INTERNERSHIP REPORT

FIELD DEMONSTRATION OF THE CAPABILITIES OF X-BAND RADAR FOR COASTAL REMOTE SENSING

David McCann
in partnership with MeyGen Ltd.
PENTLANDX

KNOWLEDGE EXCHANGE: FIELD DEMONSTRATION OF THE CAPABILITIES OF X-BAND RADAR FOR COASTAL REMOTE SENSING.

FINAL REPORT
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DAVID L. MCCANN & PAUL S. BELL
SUMMARY

This final report forms a summary of the aims, results and conclusions of a knowledge exchange internship conducted between the National Oceanography Centre and MeyGen Ltd.

A marine X-Band radar with an OceanWaveS WaMoS II radar recorder was deployed overlooking the Inner Sound of Stroma and operated for a period of 3 months. Sequences of radar images of the sea surface to a range of almost 5km were collected and post processed using NOC algorithms to map water depth and current vectors across the site.

Since the quality of sea surface backscatter is related to sea state there were numerous periods when there was insufficient data to yield useful results. In addition, the range of 4.8km up to which the data was recorded is towards the upper limit of the useful range of such data for this purpose. Despite these caveats, data returns at locations across the site varied from around 20% to 80% over time depending on range from the radar and sheltering from the ambient waves. Depth and current measurements were produced on a 200m grid across the MeyGen lease area, with each measurement point being derived from an 800m² area of the image centred on that point.

Tidal current vectors were compared with an ADCP survey record that overlapped the period of radar deployment. The ADCP deployment was bordering on an area of persistently weak radar backscatter due to sheltering of waves from the Island of Stroma. Despite the relatively poor radar data coverage in that area, the radar derived currents at these locations compare favourably with depth means of the ADCP data in both cases. Tidal harmonic analysis was performed on the available current vectors at the centre of each radar measurement cell in the focus area of the MeyGen lease. The main four harmonic constituents for the area ($M_2$, $S_2$, $N_2$ and $M_4$) show realistic spatial variations in amplitude and phase that compare favourably with analysis of the ADCP dataset. Directional misalignments of the flow between flood and ebb were calculated across the analysis area and varied between 0 and up to 50°, with the regions of highest directional misalignment being associated with the sharp change in channel direction at the foot of Stroma.

Due to the patchy nature of the radar results in both time and space and the limited length of the record, it is not advisable to attempt to use a harmonic fit from these current measurements to predict future tidal current patterns. If predictions of tidal currents are required from short records such as this, it is advised that the radar derived current data be used to help calibrate and validate 2D hydrodynamic models and that the modelled currents be used for predictive purposes and energy yield calculations. Prediction of accurate current patterns may be both possible and successful with a longer record such as has been collected at the EMEC tidal site (installed late 2011) by NOC under the FLOWBEC project.

Other types of analyses that have been performed on the radar data include an analysis of tidally modulated sea surface roughness, which has highlighted regions of above average surface roughness associated with either bathymetric features or horizontal shear zones around headlands, depending on location. Tracking of multiple small targets (mostly birds in flight) has been demonstrated, but shown to be limited to around 2km from the radar at this site. This is not sufficient range to cover the MeyGen lease area, and so a full analysis of the dataset has not been performed. The intention had also been to run a waterline analysis to map intertidal areas of the study area, but an initial inspection of the raw data indicated that intertidal areas were such a small proportion of the site that it was not deemed productive to commit to this analysis.

In summary, a range of spatial data products has been derived from a 3 month radar deployment at the Inner Sound of Stroma. The percentage of good quality radar derived currents from a deployment of this length was insufficient to provide records suitable for harmonic current prediction based on radar data alone. However, comparison of the radar derived currents with concurrent ADCP data was sufficiently good to indicate that longer deployments may well be suitable for this purpose. Short deployments such as this may however prove invaluable for model calibration/validation, and the insights into the locations of shear zones and other hydrodynamic features help to place in-situ measurements into the context of the whole site.
MeyGen is on target to becoming a world leader in the tidal energy industry, with plans to install their demonstration array in 2015. The water that flows through the Inner Sound is the fuel for their turbines, so the ability to predict the available energy in the flow with certainty is of absolute importance for project viability and investor decisions. The ability to accurately predict loads from tides, waves and turbulence on the turbines will also reduce the risk of damage to the turbine without the need to overdesign the structure and incur added cost. MeyGen have successfully carried out numerous ADCP/AWAC campaigns from 2009 – 2013 and have a DHI Mike21 model calibrated to these points for estimating yield and array effects. At these locations MeyGen has a good confidence in their predictions; however the horizontal shear over the site causes a lot of uncertainty in regions not directly measured by ADCPs.

MeyGen collaborated with the NOC on the PentlandX project in early 2013 to gain further understanding of the conditions at their site and to add confidence to the selection of demonstration array location. The importance of flow knowledge over the entire site becomes prominent when planning for future phases where intelligent locating will be required to maximise energy yield. MeyGen intend to use the radar data to validate and possibly calibrate their Mike21 model, which will in turn be used for the prediction of tidal flows in the future. The sea surface roughness gives precise locations of turbulent shear layers which should be avoided by turbines. This is information that cannot be generated with certainty by models and is invaluable to the MeyGen project.

Overall MeyGen are delighted to have been part of PentlandX and look forward to utilising the results for site understanding and model calibration. MeyGen are satisfied that the flow results are of high quality due to the robustness of the NOC checking; they would like to have accurately predicted wave heights but understand that the methods for doing so have not yet been developed. MeyGen wish to enjoy a lasting relationship with the NOC and hope to collaborate in future radar deployments and in the development of the technology.

Sarah Crammond, Project Analyst, MeyGen Ltd.
1. INTRODUCTION

The Natural Environment Research Council (NERC) Marine Renewable Energy Knowledge Exchange (MRE KE) internship scheme is designed to provide businesses involved in the MRE sector the expertise, analytical tools and survey data gained by NERC funded research. The two stated objectives of the NERC MRE KE scheme are to:

1) Initiate collaborations between academics and business which lead to the application of NERC science to provide demonstrable benefits to the MRE sector
2) Generate evidence and case studies of how businesses have or could use NERC science to introduce innovation and benefits to their business.

‘PentlandX’ was a knowledge exchange internship set up between the National Oceanography Centre (NOC) and MeyGen Ltd. – a MRE company currently planning to install a tidal stream array in the tidal race of the Inner Sound of Stroma, North Scotland (Figure 1.1). MeyGen have recently been granted consent by the Scottish government to develop an 86MW primary stage installation, with a demonstration array of 6 turbines planned to be deployed in early 2014 and commissioned in 2015. MeyGen is also in competition for the Scottish Government’s £10M ‘Saltire prize’, the winner of which will be the individual, company or organisation that produces the most amount of MRE over a two year period with a baseline of 100GWh by January 2017.

MeyGen and the NOC identified the following key areas where NERC-NOC science could specifically benefit MeyGen’s endeavours in the Inner Sound of Stroma and act as a demonstration to the MRE sector of the capabilities of such systems and associated analyses:

- Provide world-leading expertise in X-band radar remote sensing of coastal oceanographic processes, specifically helping to describe and explain both what radar can and cannot do.
- Contribution to MeyGen’s knowledge of flow dynamics in the Inner Sound and allow MeyGen to develop models to a point of high confidence which can be used for exact turbine placement
- Provide a higher understanding of wave conditions at the site which are vital for predictions of turbine fatigue, installation planning and safety management
- Help reduce future costs by reducing the need for further (costly) in-situ surveys

To achieve this, the NOC conducted a 3-month field campaign taking X-band radar measurements of an area covering the MeyGen lease in the Inner Sound. The data were then post-processed at the NOC and the subsequent data products made available to MeyGen for their further analysis and comparison. Validation data (ADCP current and wave measurements) were provided by MeyGen.
Figure 1.11. Location of the project area and the extent of the MeyGen Inner Sound of Stroma (red, inset) and the nearby Scottish Power Renewables Ness of Duncansby (blue, inset) lease areas.

