Article

Beam to Chart
A Case Study of the LIDAR Survey of the Sound of Harris

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Abstract
Tenix LADS Corporation conducted the LIDAR survey of the Sound of Harris in March 2004, for the Maritime and Coastguard Agency (MCA). The survey was conducted using the LADS Mk II system. The survey area was most complex with many islands, shoals and narrow channels (see Figure 1). Survey data extended from topographic heights up to 50 metres above the sea surface to maximum depths of 25 metres below chart datum.

Résumé
Tenix LADS Corporation a exécuté un levé LIDAR du passage Harris en mars 2004, pour la MCA (Maritime and Coastguard Agency). Le levé a été effectué à l'aide du système LADS Mk II. La zone de levé était très complexe, avec de nombreuses îles ainsi que de nombreux hauts fonds et passages étroits (voir Figure 1). Les données des levés vont de hauteurs topographiques atteignant 50 mètres au-dessus de la surface de la mer jusqu'à des profondeurs maximum de 25 mètres au-dessous du niveau de référence des cartes marines.

Resumen
Tenix LADS Corporation llevó a cabo un levantamiento LIDAR del Pasaje de Harris para la Agencia Marítima y de Guardacostas (AMG), en Marzo del 2004. El levantamiento fue realizado utilizando el sistema LADS Mk II. El área del levantamiento era bastante compleja, con muchas islas, bajos fondos y canales angostos (ver Figura 1). Los datos del levantamiento comprendieron desde alturas topográficas de hasta 50 metros sobre la superficie del mar, hasta profundidades máximas de 25 metros por debajo del dátum de la carta.

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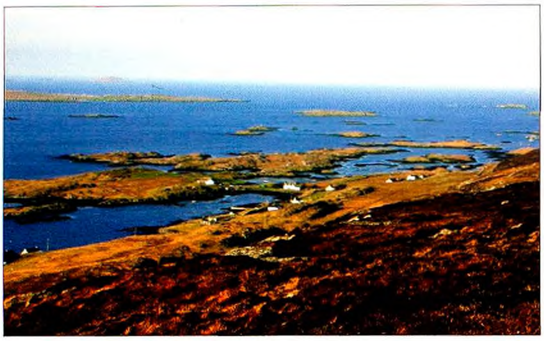

Figure 1 – The Sound of Harris.

The survey identified an extremely large number of significant changes to the existing nautical chart BA 2642. The data was then passed to the United Kingdom Hydrographic Office (UKHO) chart branch for assessment and charting action, where it has presented significant challenges due to the complexity of the area, deficiencies of the existing chart and appropriateness of current processes for handling data of this type.

This paper outlines the data collection phase of the project and focuses on the processing, reporting and charting of the LIDAR data. In addition, the philosophy adopted for selecting items for the chart comparison and techniques used to review and present the large amount of significant items are described. The handling of the data by the Chart Branch UKHO is then discussed, including comparisons with older surveys, examining the adequacy of current navigation channels and navigation aids, planning new channels and planning the chart update programme. Furthermore, lessons learned from the survey and charting perspective are presented, and suggestions for future LIDAR surveys are made.

Survey Requirement

The Sound of Harris is situated in the Outer Hebrides which is a long island chain situated off the northwest coast of Scotland. The Sound of Harris is the stretch of water between the island of Harris in the north and the island of Uist in the south. It connects the Little Minch on the east side of the Outer Hebrides with the North Atlantic on the west side.

The Sound of Harris is an extremely complex rocky area six nautical miles wide, last surveyed using single-beam echo sounders in the 1950s. There are two twisting routes through the sound, a car-ferry route across it, and numerous connecting passages used by local craft and an increasing number of visiting yachts. The ferry route is a particular cause for concern as it crosses a number of very shoal patches, some of which are rocky, and it was also believed that uncharted rocks could exist close to the route. A panoramic view of part of the Sound of Harris is provided at Figure 2.

The aim of the survey was to provide hydrographic data to update chart BA 2642 of the Sound of the Harris. This was documented in the Scope of Work of the Maritime and Coastguard Agency (MCA) contract TCA 3/7/668, dated 11 March 2004, 'LIDAR Hydrographic Survey of Sound of Harris'. The survey was conducted using the LADS Mk II system.

The main requirement of the survey was to collect data compliant with IHO Order 1 position and depth accuracy and target detection. The area was surveyed at 3x3 metre spot spacing and 200% coverage. A standard format of survey specification was used. The formal appraisal of the survey will consider ways in which specifications may need to be adapted for future surveys, which may employ LIDAR techniques.

Figure 2 – Sound of Harris panorama.

Survey Area

The survey area encompassed an area of 146km² covering the eastern half of the sound. It extended from the south coast of Harris to the north coast of Uist, including the islands of Ensay, Killegray, Groay, Lingay, the eastern side of Berneray as well as many smaller islets and drying rocks. Leverburgh and Bays Loch Harbours (both used by the car ferry) were surveyed along with all existing ferry routes and shipping channels. An image of the survey area is displayed in Figure 3.

Field Operations

Survey operations were based at Stornoway Airport. A processing office was established at the airport. Personnel arrived in Stornoway on Wednesday 3 March 2004. The aircraft arrived at Stornoway airport on Saturday 6 March. From 5 to 8 March tide gauges were deployed and the first sortie was flown on Wednesday 10 March. The final sortie was flown on Sunday 4 April, tide gauges were recovered from 5 to 7 April and remaining personnel departed from the field on Wednesday 7 April 2004.

Flying operations were conducted during daylight hours. Flights were timed to take advantage of favourable weather conditions and coincide with certain states of the tide. A total of 12 sorties were flown using the LADS Mk II system. The average sortie duration was 6 hours and 4 minutes with an average time on task of 5 hours and 4 minutes.

