Computation and visualisation of historical geographical data for acoustic channel modelling

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1 *Abstract*

The paper describes how historical geographical data in the form of depth soundings have been used to improve the understanding of hydroacoustic signal propagation through a large ducted water channel. The geo-computational elements of the paper fit within the larger framework of research into underwater vehicles, subsea communications and imaging, carried out by the Ocean Systems Laboratory over the past 25 years. The paper includes a brief review of these activities and of the original hydrographic survey of Loch Ness, carried out around 100 years ago. The method of digitising the original data and the production of 3D static and moving visualisations is then discussed in the context of acoustic channel modelling, and the paper concludes with an outline of continuing work in relation to simulated test environments.

2 *Introduction*

2.1 Theme of Paper

The purpose of this paper is to describe how historical geographical data has been used to give a clearer understanding of actual observed effects in relation to the modelling and experimental validation of underwater acoustic signals. Depth soundings which were collected meticulously 100 years ago are believed to be a reliable data set for this study and visualisations which have been produced recently have in fact explained certain anomalous signals. The application of these basic geo-computational techniques is proving to be of considerable value in the generation of simulated test environments for on-going research.

2.2 Background

Research activities in Underwater Technology at Heriot-Watt University began in 1969 following a survey carried out to identify a totally new research direction for the Department of Electrical and Electronic Engineering (Dunbar, 1970). Research studies were initiated into subsea vehicles, instrumentation, viewing, communication and navigation, and activities were focused on a major project which had the objective of designing, building and operating Scotland's first remotely operated vehicle (ROV) system. The first ANGUS vehicle was successfully tested in deep water in 1973 (Dunbar, Holmes, 1975) and the ANGUS 002 and 003 vehicles followed in 1976 and 1979, in the development of ROV systems with automatic control and navigation (Russell, Dunbar, 1990).

From 1976 studies expanded into tetherless vehicle systems (now 'AUVs', Autonomous Underwater Vehicles) and this forced the development of through-water communication systems (Dunbar, Carmichael 1990), sonar systems, and sub-surface video transmission and bandwidth compression techniques (Dunbar, Settery, 1985). ROV and AUV trials were carried out in test tanks, harbour areas, from ships at sea and in Scottish lochs, and it was during experiments in Loch Ness that a World War II Wellington bomber was located on the bottom of Loch Ness and eventually recovered in 1985 (Holmes, 1991). More recently, a European Community Marine Science and Technology (EC-MAST-II) project managed by the University used Loch Ness as one of the test locations.

The project (1992-1996) was entitled European Experimentally Validated Models of Acoustic Channels ('EEVMAC') and it had as its prime objective the precise measurement and data logging in absolute terms of hydroacoustic signals in the 2kHz to 80kHz range, with various modulation formats, transmitted over various ranges underwater, together with associated oceanographic and environmental parameters. The data would then become available for the validation of acoustic channel propagation models (Dunbar, McHugh et al, 1994).

3 *Hydroacoustic communications and modelling*

Modelling the path, the spreading loss, and the attenuation of hydroacoustic signals is a complex process, particularly for regions with multiple boundaries which lead to multipath propagation, and many models have been developed with various degrees of precision (Buckingham, 1992). Model development is often application driven: for instance, modelling of the multipath environment in a search for automatic methods of cancelling multiple echoes in a time-varying environment (Dunbar, Carmichael, 1989); and the development of models for the simulation of synthetic sonar images (Bell, 1995), to aid the interpretation and classification of sonar and sub-bottom seismic images (Linnett, 1991).

Mathematical models and simulations require real test data for their validation and correction, and the gathering of such data under carefully controlled conditions has been carried out successfully within the EC-MAST-II project 'EEVMAC', mentioned above. Currently, work of a similar nature is being carried out within the EC-MAST-III project 'PROSIM', which is an impulse signal variant of EEVMAC.