1.2. X-BAND RADAR OCEANOGRAPHY

Radar (RAdio Detection And Ranging), in its simplest form, comprises a microwave emitter coupled to a transmit/receive (RX/TX) antenna. Discrete pulses of microwave energy in a narrow frequency band are emitted down-range from the antenna where they come into contact with a variety of objects. Microwave energy that is absorbed and re-emitted or reflected back to the radar (back-scattering) is collected by the antenna and subsequently analysed to produce an analogue video signal representing back-scattered energy with range from the radar. If the antenna is rotating then this process is repeated through 360°, producing a map of backscatter intensity in range-bearing polar coordinates.

X-band radar is a designation given to the microwave band with frequency between 8—12GHz and wavelength between 2.5—3.75cm. X-band is therefore ‘centimetric’, capable of resolving relatively small objects or features and is consequently ideal for use as surveillance radar. The maritime industry has adopted X-band radar as a primary surveillance and navigation tool, being ideal for locating ships or other objects on the sea surface at long range and in bad weather. This radar frequency also generates strong backscatter from rainfall and is hence is commonly used for weather radars.

The use of X-band radar as a remote sensing tool for coastal oceanographic processes centres on the measurement of wind wave parameters (namely period and wavelength) via the phenomenon of Bragg resonant scattering of incident centimetric microwaves — producing an effect known as ‘sea clutter’. Time-indexed images of sea clutter are analysed to calculate wave parameters. A suite of algorithms developed at the NOC are then used to relate local variations in wave parameters to changes in water depth (due to bathymetry) and tidal currents through classical wave theory.
Radar caveats

Of vital importance, when interpreting radar data, is a thorough understanding of the mechanisms by which one is able to remotely measure tidal currents and bathymetry. Allowing users a complete consideration of what radar cannot do was therefore one of the primary objectives of the project. The interpretation of remote sensing data often requires subtle considerations and is always required to be placed in context, otherwise erroneous and potentially damaging conclusions could be drawn from the results. The main caveats to interpreting the radar data presented in this report are listed below:

- Radar-derived variables constitute an area measurement. The nature of the type of wave analysis applied here requires a finite area of the sea surface be analysed and so any calculated variables relate to that area as a whole. It is vital this is taken in consideration when comparing radar-derived parameters to in-situ, point measurements as a like-for-like comparison in areas with strong spatial gradients may not be possible.
- The use of harmonic constituents calculated from short record lengths to drive predictions outside of the data period should be treated with extreme caution. This is exacerbated by the reliance of radar on a sufficient level of sea clutter which can reduce the record length even further after quality control has removed measurements of poor quality.

Critically, the calculation of secondary variables (currents, bathymetry) is only possible if primary wave measurements of sufficient quality are present. The quality of radar images of waves depends on wave height (larger waves provide stronger backscatter), wind speed and direction (wind is required for the Bragg scattering effect, direction defines areas of wind shadowing from land or other structures). The propagation of the emitted and scattered electromagnetic wave is also subject to power loss at range due to the inverse-square radiative effect and as such the signal to noise ratio decreases with range, affecting the quality of long-range measurements. Radars are also better at imaging waves with a significant along-beam rather than across-beam component, making measurements of period and wavelength from images of waves with a small or zero along-beam component difficult.

1.3. SITE SELECTION

Site selection is particularly important for ground-based radar oceanography as the measurement instrument is fixed in space, surveying an area from that location. Additionally, the nature of Marine Renewable Energy sites often finds them placed in remote locations, forming a challenge for traditional fieldwork and survey techniques and often requiring a unique, tailored solution. Site assessment and selection is therefore a vital part of the planning process. The following are the primary concerns when considering a radar survey site:

**Line of sight**
The electromagnetic waves emitted from the radar antenna travel in straight lines (rays) and as they cannot pass through the majority of materials they are subject to shadowing. The ground area that can be seen by eye at the antenna level represents the field of view of the radar. Antenna position must therefore have an unrestricted view over the survey area.

**Height above sea level**
The radar beam is fan shaped, with the horizontal (angular) beamwidth being an inverse function of antenna length – a 2.4m long antenna having a horizontal beamwidth of around 0.8°. The vertical beamwidth is approximately 20° with the upper extent of the beam approximately horizontal. This vertical beam spread allows the radar to image areas of the surface in close proximity to the antenna, however if the antenna is relatively close to the mean sea surface the beam is essentially at a grazing angle. At this extreme, the beam can be shadowed by wave crests and other surface effects as well as reducing the beam footprint which can severely affect data quality. Therefore the radar antenna should ideally be positioned high above the sea surface, allowing the beam to reach all areas of the sea surface with minimum wave shadowing. A minimum height of 10m above mean sea level is recommended, and
preferably towards 30-50m above sea level, but the higher the better as image quality will improve dramatically with height.

**Accessibility**
The radar and its associated equipment require electrical power, preferably from a mains grid connection. Additionally, data acquisition should allow precise time stamping which can be easily obtained by maintaining an accurate real time clock in the radar computer via a connection to the internet. This internet connection can also serve to transfer recorded data from the radar computer to a remote location. Although the equipment is, in theory, stand-alone it may require relatively frequent servicing or troubleshooting. All of these considerations require a site that is accessible and close to commercial or residential utilities.

**Transmit License**
It is a legal requirement in the UK that the operator of marine radar equipment from a land based location obtains a valid transmit license from Ofcom. Each application is assessed by the Civil Aviation Authority (CAA), the Marine Coastguard Agency (MCA) and the Ministry of Defence (MoD) to ensure that the planned radar is unlikely to interfere with existing radar installations. These approvals can take several months to be considered by the appropriate committees, so applications should made well ahead of planned field operations. Once approved, the license currently costs £40 per year to maintain.

**1.4. FIELD DEPLOYMENT**

The field site was chosen to provide a clear view across the Inner Sound of Stroma, to have sufficient elevation above MSL (to increase data quality), to be discrete and invisible from roads for security and to be relatively accessible for maintenance. A suitable site in a field directly overlooking the Inner Sound was identified (Figure 1.41). The field ends in a cliff approximately 8m above MSL and enjoys unobstructed views across most of the Firth. Unfortunately due to the distance from the nearest mains grid connection (~500m) and lack of internet service alternative energy and timing solutions were necessary. Deployment of equipment was completed in mid February 2013 and operations began on the 5th March.

![Figure 1.41. Location of the chosen radar deployment site (A) in Huna, overlooking the Pentland Firth (B). The nearest property was approximately 500m away (C). Image ©2013 Google, DigitalGlobe, Getmapping plc.](image_url)
Figure 1.42. The deployed radar antenna (A), equipment enclosure (B) generator (C) and power supply (D) at the field site in Huna, North Scotland.

Figure 1.43. View of the instrument equipment inside the installation enclosure. Visible is the Radar computer (A), WaMoS interface (B), TimeTools GPS unit (C), WaMoS II radar computer (obscured, D) and radar display screen (E).
Figure 1.44. The deployed radar installation with NOC scientist for scale.

