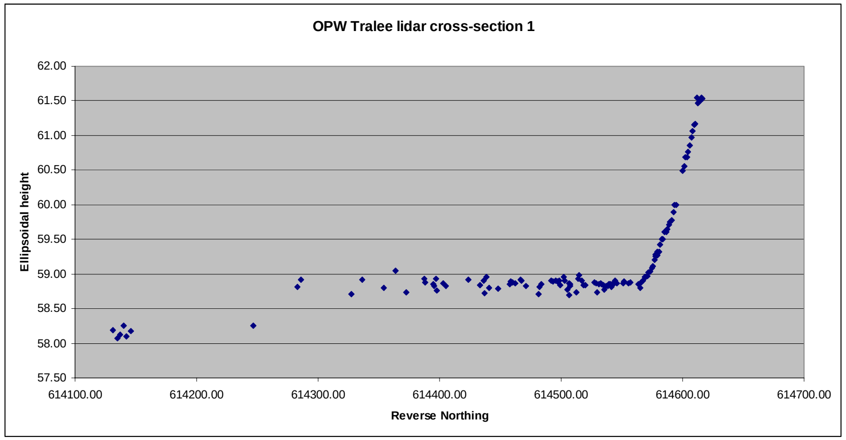
▲ Topo.

Bathy. ▼



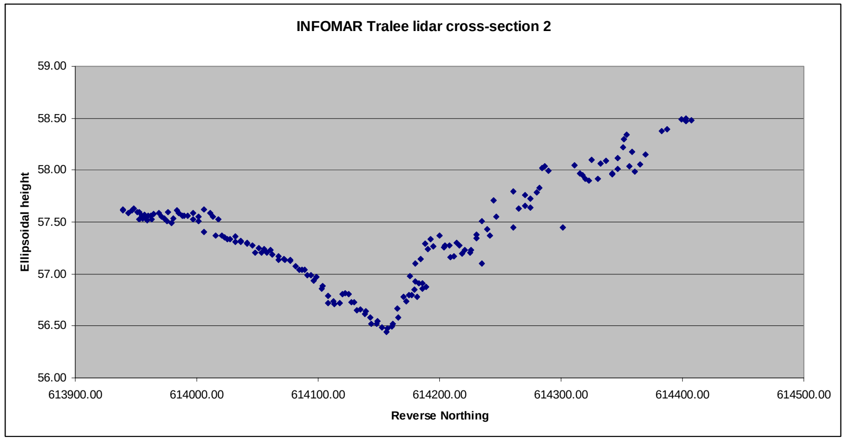
◀ Offshore Onshore ▶

◀ Offshore Onshore ▶



▲ Topo.