4 *Original hydrographic survey of Loch Ness*

4.1 Historical document

A bathymetric survey of Scottish fresh-water lochs was carried out by Sir John Murray and Laurence Pullar over the years 1897 to 1909 (Murray, Pullar, 1910), and consequently the year of this present conference has particular significance. The survey was an outstanding scientific achievement and a reading of the original documents leaves one with a sense of admiration and respect for the investigators when one considers the scale and precision of their measurements in the light of the experimental equipment at their disposal. To quote from the introduction to their report:

"During the course of the Lake Survey work 562 of the Scottish fresh-water lochs were surveyed…..all lochs were surveyed on which boats could be found at the time the work was being carried out…..To transport a boat to many of the remote lochs in the Highlands would have entailed much labour and difficulty, not to speak of the objections of proprietors, keepers, and others, who do not wish to have grouse moors and deer forests disturbed at a time of year when the lochs are most accessible."

It was an immense undertaking, which included in addition to the depth soundings, observations and measurements relating to topographical, geological, physical, chemical and biological features.

4.2 Method of survey

For deepwater lochs the *'F.P.Pullar sounding-machine'* was employed. This was a well designed and engineered mechanism which included a drum containing over 1000 feet of three strand galvanised steel wire which passed over a pulley having a circumference, to the centre of the wire, of precisely one foot, and a group of measuring dials recording feet, tens of feet, and hundreds of feet as the sounding weight was lowered to the bottom. It was thus possible to make precise depth measurements without difficulty. It was more complicated to determine the position of the soundings. Various methods were tried but *"it was found that the* *most accurate method was to take the soundings as quickly as possible while rowing across the loch from one point to another. The soundings were taken, say, every thirty strokes of the oars, and the total number of the soundings was placed equally along the line, thus distributing any errors"*. The method was found to be *"extremely accurate for long, narrow lochs"*, of which Loch Ness is a prime example.

In the case of Loch Ness, over 1000 soundings were taken during the course of 79 across-loch transects. On completion of the survey the soundings were transferred to 6-inch Ordnance Survey maps of the area. Later, clean tracings were plotted on cloth and contour lines of depth were drawn in at equal intervals. These original tracings later became the source data for an Admiralty chart of Loch Ness which continues to be published as chart number 1791. Additional soundings of a small area at the North end of the loch were taken in 1918, to provide greater detail near the entrance to the Caledonian Canal; however, the 79 transects remain the primary data archive.

4.3 Current survey technology

More recently, various sonar surveys of the loch have been carried out, the most comprehensive and detailed to date being undertaken during the course of 'Project Urquhart'. In July 1992 a survey vessel employing a state-of-the-art multibeam swathe echosounder carried out a detailed sonar survey of the loch and as a result 3-dimensional views of the loch were computed and publicised (Witchell, 1992). Discussions are underway with the organisation holding the sonar and sub-bottom seismic data with a view to comparing and developing the two approaches to 3-dimensional visualisation.

5 *Examination and formatting of the original data*

Copies were obtained of the original maps of Loch Ness, bearing the actual soundings across the 79 transects, and by enlargement were overlaid on a montage of current 1:25000 scale Ordnance Survey (O.S.) maps of the area. By comparison between the old and new maps, the modern O.S. co-ordinates were deduced for the shore (zero level) ends of each transect. Then, by linear interpolation, the equivalent O.S. easting and northing grid points were computed. The interpolation was based on the assumption that the soundings were equally spaced, the same assumption as made by the original surveyors. An example of such interpolated data is given below, for the first transect from the SW end of Loch Ness, near to Fort Augustus.

Sounding	Easting	Northing	Depth (ft)	Depth (m)
Nth shore	2 384 000	8 092 000	0	0
1	2 384 400	8 091 400	3	0.91
2	2 384 900	8 090 900	94	28.65
3	2 385 300	8 090 300	160	48.77
4	2 385 800	8 089 800	227	69.19
5	2 386 200	8 089 200	250	76.20
6	2 386 700	8 088 700	241	73.46
7	2 387 100	8 088 100	207	63.09
8	2 387 600	8 087 600	56	17.07
Sth shore	2 388 000	8 087 000	0	0

All 79 transects were examined in this way and 79 [x,y,-z] data files based on absolute O.S. co-ordinates were produced for use in subsequent analysis.