Figure 1.45. The remote hybrid power solution from OffGrid Energy Ltd (A), connected to the 6kVa diesel generator (B).
The radar unit consisted of a Kelvin Hughes Nucleus 3000 X-band transmitter and receiver coupled to a 2.4m horizontally polarised antenna mounted on a scaffold approximately 12m above MSL (Figure 1.42). The raw radar video signal was intercepted by a WaMoS II radar computer through a WiBA interface (supplied by OceanWaveS GmbH) and converted into time-stamped, digitised images of radar backscatter intensity. As there was no internet connection available to the site the onboard clock aboard the WaMoS computer was corrected for clock drift by a GPS time-keeper (supplied by TimeTools Ltd.), of particular importance as accurate image timing forms the basis of all subsequent tidal analysis. All of the recording equipment was housed inside a purpose-built wooden enclosure installed within the footprint of the antenna scaffold for added stability (Figure 1.43). The digitised images were packed and compressed into binary files every sample period by NOC compression routines for later analysis, however the WaMoS High Resolution Current (HRC) routines ran in real time with the output also stored (in ASCII format) for external secondary analyses. The data rate, after compression, was approximately 100Mb every 15—20 minutes which provided an onboard capacity (due to a 1Tb HDD) of approximately 3—4 months.

As the site was too far from the nearest buildings for a mains electricity connection, power was supplied by a 6kVA diesel generator (C, Figure 1.42, B, Figure 1.45). To keep refuelling to a minimum (and thus minimise the ecological and financial impact of excessive fuel use and maintenance time) a novel power solution was provided by OffGrid Energy Ltd in the form of a Grid2Go ‘hybrid power cube’ (D, Figure 1.42, A, Figure 1.45). The solution contained a bank of lead acid batteries connected to an intelligent inverter/charger unit. The equipment continually ran off the battery bank through the inverter and when the batteries reached a set discharge threshold (60%) the generator was activated via an auto-start cable allowing recharging of the batteries. In this way the generator only ran for 6 hours every 3 days, minimising fuel use, pollution and noise impact to the surrounding residents.
1.5. SURVEY OPERATION

One of the benefits of remote sensing is the potential ability to collect vast volumes of data over a wide area and long period for a relatively low cost. This is especially true when compared to the expenses incurred when working at sea, involving vessel time and crew costs for both deployment and retrieval. Although comparatively expensive to purchase, radar equipment may be installed permanently, requiring little maintenance cost and running for the most part autonomously.

Due to the remote location of the installation a unique power solution was required. The use of OffGrid Energy’s Grid2Go power unit enabled not only a stable, continuous power supply (essential for computer equipment) but also helped to considerably reduce emissions compared to the alternative of running a portable generator continuously. The cost in maintenance time was also significantly reduced thanks to infrequent refuelling (once every 5-6 days) as well as considerably reduced fuel use (Table 1.51).

The use of OffGrid’s energy solution resulted in 13% of the fuel use that would have been incurred through continuous generator operation (Table 1.52). Using carbon dioxide emission (CO₂e) conversion rates published by The Carbon Trust and calculating the cumulative electrical energy use over the survey period the estimated CO₂e for the installation was only approximately double that which would have been incurred if national grid energy had been used and almost 10 times less than if the generator had run continuously.

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<tr>
<th>Table 1.51. Fuel use over the survey period and the equivalent use if the generator was run continuously</th>
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<td><strong>Total diesel fuel used (l)</strong></td>
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<td>Diesel generator engine run time (hr)</td>
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<td>Measured average fuel consumption (l/hr)</td>
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<td><strong>Fuel use if run 24 hours continuous (l)</strong></td>
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<th>Table 1.52. Estimated CO₂e for the survey period and the equivalent if mains grid energy was used. CO₂e conversion rates from The Carbon Trust</th>
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<td>CO₂e for diesel fuel (kg/l)</td>
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<td>CO₂e for grid energy (kg/kWh)</td>
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<td><strong>Total CO₂e for deployment (kg)</strong></td>
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<td>Total CO₂e if run 24 hours continuous (kg)</td>
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<tr>
<td>Calculated energy use (kWh)</td>
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<td><strong>Estimated total CO₂e if using grid energy (kg)</strong></td>
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2. METHODS AND DATA DESCRIPTION

2.1 RAW DATA

The installation was in constant operation between 5th March and 11th June 2013, a total of 91 days. The system was set to record for intervals of 128 images (frames) every 20 minutes. Due to the rotation speed of the antenna (approximately 2.5s depending on wind gust) this produced 5.5 minutes of continuous measurements every 20 minutes. During the radar’s dormant periods the WaMoS High Resolution Current (HRC) analysis was performed automatically, followed by the compression, packing and saving of results files to HDD.

An example of the raw data can be seen in Figure 2.11, representing one rotation of the radar antenna and therefore a snapshot of the sea clutter conditions at the time. Individual wave crests are clearly visible in the image (A), as is the Isle of Stroma (B), the returns from objects on the land (left and right of the wave patterns, C) as well as the radar reflector on Duncansby Lighthouse (distinctive, vertical stripe, D). This particular radar return proved invaluable in the role of transforming the raw data to the correct coordinates as the position of both the Radar and the lighthouse are both known and so the reflector return can be used to rotate the data to the correct bearing. For the majority of the analyses, however, a Cartesian transformation of the data was required – the result of which can be seen in Figure 2.12. Here the wave patterns are now recognisable as a North-Westerly wave event that has interacted with the Isle of Stroma to cause multiple diffraction and interference patterns.

Figures 2.13 to 2.15 show examples of Cartesian transformed snapshots of data considered to be of poor, normal and excellent quality, highlighting the large variation in wave conditions and radar images at the site. Images such as Figure 2.13 do not provide enough wave information to form the basis for current analysis while those such as Figure 2.14 would provide current vectors across areas where wave returns are visible. Images during large wave events such as Figure 2.15 would provide current information across the majority of the survey area.

![Image](image-url)

**Figure 2.11.** Example of a digitised polar ‘snapshot’ image representing one rotation of the radar antenna.
Figure 2.12. Example of a digitised ‘snapshot’ image, mapped onto UTM Cartesian coordinates.

Figure 2.13. Example snapshot of poor quality data from a very calm period with no waves.

Figure 2.14. Example snapshot of normal quality data during average wave conditions. Wave patterns are clearly visible.
Figure 2.15. Example snapshot of excellent quality data during a period of large, Easterly waves.

2.2. WaMoS II SET-UP

The OceanWaveS WaMoS II radar computer was deployed primarily to provide the time-stamped, digitised polar radar images that are vital for all NOC analytical methods. However the WaMoS HRC analysis was also employed in real-time on site (i.e. in-between measurement periods) to assess their applicability to such a dynamic environment. During pre-deployment trials it was found that the HRC analysis could not run in the time between measurement periods when the NOC compression routines were included in the workload. In order to keep the processor free of unfinished tasks while recording raw data it was decided to scale down the HRC analysis settings to a lower resolution and so to compete for less processor time.

As such the WaMoS HRC algorithm was set up to only use 64 images out of the 128 that were recorded. This significantly decreased calculation time but unfortunately degraded the quality of the results generated by the HRC analysis. In addition, when it was found that the radar data quality was particularly poor in the area of most interest to MeyGen due to that area being relatively sheltered from wind and waves, the size of the analysis box used by the NOC algorithms during post processing was increased to 800m square (and translated at a quarter of that box size – 200m), allowing useful current vectors to be calculated from extremely weak signals.

Any comparison between the NOC and HRC data must take these factors into account as the comparison is not like-for-like. Tests have subsequently indicated that the WaMoS algorithms are of equivalent accuracy when run at the same settings as the NOC version.

What is clear from this is that individual sites require individual setups to the data analyses to optimise the outputs for the particular project.