Bathy. ▼

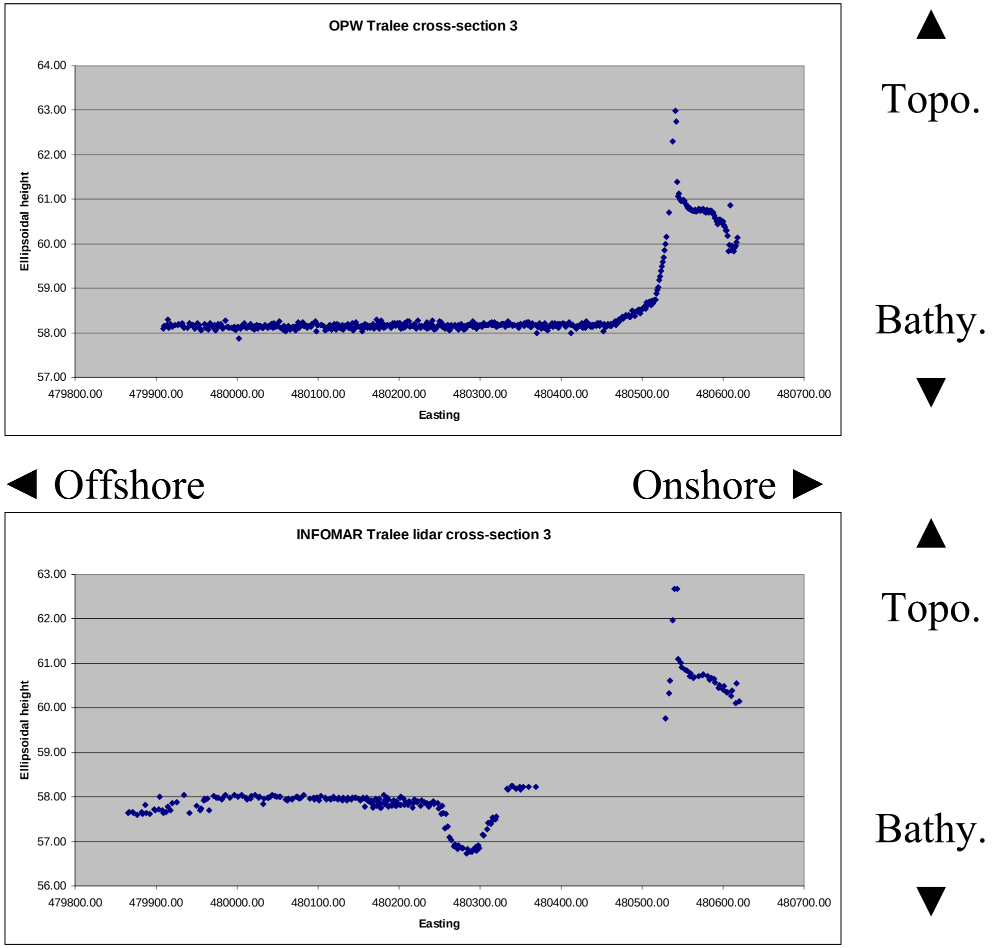


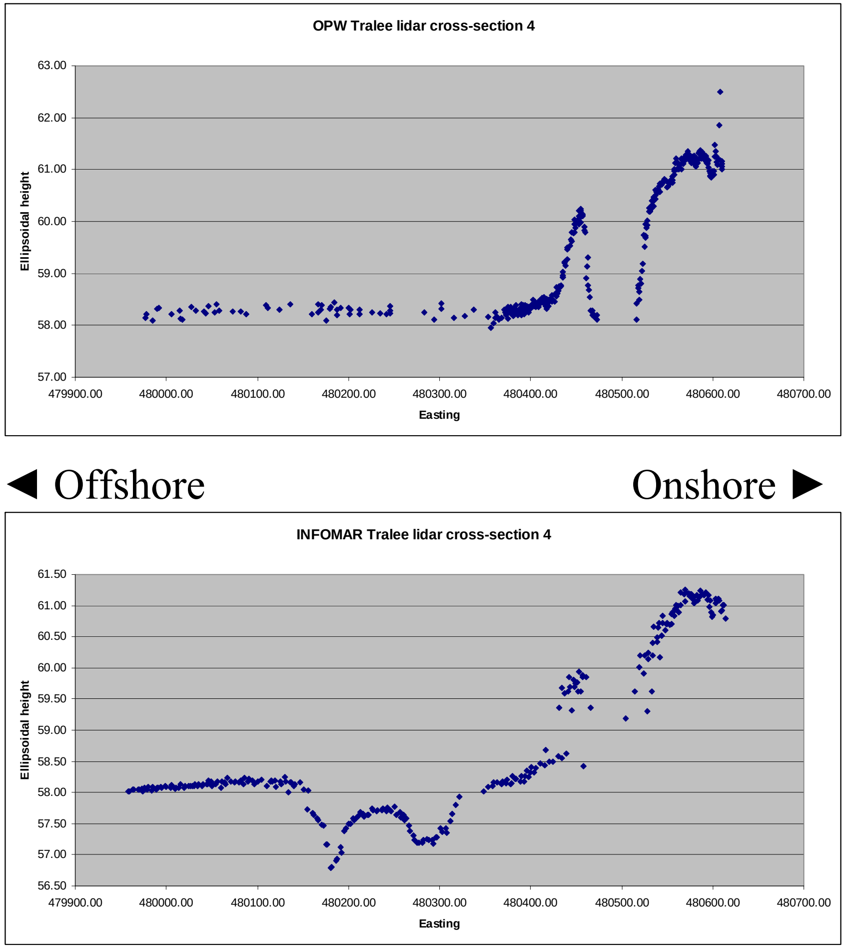
Top – Figure 4.27(a) Cross-section 1 OPW LiDAR

