Contents

Maerl section 2
  Maerl deposits and dynamics – exploitation and conservation 2
  Previous survey techniques 2
  Use of video survey 3
Assimilation of SUMARE data 3
  Numerical results (Living and Dead Maerl concentration) 5
  Numerical results (Stochastic shape models) 7
Use of SUMARE techniques in maerl survey 9
  Quantification of living and dead components in maerl beds 9
  Temporal monitoring of living and dead components – conservation and exploitation 11
  Mapping distinct features in a maerl bed 12
  Image mosaicing 13
Value to maerl survey 13
Difficulties and limitations 14
Other habitat mapping applications 15
Appendix A: Estimation of percentage of bottom occupied by Maerl 16
Appendix B: Modelisation of dead-Maerl patches as Random Closed Sets 19
References 22

SUMARE D5 Data assimilation

Maerl section

Maerl deposits and dynamics – exploitation and conservation

As described previously in SUMARE Deliverable D1, maerl is a calcareous alga which forms large deposits or “beds” on the seabed. Maerl has a variety of commercial applications and is extracted from the seabed in large volumes, especially from around the Brittany coast of France, but also from around the UK and Ireland. Maerl also has high conservation value as it provides a habitat for a large number of other algae and fauna species. There is currently a need to map maerl beds in greater detail, in terms of the spatial distribution of different maerl features and in quantifying the area coverage of these features at different sites. The maerl features of primary concern are deposits of living and dead maerl. For commercial purposes, the extraction of dead maerl is advantageous as it has less associated organic material, so requires less processing before sale. Extraction should also focus on regions of dead material so that living areas are undisturbed and left to grow, from which dead maerl will be derived, adding to deposits of dead material. From a conservation viewpoint, little is known about the spatial distribution of maerl. As maerl beds can cover very large areas of seabed, there is a need to delineate the outer boundaries of this habitat at sites where it is known to occur. Within each maerl site, it is also of interest to know the occurrence and spatial distribution of living and dead material, as the associated biology of the two forms differs and overall, as this aspect can give an indication of the biological status of a particular site. For example, a large region of seabed covered in exclusively dead maerl with no living material nearby is probably a relict bed which is not actively growing. In contrast, a site in which there is a mosaic of living and dead maerl patches is an actively growing site, which may include large deposits of dead maerl, composed of material being swept away from living patches by currents. Monitoring methods can benefit from this information and can be used to gauge the impact of human activities on maerl habitats (Birkett et al 1998).

Previous survey techniques

Traditional maerl survey techniques relied on a combination of dredge survey and grab/core samples (O’Conner et al 1993; Hall-Spencer 1995). While these methods are effective at gathering detailed information at specific locations, they cannot deliver information on larger scale attributes such as the distribution of living and dead material. To do so would require massive investment of time and finance, making such methods impractical and uneconomic. Diving also involves an element of human risk. Recent attempts involving side-scan sonar (Davies et al 1997) have succeeded in collecting acoustic data on large regions of seabed where maerl is known to occur, e.g. the Sound of Arisaig SAC on the west coast of Scotland and Rousay Sound in Orkney. The results of these surveys have proved effective at discerning different seabed habitats, distinguished by their physical attributes. However, the different acoustic signals do not correspond closely with deposits of living and dead maerl which are easy to distinguish visually. Consequently, this method cannot be used to delineate and/or quantify the area of seabed covered by living and dead material.

Use of video survey

Video footage of maerl beds has been recorded by diver, Remote Operated Vehicle (ROV) and towed sled surveys (Birkett et al 1998). Diver held video is usually limited to a small area although ROV and towed sled video has the potential to cover larger areas of seabed in order to get a better understanding of the large-scale distribution of maerl. In all cases, however, the examination of video footage is reliant on human interpretation, which can be problematic, time consuming and subjective. This prevents the use of video footage collected and analysed in this way being used to provide reliable and repeatable information on the maerl features described above.

Assimilation of SUMARE data

The SUMARE project aimed to develop techniques which could make much more effective and reliable use of seabed video information, relative to other survey methods. These techniques revolve around the visual characteristics of maerl recorded in video footage acquired during the Orkney sea trials (See SUMARE Deliverable D8.1, D8.2). The achievements in terms of the data acquisition are described in detail in SUMARE deliverables D7.1 and D7.2 and are summarised below.

i. An image classification algorithm was developed which can classify video footage of maerl recorded as the ROV-mounted video camera passes over the seabed. The algorithm has been developed to recognise living maerl, dead maerl, sand and macroalgae, at a variety of altitudes off the seabed. The classification algorithm is a combination of an unsupervised image segmentation algorithm (See Deliverable 4.1) that is followed by a labeling step. This labeling of the segmented regions is based on a database that describes the characteristics of interesting materials (See Deliverable D3.3a). Once the database has been created (requiring expert knowledge) the classification of the raw images is fully automatic.