2.3. ANALYSIS METHODS

The purpose of the project was primarily to provide MeyGen with additional hydrodynamic data to supplement and provide context to the in-situ survey and modelling work they had previously contracted. An additional, secondary aim was to provide MeyGen with expertise and guidance in the emergent field of radar oceanography – particularly to provide evidence to demonstrate the potential effectiveness of a permanent radar installation overlooking the Inner Sound of Stroma. To achieve this, a range of NOC research-grade analyses were applied to the radar data set to provide an overview of the state-of-the-art in radar oceanography research. Additionally, the commercially-available WaMoS HRC mapping toolbox was applied to provide an overview of the capabilities and limitations of the
state-of-the-art in the commercial sector, although as mentioned in Section 2.2 the analytical capability was scaled back due to processor time and so shouldn’t be taken as the true capability of the system. To this end, the following analyses were applied:

- NOC bathymetric inversion
- NOC current calculation
- WaMoS High Resolution Current (HRC) mapping
- Tidal harmonic analysis of NOC derived currents
- WaMoS significant wave height calibration
- Tidally-coupled surface roughness imaging
- Small target tracking (e.g. Birds) with the NOC tracking program ‘GANNET’

To validate and calibrate the radar outputs the following additional survey records were analysed and applied:

- 600kHz 4-beam ADCP survey [MeyGen / Environmental Research Institute (ERI)]
- Side-scan Sonar bathymetric survey [Marine Scotland Interactive (MSI)]

A description and brief explanation of the methods of analysis are given below:

**Bathymetric inversion**

This method relies on the known relationship between wavenumber \( k \), wave frequency \( \sigma \) and mean water depth \( h \) – the dispersion relation. Within a region defined by \( \sigma, k \) is directly affected by \( h \) so that tracking changes in \( k \) can effectively provide the spatial change in depth due to bathymetry. This is a non-trivial task, however, as \( k \) and \( \sigma \) are interrelated and both are affected by the presence of an underlying current. The calculation of wave parameters requires the analysis of a finite area of sea surface – ideally enough to encapsulate at least one wavelength. This carries the assumption that the wavenumber and frequency spectra across the discrete analysis area are homogenous. The analysis algorithm therefore works on areas of sea surface typically 100-200m across and transposes this area step-wise in order to produce a map of calculated bathymetries. Further details on the bathymetric inversion method can be found in Bell (2009a; 2009b) and Bell & Osler (2010).

**Current calculation**

As mentioned previously, the magnitude and direction (relative to the wave) of an underlying current has an effect on \( k \) through its effect on the dispersion relation. Identifying the effect on \( k \) for multiple, superimposed waves enable the analysis to converge onto this effect – increasing the accuracy of the calculated current. The NOC current algorithm follows the methods described in Senet et al (2001), resolving the effect of the mean current on the dispersion relation. However the NOC analysis differs in that it searches parameter-space for a best-fit solution which greatly increases computation time but leads to a more robust current calculation. As with the bathymetric inversion algorithm the current analysis works step-wise across the survey area to produce a map of currents using the assumption of homogeneity in the flow field across a discrete analysis area. These currents are therefore representative of the conditions across the finite area used in the step-wise analysis. This produces an area measurement which can be problematic when strong sub-grid-scale flow structures are present. Further details on the method can be found in Senet et al (2001), Hessner & Bell (2009b), Bell (2010) and Bell et al (2012).

**ADCP validation**

The ADCP survey was pre-processed by ERI before its use for validation and comparison at the NOC. For comparison with radar-derived currents the depth-averaged ADCP velocity components were calculated and the radar-derived currents were space- and time-interpolated to the ADCP records using a simple linear interpolation. This was necessary as the ADCP measurements were taken at different times and a different location to the radar survey intervals and measurement grid.
Tidal harmonic analysis

Harmonic analysis involves fitting harmonic waves (tidal constituents), via a method such as ordinary least-squares, to a continuous or discrete record of tidal velocities or surface elevations. In the case of currents the $u$ and $v$ velocity components are treated as separate records. The open-source tidal analysis and prediction toolbox ‘UTide’ (Codiga, 2011) was chosen to be applied in this work due to its ability to handle non-continuous data series – other tidal analysis code such as the popular ‘T-tide’ package do not handle non-continuous data. UTide attempts to fit up to 40+ tidal constituents to a tidal current record, discarding fits that show a poor signal to noise ratio. The program also provides information on mean tidal current vectors. Harmonic analysis is very sensitive to the quality and record length of input data – both of which must be taken into consideration when interpreting results.

Wave height calibration

The standard method to estimate the significant wave height ($H_s$) of a wave field imaged by X-band radar is to relate the calculated Signal to Noise Ratio ($SNR$) from the fit to the dispersion relation to $H_s$ via a linear calibration curve, requiring a calibration data set of sufficient length and quality. The method was originally developed for synthetic aperture data and subsequently applied to offshore applications. The method carries the assumption of wave field homogeneity, and as such its validity in highly inhomogeneous areas such as this is untested. Details on the method can be found in Alpers & Hasselmann (1982) and Nieto Borge et al (1999).

Tidal surface roughness

The imaging mechanism of radar is solely reliant on reflected (back-scattered) microwave energy from objects down-range of the antenna. Sea clutter is highly non-linear and is comprised of backscatter from numerous sources all with independent temporal and spatial characteristics. However the backscatter response from waves (via Bragg scattering) is characteristically periodic – therefore averaging the signal over a suitable period has the effect of removing the contribution due to waves. Time-lapse radar images, created from 128 scans of the antenna, provide information on the general clutter environment of the sea-surface. Spatial changes in the condition of the sea surface (surface roughness) therefore will be evident in the spatial pattern of average clutter. The NOC tidal surface roughness analysis correlates these time-lapse radar images to an appropriate phase of the $M_2$ tide, allowing the discrimination of surface roughness conditions in terms of tidal phase.

Small target tracking

The NOC’s small target tracking program (GANNET) employs a simple but robust multiple target Global Nearest Neighbor (GNN) data association routine with a Singer-type dynamic model of bird flight (Singer, 1970) via an Extended Kalman Filter and Clutter Map Constant False Alarm Rate (Skolnik, 1990). The program works directly on raw polar radar images in near real-time and produces a track file for each 5 minute survey period containing target positions and speeds with time, track curvature and target properties. Further details on the methods employed can be found in Blackman (1986) and Skolnik (1990).
2.4. QUALITY CONTROL

Quality Control (QC) techniques are an important part of remote sensing and are especially so in the analysis of radar data. This stems from the fact that the raw input data (radar images) are not an explicit measure of anything more than an arbitrary magnitude return at bearing and range. Any measurements are a result of an implicit analysis of these returns with errors propagated forward from the initial quality of the images.

Two separate QC techniques were applied to the HRC and NOC datasets respectively, with the NOC QC mechanisms being present within the algorithms and those for the HRC data being performed as post-processing. The HRC QC technique is based on the signal to noise ratio (SNR) calculated by the WaMoS standard wave analysis (used to estimate significant wave height) and stored in the HRC output ASCII files. The relationship between data quality and SNR was quantified and then maps of SNR were converted to a threshold for the exclusion of poor quality data. However being a simple, universal threshold the HRC QC method does not always exclude bad data where the SNR is close to the limit. The NOC QC technique is more robust and is based on a correlation process which allows poor quality data to be identified and flagged before the output phase. In practical terms there is no difference between the two QC methods as the end result is to exclude records that contain current vectors that are unrealistic (e.g. wildly diverging, noisy vectors that do not obey the laws of continuity). However the NOC QC process works directly on the ‘believability’ of the calculated currents, whereas the HRC QC process is a simple signal level threshold. The end result of both QC techniques is to remove data that is deemed to be of insufficient quality and therefore there is a reduction in the data record length in both data sets. Figures 2.41 and 2.42 show the effect on data record length for both data sets as percentages of the total recorded data (i.e. 91 continuous days).