Bottom - Figure 4.27(b) Cross-section 1 INFOMAR LiDAR

Top – Figure 4.28(a) Cross-section 2 OPW LiDAR

Bottom - Figure 4.28(b) Cross-section 2 INFOMAR LiDAR



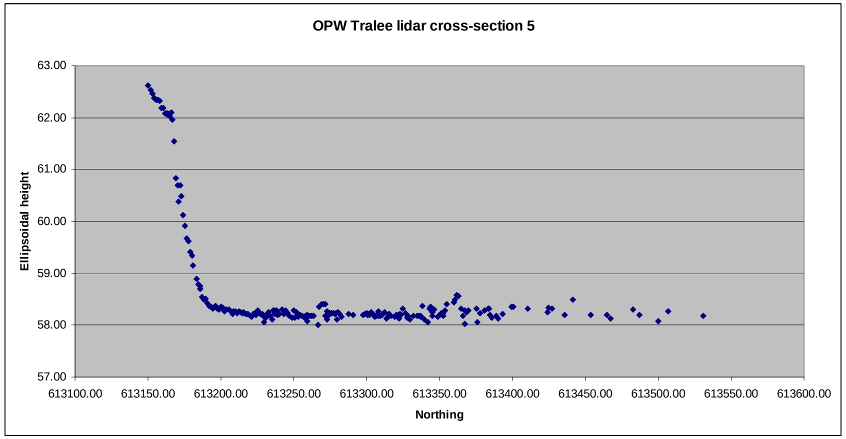


Top – Figure 4.29(a) Cross-section 3 OPW LiDAR

Bottom - Figure 4.29(b) Cross-section 3 INFOMAR LiDAR

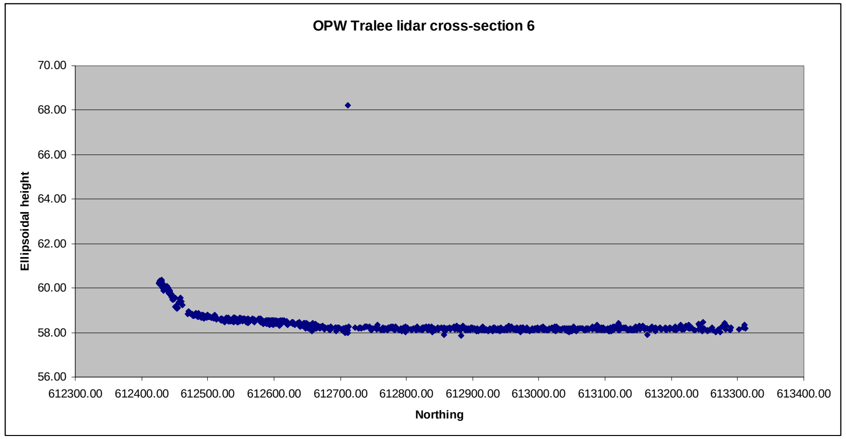
Top – Figure 4.30(a) Cross-section 4 OPW LiDAR

Bottom - Figure 4.30(b) Cross-section 4 INFOMAR LiDAR



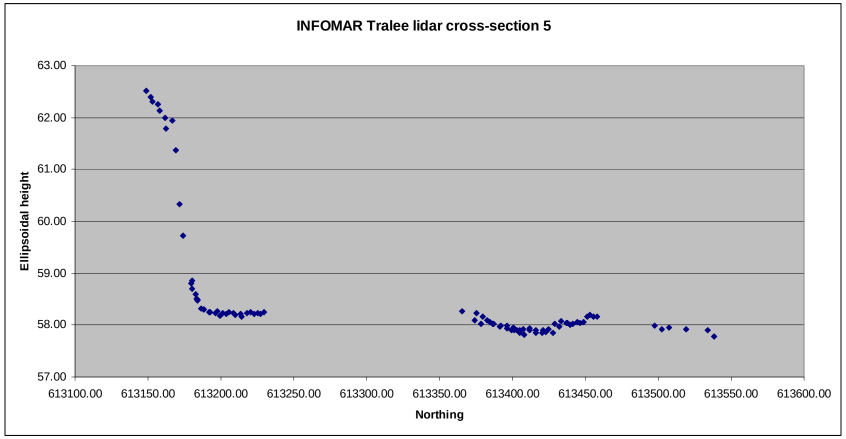
▲ Topo.