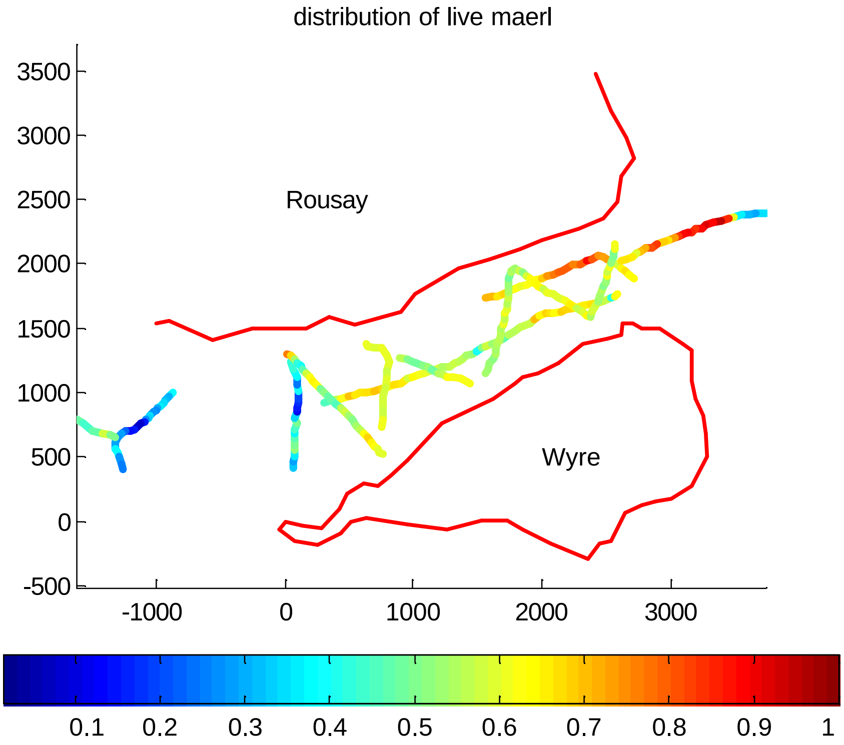
ii. The information derived from the image classification algorithm can be used to influence the navigation of the ROV in real time. In this way it was possible for the ROV to autonomously navigate along boundaries between different maerl features, termed “contour tracking” (See Deliverable 4.1). For example, the ROV was able to follow the boundary around a large bank of dead maerl (approximately 150m in length), mapping the shape of that boundary in the process.

iii. Post-survey analysis of the classified video footage can allow the quantification, in terms of area occupancy, of the different maerl features which the algorithm is capable of recognising. For example, in a given section of footage, post-processing can produce an estimate of living maerl present in the area of seabed (perhaps as a percentage) captured by that footage. Fitting of stochastic shape models to the observed maerl patterns, which is one of the contributions of the project, can provide estimates of several other indices besides occupied area, such as the frequency of occurrence of patches in each area, their isotropy and their average size. Correlation of these indices with geophysical parameters can enable the ellaboration of more detailed models of maerl distribution, in terms of the region's characteristics.

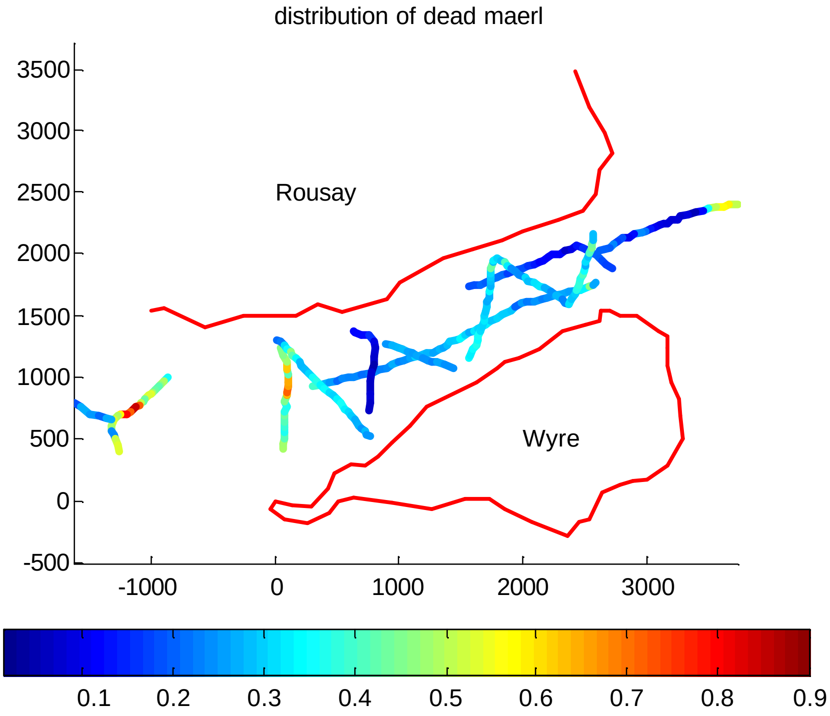
iv. Mosaicing of video footage was also developed which can illustrate particular areas of seabed. This technique can be employed usefully to show larger areas of seabed than can be viewed in a single video frame. Mosaics can effectively illustrate large areas of seabed with different characteristics, much more effectively than single frames, or to show the shape of individual features, e.g. the shape of the boundary around the large bank of dead maerl, previously mentioned above.

These techniques are certainly novel from the point of view of maerl surveying methods and are also novel in terms of marine resource survey in general.