The key LADS Mk II functionality that is relevant to this survey is as follows:

- Sounding rate of 990Hz.
- High powered laser. The laser operates at up to 7.2mJ transmitted power and was adjusted to provide 5mJ of measured power below the aircraft. High laser power is essential in LIDAR bathymetry systems to overcome losses in the atmosphere, scattering and absorption in the water column due to turbidity and reflection and absorption by the seabed.
- Wide aperture receiver of 180mm. The aperture of the receiver is important as the received laser signal varies as the square of the receiver diameter.
- Variable sounding density. The area was sounded

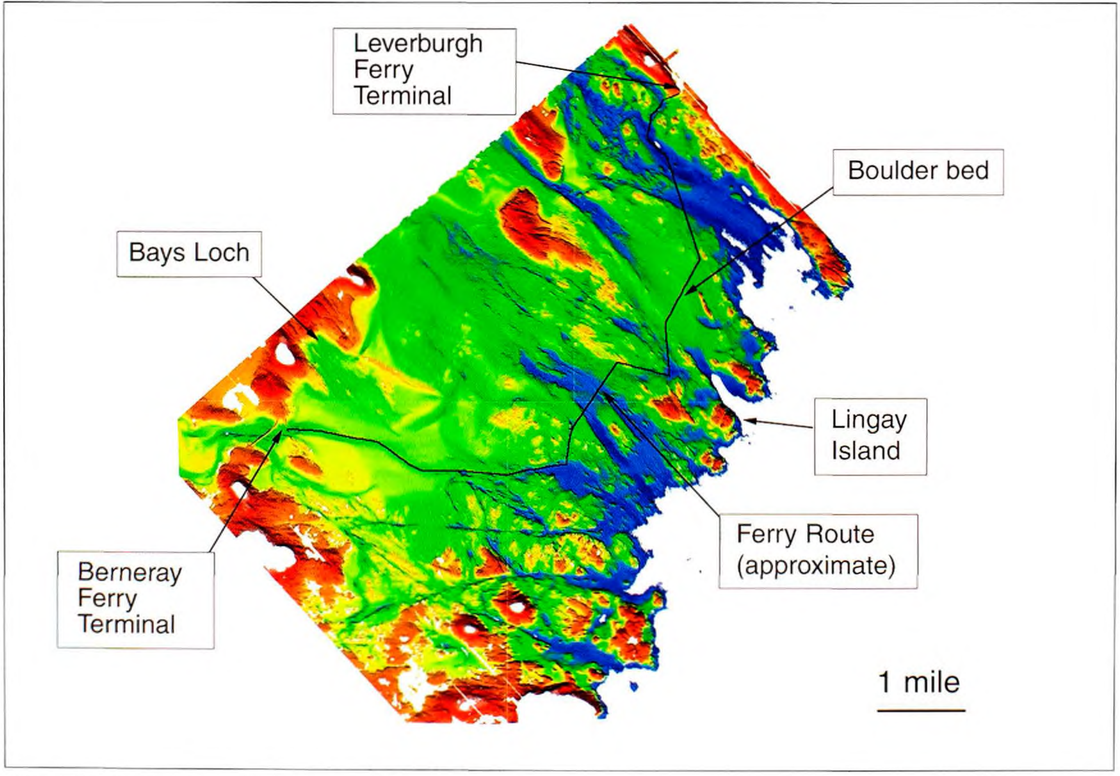

Figure 3 – Image of area surveyed by LIDAR.

at 3x3 metre laser spot spacing in order to achieve IHO Order 1 target detection.
- Variable operating altitude with constant swath width. The system was operated at altitudes between 1200 feet and 2200 feet. 1200 feet was required at certain times to operate under the low cloud base and 2200 feet was required in certain parts of the survey area to avoid high terrain.

Main lines of soundings were flown to collect data at a density of 3x3 metres which has a swath width of 100 metres at an aircraft ground speed of 150 knots. Lines were flown along an orientation of 358°/178° at a spacing of 80 metres. Inter-lines were later flown to provide 200% coverage of the survey area. As far as possible, the inter-lines were flown at a different state of the tide compared with the original main lines. This strategy was effective in minimising gaps in the survey area due to white water or turbidity. As well as improving the coverage of the area this approach provided redundancy over all features, which was extremely valuable during the data processing and chart comparison phases.

A number of flat areas of seabed were identified for use as benchmark areas. These were surveyed on each sortie to provide repeatability checks of depth measurement. Four cross lines were also flown across the survey area. The benchmark areas and cross lines provided daily checks of system performance and the tide model.

Weather conditions were in general suitable for LIDAR survey operations. Winds were predominantly from the south, southeast and southwest. The western side of the survey area was exposed to the North Atlantic and some swell was experienced on several occasions. One survey flight was aborted due to poor weather conditions and a large swell. The majority of data from this sortie was discarded and reflown.

In general, the water was clear and most suitable for survey by LIDAR. On occasions, the water clarity was reduced. This occurred during higher sea states, during periods of significant swell and when there were strong tidal streams. Higher sea states caused mixing, swell interacted with the seabed in shallow water and the strong tidal streams created eddies and overfalls in narrow passages and over rough areas of seabed. These factors suspended fine sand from the seabed, which reduced the laser penetration.

A water clarity management plan was adopted to minimise these effects on the data. Survey flights were timed to correspond with periods of suitable weather and sea conditions as well as the desired state of the tide. Operations were conducted in the lee of islands in more sheltered areas where possible.

On 5 March a reconnaissance of the survey area was conducted by boat and Secchi disc measurements were taken. Secchi disc observations of between 8.5 and 12.5 metres were recorded. During the survey, maximum laser depths were measured to approximately 25 metres (reduced for tide).

Geodetics and Positioning

Real-time positions of the LADS Mk II system were derived from an Ashtech GG24 GPS receiver using the Thales SkyFix Wide Area Differential GPS (WADGPS). WADGPS corrections were primarily obtained from the SkyFix reference station in Sumburgh, Shetland Islands. Real-time positions were referred to the WGS84 datum.

A local GPS base station was established on the main communications mast on the roof of the Stornoway Airport control tower. In addition, three temporary check marks were positioned on the tarmac at Stornoway Airport. These were used to perform a static check of all positioning systems.

KGPS positions were determined relative to the local GPS base station on the ETRS89 datum and the GRS80 spheroid. KGPS positions were then applied to all soundings.