Bathy. ▼



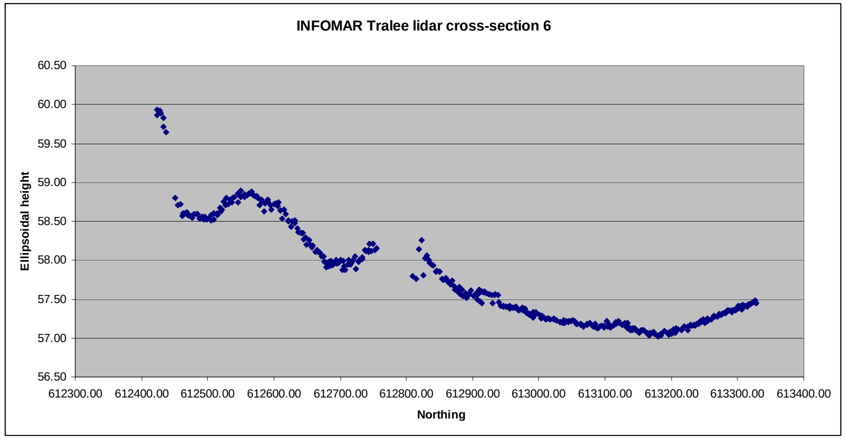
◀ Onshore Offshore ▶

◀ Onshore Offshore ▶



▲ Topo.

Bathy. ▼



Top – Figure 4.31(a) Cross-section 5 OPW LiDAR

Bottom - Figure 4.31(b) Cross-section 5 INFOMAR LiDAR

Top – Figure 4.32(a) Cross-section 6 OPW LiDAR

Bottom - Figure 7.32(b) Cross-section 6 INFOMAR LiDAR

5 Conclusions

Successful LiDAR integration was achieved between all three aerial LIDAR datasets in each of three LiDAR overlap areas in both the onshore-to-offshore and the offshore-to-onshore integration tests. LiDAR elevation errors highlighted by external validation with post-processed FastStatic GPS were all within the ranges outlined by data suppliers. Close parity of the error ranges detected in the three candidate integration datasets also suggested that no systematic errors were introduced during any of the datum transformations applied for the onshore-to-offshore or the offshore-to-onshore integration tests.

Subset area comparison tests applied in the Sligo, Galway and Tralee LiDAR overlap areas further confirmed that no systematic differences were evident between the three LiDAR datasets tested in the onshore-to-offshore and the offshore-to-onshore integration tests. The combination of the validation results and the subset area comparison tests indicated that integration from onshore-to-offshore and from offshore-to-onshore integration were not subject to any substantial difficulties.

Offshore elevation mismatches were noted between the OPW and the INFOMAR LiDAR data in within the Galway and Tralee LiDAR overlap areas. These mismatches appear to have been due to the presence of water-surface returns in the OPW topographic LiDAR survey data. Offshore elevation mismatches were not noted in the Sligo test area, suggesting that full integration is possible in the Littoral zone if the OPW topographic data have been captured at low water.

These results suggest that there may be potential opportunities to reduce future INFOMAR bathymetric surveys in areas where OPW data have been captured at low water. It is even more likely however that existing INFOMAR data may have potential re-use value to other agencies or individuals that are interested in aerial LiDAR mapping in the Irish coastal zone. The representation of the offshore sub-surface in the INFOMAR data, and the relative ease with which it can be integrated with onshore LiDAR suggests that it offers additional potential outside of its defined use within INFOMAR. Furthermore, the accuracies that were highlighted within the onshore component of the INFOMAR bathymetric LiDAR suggest that DSM-processed onshore INFOMAR bathymetric LiDAR data may offer scope for integration with onshore mapping-grade LiDAR in rural areas. The INFOMAR data also undoubtedly presents valuable opportunities for geospatial research in Ireland.

6 References

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7 Appendices

Appendix 1: Post-processed FastStatic GPS validation data used in this study

Appendix 1a: Sligo

GPS validation data (Vt_prec = vertical precision defined by post-processing)