Numerical results (Living and Dead Maerl concentration)



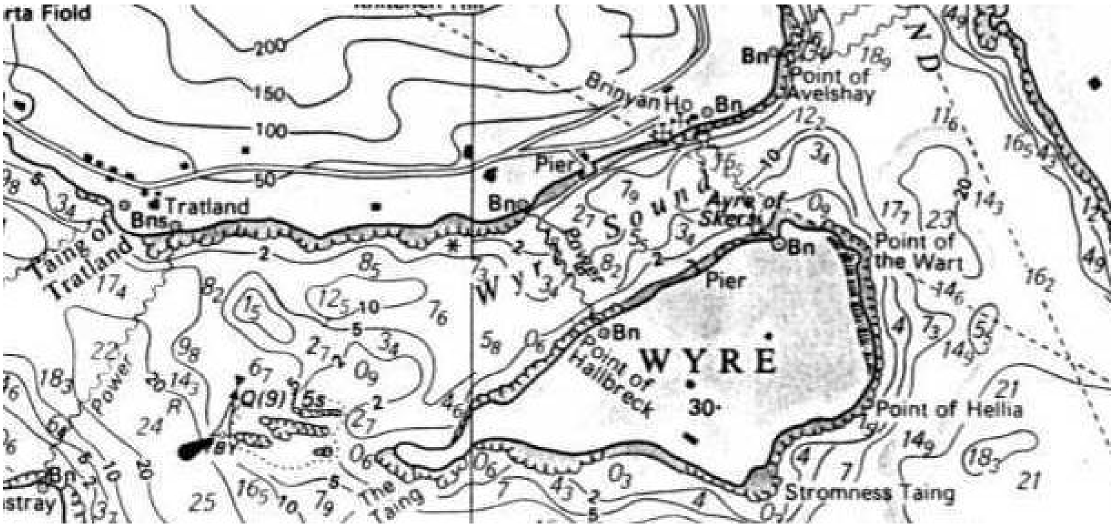
distribution of live maerl



distribution of dead maerl

The two plots above show the estimated percentage of bottom occupied by living (top) and dead (bottom) maerl along the tracks observed during the September 2002 survey.

The navigation chart for the Wyre Sound area is shown below. It shows that the western entrance to Wyre Sound is



Navigation chart for Wyre Sound showing bathymetry of the area.

Analysis of these two maps suggests the following conclusions:

- Concentration of living material is larger on the Eastern part of the Sound, decreasing gradually as we move West.
- Concentration of dead material is higher in the Western part of the Sound.

Research into why the character of maerl beds vary, e.g. in terms of the occurrence of living maerl, is limited. Water depth (and clarity), water currents and wave exposure are recognised as important factors which control the occurrence of maerl. Such data for the Wyre Sound area is limited. A bathymetric chart is shown above. The rising tide flows east through the Sound (max velocity ~1.25 ms^{-1}) and is probably slightly stronger than the falling tide (the net movement of water through the Orkney Island is from west to east), which flows to the west. There is insufficient knowledge on these two parameters to know how they may be responsible for the observed distribution of maerl in the Sound. However, wave exposure in the western approaches to the Sound is considerably greater than in the more sheltered eastern area. It is possible that this greater wave exposure, coupled with the shallower depths here may result in levels of disturbance and water turbidity that hamper the growth of maerl.

This theory could be tested by follow-up surveys in the area, e.g. turbidity measurements, as well as more detailed bathymetric and current surveys, combined with maerl growth experiments at different sites.

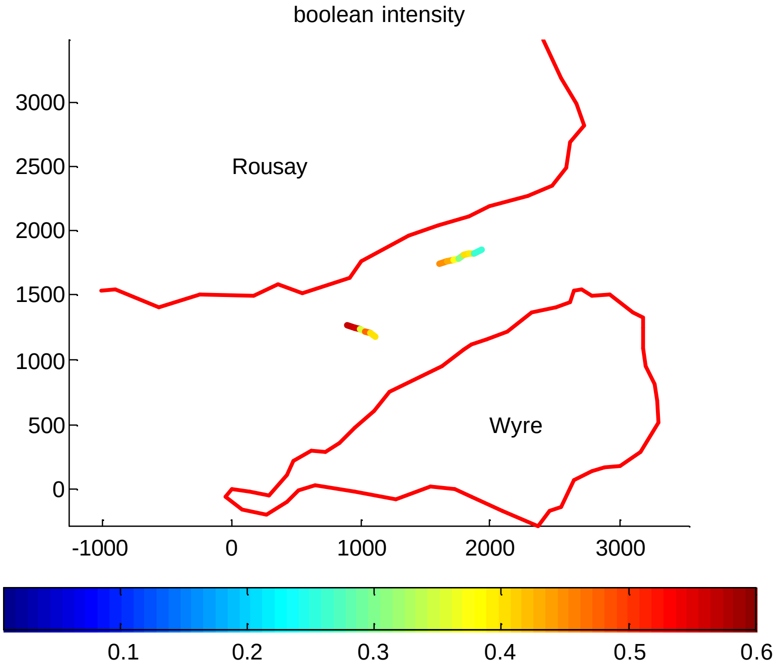
The observations illustrated in the above plots represent a fundamental improvement in our knowledge regarding the distribution of maerl in Wyre Sound. Further analysis of the data will produce more detailed information on the occurrence of maerl in the area, e.g. variation in living maerl coverage and patch size between different sites and the location of significant deposits of dead maerl. The same techniques can be applied to maerl beds elsewhere with similar results.