6 *Generation of 2D and 3D images*

6.1 Preparation of data

To improve interpolation between lines of soundings the 79 data files were padded with zeroes at points beyond the N and S ends of the transects, to aid the performance of a 'N nearest neighbours' algorithm. The positions of the augmented transects are shown in figure 1. Although it would have been possible to create [x,y,z] files to include *above* waterline elevations by inspection of the original maps, the intention was to merge the historic sub-surface data files with contemporary O.S. digital data files of surrounding terrain.

6.2 Computation and visualisation of data

The original height data refers to a narrow region which traverses from South-West to North-East and therefore within the bounding rectangle of Loch Ness the data points in total are very sparse. To simplify the computations the co-ordinate system was rotated by 38 degrees anti-clockwise, to produce in effect a vertical bounding rectangle. Prior to rotation each data point consisted of an easting

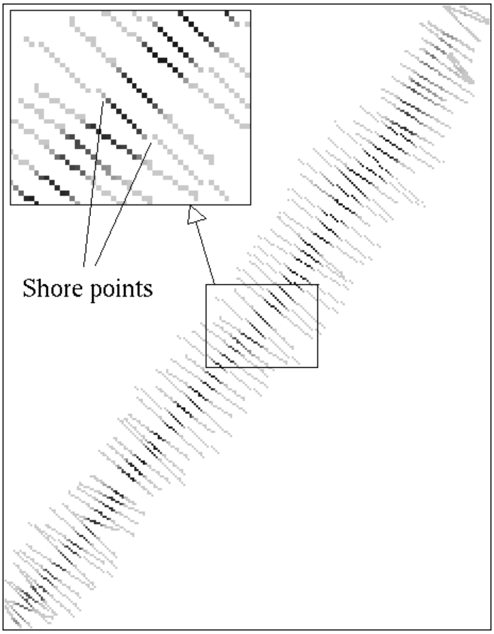

Figure 1: Original transects with augmented zeroes

and northing and depth value. The data points were not uniformly distributed so they were interpolated to achieve a uniform distribution which produced a three-dimensional scene consisting of 100m x 100m grid squares. This produced a coarse rendition so the image was scaled by a factor of 5 to produce 2.8 million polygons. This then produced an image of size 675 x 2100 pixels representing an area of 13 kilometres by 42 kilometres. The contemporary O.S. digital survey data is gridded at 50m x 50m intervals and spot heights in metres at these intervals are given. The two data sets were merged after alignment, the O.S. survey data thus providing the landscape surrounding Loch Ness. A straight line two-dimensional rendition of the two data sets is shown in figure 2, where the water level contour is the common factor between the two plots.

6.3 Interpolation of data

To interpolate values in the grid points the standard method of N nearest neighbours was used (Davis, 1988). This approach was used primarily because of its relative efficiency on dealing with the irregular and sparse nature of the original data set. For each grid point (k), N nearest points from the data set are found (N is usually in the range 3 to 6), and the height in the grid point is calculated as a weighted average:

7 Production of a 'fly- through' of Loch Ness

The 3D scene was rendered using a custom- designed program on a Silicon Graphics 02 computer. Commercial packages were considered but data handling software under development by the research team for other image interpretation applications proved to be more cost effective