Geodetic observations were also conducted to determine the spheroidal heights of the tidal benchmarks.

The raw data from these observations was provided to Ordnance Survey to assist with geoid modelling.

Datum and Tides

Automatic tide gauges were installed at Leverburgh and Bays Loch. In addition two bottom mounted offshore gauges were deployed east of Lingay Island. Thirty days of observations were collected from all four gauges.

A tidal analysis was conducted which enabled an independent establishment of Lowest Astronomical Tide (LAT) to be derived from the observations. Data from the bottom mounted offshore gauges at Lingay Island were found to be consistent with the other two sites and was not utilised in the final

Figure 4 – Sound of Harris – islets and rocks.

tidal model.

Attempts to recover the existing Chart Datum proved difficult due to inconsistencies in some of the benchmark relationships. All soundings were initially reduced to LAT as determined from the 30-day observations at Leverburgh and Bays Loch. Final data was reduced to Chart Datum relative to the hydrographic benchmarks at Leverburgh and Bays Loch.

Data Processing

The Sound of Harris is a highly complex area with dozens of small islands and hundreds of submerged rocks and shoals. This can be seen in Figure 4. Sand wave action is evident in many of the sandy areas, whilst many of the rocky shoals are covered in boulders and kelp. This required careful processing and review of the data.

Processing of the data was commenced in the field. This enabled the data quality to be assessed and the progress of the survey to be monitored. The survey area was far too complex for data processing to be completed during field operations and this was completed in the survey depot.

The data processing sequence followed is displayed in Figure 5. Once the data was downloaded from the aircraft it was automatically processed to produce individual depths from each returned laser pulse. The data was then reviewed and accepted for further processing or rejected and listed to be reflown. The accepted data was then cleaned using a series of filters and batch editing techniques and coverage plots were generated. This process was completed within 24 hours of collection.

The data was then validated and checked to ensure all false or incorrect data was removed. The data was then independently quality controlled prior to being approved for use by the surveyor in charge. Due to the complex nature of the survey area, this was an intensive process.

A particular challenge was presented by parts of the survey area where many boulders exist on the seabed. A Bottom Object Detection algorithm was utilised to detect the presence of small features on the seabed by their characteristics on the raw laser waveforms. A filter was used to correlate returns from overlapping data

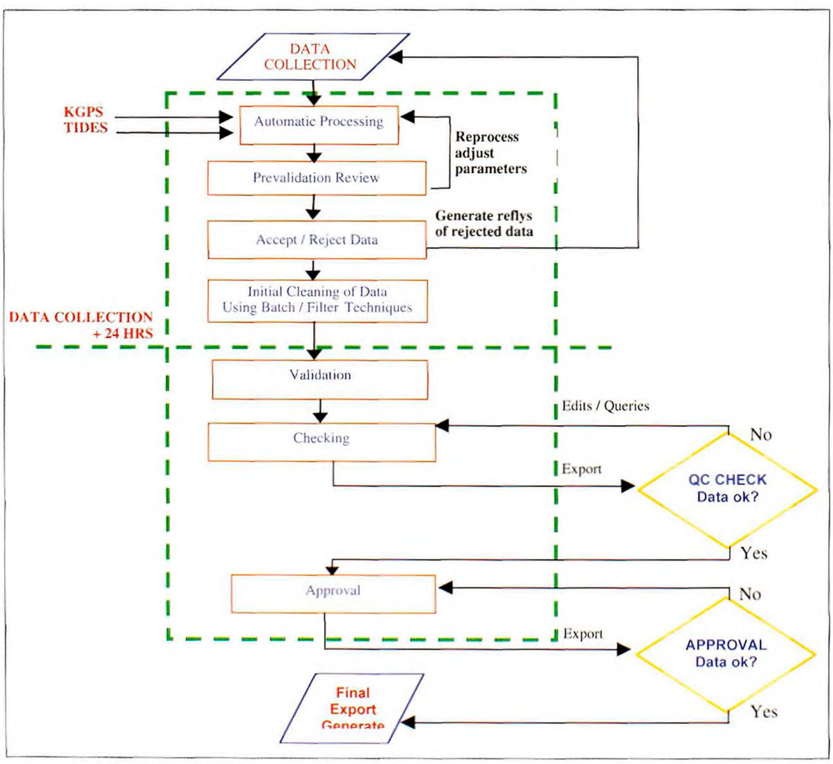

Figure 5 – LADS Data processing flow diagram.

over a nominated radial range. This enabled features which were supported to be retained, and returns that were not correlated to be flagged for operator review. This process is designed to discriminate real objects from noise in an efficient manner.

Kelp was also observed along the rocky coastlines of most of the islands and on many of the submerged shoals. Kelp absorbs energy and lowers the amplitude of the returned laser signal. This requires careful review which must be considered in determining the time to process the data.

The LIDAR data ranged from depths of up to 25 metres to topographic heights of approximately 50 metres. The bathymetric and topographic data was collected at the same time, by the same sensor, at the same density and to the same datum. This provided seamless data across the land water interface. The data contains both natural features and man made objects such as wharfs, jetties and buildings.

Reporting

The survey was reported using the UKHO format. Digital data was provided in formats compatible with CARIS and Fledermaus. In addition, digital quality control sheets were generated in Microstation containing a sun-illuminated image, depth data at a scale of 1:10,000, geo-referenced chart image and the selected depths from the Chart Comparison. These were provided to assist in the assessment of the data.

To achieve IHO Order 1 feature detection, data was collected at 3x3 metre laser spot spacing and 200% coverage. In addition, high amplitude raw laser waveform returns from the seabed are required. In a similar way to maximum depths, target detection is affected by:

- Noise from ambient light, particularly sunlight. A green narrow band filter is designed to remove sunlight noise.
- Turbidity in the water column. This is the largest source of noise and signal losses occur through scattering and attenuation.
- The size, reflectivity and composition of objects on the seabed. For example, kelp-covered rocks will absorb more light than white sand and the raw laser waveform will be of lower amplitude. Structures with holes or gaps may also be harder to detect.