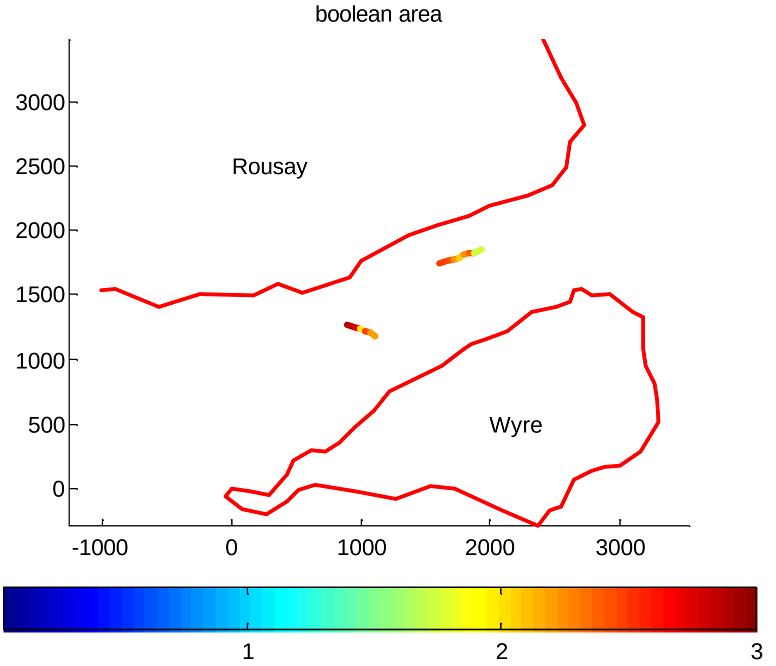
Numerical results (Stochastic shape models)

One of the innovative contributions of Sumare concerning the maerl mapping problem is the proposal of using stochastic shape models to characterise, in a statistical way, the spatial distribution and the shape of the maerl patches.

We did not have the chance to completely process the acquired video data using this approach, and that study will have to be conducted after the project is finished. The plots below give an indication of the kind of information that we can produce based on this formalism.

Along small portions of tracks T3 and T6a, we show below color-coded maps of the estimated patch intensity and average size for dead maerl. The intensity represents the average number of patches per square meter and the size is indicated in square meters.





Other indicators of interest may be derived, such as average distance between patches, or measures of isotropy of the patches shapes. We believe that this more detailed information (compared simply to percentage of bottom surface covered by a feature) can help discriminate in a more fine way the disticnt types of habitat organisation, and to relate them to the site's charcetristics (depth, water currents, turbidity, etc Details on the computations of the plots above are given in Appendix B.

Use of SUMARE techniques in maerl survey

The techniques developed in SUMARE can contribute important data in relation to maerl extraction policy as well as help to provide more knowledge for use in maerl conservation, as outlined by Birkett et al (1998).

Quantification of living and dead components in maerl beds

The image classification algorithm provides the worker with an automatic and robust method for capturing the presence of living and dead maerl material in terms of their area occupancy on the sea floor. Although human operators have been able to perform this task quite easily, the resolution of the algorithm means that it is also possible to quantify the area of living and dead material in each still frame and for sequences of frames which covers tracts of seabed, e.g. in a mosaic. The ability to accurately quantify the area coverage of living and dead maerl did not previously exist, so represents a useful step forward in this type of survey. An example of a raw and classified mosaic is shown in Figure 1.

Figure 1: Raw (top) and classified (bottom) mosaics showing patches of dead maerl, surrounded by living Maerl.

Very simply, this capability allows the worker to determine the ratio of living to dead maerl at an individual site, or with more work, over an entire maerl bed. This can provide some preliminary answers as to the type of maerl bed being surveyed, e.g. if it is almost entirely composed of dead maerl then it may be a relict bed which has “died out”. In contrast, a bed with a greater proportion of living material is more likely an actively growing maerl bed. Such knowledge is useful, especially in planning extraction activity, which should be steered away from areas of living maerl and focus on deposits of dead maerl. These determinations are necessary but could probably be made by using a ROV with manual skilled-eye appraisal of untreated video footage (although the image classification can provide much more accurate estimates of area coverage of living and/or dead maerl).

Where SUMARE techniques become more useful is in more detailed analysis of distribution of maerl on the sea floor. On an individual site basis they allow a more detailed examination of the small and large-scale distribution of maerl. This can be particularly useful at sites where a mixture of living and dead material occurs. Living material may occur in large distinct patches several metres in width or in much smaller patches, with dead maerl in between (see Figure 2). It is unclear what environmental factors have an influence on this aspect of maerl distribution but the ability to quantify patch size provides an appropriate basis to examine the variability in this aspect between different sites and consider the physical and/or biological factors which may be involved. Such knowledge would contribute to the understanding of maerl bed dynamics, particularly those factors which are important to their existence.

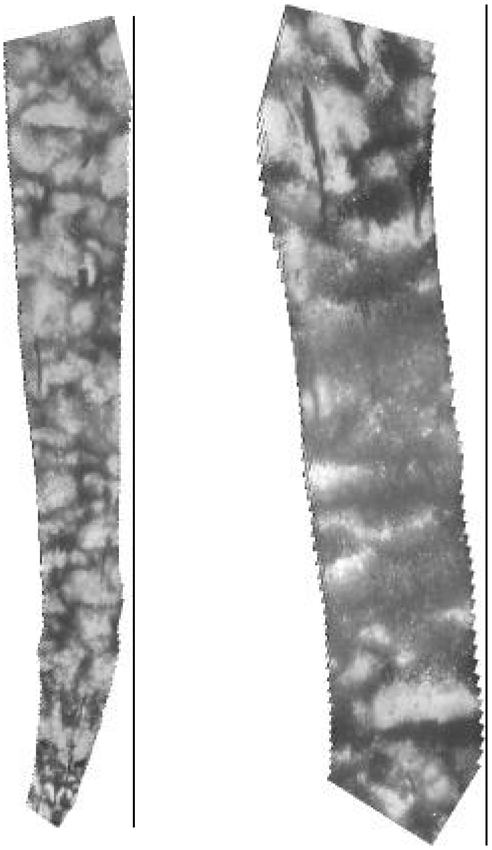


Figure 2: Mosaics illustrating differences in the size of living maerl patches at two different sites.