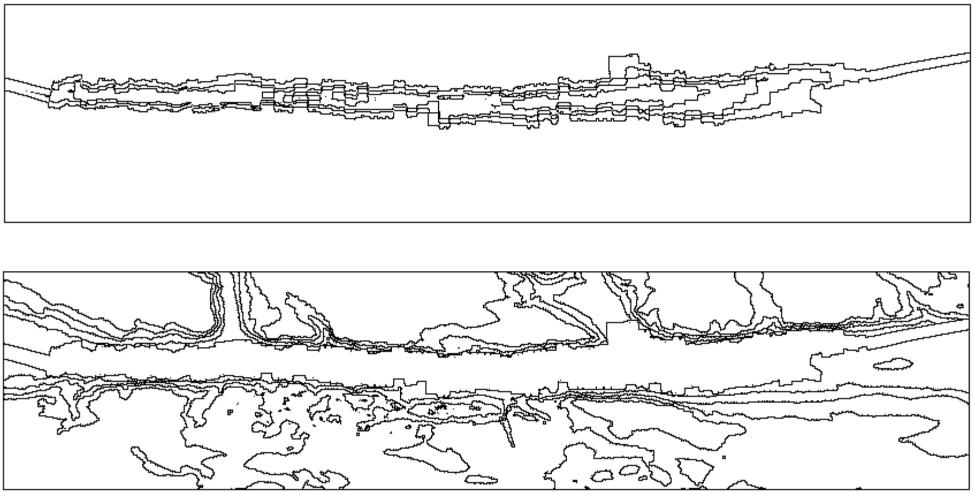

Figure 2: 2D rendition of Loch Ness: sub-surface contours (upper), surrounding terrain (lower)

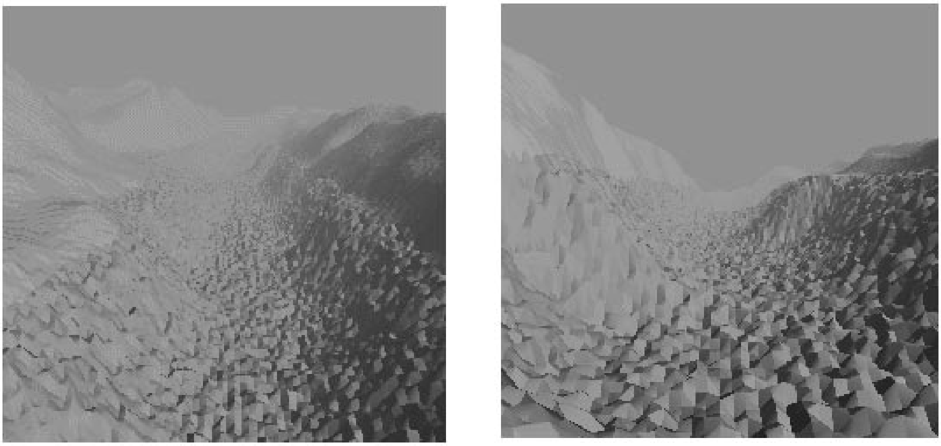

Figure 3: 3D renditions of Loch Ness using combined data sets, for southern and central sections of the loch

and flexible in manipulating data sets from different sources. The system requires an "observer" position and a "look-at" position. From this data the perspective view is computed and the image is saved as a single frame. This process is repeated about 2000 times to produce a movie. For each frame the "observer" and "look-at" positions are changed slightly to create the impression of movement. These effects may be observed in a video sequence, which will be presented at the conference.

8 *Application to acoustic channel modelling*

8.1 Ray tracing model

In trying to predict the characteristics of an underwater acoustic signal that might be received at a particular depth in the water column, and at a particular range from the transmitter, a ray-tracing model is helpful. The path that a particular ray will follow is a function of the sound velocity in regions of water through which the ray passes, and in turn, the sound velocity is a function of temperature, salinity (or electrical conductivity) and pressure. Since these last three parameters are not constant, one must have knowledge of their spatial (and temporal) distribution in the three dimensional region of interest in order to make a sensible estimate of the ray path. Consequently, a common measurement made in underwater acoustics is a 'CTD' (Conductivity, Temperature, Depth) profile, and the more CTD profiles that are available along the route of the acoustic pressure wave, the greater is the precision with which one can predict its path. As a result of the variation of sound velocity with depth, sound ray paths are in general curved, and a typical ray plot will illustrate computed ray paths for a selection of launch angles. Examples of such ray paths are shown in figure 4 where ray plots have been computed for Loch Ness using typical measured CTD values. Ray tracing models become sophisticated when absorption, reflection and scattering coefficients at surface and seabed, seabed stratification and topography, and frequency dependent attenuation are also taken into account (Bell, 1995).