![Figure 2.41. Data coverage (Percentage of 91 days) for the HRC data set](image-url)
3. RESULTS

3.1. NOC BATHYMETRIC INVERSION

The NOC bathymetric inversion algorithms were applied to the full 91-day radar record. The NOC algorithms act to converge on the most probable bathymetry over time, providing a stable map of water depths with a horizontal resolution of 200m across the radar effective range (Figure 3.11).

Bathymetric inversion is highly dependent on wave conditions however, as the maximum depth is effectively set by the wavelength and period of waves measured across the site (Bell & Osler, 2011). With this taken into account the limit of wave-inversion deduced bathymetry is recommended in this case to be set at 40m below mean sea level (MSL).

Figure 3.11. Radar-derived bathymetry (m below MSL) across the survey site from the NOC bathymetric inversion algorithm. The lease areas of MeyGen (left) and Scottish Power Renewables (right) are shown for reference. Light grey denotes land, the red diamond the radar antenna and the red arc the radar maximum range.
It was possible to partially validate the bathymetric inversion due to the presence of a side-scan sonar survey of the area provided by Marine Scotland Interactive (MSI). Figure 3.12 shows the extent of the MSI survey in relation to the study area and Figure 3.13 shows the absolute difference between the MSI (interpolated to 200m horizontal resolution) and NOC surveys. There is a slope visible in the comparison, related to the effect of maximum wavelength and wave period recorded during the survey and their impact on the maximum wave penetration depth (Bell & Osler, 2011). The slope is expected to reduce to 1:1 at shallower depths.

Unfortunately due to the limited range of comparable depths measured by the MSI survey there is no comparison with depths normally considered within the range of depth inversion analysis (< 20m). This is evident by the deviation from unity in depths greater than 40m (red dots, Figure 3.13), where the penetration of the waves is not sufficient to accurately determine water depth.

Figure 3.12. Side-scan sonar bathymetry (m below MSL) at 10m horizontal resolution from Marine Scotland survey.
3.2. WATERLINE METHOD

The recently developed NOC waterline method was planned to be applied to the survey dataset in order to provide bathymetric information in the intertidal zones where data from traditional survey techniques and bathymetric inversion are not available. The method requires an intertidal area in order to function, and as the coastline around the Pentland Firth is predominantly formed of steep, rocky cliffs there is not enough intertidal area for a waterline analysis to add value to the present data. Figure 3.21 shows an image of a representation of the maximum intertidal area during the survey, calculated from the difference between images of high and low water during spring tides. The bright white areas in Figure 3.21 represent the maximum extent of the intertidal zone in the area that is in line-of-sight of the radar, derived from the difference between images recorded at low and high water during Spring tides. The NOC waterline analysis was therefore not conducted on this data set.

Figure 3.13. Comparison between radar-derived and sonar measured bathymetry. Measurements over 40m below MSL are shown in red.

Figure 3.21. Representation of the maximum extent of the intertidal zone within line-of-sight of the radar (bright white areas).
3.3. INSTANTANEOUS CURRENTS

The instantaneous currents represent the bulk of the data supplied to MeyGen, to be used for model comparison, validation and further post-processing. The data was supplied post-processed with QC parameters included and formed a significant part of the knowledge exchange.

WaMoS HRC data

The commercially-available WaMoS HRC analysis was applied in real-time on site, with the algorithms running after every measurement period. The 91-day survey period is represented by 7322 HRC files in ASCII format, containing current magnitude and direction and swell wave parameters (wavelength, period and direction of propagation) as well as the signal and noise levels (used to estimate significant wave height).

Figure 3.31 shows an example of the instantaneous current vectors produced by the HRC toolbox with QC mask applied created from 64 images during an arbitrary ebb tide. In this particular instance the swell direction was Easterly (i.e. from the East), providing a higher quality of wave data towards the East and Centre of the radar area. However wave penetration towards the West of the Inner Sound (A) was not sufficient to resolve the wave parameters and therefore the current speed and direction is not well defined. This is compounded by the fact that the HRC analysis had to be run with a decreased number of images (64 rather than the full 128) which significantly decreases the HRC algorithm’s ability to pick out current parameters when the wave input data is relatively poor. Data points that did not pass QC are blanked out in grey.

Figure 3.31. Example of instantaneous current vectors (ms⁻¹) calculated by the WaMoS HRC mapping toolbox during an ebb tide at 12:40 on the 23rd April 2013.

NOC analysis data

The NOC analysis comes with a significantly higher computational cost over the HRC toolbox which prevented its application in real-time on-site. The computational cost rises considerably with the number of data points considered (the horizontal resolution combined with the extent of the survey area) and as the project was primarily focused on MeyGen’s needs it was decided to limit the NOC current analysis to an area encompassing the extent of the MeyGen lease. Figure 3.32 shows an example of the instantaneous current vectors produced by the NOC toolbox with QC mask applied created from 128 images during the same period as in Figure 3.31. These calculated currents form the basis of the majority of analyses described in this report.
The higher quality of the NOC results is thought to be largely the result of the increased number of images and larger analysis area used by the NOC analysis in post processing. It is also thought that the HRC and NOC analyses would yield comparable results if run with the same settings, but there was insufficient time to apply these higher quality settings to the HRC during this deployment. Further analysis on the existing dataset using the HRC algorithms at more optimum settings may be carried out at a later date allowing a like-for-like comparison between the two methods.

As mentioned in Section 2.4 and highlighted in Figure 2.42 the impact of quality control techniques on data record length was heterogenous across the NOC analysis area. Unfortunately this has a significant effect on other analyses that rely on the calculated currents. Figure 3.33 shows the best example of calculated current time-series from a point in South-Eastern corner of the NOC analysis area. Here the effects of QC techniques are evident as gaps in the record, co-incident with periods of extremely low wave and wind activity. The 'jump' in recording around the 23rd March (A in Figure 3.33) is due to maintenance work that temporarily interrupted data recording. Figure 3.33 can be taken as a representation of good radar-derived current data, however due to the lack of proximity of ADCP validation data this particular time-series cannot be validated.

Figure 3.32. Example of instantaneous current vectors (ms$^{-1}$) calculated by the NOC research-grade analysis during an ebb tide at 12:40 on the 23rd April 2013.

Figure 3.33. Example of the best time-series (in terms of record length) of flow magnitude (ms$^{-1}$, top panel), and $u$ and $v$ velocity components (ms$^{-1}$, mid and bottom panels respectively) from the survey.
3.4. TIDAL MISALIGNMENT

The deviation of a tidal flow from rectilinearity, it’s ‘misalignment’, may be a useful measurement for determining the efficiency of a tidal turbine at a particular location. A perfectly rectilinear tidal flow has a flood direction 180° from that of the ebb and therefore the turbine axis can simply be installed in line with the flood or ebb direction. However inertial effects from curving flows (e.g. around islands and headlands) and the channelling action of bathymetry can cause the flood or ebb flow directions to deviate from one another. Without a turbine that is able to change its rotary axis between tidal phases the flow speed incident on the turbine axis is reduced proportional to \( \cos(\theta) \) where \( \theta \) is the misalignment in degrees. Mapping the misalignment is therefore useful for both efficient turbine placement and the calculation of the degree of axial movement the turbine might need in order to extract the maximum amount of power from the flow.