This leads on to the construction of models to estimate sustainable rates of maerl extraction. Models would be based on the export of dead material from areas of actively growing maerl. The export of dead material would be assumed to vary directly with the area of living maerl occupying the sea floor. However, the calculation of a sustainable extraction rate would require the input of other data apart from that which SUMARE techniques could provide. For example, for a particular area of dead maerl from which extraction is proposed, one would have to delineate the living maerl beds which are contributing dead material to that site. To conduct this study, one must consider the coupling between the physical transport processes (currents and tides) and the biological parameters describing the growth of living material and the production of dead maerl from living maerl. Combined with data generated using SUMARE techniques, i.e. periodic estimates of the area of living maerl at certain sites, a position would be reached where it would be possible to start estimating sustainable extraction rates. So while data generated from SUMARE are essential to the modelling process, it is important to appreciate that there are other data requirements, in particular in terms of the transport model, the generation of which is outwith the scope of this project.

Temporal monitoring of living and dead components – conservation and exploitation

The capabilities outlined in (i), above, can be put to good use in monitoring the temporal status of maerl beds. This may be done to monitor the natural changes in maerl bed characteristics, e.g. variation in the amount of living maerl at a particular site, or to study the effects a particular activity may have on a maerl bed. Long-term monitoring is especially important for maerl beds which are actively growing, as more conservation value is attached to these sites. There are a variety of activities which can affect living maerl beds, the most obvious being direct extraction of maerl for commercial use but also including other mineral extraction activities, aquaculture, sewage discharges, fishing activities, etc. In most cases, negative impacts would include the death, and hence reduction in area, of living material by smothering or decreased light availability caused by an increase in water column turbidity. Maerl extraction activities should focus on large deposits of dead material in order to limit impact on the living resource. Temporal monitoring would also be required to gauge the effect of extraction of the size of the dead resource being exploited. In this sense, this application is similar to the monitoring of the sand banks, the other application considered in Sumare. In fact, in both cases a in-depth study requires data assimilation techniques that bring into consideration the transport phenomena produced by the motion of the water mass. While, in the case of the sand dunes, the pertinent observations are the bathymetry maps, for the maerl application, it is its spatial distribution that is relevant. While it seems difficult to obtain macroscopic models of the sand bank surfaces, it seems that the Random Closed Set models do provide, for the maerl application, a macroscopic model that can be exploited to decrease the complexity of data assimilation.

Temporal monitoring of maerl beds is best achieved using consistent and accurate methods in survey work – methods which can be repeated from one survey to the next. The techniques developed in SUMARE would ensure levels of accuracy and consistency between successive maerl surveys which are not currently available.

Mapping distinct features in a maerl bed

The contour tracking capability of the ROV Phantom can be used to map the boundaries of specific features in maerl beds given that they have sufficiently distinct boundaries. During the sea trials carried out in SUMARE, a large bank of dead maerl was surveyed which had previously been the site of maerl extraction. The contour tracking capability of the ROV Phantom provided a partial illustration of the boundary of the dead maerl bank, i.e. a section of approximately 100m in length was mapped, shown in Figure 3. Again, the value of this technique would become apparent in long term monitoring surveys. For example, it would allow workers to determine whether or not features such as large banks of dead maerl were changing in terms of shape or area. This obviously has application in maerl extraction as it would allow the impact on the extraction site to be followed. The technique would also be useful in general maerl bed monitoring to see if and how such features vary in shape and area, naturally or due to some anthropegenic activity.

Figure 3: A mosaic showing the ROV in contour tracking mode along the outer boundary of a bank of dead maerl.

Image mosaicing

The image shown in Figure 3 shows a nice example of image mosaicing. Image mosaicing represents an effective tool for the presentation of visual data and goes beyond the single image or snapshot of video footage. In the case of maerl surveying, mosaicing has not been used before, but is a useful way of illustrating the physical characteristics of maerl features which are too large to show on a single frame. It is also useful to show the shape of particular features, when used in conjunction with the contour tracking mode of the ROV Phantom. This is nicely demonstrated in Figure 3, above, where the boundary of a dead maerl bank was mapped. The ability to view larger seabed "footprints" can also be used to get a better appreciation of the small-scale distribution of living and dead maerl at different sites, as illustrated in Figure 4.

Figure 4: Mosaic showing a continuous section of video footage which has also been classified according to the presence of living maerl (dark patches) and dead maerl (white patches).

Value to maerl survey

The techniques developed in the course of the SUMARE project represent a considerable step forward from traditional maerl survey techniques. They present, for the first time, a method for the quantification of living and dead maerl deposits on the seabed. While this may previously have been possible using raw video footage and skilled eye assessment, the SUMARE image classification algorithm is more objective, accurate and repeatable, as well as being an automatic process. This represents a considerably more efficient way of collecting information on the physical characteristics, i.e. small and large-scale distribution of maerl over the sea floor.