The LADS Mk II system is designed to detect objects on the seabed by:

- Data density. Using the 3x3 metre laser spot spacing mode of sounding.
- System design factors. Important aspects are high laser power, wide aperture receiver and high gain low noise photomultiplier tube. This approach provides the high amplitude low noise raw laser waveforms required for target detection.
- Algorithms to detect features on the seabed and discriminate them from noise.

The outcome is that IHO Order 1 target detection may be achieved to a lesser depth than the maximum LIDAR depth in the survey area. This is ultimately due to the collection of high amplitude low noise waveforms by the system. For example, target detection on a kelp covered rock may be achieved to a depth of 15 metres of water, whereas a flat sandy bottom may be detected to a depth of 20 to 25 metres in the same environmental conditions.

In the Sound of Harris, IHO Order 1 feature detection was achieved to a depth of 14 metres (reduced for tide). In depths of greater than 14 metres, the lower amplitude returns that were collected did not achieve IHO Order-1 feature detection.

The comparison of the survey to the chart was a significant task. The choice of what to include, and what to leave out, was very subjective, due to the large number of features and significant differences to the chart. In consultation with UKHO chart branch staff, a philosophy was adopted to report the more significant features from the perspective of vessels capable of navigating in the area. Factors such as the shoalest depth, most seaward feature and proximity to the channels were considered. Even adopting this approach, some 600 chart comparisons were reported. This is discussed more fully in Section 9.

The results of the chart comparison were provided in a spreadsheet. The format of this product has been developed from experience conducting surveys for MCA/UKHO and NOAA. Separate fields are provided for each different attribute instead of lumping them together in a mass of text. This facilitates digital queries with minimal manual handling. In addition, each item is provided with an image of the Raw Waveform Display and Local Area Display of soundings in the vicinity. These images are provided in a separate sub-directory which is hyperlinked to the spreadsheet. This facilitates

consistent compilation and review of the data and has also been extremely useful in answering subsequent queries from UKHO.
A composite .dgn file was also created of the chart, LIDAR soundings, sun-illuminated image of the LADS data and consecutive chart comparison number. This also facilitated the management and review of the 600 shoals in this complex area.

Quality Control

A number of checks were conducted on the data.
The positioning systems were checked by a static position check prior to commencing data collection. A scatter plot was produced of each positioning system which was compared with the known position calculated from the surveyed marks on the tarmac. A dynamic position check was also conducted between the real-time WADGPS and KGPS positions. The vector difference between each position was determined for each second of data collection, as well as the minimum and maximum values of other confidences such as the number of satellites, PDOP etc.
A depth check (benchmark) was conducted on each survey flight by surveying a number of flat areas of seabed. This enabled the repeatability of the system to be checked between sorties. Cross line comparisons were also conducted between the cross lines and main lines of sounding throughout the survey area.
Survey operators validated the sounding data and all work was checked by more experienced hydrographic surveyors. A review of the entire survey was then conducted using the Tenix LADS QC Tools software. This provided a global interactive review of the survey area. A Triangular Irregular Network model was created and the data was contoured and visualised in 3D. The survey area was also binned and images were produced of differences within each bin.
The data was then checked and reported against chart BA 2642.

Chart Comparison

The normal procedure in the UKHO for examining a new survey and carrying out a formal appraisal of the quality of the survey was challenged by the quantity of data, the extremely complex nature of the area, and the relative novelty of the LIDAR technique to UKHO. Although a couple of small LIDAR surveys had previously been examined by UKHO, this was the first time that a large complex survey had been handled. In addition, the process was complicated by the unusual nature of chart 2642, which is skewed off true north by 45° in order to show the whole of the Sound of Harris on one normal-sized sheet.
The survey was first appraised by experts in digital bathymetry, geodesy and tides, and after a few initial queries had been answered, the data was pronounced fit for use and passed to the chart branch as both reduced density digital datasets and as hard copy graphics – colour-banded depth plots. The job of the chart branch is to examine the data for dangers that need to be issued immediately through Notices to Mariners (NM), and then to complete the survey appraisal process. Both tasks entail examination against the existing charts and older surveys. In this case it was immediately apparent that the scale of the changes would require a new edition to the existing chart, as the number of changes was too large to be handled by a hand-correction NM. The need to completely redraw the chart in due course had already been appreciated, and a design for the new chart had been agreed with users. The task facing the chart branch was thus to:

- Examine the survey in as short a time as possible and issue Notices to Mariners.
- Examine the list of 600 chart comparisons in the report of survey at the same time.
- Carry out the usual survey appraisal.
- Examine the LIDAR technique in detail to inform future survey specifications.
- Issue a 'stop gap' new edition of the existing chart as soon as possible.
- Redraw the chart in a new format - probably within one year of completing the other tasks.
- Minimise the duplication of effort while so doing.

The plans for this exercise went through several versions. Each one was changed as difficulties were found with the approach adopted. At the time of writing, the chart branch team is on 'Plan J'.
'Plan A' was to review the list of 600 chart comparisons by compiling them directly into the 'stop gap' new edition. This did not work as it was found that the new picture was so different from the old that the area around each significant depth had to be redrawn. 'Plan B' was then to recompile small

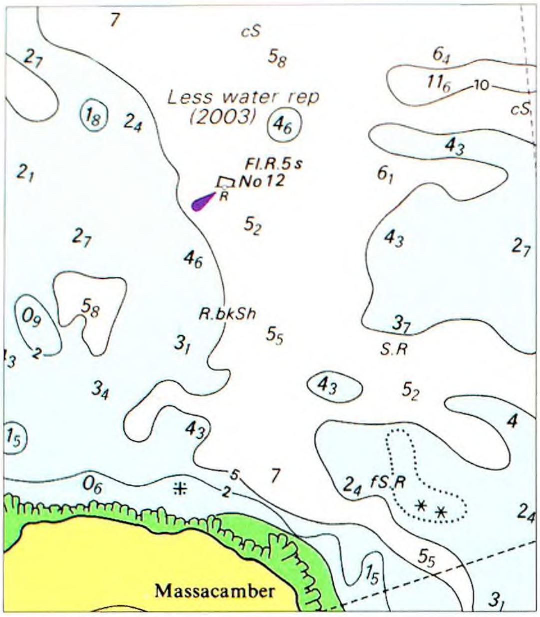

Figure 6 – chart before LIDAR survey.