Figure 3.41 shows the average absolute misalignment \( \theta \) derived from the NOC radar data set, defined as (Goddijn-Murphy et al, 2013)

\[
\theta = |180 - (\theta_F - \theta_E)|
\]

where \( \theta_F \) and \( \theta_E \) are the average flood and ebb directions respectively. The observed pattern and magnitude of the misalignment is broadly similar to that found by Goddijn-Murphy et al (2013), with a peak of around 50° coinciding with a bend in the channel and the lower tip of the Isle of Stroma. As the method assumes a tidal flow with relatively stable flood and ebb directions a QC method was applied using a result from the tidal harmonic analysis described in Section 3.6. Here the percentage of spectral energy accounted for by the \( M_2 \) harmonic (principal Lunar semidiurnal), \( EM_2 \), as calculated by the harmonic analysis was used as a QC threshold – any data points where \( EM_2 < 70\% \) are denoted in grey on Figure 3.41. This method successfully masks off the suspect area of data quality to the North and West of the MeyGen lease.

3.5. VALIDATION WITH ADCP SURVEY DATA

An independent ADCP survey conducted by the ERI coincided with the radar deployment between the 6th and 20th March 2013. Co-incident recordings were unfortunately not numerous, with only 14 days of data cross-over. This was further compounded by the strict quality control scheme applied to the NOC radar-derived currents that omitted large proportions of the co-incident data set due to a lack of suitable waves (low sea clutter conditions) at the time. However, due to quality control the data that remains is of a suitably high standard for comparison and validation.

Figure 3.51 shows the calculated depth-averaged flow velocities (10 minute averaging) from the ERI survey compared with co-incident radar-derived velocities from the NOC analysis. The radar data was linearly, spatially interpolated from the 200m NOC grid resolution to the ADCP location and
temporally interpolated to the ADCP measurement times. **Figure 3.52** shows a section of the validation time series where data cross-over occurred.

The resolution of the $u$ (positive East, positive Flood) velocities by the radar are significantly better than the $v$ (positive North) component. This is due to the effect of an area measurement (the radar) attempting to resolve sub-grid scale flow features such as eddies and migrating horizontal shear zones within the analysis box. The NOC analysis assumes homogeneity in the currents across the analysis box area so that the calculated current at each grid point represents the current over each analysis area. Clearly in such a hydrodynamically complicated area as the Pentland Firth sub-grid scale flow structures will be prevalent – especially in the area of the MeyGen lease where rough bathymetry and a constricted tidal flow interact with the Isle of Stroma and its associated rocky outcrops. However the relative importance of these sub-grid scale features will be proportionate to the overall tidal flow – i.e. small perturbations to a small measurement will be more important than small perturbations to a large measurement.

This is due to the position of the ADCP survey location with respect to the prevailing direction of wave propagation, rectilinear nature of flood-ebb flows and the position relative to the radar beam. At the ERI survey location the North-Easternly waves of the time had refracted to true Easterly, running perpendicular to the radar beam. Waves are modulated by the component of the current running in the direction of wave propagation. As the waves were Easterly the small $v$ component of the East-West rectilinear currents at that location did not affect the period and wavelength of the waves enough to be resolved by the radar.

This asymmetry in velocity component resolution also has an effect on the $u$ velocities. In **Figure 3.51** and 3.52 the waves were Easterly, i.e. propagating to the West and opposing the Flood. Waves that are directly opposed by a current have a tendency to ‘back-up’, increasing their amplitude (wave height) and consequently their associated signal to noise ratio. This tends to increase the accuracy of resolved currents that are in opposition to the direction of wave propagation, reducing the error of Flood currents in **Figures 3.51 and 3.52**. The overall comparison is degraded predominantly by the lack of resolution of the $v$ velocity component which shows a strong mean flow and tidal behaviour that is not semi-diurnal.

**Figure 3.51.** Comparison between the depth-averaged ADCP velocities from the ERI survey and co-incident radar-derived velocities from the NOC analysis.
Figure 3.52. Example time series of depth-averaged current magnitude (top panel), \( u \) velocity component (mid panel) and \( v \) velocity component (bottom panel) for the ERI ADCP survey (black) compared to co-incident radar-derived current data (red).

### 3.6. TIDAL HARMONIC ANALYSIS

The provision of accurate tidal harmonics is essential for the determination of tidal energy yield. As the energy yield is directly related to MeyGen’s success as a company it was agreed that the provision of tidal harmonics would constitute a clear benefit to the company in helping to identify optimum locations for turbine placement. One of the major benefits of radar-derived tidal currents is that they are calculated over both a wide area and (potentially) over a long time period. This allows tidal harmonic analysis to be conducted across the survey area – producing a map of constituent harmonics.

As in Section 3.5, comparison with the ERI ADCP survey was possible. The harmonic analysis was applied to the ADCP record as well as co-located current vectors from the NOC analysis using the open-source tidal analysis package UTide (Codiga, 2011). Tables 3.6.1 shows the results of the comparison for the four most important harmonic constituents in this area – The principal Lunar semi-diurnal (\( M_2 \)), principal Solar semi-diurnal (\( S_2 \)), larger Lunar elliptic semi-diurnal (\( N_2 \)) and the shallow water overtide of the principal Lunar (\( M_4 \)). Although only four constituents are listed here, UTide calculates the amplitudes and phases of over 40+ constituents (if resolvable in the time series) in order to describe the observed tide. The result variables are as follows: \( A_{maj} \) and \( A_{min} \) are the major and minor tidal ellipse magnitudes (comparable to the \( u \) and \( v \) velocity components), \( G \) is the tidal phase in degrees relative to Greenwich, \( E \) is the percentage of spectral energy accounted for by the constituent (i.e. its importance in the shape of the wave), \( U_{mean} \) and \( V_{mean} \) are the mean \( u \) and \( v \) velocity components, \( Var \) is the percentage of variation described by the harmonic fit and \( E_i \) is the percentage of spectral energy accounted for by the top four constituents combined.
Table 3.61. Comparison of outputs from UTide between the ERI ADCP survey and co-located NOC-derived currents.

<table>
<thead>
<tr>
<th></th>
<th>ERI ADCP</th>
<th>Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_{maj}$</td>
<td>$G$ (°)</td>
</tr>
<tr>
<td>$M_2$</td>
<td>2.66, -0.11</td>
<td>240</td>
</tr>
<tr>
<td>$S_2$</td>
<td>1.01, -0.06</td>
<td>274</td>
</tr>
<tr>
<td>$N_2$</td>
<td>0.47, 0.03</td>
<td>198</td>
</tr>
<tr>
<td>$M_4$</td>
<td>0.26, -0.01</td>
<td>305</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$U_{mean}$, $V_{mean}$</th>
<th>Var (%)</th>
<th>$E_4$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.29, -0.43</td>
<td>98.3</td>
<td>94.8</td>
</tr>
<tr>
<td></td>
<td>0.099, -0.64</td>
<td>98.1</td>
<td>90.7</td>
</tr>
</tbody>
</table>

The subtle differences between radar and ADCP-derived constituents can mostly be described by the difference in an area and in-situ, point measurement. The hydrodynamics of the inner sound is such that spatial patterns of tidal currents vary considerably and so a measurement that represents an area (such as radar) should not be expected to match an in-situ measurement from somewhere within that area precisely. The same holds for calculated tidal harmonic constituents, these being the direct product of a series of velocity components.

With this in consideration, the comparison between radar and ADCP derived tidal harmonics is largely excellent, especially with $A_{maj}$ (the $u$ velocity component). Differences in the tidal phase $G$ and the mean velocity components $U_{mean}$ and $V_{mean}$ are likely direct products of an area measurement due to sub-grid-scale spatial differences in velocity caused by flow around Stroma and through the channel of the Inner Sound. The inability of the radar to successfully resolve the $v$ velocity component in the area of the ADCP surveys is clearly evident in the differences in $A_{min}$.

Harmonic analysis was applied to each grid point in the NOC dataset where sufficient data was available. Figure 3.61 shows the absolute magnitudes of the amplitudes of the four top tidal current constituents and Figure 3.62 shows their phases relative to Greenwich. The sensitivity of the analysis to poor data is visible in the noisy areas towards the north of the analysis area where wave shadowing and the prevalence of sub-grid-scale flow features degrade the analysis.