Maerl exploitation activities continue, most notably in Brittany. Extraction activities in the UK and Ireland are smaller in scale and are under pressure to limit or cease activity due to maerl conservation concerns. SUMARE technologies are not likely to resolve this conflict but have a valuable contribution to make by informing extraction policy so that minimum damage is done to deposits of living maerl and that deposits of dead maerl may be extracted at a sustainable rate. Controversy will persist in some cases though, e.g. where relict beds are being exploited there is no living maerl replenishing deposits of dead material, so the extraction potential is finite. SUMARE technologies can still be used in such cases to monitor the rate of depletion of the resource. It is worth repeating, however, that with specific reference to the construction of sustainable extraction models for maerl, data generated by SUMARE is insufficient and other data requirements are outside the scope of the project.

SUMARE data can have direct use to conservation of maerl, especially so in long-term monitoring of maerl beds. Maerl beds are included as Annex I habitats in the 1992 Habitats Directive (92/43/EEC) and special areas of conservation (SACs) supporting significant maerl habitats have been designated throughout the UK and Europe. These designations recognise that although maerl has a limited distribution, the maerl habitat contributes greatly to biodiversity in shallow marine environments. Data gaps exist in the understanding of how maerl beds function and how the distribution of maerl varies in space and time. In addition, there is potential for the stability of maerl habitats to be affected by various activities, apart from direct extraction. Indeed, in subtle cases it would be difficult to distil anthropogenic impacts in light of a lack of knowledge regarding natural variation in maerl bed characteristics. SUMARE techniques would provide fundamental information on maerl bed dynamics which would then provide a platform to examine natural versus anthropocentric changes.

Difficulties and limitations

Although the automatic processes developed in SUMARE lend greatly to the efficiency of the process, a degree of human input is still required. The image classification process required the time-consuming construction of an image database, which acts as a “dictionary” for the algorithm against which to compare raw images. In this context, the algorithm can only recognise and classify features which it can reference in the database. This obviously presents a problem if the image captures areas or features in the course of a survey which do not match any of the categories in the dataset. This problem is partially allieviated by the fact that our classification method is based on statistical models of the observed image regions, which have an associated degree of confidence to each classified image area. These can be combined to characterize the uncertainty of the overall estimation of living/dead maerl present in any given area.

The learning images in the reference database were collected from Wyre Sound, Orkney, during the 2000 sea trials. The 2002 sea trials were carried out over the same regions, so one would expect that the algorithm would be able to automatically classify the different maerl features. It may be the case at different sites, maerl has differing characteristics and would not match the database learned in Wyre Sound so closely. It may be necessary to construct a new image database for each new site which is surveyed, e.g. a site elsewhere in Orkney or on the Scottish mainland. It is thought that the visual properties of maerl do not vary much, even between far-removed sites, but the possibility of additional prior learning at new sites should be appreciated.

The contour tracking method presently implemented, and which has been tested at sea, requires a sharp visual boundary to follow. While such a boundary existed around part of the large bank of dead maerl in Wyre Sound, such features were generally absent from other pats of the survey area. Indeed, indistinct boundaries are a typical feature of marine benthic habitats. In the project we formulated an alternative approach to boundary acquisition, directed at delineating regions of distinct spatial distributions of a given resource. This approach, which seems to be much more appropriate to this application, is not yet operational and implemented in the platform, due to lack of time and limited human resources available during the duration of Sumare. However, its formalisation consitutes, in itself, a major contribution of the project, which should be developed further in future studies.

Other difficulties relate to the navigational potential of the platform used to carry the automatic sensors. The ROV Phantom has good manoeuvring ability but can only cope with water currents of up to 2 knots (~$1ms^{-1}$). In practice, this ability was restricted somewhat by drag and water current effects on its umbilical while deployed in the field. Again, the experiments conducted in Sumare were intended as a demonstration of the feasibility and adequacy of the methodologies proposed, and suffer from the limitation of the research prototype platforms that are operated by the consortium partners. We stress again that the approaches, algorithms and methodologies proposed are platform independent. In particular, all the work concerning visual tracking, spatial statistical modeling and video segmentation can be carried over, without modification, to a more powerful underwater vehicle. The same comment applies to the lack of precise geographic position of the ROV Phantom, preventing accurate geo-referencing of the acquired data. This limitation can be partially overcome by installing a GPS receviver on the platform, enabling position fixes at the surface. Smoothing techniques, previously developed by some consortium partners, can then be used to correct the trajectories between these fixes, providing a satisfactory level of spatial accuracy.