8.2 Visualisation of 3D acoustic environment in Loch Ness

Ray tracing models as illustrated above can predict multipath signals and over path lengths of several kilometres it is normally observed that multiple reflected signals arrive very shortly after the direct path signal, if the distance/depth ratio is large, which was the case for Loch Ness. However, unlike similar hydroacoustic trials carried out in the Mediterranean Sea, in an open area with a fairly flat seabed, in the case of Loch Ness multiple signals were observed after an unexpectedly long delay.

During field trials in 1995 a set of 1.9kHz ASK test transmissions were made over a path length of 7 km, the acous-

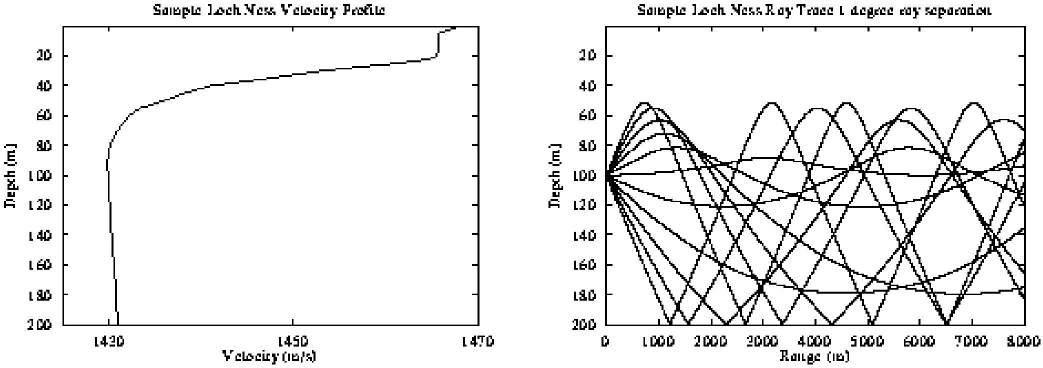

Figure 4: Typical sound velocity profile and ray trace for Loch Ness

tic projector and receiving hydrophones being at mid-water depth. These tests were performed along the centre line of the SW section of Loch Ness, in a stretch of water where the loch width was approximately 1.5 km. For a water depth of 200m and a direct path length of 7km, first and second multiple signals could be expected to arrive within 20ms of the direct ray, and this was observed to be the case. A additional group of signals was observed however with a delay of approximately 100ms. A short calculation as follows indicates that these signals are likely to be due to reflections from the sides of the loch, as visualised notionally in figure 5.

The path length for a mid-water signal undergoing a single reflection in the horizontal plane in such a location would be 7.16 km, as compared with a straight line path of 7 km. Consequently, the difference in propagation times would be the path difference divided by the speed of sound, i.e. 160m /1430 m/s = 0.112 s. When recordings of the test signals were examined in detail in the region of 0.1s from the start of the received pulse, evidence was found of significant constructive and destructive interference on the signal, a characteristic of multipath signals. An example of such a signal is illustrated in figure 6. There was also the normal evidence of surface and bottom reflections, earlier in the received signal, but reflections with such a delay and magnitude would have been unusual for open water situations.

Figure 5: Notional visualisation of direct and side-reflected ray paths

9 Conclusions

It is believed that geographical visualisation adds a dimension to acoustic modelling that considerably enhances the understanding of the overall communication or sonar process. Consequently, the technique is being further developed for more detailed analysis of existing acoustic data, from Loch Ness and other test sites. Moreover, the experience gained through this present investigation suggests that the 3D visualisation is a valuable framework for a simulated test environment, where signals from multiple sensors may be fused and observed.