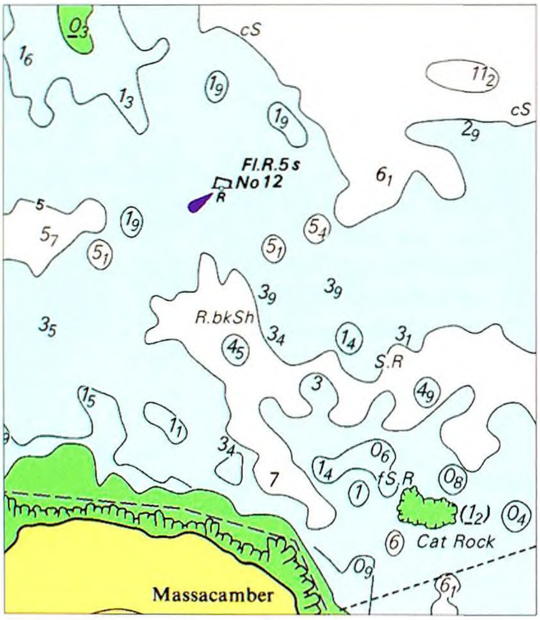

Figure 7 – chart after LIDAR survey (partially complete compilation).

areas as necessary from the full survey data; but these grew so much that it became easier to redraw completely, with the aim of then re-using the work in the eventual new chart – this was 'Plan C'. But that became too time consuming. To cut a long story short, 'Plan J' is to recompile the chart along the main routes through and across the Sound, and apply 'Caution – Depths' notes to the rest of the area.

The chart comparison is very simply described: the area looks nothing like the existing chart. As an example, before and after depictions of one small area are shown in Figures 6 and 7.
The main issue in carrying out the chart comparison is how far the surveyor should go in reporting differences, and how much should be left to the hydrographic office. This was discussed by Tenix, MCA and UKHO before the list of depths in the Report of Survey was prepared – this resulted in the list being a mere 600 items long instead of a projected 1500 items, but it is still far too long. The compilation of a list is also a process which is open to human error, and the list has to be examined closely if only to detect any typographical mistakes that could mislead future users of the data. The likely outcome of the review of this aspect of the survey in the final appraisal report is that lists of depth comparisons in areas such as the Sound of Harris are more of a hindrance then a help. It is very helpful to have detailed reports for uncertain depths – such as over rocks covered in kelp – but it is a hindrance to have the rest of the survey described in narrative form. Guidelines will need to be drawn up for chart comparisons in such areas.
Significant shoal depths that needed to be issued by NM were sent to UKHO via Hydrographic Note at an early stage of survey processing, and these formed the subject of a (non chart-correcting) Preliminary Notice to Mariners – a (P)NM. This procedure should in future be a sufficient means of reporting new depths that need to be issued by NM, but more helpful guidelines are needed here to cater for complex rocky areas.

Comparison with Other Surveys

The Royal Navy conducted the previous complete survey of the area in the 1950s using single-beam echosounder and traditional techniques for depicting areas of low water-rock. However, this survey cannot be completely superseded by the LIDAR because:

- There are patches of rock shown on the old survey that could not be measured by the LIDAR due to the presence of kelp.
- The old survey distinguishes between low water rock and drying sand.

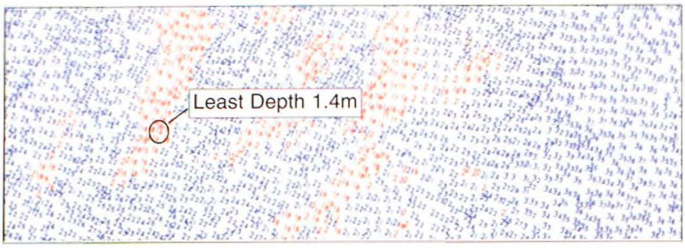

Figure 8 - LIDAR survey across boulder bed.

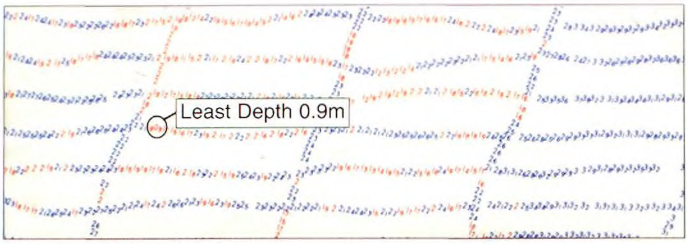

Figure 9 - Acoustic survey across boulder bed.

Future LIDAR developments to incorporate ground discrimination techniques may deal with the latter problem. Polygons delimiting kelp areas were rendered as part of the survey. Digital imagery may also be useful to determine the nature of the drying line and shoreline. In late 2005, a new digital camera is being fitted to the stabilised platform of the LADS Mk II Airborne System and improved images will be collected. The use of improved geo-referenced photo-mosaiced images will be able to be used for interpretation of data in the nearshore area.

A number of areas along the ferry route have been surveyed for Comhairle Nan Eilean Siar (CNES, Western Isles Council) and the Northern Lighthouse Board (NLB) by contract surveyors in the last five years. These surveys are positioned by DGPS and use modern single-beam echo sounder at very close line spacing. Comparison with these surveys shows excellent agreement with the LIDAR over areas of smooth seabed, and very good agreement over most areas of rock outcrop.

However, there is one area where neither survey technique could produce a definitive picture, that being a very shallow area of boulders. Unfortunately, this is one of the critical shoal patches that the car ferry passes over several times each day, so it has received close attention. As might be expected, the single-beam survey of this area revealed a few depths that were a decimetre or so shoaler than found by the LIDAR, and the LIDAR found boulders that fell in between the single-beam echo sounder lines. It is thought that the nature of the boulders makes it difficult to detect the very top points using LIDAR.