Other habitat mapping applications

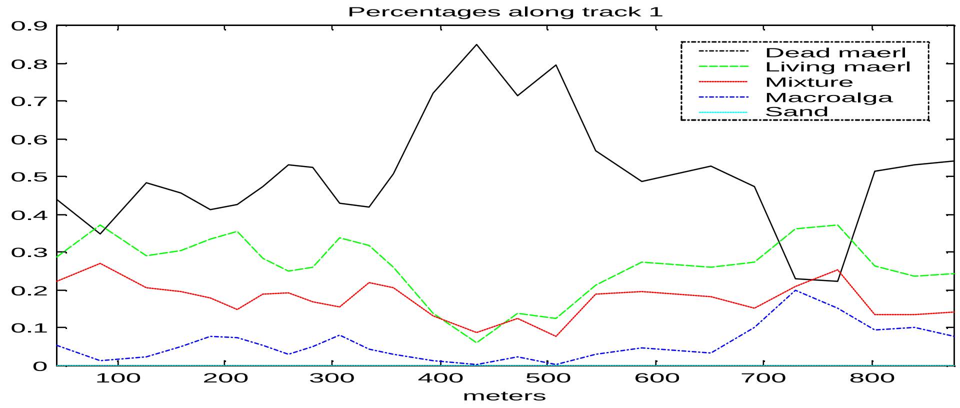
SUMARE techniques can be applied to a variety of marine survey examples where the focus of study involves a feature with distinct visual attributes. In practice this could involve other seabed habitats, such as seagrass (*Zostera* sp, *Posidonia* sp.) beds biogenic reefs, e.g. coral reefs (tropical and cold water reefs such as *Lophelia* sp.) or serpulid reefs, and more simple bedrock outcrops. The process would be similar in that an image database would have to be constructed for the features of interest. Marine habitat mapping has taken on greater importance in recent years, e.g. through the ICES Working Group on Marine Habitat Mapping. In relation to other habitats, SUMARE techniques can be used to achieve the same goals, e.g. examination of physical distribution on the seabed, monitoring of natural variability and impacts of anthropocentric activities.

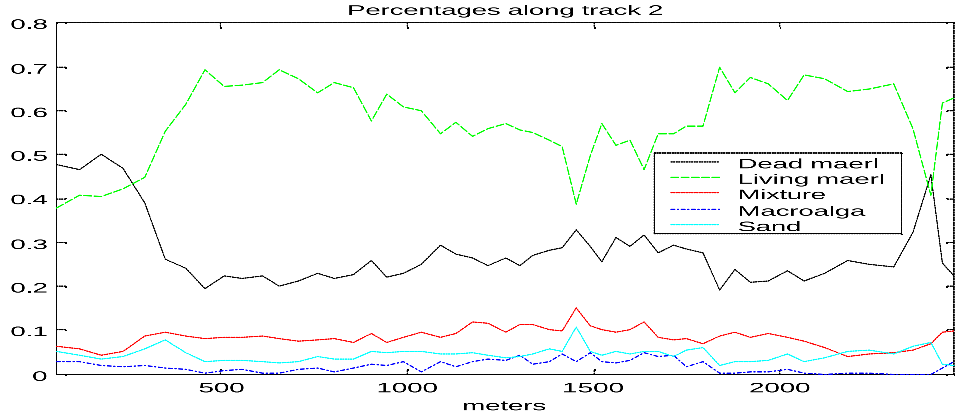
Appendix A: Estimation of percentage of bottom occupied by Maerl

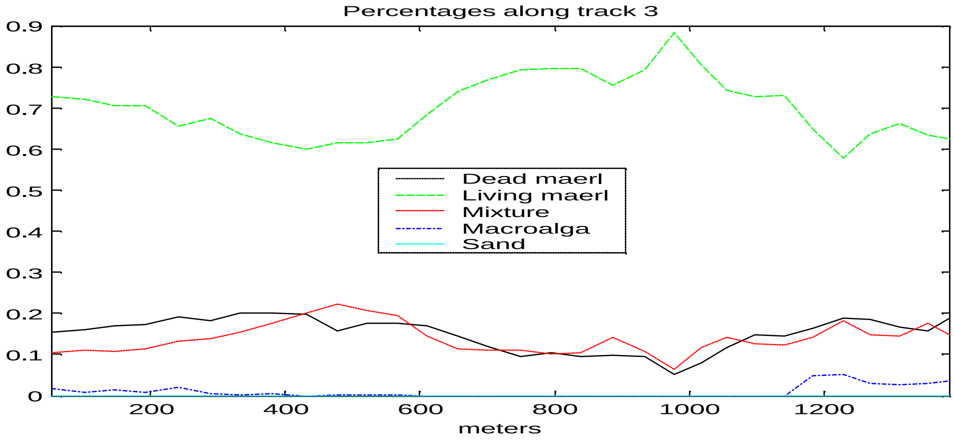
The Figures below show plots of percentages of various types of material along the track (horizontal axis is distance in meters from track start) for the entire set of images acquired in Wyre Sound. This data is the same as the colour-coded maps included in the Deliverable body. The database on which the classification is based contains entries for five different materials that are predominant in Wyre sound:

- Dead maerl
- Living maerl
- Mixture of dead and living maerl
- Macroalga
- Sand

As a very general comment we should note that some misclassifications can occur, e.g. sand is often classified as dead maerl (and vice versa), since their visual aspect is very similar, in particular when the observations are obtained at large altitudes. The same thing happens for macroalgae and living maerl.