By setting up a flexible geographical framework in which to insert data as it becomes available the investigator has a

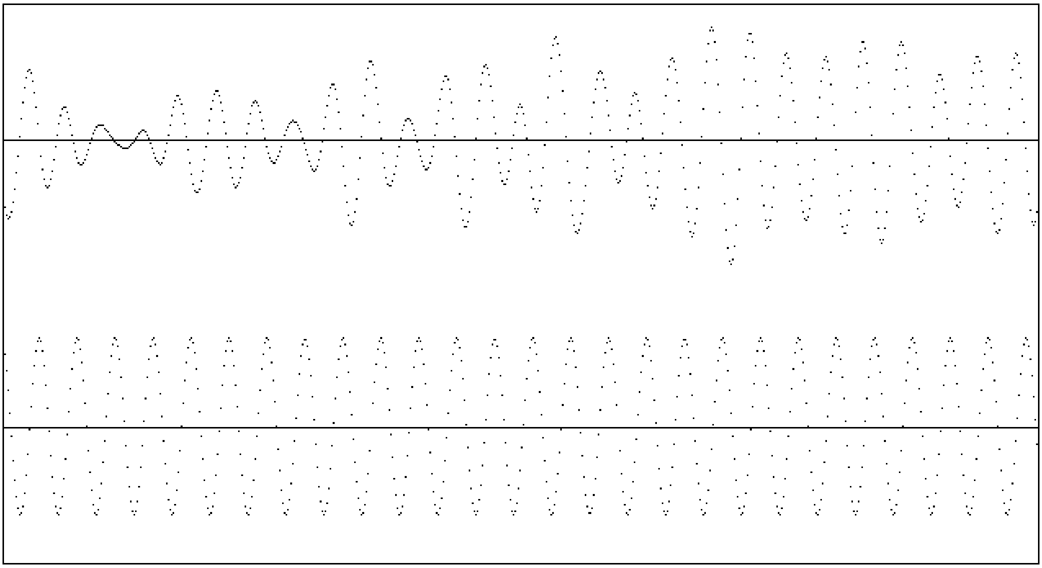

Figure 6: First arrival of signal reflected from side(s) of Loch Ness: lower trace is reference