Had the ferry route not passed over the top of this boulder bed, the LIDAR technique would have been quite adequate in defining an area to be avoided by shipping. This is the case over the rest of the survey area, where the LIDAR has defined the routes and anchorage areas that are safe to use. The intervening rocks, once delineated, are no-go areas, and there is little requirement to know the exact least depth over them. It is considered that the only way to survey this type of area definitively is to use a mark-one eyeball to find the top of each boulder, and total station on a long pole to measure its height. In hindsight, it would have been appropriate to specify this area to be surveyed by LIDAR at 2x2 metre laser spot spacing.

Not only has the LIDAR defined the safe routes, it has indicated a number of possible alternatives to the section of the ferry route crossing the boulder bank. UKHO has supplied NLB and CNES with a list of places to be investigated in more detail. This aspect of the LIDAR survey should bring further benefit to the inhabitants of the Outer Hebrides.

The LIDAR survey also revealed that many of the charted beacons in the sound were out of position by up to 40 metres. In order to verify this finding, NLB's *MV Pole Star* was asked to position all the beacons using direct DGPS measurements. They did this enthusiastically within a few days of being asked. The results generally agreed with the LIDAR positions to within 1 metre.

A comparison between the LIDAR survey and the Ordnance Survey mapping of the MHWS and MLWS contours is yet to be carried out at the time of writing. A similar comparison between a LIDAR survey on the island of Coll and the OS mapping revealed very close agreement. At MHWS, differences were found in rocky areas that were thought to be due to the difficulty of determining the position of this contour using photogrammetric techniques in such terrain; elsewhere, differences could be attributed to sediment movement between the time of the mapping and the survey period. At MLWS, the LIDAR had detected all of the low water rock shown on the mapping, together with a number of additional patches. This is to be expected since the photographic sortie for the mapping had not been flown exactly at low water.

Planning Chart Update Programme

The need to issue Notices to Mariners updates to the charts has been mentioned earlier. In addition to the (P)NM based on the initial hydrographic note rendered by Tenix, a number of other chart-correcting NMs have been issued for depths close to the ferry route.
NLB have also used the survey to help reposition some buoys, which has resulted in the issue of further NMs.

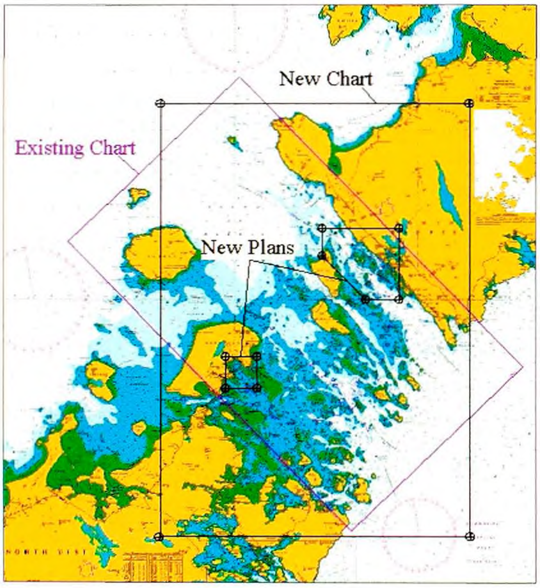

Figure 10 – Limits of the existing chart and future new chart (with inset plans).

The 'stop-gap' new edition of the existing skewed chart 2642 has been planned to use the minimum of resources to redraw the main routes only.
The replacement new chart has undergone an extensive user consultation process. The difficulty faced by the chart designer in an area such as this is that it is not possible to create a chart at a suitable scale covering the whole of the area needed on a single standard sheet. Splitting the area into two sheets would create overlaps on one or more of the main routes, and these would all fall in areas where a change of chart is the last thing the mariner would want. This is the reasoning behind the design of the present skewed chart. However, the skew makes the chart difficult to use in practice. The final design uses A0-sized paper and goes to the maximum width possible. The chart will also carry large-scale plans of harbours and critical channels.

The compilation of the new chart will bring further challenges as UKHO decides how best to use the mapping and survey data available. This will be decided after the appraisal process has been completed and the results of the comparisons between the LIDAR data and other sources are available. It is likely that the source data will be used in the following order:

- Draw the coastline and topography from the large scale Ordnance Survey mapping, except where the LIDAR shows that the coastline has migrated.
- Include the LIDAR survey in full:
  1) Take depths from the usual shoal-biased depth plot at chart scale.
  2) Add relevant deeps from a deep-biased plot.
  3) Use a contour plot from the full dataset at 0m to indicate the true extent of low water rocks, so that a distinction can be made between isolated rocks and rocky areas. Chart scale depth plots in this type of seabed would tend to join isolated rocks together, giving a misleading impression.
  4) Use a contour plot at 2m to ensure that significant narrow navigational channels are shown sensibly. Chart scale plots tend to close-off such channels.
  5) Use the old 1950s survey to determine where to show low water rock and where to show a plain drying line.
- Examine the existing chart and the LIDAR survey's kelp polygons to determine which rocks need to be retained. Show the kelp symbol where indicated by the polygons.
- Examine the recent single-beam surveys and insert shoaler depths.
- Use any later surveys in preference to the LIDAR – a large environmental survey is being undertaken by Scottish Natural Heritage, which will overlap the LIDAR over a shoal sand bar that is known to be mobile. The big storm on 11 January 2005 may well have moved this bar considerably.
- Insert beacons from the positions obtained by

MV Pole Star and buoys from NLB records.
- Use the existing chart and older surveys to complete areas of the chart outside the newly surveyed area. Some of this work will entail going back to 19-century lead-line surveys with depths in fathoms.

And if that was not enough, the chart needs to reflect the conversion of names to their Gaelic forms, for which a new policy is being devised in conjunction with Ordnance Survey. The new chart will be the first to use this new naming policy.

Lessons Learned

Overall, the survey of this extremely complex area was well executed. However, in all surveys a number of lessons are learned about issues which may have been handled better. As this was the first time that LIDAR had been used in the UK for such an extensive shallow water survey, some of the lessons are fundamental to the specification and conduct of future surveys.