NAME	Lat wgs deg	Lat wgs min	Lat wgs sec	Lon wgs deg	Lon wgs min	Lon wgs sec	Elev GRS80	HZ_PREC	VT_PREC	RMS	Comment
slgfstat04	54	16	44.292	-8	29	10.605	61.35	0.001	0.002	0.004	
slgfstat07	54	16	56.973	-8	29	30.417	61.44	0.002	0.002	0.004	
slgfstat22	54	16	36.368	-8	28	54.066	61.17	0.001	0.002	0.004	
slgfstat41	54	16	45.954	-8	29	1.0631	64.26	0.001	0.002	0.005	
slgfstat53	54	16	43.232	-8	28	30.48	60.94	0.001	0.002	0.006	
slgfstat10	54	16	50.492	-8	29	37.579	62.31	0.002	0.003	0.005	
slgfstat12	54	16	50.719	-8	29	52.288	60.6	0.002	0.003	0.005	
slgfstat13	54	16	43.315	-8	29	29.31	61.25	0.002	0.003	0.005	
slgfstat14	54	16	38.582	-8	30	55.176	60.69	0.002	0.003	0.006	
slgfstat15	54	16	40.188	-8	30	51.74	60.54	0.002	0.003	0.006	
slgfstat19	54	16	43.341	-8	29	8.8595	61.29	0.002	0.003	0.005	
slgfstat20	54	16	39.343	-8	28	59.205	61.17	0.002	0.003	0.005	
slgfstat37	54	16	52.851	-8	29	8.4097	70.94	0.002	0.003	0.005	
slgfstat38	54	16	51.818	-8	29	7.8757	70.62	0.002	0.003	0.005	
slgfstat39	54	16	50.816	-8	29	10.076	62.81	0.002	0.003	0.006	
slgfstat40	54	16	47.106	-8	29	5.5748	60.97	0.002	0.003	0.004	
slgfstat43	54	16	53.332	-8	29	4.5832	75.33	0.002	0.003	0.005	
slgfstat50	54	16	57.543	-8	28	35.634	62.21	0.002	0.003	0.006	
slgfstat51	54	16	56.812	-8	28	38.116	62.83	0.002	0.003	0.007	
slgfstat52	54	16	56.044	-8	28	38.747	63.73	0.002	0.003	0.006	
slgfstat56	54	16	34.641	-8	28	37.838	62.07	0.002	0.003	0.005	
slgfstat03	54	16	42.865	-8	29	3.5856	60.92	0.001	0.004	0.006	
slgfstat09	54	16	55.95	-8	29	42.556	62.32	0.003	0.004	0.006	
slgfstat18	54	16	42.075	-8	29	7.7192	61.37	0.002	0.004	0.006	
slgfstat25	54	16	31.668	-8	28	45.635	60.94	0.004	0.004	0.008	
slgfstat32	54	16	28.938	-8	28	41.867	61.02	0.001	0.004	0.005	
slgfstat45	54	16	54.879	-8	28	57.981	65.63	0.003	0.004	0.005	
slgfstat54	54	16	48.635	-8	28	30.277	69.72	0.002	0.004	0.005	
slgfstat06	54	16	52.682	-8	29	25.102	61.06	0.003	0.005	0.007	
slgfstat21	54	16	38.233	-8	28	57.417	61.29	0.003	0.005	0.005	
slgfstat24	54	16	32.472	-8	28	47.657	60.98	0.005	0.005	0.009	
slgfstat27	54	16	35.407	-8	28	38.391	61.92	0.003	0.005	0.006	
slgfstat29	54	16	36.422	-8	28	34.588	63.68	0.002	0.005	0.006	
slgfstat33	54	16	28.517	-8	28	44.913	61.27	0.002	0.005	0.007	
slgfstat42	54	16	45.612	-8	28	53.232	65.5	0.003	0.005	0.006	
slgfstat44	54	16	51.044	-8	28	56.606	73.94	0.002	0.005	0.005	
slgfstat49	54	16	58.577	-8	28	36.278	61.72	0.003	0.005	0.006	
slgfstat55	54	16	56.128	-8	28	35.958	63.31	0.002	0.005	0.006	
slgfstat05	54	16	47.134	-8	29	16.51	61.47	0.003	0.006	0.008	
slgfstat11	54	16	44.726	-8	29	42.474	60.48	0.004	0.006	0.008	
slgfstat28	54	16	35.553	-8	28	35.374	63.63	0.003	0.006	0.006	

slgfstat34	54	16	27.688	-8	28	46.322	61.11	0.003	0.006	0.007	
slgfstat31	54	16	33.206	-8	28	36.482	63.25	0.002	0.007	0.007	
slgfstat35	54	16	27.884	-8	28	49.939	61.22	0.004	0.007	0.007	
slgfstat16	54	16	43.2	-8	30	48.289	60.36	0.006	0.008	0.009	
slgfstat26	54	16	33.814	-8	28	37.974	63.26	0.007	0.008	0.008	
slgfstat08	54	16	42.774	-8	29	24.756	61.5	0.009	0.009	0.008	
slgfstat30	54	16	32.626	-8	28	37.801	62.91	0.003	0.009	0.006	
slgfstat01	54	16	38.572	-8	29	18.848	63.37	0.006	0.01	0.008	
slgfstat02	54	16	38.699	-8	29	7.6513	60.68	0.007	0.01	0.01	
slgfstat17	54	16	43.353	-8	30	47.612	60.58	0.009	0.01	0.008	
slgfstat23	54	16	34.96	-8	28	51.894	60.82	0.008	0.01	0.01	
slgfstat46	54	16	56.256	-8	28	42.167	61.6	0.007	0.01	0.007	
slgfstat47	54	16	57.488	-8	28	40.985	61.01	0.01	0.01	0.003	