Figure 3.61 Absolute magnitudes (ms$^{-1}$) of the amplitudes of the four top tidal constituents from harmonic analysis of the NOC dataset.
Figure 3.62 Phases (degrees) of the four top tidal constituents from harmonic analysis of the NOC dataset.

Figure 3.63 shows the mean velocity vectors from harmonic analysis, comparable to an average of each velocity component over the survey period. There are significant mean flows in the Inner Sound, driven by asymmetrical tidal forcing through the channel and around the Isle of Stroma. Tidal residual circulations such as this are common in complex coastal environments, driven by inertial flows around complex geometries and bathymetries (Yang & Wang, 2013). Considering that the calculated mean flows are similar to those seen in the ERI ADCP record (Tables 3.61) and that the vector directions and magnitudes are consistent and stable it is concluded that the mean flow pattern in Figure 3.63 is real and not a by-product of the harmonic analysis.

Figure 3.63. Mean velocity vectors (ms\(^{-1}\)) from harmonic analysis of the NOC data set.
**Effect of record length on tidal harmonic analysis**

Due to the spatially varying impact of QC on the NOC current data set the length and quality of record length was variable across the survey site. Unfortunately this can have significant implications for the quantity and quality of tidal harmonic constituents the analysis software is able to fit to the velocity record. Stiven et al (2011) showed that the impact of record length on the use of tidal harmonic predictions to drive resource estimation can introduce significant errors in annual revenue (over 14% in the example presented). It is therefore not recommended that harmonic constituents derived from this current data set be used to drive tidal predictions where accuracy is vital for operations.

### 3.7. WAVE HEIGHT CALIBRATION AND ESTIMATION

The standard method to estimate the significant wave height ($H_s$) of a wave field imaged by X-band radar is to calibrate the calculated Signal to Noise Ratio ($SNR$) to a co-incident set of wave height measurements (Alpers & Hasselmann, 1982). In this case the ERI ADCP survey included an $H_s$ calculation, enabling an attempt at wave height calibration for the site. $H_s$ is subsequently estimated as

$$H_s = A + B \sqrt{SNR}$$

where $A$ is the intercept and $B$ is the slope of the fit between the $SNR$ and the calibration $H_s$ data set respectively. The $SNR$ is calculated by the WaMoS II radar computer and is related to the fit between measured wave parameters and the dispersion relation. The $SNR$, like all other radar-derived parameters is an area measurement representing the conditions across a grid cell (in this case over 300m square). Figure 3.71 shows the $SNR$ record from the grid cell covering the ERI ADCP survey location (red line), coincident with the $H_s$ survey duration (black line). To relate the $SNR$ to measured $H_s$, a calibration curve is calculated (Figure 3.72) using an ordinary least-squares regression. Due to the significant scatter, outliers were defined as points with residuals greater than one standard deviation from the fit (red points) which increased the coefficient of determination ($R^2$) from 0.52 with outliers to 0.8 without. The fitted calibration curve was then applied to the $SNR$ record to form an estimate of $H_s$ (Figure 3.73).

Clearly in this case the assumption of a linear relationship between $SNR$ and $H_s$ is not valid, evident by the significant scatter in Figure 3.72. The result is a wave height estimate that is broadly similar to the calibration data set but has significant differences throughout. Previous studies have identified strong dependencies of the calculated $SNR$ on wave direction relative to the antenna which can have a large effect on the estimate of $H_s$ (Lund et al, 2013) – a problem that will certainly be evident in such a dynamic wave environment such as the Inner Sound, even with a fixed antenna position. The assumption of homogeneity is most likely invalid for such a geometrically and hydrodynamically dynamic area such as the Inner Sound of Stroma, the problems of which are exacerbated by the presence of only a single, short calibration data set. This is not a problem restricted to the present survey however, as co-incident calibration data is often difficult to obtain. It is therefore recommended that the present wave height estimates are not of sufficient quality on which to base operational decisions, requiring additional, longer calibration data sets to perform a spatial calibration without the limiting assumption of wave field homogeneity.
Figure 3.71. SNR calculated by the WaMoS II computer over the ERI ADCP location (red line) for the period coincident with the ADCP $H_s$ record (black line).

Figure 3.72. SNR to $H_s$ calibration curve for the grid cell covering the ERI ADCP survey. The fitted curve ignores outliers with residuals greater than one standard deviation from the fit (red points).
3.8. TIDAL SURFACE ROUGHNESS ANALYSIS

The NOC tidal surface roughness analysis correlates 5-minute (128 scan) long-exposure radar images with their associated phase relative to the $M_2$ tide. Images from a full spring-neap cycle (so as to include spring-neap variations) are stacked in discrete phase bins and subsequently averaged, producing an average surface roughness image related to a particular tidal phase. Surface roughness structures that appear on these phase-correlated images consistently occur during every tide with ephemeral backscatter signals (e.g. vessels and small targets, individual wave events) being averaged out in the process. Consistently occurring roughness signatures will include bathymetrically-locked vertical turbulent eddies (e.g. from flow separation over rough bathymetry and dunes), turbulent surface wakes from flow obstructions and strong spatial gradients of surface roughness due to horizontal shear.

Figure 3.81 shows the surface roughness signature associated with slack water in the tidal cycle. Here no distinct roughness structures can be distinguished as the images it is comprised of are correlated with a relative lack of hydrodynamic activity. The image associated with the flood tide is significantly different (Figure 3.82). Here four roughness structures of particular interest can be identified. There is a distinctive line of high roughness (A) with an origin at the rocky outcrops off the West coast of the Isle of Stroma, the wake of which extending over 3km into the inner sound. A possible shear-zone is associated with this wake (B), with a significant drop in surface roughness to the North of the wake line. The obstructing effect of the Isle of Stroma on the flood-tidal flow would suggest this is indeed an area of decreased tidal currents (and therefore surface roughness) and the fact that the image is comprised of time-lapse images from a number of wind and wave conditions suggests it is not due to a wind- or wave-shadowing effect that would provide a lack of radar backscatter. There is a distinctive set of wave-like surface structures (C) associated with the known location of a field of large underwater sand dunes. These can therefore be taken to be the result of flow separation over the dune crests, creating an increased level of surface roughness down-stream due to the presence of large, vertical turbulent eddies. There is also an increased area of roughness over the known position of an extensive sand-bar (D). The surface conditions are consistently choppy in this area owing to the interaction of waves, shallow water and strong flows. Figure 3.83 shows the associated image for ebb-tidal conditions. Here there are two distinct wakes from the rocky outcrops of the Isle of Stroma (A) and similar returns due to flow separation over the dune field (B). The distinctive shear-zone seen in the flood tide does not appear to be present during the ebb, possibly due to the asymmetrical shape and orientation of the Isle of Stroma relative to flood and ebb flows.
Figure 3.81. Mean surface clutter during periods of slack tides.

Figure 3.82. Mean surface clutter during periods of flood tides.

Figure 3.83. Mean surface clutter during periods of ebb tides.
3.9. SMALL TARGET TRACKING

Recently developed at the NOC, the research-grade small target tracking algorithm GANNET (GlobAl Nearest Neighbour targEt Tracker) was applied to the raw image data described in Section 2.1. At its core, GANNET employs simple yet robust Global Nearest Neighbour (GNN) data association solved via the Munkres assignment algorithm coupled with a Singer dynamic acceleration model of bird flight (Singer, 1970) and an Extended Kalman Filter (EKF). Target detection and discrimination from sea clutter is accomplished using a ‘cluttermap’ Constant False Alarm Rate (CM-CFAR) technique and a four-dimensional target state vector (position, radar return density and target pixel cluster size) using image morphological functions. The output is a set of target tracks consisting of target number, time, position, speed, path curvature, return density and cluster size over a 5 minute, 128 scan radar measurement period. An example of the ASCII formatted GANNET output file can be seen in Appendix I.