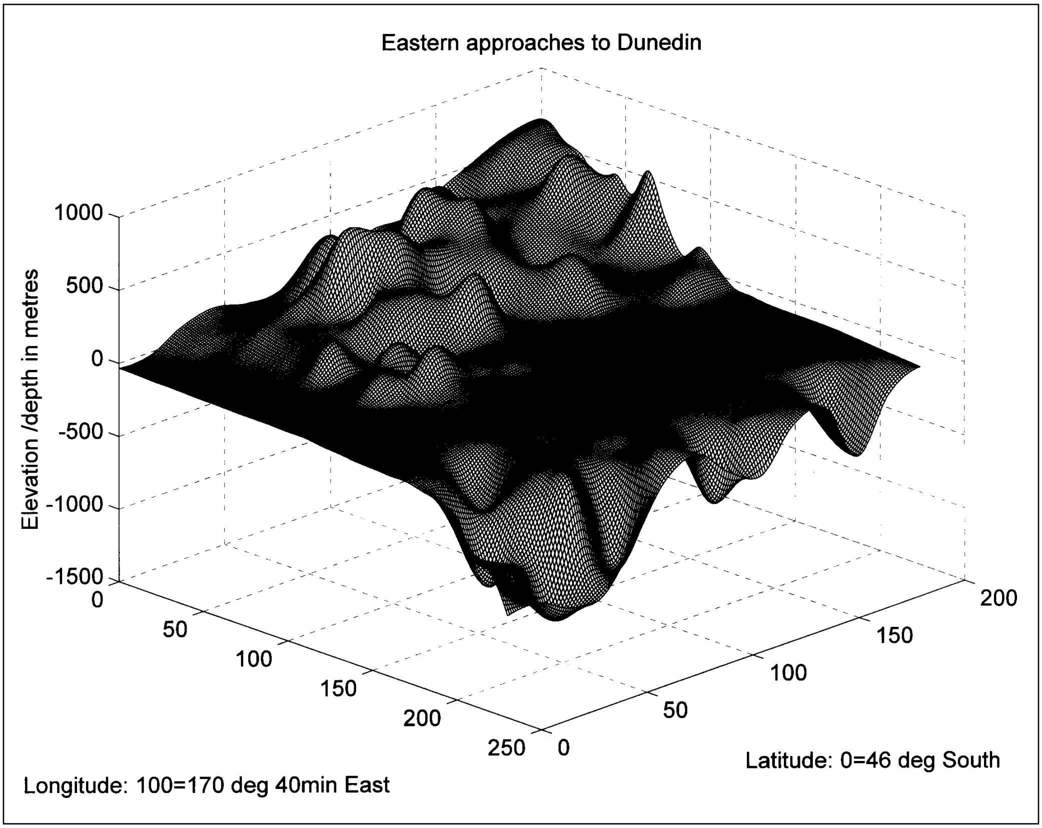

Figure 7: Visualisation of approaches to Dunedin, from limited data set.

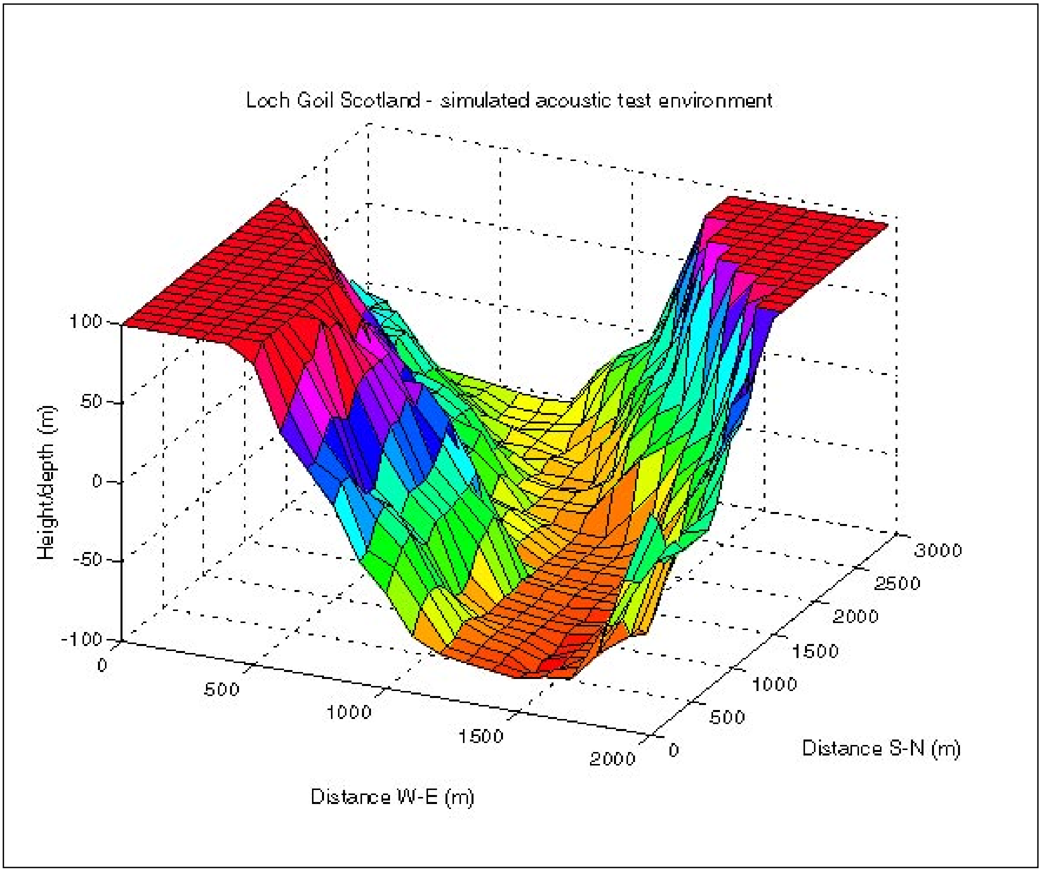

Figure 8: Visualisation of Loch Goil acoustic channel.