Appendix 1b: Galway

Galway GPS validation data (Vt_prec = vertical precision defined by post-processing)

NAME	Lat wgs deg	Lat wgs min	Lat wgs sec	Lon wgs deg	Lon wgs min	Lon wgs sec	Elev GRS80	HZ_PREC	VT_PREC	RMS	Comment
orafstat05	53	16	24.758	-8	56	53.223	60.82	0.002	0.003	0.008	
orafstat32	53	15	52.439	-8	55	30.068	62.62	0.003	0.004	0.012	
orafstat26	53	15	56.34	-8	55	51.092	61.85	0.001	0.004	0.01	
orafstat11	53	16	26.495	-8	55	54.462	62.32	0.002	0.004	0.009	
orafstat33	53	15	52.26	-8	55	22.504	62.93	0.004	0.005	0.011	
orafstat21	53	16	0.5468	-8	55	33.64	61.94	0.005	0.005	0.013	
orafstat54	53	15	21.954	-8	55	45	71.47	0.005	0.005	0.016	
orafstat46	53	15	36.438	-8	55	58.88	61.03	0.003	0.005	0.014	
orafstat47	53	15	39.902	-8	56	8.8339	61.41	0.002	0.005	0.01	
orafstat43	53	15	45.166	-8	56	12.178	62.9	0.003	0.005	0.012	
orafstat04	53	16	23.524	-8	57	4.4997	61.75	0.003	0.005	0.013	
orafstat35	53	15	49.132	-8	55	28.959	64.52	0.004	0.006	0.011	
orafstat36	53	15	42.929	-8	55	30.013	64.93	0.005	0.006	0.012	
orafstat20	53	16	3.8215	-8	55	39.97	62.07	0.005	0.006	0.015	
orafstat51	53	15	25.93	-8	55	42.348	66.61	0.003	0.006	0.012	
orafstat15	53	16	19.957	-8	55	45.5	61.32	0.004	0.006	0.012	
orafstat40	53	15	45.403	-8	55	46.273	64.04	0.003	0.006	0.012	
orafstat41	53	15	52.421	-8	55	59.354	64.79	0.003	0.006	0.013	
orafstat10	53	16	32.023	-8	56	3.0647	65.21	0.003	0.006	0.01	
orafstat18	53	16	11.04	-8	55	22.649	66.33	0.006	0.007	0.017	
orafstat34	53	15	56.929	-8	55	25.59	62.11	0.004	0.007	0.009	
orafstat12	53	16	20.974	-8	55	49.191	61.74	0.005	0.007	0.013	
orafstat03	53	16	22.932	-8	57	20.131	67.95	0.004	0.007	0.016	
orafstat52	53	15	25.839	-8	55	33.37	66.69	0.005	0.008	0.016	
orafstat17	53	16	6.2008	-8	55	36.549	62.58	0.005	0.008	0.016	
orafstat25	53	15	56.863	-8	55	47.913	62.3	0.003	0.008	0.015	
orafstat30	53	16	3.0241	-8	55	52.659	64.46	0.009	0.008	0.014	
orafstat58	53	15	19.603	-8	56	11.766	64.11	0.003	0.008	0.016	
orafstat31	53	15	51.475	-8	55	38.594	65.48	0.005	0.009	0.018	
orafstat37	53	15	54.95	-8	55	45.258	63.29	0.006	0.009	0.014	
orafstat39	53	15	50.05	-8	55	51.146	63.63	0.005	0.009	0.014	