First, it is appropriate to record some things which went according to plan:

- The timing of the survey was good. Clear water conditions were experienced in March, although weather conditions were variable.
- LIDAR was the correct tool to use for this area as the shallow water and numerous rocks would have required a very long time for a multibeam boat survey. A pilot survey had been conducted the previous year in Plymouth Sound and a small survey had also been conducted in a similar rocky area off the Scottish island of Coll. These surveys demonstrated the capability of LIDAR, however because they were of small size did not address the downstream data handling issues of a large LIDAR survey.
- 3x3 metre laser spot spacing was an appropriate data density, with the exception of the boulder bed, which should have been specified and surveyed at 2x2 metre laser spot spacing.
- The standard techniques used by Tenix for processing the data and for recording the survey in the MCA/UKHO report of survey format worked well overall.
- The LIDAR survey has identified a number of potential new routes across a critical part of the Sound of Harris. These will need to be closely investigated, tested and marked by new buoyage before use, but the possibility is now available of avoiding the most dangerous shoal restriction on the route over a boulder bed.
- The survey has also been of immediate use to the Northern Lighthouse Board in determining whether or not new buoys were needed in certain locations, and to position them to best advantage.

Lesson 1 – Specify the method for establishing vertical datum

Establishing the sounding datum in this area took much effort and was not finally resolved until the very end of the survey. The main problem was the state of the existing benchmark and levelling records, which had posed difficulties for other projects. For example, a new berth constructed some years previously had to be modified when it was found that the actual tidal levels were not as recorded. It was known that discrepancies had been detected by various levelling surveys across the Sound, and that some of the benchmark descriptions may have been erroneous.

In the field, locating some of the benchmarks was at times difficult and more use may have been made of local knowledge. Queries referred to Ordnance Survey about the levelling resulted in them contracting another company to carry our confirmatory measurements. An attempt was made to re-establish chart datum independently of the historic data, but was abandoned when it was realised that tidal measurements over several years would be needed. Fortunately, the availability of a local expert on the subject of vertical datums allowed the issues to be identified, and avoided any need to return to the survey area after the field campaign.

In the end, tides were applied relative to the benchmarks used for the 1950's and 1960's echosounder surveys of the Sound. This enabled the survey to be rendered on the historical chart datum and thus allowed the chart to be consistent both internally and with other charts. In due course, better connections may need to be established between these historic benchmarks and the spheroid if the survey data for this area is to be integrated into a consistent regional model.

The lesson learned is that when working in areas where there is doubt about the state of historical vertical datum records, the survey contract needs to specify how chart datum is be recovered and should detail any additional measurements that need to be made.

Lesson 2 – Reporting Differences Compared to the Chart

The standard Report of Survey format proved to be woefully inadequate for rendering the comparison between the survey and the chart in this case and encumbered the identification of depths that needed to be issued by Notices to Mariners. Following the guidelines for a normal echo sounder or multibeam survey in such complex water resulted in a list of 600 differences. This encouraged a number of typographical errors to find their way into the list, with no means of spotting them easily. It also meant that it was impossible for the cartographers to quickly identify the critical depths for which Notices to Mariners were required.

The surveyors and cartographers discussed this problem after the comparison had been started and the size of the list had been estimated initially at well over 1500 items. Unfortunately, the final list of 600 items still turned out much larger than had been anticipated using the more selective reporting criteria agreed at the time. After examination of the list by UKHO, further depths were identified that could have been added to it, showing that different selection criteria would be needed to reduce the list to manageable proportions.

The list actually fulfils two functions – to report on the surveyor's findings on examining the returns for each rock in detail, and to identify depths that may warrant NM action. In a boat survey, there is usually a fair degree of overlap between the depths which need close inspection and those which need to be considered for NM. Also, boat surveys, being in relatively open water, may result in a list of up to around a dozen items, which is thus easily assimilated. LIDAR, however, can cover large areas of shallow and inter-tidal water, which are well away from the usual routes; these areas contain depths that need close inspection but are quite irrelevant for immediate NMs, and produce much larger lists using context-free difference criteria.

The most important method for the surveyor to report on NM-worthy items is a Hydrographic Note rendered early in the processing of the survey. This was done for the Sound of Harris survey, and covered the main depth differences found along the ferry route. What was not appreciated by all concerned was the desirability of rendering further H-Notes as the processing proceeded and further depths were identified close to the ferry route and other routes. Future survey specifications should call for Hydrographic Notes to be rendered at any time during surveying or data processing as new dangers are identified. Even if this results in several such notes rendered on a weekly basis, it would be an effective way of promulgating the most significant findings of the survey.

Such a process would relieve the need for the final survey-chart comparison to be used to identify NM-worthy items. The list would then become a simply a record of the depths that the surveyor has needed to examine closely. The list could easily identify those depths for which H-Notes have been rendered, and record any corrections to the originally reported values.

Lesson 3 – Object Detection

When the survey was specified, full IHO Order 1 object detection was required. When the results were assessed, it was clear that this would have been impossible to achieve with 100% certainty in an area as complex as the Sound of Harris, unless considerable extra expense had been incurred in conducting not only a multi-beam survey over complex areas, but also examining a large number of individual rocks using divers and similar methods. However, the LIDAR survey has achieved 99% of what is required in this area in that it has detected all of the rocks and obstructions and has identified places where the rocks have been hidden by kelp or surf. It is difficult to envisage a geological feature that would not be detectable by LIDAR.

In almost all of these cases, it is not actually necessary to know the absolute least depths over the rocks. Most users need to know only that there is a rock - they will then avoid it and will never deliberately risk testing the accuracy of the survey. Only marines on a beach landing exercise might wish to surprise everyone in this manner, and it would be uneconomical to survey the whole of a country like Scotland to such a level of precision for that reason alone. The traditional need to find the least depths over all rocks was practically limited to navigable channels and immediately adjacent areas. It does not necessarily extend to every rock in the whole of an area.