The original aim of conducting small target tracking in the study area was to assess the density of bird activity over the MeyGen lease. However upon tuning the program to the Inner Sound data set an effective tracking range of less than 2km from the antenna was observed (Figure 3.91), falling short of the MeyGen lease area and therefore being unable to provide the coverage required to form an assessment of bird activity in the area. As such, GANNET was not run over the entire data set but an example of a possible form of data product can be seen in Figure 3.92. Traditional surveys of seabirds involve single or multiple spotters recording bird behaviour and approximate positions within a limited range dictated by visibility and limited scope dictated by the number of seabirds a human operator can track simultaneously. Radar has the advantage of being able to simultaneously track multiple targets over a wide area and in conditions a human observer cannot (e.g. during the night). However radar does not explicitly track seabirds – target discrimination is a nontrivial problem requiring numerous assumptions and tuning parameters. GANNET could therefore be a useful augment to traditional bird surveys in the future where the 2km effective tracking range is not a limitation.

Figure 3.91. Target tracks coloured by target speed (ms⁻¹) for a 5 minute period beginning 16th March 2013 06:15am. The solid red line denotes the maximum radar range and the dashed red line denotes the 2km maximum effective range for the tracking program.
**Figure 3.92.** Example product from the tracking program outputs showing target counts over a 3 hour period between 05:00 and 08:00am on the 16th March 2013.
4. FINAL CONCLUSIONS AND RECOMMENDATIONS

The application of X-band radar to an area as dynamic as the Inner Sound of Stroma was challenging both operationally and scientifically. The vast range of weather, tidal current speeds and wave conditions produced a data set that exceeded all expectations that will benefit both MeyGen and the NOC. Final concluding remarks on topics covered in this report are presented below.

Radar-derived bathymetry

The radar-derived bathymetry for this deployment has produced a bathymetric map of the Inner Sound to 160m horizontal resolution. Unfortunately without a validation bathymetric survey that extends to the shallow water (<20m) areas there is little data for a good comparison at this time. It is recommended that radar-derived depths > 40m below MSL should not be trusted as this is pushing the analysis method far beyond the accepted limits for wave-inversion.

Radar-derived tidal currents

Calculating the speed of tidal flow from a remote position on land using microwave images of the sea surface is a non-trivial exercise. With careful consideration of the limits of X-band radar images and the analytical methods applied to them, the resulting tidal current dataset is excellent, attested by the quality of the ADCP validation. It is therefore concluded that the radar-derived tidal current dataset from the NOC research-grade analysis, once the recommended QC has been applied and limitations are taken into account, can be used for further model validation/comparison and to form the basis of resource estimation and future locations of in-situ surveys.

Tidal harmonic analysis

It is concluded that due to the ‘gappy’ nature of the quality-controlled radar-derived current dataset that any tidal predictions using tidal constituents calculated from harmonic analysis of this data should be treated with extreme caution. Predictions of tidal currents far into the future or past (outside of the input data period) are very sensitive to input data record length — an issue that must be considered when conducting tidal prediction from any data set (Stiven et al, 2011). It is not recommended that harmonic constituents calculated in this project solely be used for predictive purposes.

Significant wave height calibration

Unfortunately, without further validation and calibration data it is not recommended that the estimated significant wave heights from this survey be used for any further analysis. The standard analysis method requires further testing in such a dynamic environment as the Inner Sound.

Sea-surface roughness

The NOC tidal sea-surface roughness analysis has produced images of sea-surface roughness related to the phase of the tide. The precise relationship between surface turbulence and radar backscatter response is as yet unknown and therefore no validated conclusion can be drawn from the sea-surface roughness data. However, the nature of the analysis excludes ephemeral backscattering events (e.g. weather, surface vessels, fauna etc), allowing us to conclude that the surface roughness signatures extracted from the analysis are correlated to tidally regular surface events likely linked to increased turbulence. It is recommended that the sea-surface roughness maps be used for context when interpreting in-situ surveys in the area.
Thanks to Mr. Alistair Cormack, for the use of his land to site the radar and invaluable help getting the radar equipment into position and keeping the generator system fuelled in our absence.

This work was undertaken as part of a Knowledge Exchange internship funded by the Natural Environment Research Council through the National Oceanography Centre, grant reference NE/K50144X/1.

Additional fieldwork costs were supported by NOC and a NERC Innovation ‘A’ award and many thanks to Gerry Scott at the NOC for facilitating the application for the Innovation ‘A’ award.
APPENDIX I

The following is an example ASCII output file from the NOC small target tracking algorithm ‘GANNET’. The file contains the tracks for each identified target (sequentially numbered) over a 5 minute measuring period as well all of the settings pertaining to the tracking code. In this case, a particularly busy period at 6:00am in mid March, 112 targets were identified, tracked and their key properties measured. The track speed, curvature, density (relative strength of radar return) and size in pixels can all be used to further discriminate between target types in post-processing.

GANNET GlobAl Nearest Neighbor targEt Tracker
v2.0 - current as of 04/JUN/2013

RECORD START DATE AND TIME.................. 16/3/2013, 06:00
LOCATION IDENTIFIER....................... jog
RECORDING DEVICE.................................. wam
RADAR LOCATION UTM (E,N).................... 494437.8538, 6500713.1917
TX/RX RANGE (m)............................. 4818.6765
UTM ZONE.................................... 30 V
RX TIME STEP................................ 2.7436s
AREA OF IMAGE BLANKED OUT DUE TO CLUTTER.... 21.2197%

DATA FORMAT:
TRACK......... TRACK IDENTIFIER
TIME.......... MEASUREMENT TIME (YYYYMMDDHHMMSS.SS)
X............. EAST UTM COORDINATE (m)
Y............. NORTH UTM COORDINATE (m)
U............. TARGET SPEED (m/s)
C............. TRACK CURVATURE
R............. TARGET RELATIVE RANGE (NORMALISED TO MAXIMUM RANGE)
TRD........... TARGET RANGE DENSITY (RADAR DENSITY / R)
CLS........... TARGET CLUSTER SIZE (pixels)

TRACKING ALGORITHM VARIABLES:
TARGET MANEUVER MODEL................................ SINGER ACCELERATION MODEL, FIRST-ORDER
MARKOV
TARGET STATE FILTERING METHOD........................ EXTENDED KALMAN FILTER
STATE-SPACE DIMENSIONS......................... 8
STATE VARIABLES............................ X,Y,U,V,Ax,Ay,TRD,CLS
MEASUREMENT VARIABLES......................... X,Y,TRD,CLS
TRACK GATE.................................. 0.2+300(R^1)
JAGGED TRACK TUNING PARAMETER.................. 50
FRAMES TO WAIT FOR TRACK DEATH................... 6
TRACK BIRTH PROBABILITY........................ 0.5
TARGET MAXIMUM ACCELERATION.................... 19.62m/s², or 2g
PROBABILITY OF TARGET ACCELERATING AT +-19.62m/s²...... 0.5
PROBABILITY OF ZERO TARGET ACCELERATION........... 0.8
TARGET MANEUVER TIME.......................... 4.1153s
SINGER ALPHA TIME............................. 0.24299s^-1
INSTANTANEOUS VARIANCE OF ACCELERATION........... 282.2926

PROCESS NOISE COVARIANCE MATRIX FOR KALMAN FILTER:

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MEASUREMENT NOISE COVARIANCE MATRIX FOR KALMAN FILTER:

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