orafstat49	53	15	31.292	-8	56	1.2768	61.24	0.004	0.009	0.015	
orafstat08	53	16	23.634	-8	56	5.0912	60.57	0.005	0.009	0.017	
orafstat42	53	15	48.693	-8	56	7.5167	63	0.005	0.009	0.016	
orafstat07	53	16	24.623	-8	56	13.623	61.11	0.005	0.009	0.017	
orafstat57	53	15	25.936	-8	56	20.865	61.9	0.004	0.009	0.013	
orafstat56	53	15	28.689	-8	56	25.496	61.88	0.006	0.009	0.011	
orafstat53	53	15	28.613	-8	55	25.24	67.25	0.015	0.01	0.02	
orafstat24	53	16	1.5955	-8	55	50.05	62.14	0.004	0.011	0.02	
orafstat09	53	16	27.322	-8	56	2.4615	63.49	0.007	0.011	0.022	RMS
orafstat48	53	15	42.564	-8	56	7.0367	64.61	0.005	0.011	0.012	
orafstat55	53	15	24.816	-8	56	33.71	61.38	0.009	0.011	0.017	
orafstat27	53	15	58.3	-8	55	52.82	62.39	0.005	0.012	0.02	
orafstat45	53	15	48.253	-8	55	53.277	63.4	0.007	0.012	0.015	
orafstat44	53	15	44.72	-8	55	58.029	63.16	0.007	0.012	0.018	
orafstat06	53	16	25.299	-8	56	35.863	61.02	0.006	0.012	0.016	
orofstat38	53	15	57.158	-8	55	38.423	65.37	0.008	0.013	0.02	
orafstat19	53	16	7.432	-8	55	33.041	64.72	0.015	0.015	0.027	RMS
orafstat23	53	16	0.3994	-8	55	41.671	61.3	0.007	0.017	0.018	
orafstat28	53	16	0.4254	-8	55	57.872	65.8	0.009	0.017	0.017	
orafstat22	53	15	58.654	-8	55	36.102	61.78	0.013	0.018	0.021	RMS
orafstat50	53	15	31.345	-8	55	52.452	62.08	0.009	0.019	0.015	
orafstat16	53	16	11.042	-8	55	38.625	62.67	0.017	0.03	0.02	

Appendix 1c: Tralee

Tralee GPS validation data (Vt_prec = vertical precision defined by post-processing)

NAME	Lat wgs deg	Lat wgs min	Lat wgs sec	Lon wgs deg	Lon wgs min	Lon wgs sec	Elev GRS80	HZ_PREC	VT_PREC	RMS	Comment
trlfstat27	52	15	21.007	-9	43	34.509	61.69	0.007	0.01	0.01	
trlfstat26	52	15	21.443	-9	43	42.22	61.65	0.005	0.009	0.01	
trlfstat37	52	15	33.384	-9	43	43.349	61.69	0.04	0.09	0.02	VT_PREC
trlfstat55	52	15	21.959	-9	43	46.385	60.8	0.003	0.005	0.008	
trlfstat36	52	15	32.182	-9	43	50.018	61.54	0.01	0.03	0.01	VT_PREC
trlfstat25	52	15	22.327	-9	43	51.959	60.4	0.005	0.009	0.01	
trlfstat31	52	15	33.995	-9	43	56.521	61.21	0.004	0.006	0.01	
trlfstat54	52	15	22.971	-9	43	56.65	60.57	0.01	0.02	0.02	
trlfstat32	52	15	39.059	-9	43	56.914	63.52	0.01	0.01	0.01	
trlfstat35	52	15	30.824	-9	43	57.782	61.51	0.003	0.008	0.01	
trlfstat24	52	15	23.388	-9	43	59.449	61.45	0.009	0.01	0.01	
trlfstat16	52	15	16.28	-9	44	0.2834	62.26	0.009	0.01	0.02	
trlfstat17	52	15	8.7746	-9	44	1.3155	64.98	0.006	0.01	0.01	
trlfstat50	52	15	32.466	-9	44	1.3571	61.39	0.003	0.004	0.01	
trlfstat33	52	15	39.095	-9	44	2.1988	64	0.02	0.03	0.01	VT_PREC
trlfstat18	52	15	2.1261	-9	44	2.3813	69.72	0.003	0.005	0.007	
trlfstat34	52	15	29.974	-9	44	2.8558	61.46	0.01	0.02	0.02	
trlfstat51	52	15	32.117	-9	44	3.0668	61.93	0.005	0.007	0.01	
trlfstat58	52	15	17.644	-9	44	4.9107	63.65	0.004	0.005	0.01	
trlfstat15	52	15	16.702	-9	44	4.9755	63.29	0.003	0.01	0.01	
trlfstat30	52	15	31.588	-9	44	5.7017	61.63	0.004	0.007	0.01	
trlfstat59	52	15	24.894	-9	44	6.2775	61.03	0.002	0.003	0.01	