Some man-made objects are difficult to detect using the present generation of LIDAR systems due to their very small extent. In this survey, for example, one of the two navigation piles marking The Reef channel was not picked up. However, a system meeting the S-44 special order requirement of a 1-metre cube could also have missed an object of this size. When considering the nature of potential obstructions, it may be that no modern acoustic or LIDAR systems can detect everything that might hole a vessel. The limitation of LIDAR in this respect is simply one point on a scale and the choice of a suitable combination of survey techniques depends on the context in which they are to be used.

Some natural features may also be difficult to survey definitively using either LIDAR or acoustic techniques. One such area is the boulder bed referred to earlier. A multi-beam survey would have been very time-consuming due to the very shallow water. It may even have been more effective to height each boulder individually using a hand-held pole. The LIDAR, however, identified a number of alternative routes, enabling any subsequent boat survey effort to be employed to greatest effect.

Lesson 4 – Combined LIDAR and boat surveys

In an area like the Sound of Harris, only LIDAR could produce the overall picture in a sensible amount of time, leaving a few areas of critical detail to be confirmed later by boat. The problem that has arisen in conducting the survey in this way is that there are a large number of depths that remain to be resolved that have to be recorded by the surveyor and then assessed for chart action by the compiler. A combined LIDAR and boat operation would enable a single definitive survey to be rendered.

This approach however creates two problems: it is difficult to specify in a contract how much boat survey may be required before the LIDAR has carried out the reconnaissance; and it takes time for the LIDAR surveyor to work out which areas the boat needs to examine.

As regards the contract, the experience with the Sound of Harris suggests that an allowance needs to be made of an area of around 5% of the total LIDAR survey area to be re-examined by boat. It would not be necessary to specify the areas in the contract, only to specify that no critical depth along present and future routes should be left unexamined. The identification of any future routes would be a matter of agreement after the main LIDAR survey had been completed.

In order of priority, the boat would do the following:

A. Examine areas of critical depths on the existing or planned routes. Multi-beam would be essential.

B. Investigate charted shoal depths that the LIDAR could not detect at all (e.g. due to kelp or surf), to avoid the need to retain odd depths here and there from old surveys.

C. Fix the positions of navigational aids for which accurate positional data is not held. The LIDAR may not find all beacons, especially small perches. In harbour areas, it may be difficult to pick out the navigational lights from other structures such as lamp standards.

D. Investigate any depths that the LIDAR surveyor classifies as 'Further Examination Necessary' (FEN).

E. If time is available, investigate depths that the LIDAR surveyor classifies as 'Further Examination Desirable' (FED).

Lesson 5 – How much investigation is needed?

Following on from what has been said earlier about there being no real need to detect the absolute least depth over every single rock away from the navigable channels, guidance needs to be given to the surveyor as to how much effort is required in investigating and presenting uncertain features in the data.

There are often shoals where a least depth has not been found, but where further examination is not required either. This can occur for a rock awash or a dangerous rock permanently covered with white water. It can also occur on a kelp-covered rock. Good coverage may have been achieved, but if there is a kelpy waveform at say 1.5 metres, it may not be possible to call least depth found because of the kelp – it may be anywhere between 1 metre or 2 metres. The actual depth does not matter - the rock has been found, and providing it is not in the channel, the idea is to navigate around it, not over it.

For other LIDAR surveys, Tenix has made recom-

mendations for additional action using the following categories where the least depth has not been found:
- FEN: Further Examination Necessary
- FED: Further Examination Desirable
- FENW: Further Examination Not Warranted.

This terminology has been adopted from that used by the Australian Hydrographic Service and is described in Australian Hydrographic and Oceanographic Instructions (AHOI) Chapter 10.

Future contracts should define the above terms in accord with the purpose of carrying out the survey.

Conclusion

The LIDAR survey of the Sound of Harris demonstrates the effectiveness of this survey technique in a difficult environment. No other method could have revealed the intricacies of this area in anything approaching a reasonable amount of time. The LIDAR detected all significant rock outcrops and has indicated a number of areas that could be examined in more detail to open up a better route for the ferry.
Perhaps the most important lesson learned is that when doing a 'first of a kind' survey, don't pick the most extensive complicated area you can find - and then do the whole of it! However, with hindsight nothing could have adequately prepared either surveyors or cartographers for the Sound of Harris.

Biographies of the Authors

Martin Wakefield has worked for UKHO since 1979 and currently leads the team that is responsible for maintaining the charts of Scotland and Ireland. In that time he has undertaken a variety of roles including the development of the ARCS raster chart service, the introduction an early automated surveying system (SIPS), numerous studies including one on digital bathymetric databases, and charting of various parts of the world. Prior to joining UKHO he worked for Decca Survey in the North Sea, having obtained a BSc in Geography and Geology.

Mark Sinclair is the Survey Program Manager of Tenix LADS Corporation. He commenced this position in 1997 and has been responsible for the program of 51 LADS surveys conducted globally. Prior to this, Mr Sinclair served in the Royal Australian Navy for a period of 20 years. During this time he navigated four ships, commanded two ships, the RAN Hydrographic School and the RAN LADS unit. He completed a Bachelor of Science in Physical Oceanography at the University of New South Wales and a Graduate Diploma in Land Data Management at the Royal Melbourne Institute of Technology.

Nigel Townsend joined the Royal Australian Navy in 1984 where he completed a Bachelor of Science (Hydrographic Studies) prior to serving as a Seaman Officer and Surveyor on numerous ships, culminating in command of the survey ship HMAS Shepparton in 2000. In 1999, he completed an IHO Cat A Graduate Diploma in Hydrographic Surveying. Mr Townsend has 15 years involvement in Hydrographic Survey Operations, including over five years experience in lidar surveying, working with both the LADS MK I system and more recently with the LADS MK II system. In 2002, he joined TLC, and has run major lidar projects in Norway, Ireland, Scotland, the Canary Islands, Italy and various locations throughout Australia. Mr Townsend is currently the Survey Manager (Adelaide) responsible for the LADS survey team operating throughout Europe, the Middle East and Australia.