powerful mechanism for data logging and analysis (Dunbar et al, 1990). As an illustration, figure 7, the Eastern approaches to Dunedin have been examined on an Admiralty chart and a 3D perspective view produced under MATLAB(R), using 23 x 14 points and cubic spline interpolation, to provide a visualisation which could be used, for example, as a first step in modelling the arrival paths of ocean acoustic signals. As a further illustration, figure 8, a section of Loch Goil in Scotland has been modelled using a similar approach, and this model is currently being used to interpret hydroacoustic signals received during recent trials.

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11 References

Bell J.M. (1995) A Model for the Simulation of Sidescan Sonar. PhD thesis, Heriot-Watt University, September 1995.

Buckingham M.J. (1992) Ocean-acoustic Propagation Models. J.Acoustique, 1992, 223-287.

Clay C.S., Medwin H. (1977) Acoustical Oceanography, Wiley-Interscience, John Wiley and Sons, New York, London, 1977, 83-106.

Davis J.C. (1988) Statistics and Data Analysis in Geology, John Wiley, 1988.

Dunbar R.M.(1970) A Survey of Underwater Technology. Heriot-Watt University, Dept. Computing & Electrical Eng., RM 70/4.

Dunbar R.M., Holmes R.T.(1975) ANGUS. J.I.E.E., Vol.21,No.2,April 1975, 433-436.

Dunbar R.M., Settery,A (1985) Video Communications for the Untethered Submersible ROVER. 4th Int Symp Untethered Sub Tech, Univ New Hampshire, USA, 1985, 140-149.

Dunbar R.M., Carmichael D.R. (1989) Adaptive Estimation of an Underwater Acoustic Channel using Real Test Data. 6th Int Symp Untethered Sub Tech, Univ New Hampshire, USA, 1989, 42-49.

Dunbar R.M., Carmichael D.R. (1990) Subsea Communications for Semi-Autonomous ROVs. Ocean Resources, Vol.2, Kluwer Academic Publishers, 1990, 185-189.

Dunbar R.M., Hennings I., Kullander L., Linnett L.M., Oskarsson O., Torlegord K., Shippey G., Vikgren K.J., Werner F. (1990) Monitoring of Seafloor Changes with Multisensors: Problems related to Positioning, Image Rectification and Classification. Int Conf on Submarine Systems, U-90, FOA, Stockholm, Sweden, May 1990, Vol.2, Paper 17.

Dunbar R.M., McHugh R., de Malet Roquefort S., Bathgate L. (1994) High-level Control of Automated Oceanographic and Acoustic Equipment and Experiments. OCEAN-OSATES 94, IEEE, Brest, France, Sept 1994, Vol.1, 678-682.

Holmes R.T. (1991) One of Our Aircraft: the Story of 'R for Robert' the Loch Ness Wellington. Quiller Press Ltd, London, 1991.

Linnett L.M., Clarke S.J., Graham C., Langhorne D.N. (1991) Remote Sensing of the Seabed using fractal techniques. IEE Electr and Comm J., Oct 1991, 195-203.

Murray J., Pullar L. (1910) Bathymetrical Survey of the Scottish Fresh-Water Lochs. The Challenger Office, Edinburgh, 1910.

Russell G.T., Dunbar R.M. (1990) Intelligent Control and Communication Systems for Autonomous Underwater Vehicles. International Advanced Robotics Programme (IARP), MBARI, Naval Postgraduate School, Monterey, CA, USA, Oct 1990, 1-14.

Witchell, N (1992) Sounding the Secrets of the Depths of Loch Ness. World, BBC, London, Oct 1992, 62-71.