trlfstat28	52	15	26.233	-9	44	6.9607	61.22	0.004	0.007	0.01	
trlfstat60	52	15	25.379	-9	44	7.0007	61.37	0.002	0.003	0.01	
trlfstat20	52	15	24.879	-9	44	7.8174	61.48	0.02	0.03	0.02	VT_PREC
trlfstat53	52	15	25.074	-9	44	8.3821	61.25	0.003	0.005	0.01	
trlfstat29	52	15	29.337	-9	44	8.6143	62.51	0.007	0.01	0.01	
trlfstat61	52	15	24.261	-9	44	8.771	61.04	0.002	0.004	0.009	
trlfstat52	52	15	30.587	-9	44	10.133	61.62	0.002	0.003	0.01	
trlfstat19	52	15	18.288	-9	44	11.057	63.35	0.01	0.01	0.02	
trlfstat38	52	15	30.777	-9	44	11.67	61.38	0.01	0.02	0.02	
trlfstat57	52	15	16.703	-9	44	13.615	62.79	0.004	0.006	0.01	
trlfstat21	52	15	23.496	-9	44	14.254	61.76	0.02	0.02	0.02	
trlfstat62	52	15	20.415	-9	44	14.594	61.82	0.002	0.004	0.01	
trlfstat56	52	15	16.869	-9	44	15.746	62.31	0.01	0.02	0.01	
trlfstat45	52	15	43.81	-9	44	15.945	62.42	0.006	0.01	0.01	
trlfstat63	52	15	21.62	-9	44	16.039	61.94	0.003	0.006	0.01	
trlfstat14	52	15	13.884	-9	44	17.03	62.48	0.004	0.01	0.01	
trlfstat64	52	15	21.944	-9	44	17.374	61.97	0.002	0.005	0.01	
trlfstat23	52	15	20.625	-9	44	17.442	61.38	0.01	0.02	0.02	
trlfstat22	52	15	23.496	-9	44	17.796	61.98	0.008	0.01	0.02	
trlfstat66	52	15	22.637	-9	44	19.663	62.11	0.001	0.003	0.009	
trlfstat65	52	15	21.463	-9	44	19.867	61.85	0.003	0.005	0.01	
trlfstat39	52	15	31.634	-9	44	19.997	61.19	0.02	0.03	0.03	RMS & VT_PREC
trlfstat13	52	15	10.852	-9	44	20.066	61.93	0.003	0.006	0.01	
trlfstat46	52	15	43.571	-9	44	22.226	62.41	0.008	0.01	0.02	
trlfstat12	52	15	3.1458	-9	44	29.028	63.23	0.004	0.008	0.01	
trlfstat40	52	15	34.346	-9	44	32.669	61.1	0.01	0.01	0.02	
trlfstat11	52	14	56.158	-9	44	36.226	66.26	0.008	0.009	0.01	
trlfstat44	52	15	41.784	-9	44	37.285	63.25	0.003	0.01	0.01	
trlfstat10	52	14	50.581	-9	44	42.89	64.07	0.007	0.006	0.01	
trlfstat43	52	15	41.379	-9	44	46.36	62.06	0.008	0.02	0.02	
trlfstat41	52	15	37.69	-9	44	47.975	60.95	0.01	0.01	0.02	
trlfstat09	52	14	46.6	-9	44	51.607	64.18	0.005	0.006	0.01	
trlfstat42	52	15	40.885	-9	44	55.384	61.36	0.006	0.01	0.01	
trlfstat49	52	16	5.9411	-9	45	11.801	60.98	0.03	0.04	0.02	VT_PREC
trlfstat08	52	14	50.616	-9	45	15.366	65.86	0.003	0.003	0.01	
trlfstat07	52	14	40.368	-9	45	16.63	65.48	0.005	0.008	0.02	
trlfstat47	52	16	6.668	-9	45	23.086	61.53	0.01	0.01	0.01	
trlfstat06	52	14	43.174	-9	45	36.167	62.24	0.003	0.006	0.01	
trlfstat05	52	14	41.729	-9	45	54.806	64.11	0.001	0.003	0.007	
trlfstat04	52	14	40.814	-9	46	6.4952	67.27	0.005	0.01	0.01	
trlfstat03	52	14	40.224	-9	46	13.968	69.72	0.003	0.008	0.01	
trlfstat02	52	14	39.237	-9	46	26.352	76.3	0.006	0.01	0.01	
trlfstat01	52	14	36.556	-9	46	37.389	83.87	0.005	0.008	0.01	