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0.6
0.5
0.4
0.3
0.2
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600
800
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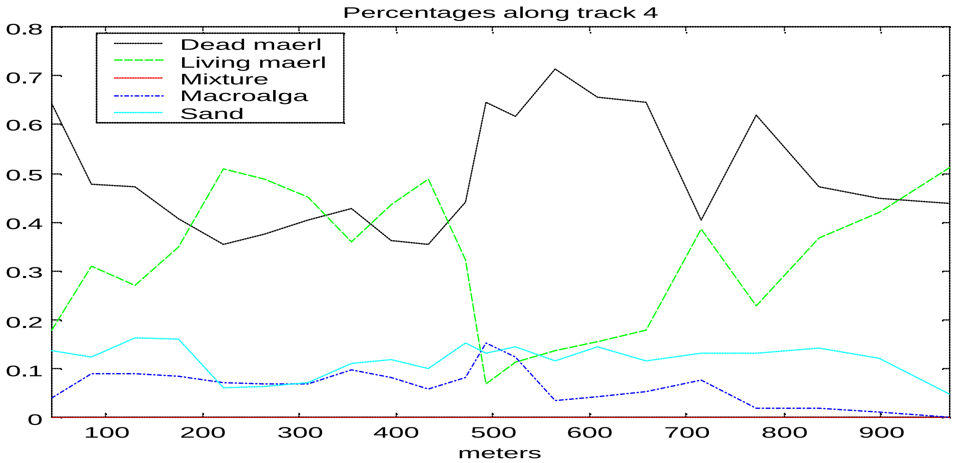
1200
meters
Dead maerl
Living maerl
Mixture
Macroalga
Sand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0.6
0.5
0.4
0.3
0.2
0.1
0
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200
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400
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600
700
800
900
meters
Dead maerl
Living maerl
Mixture
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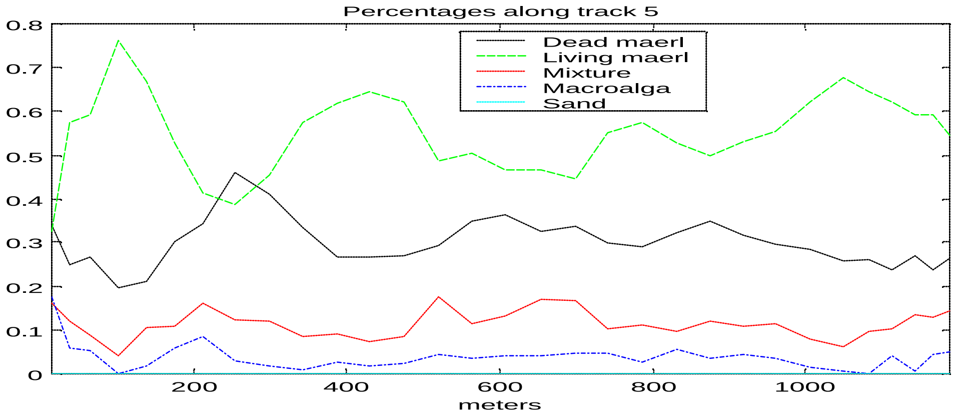
Sand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0.4
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0.2
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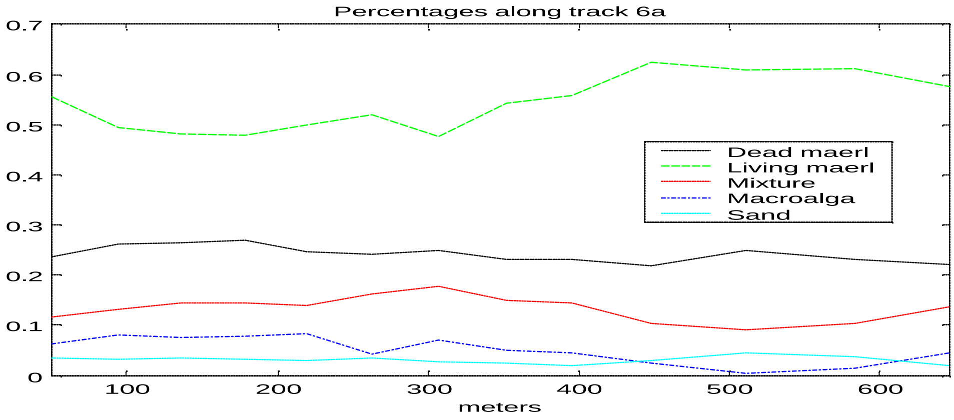
meters
Dead maerl
Living maerl
Mixture
Macroalga
Sand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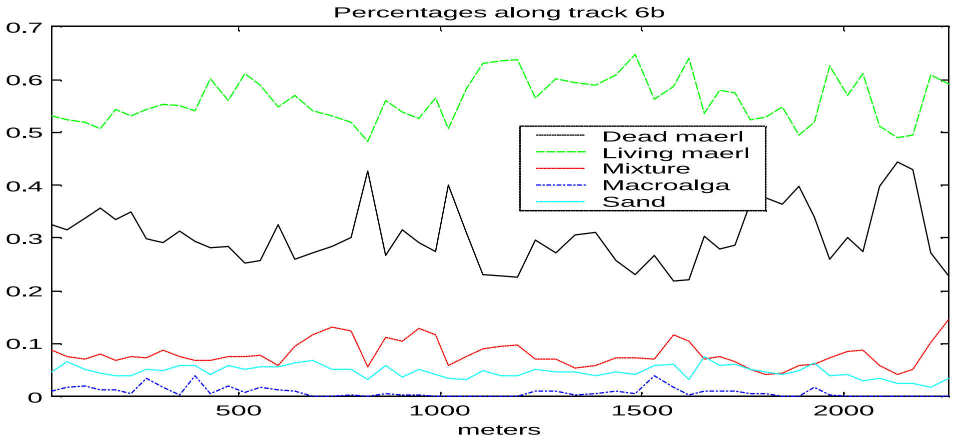
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Living maerl
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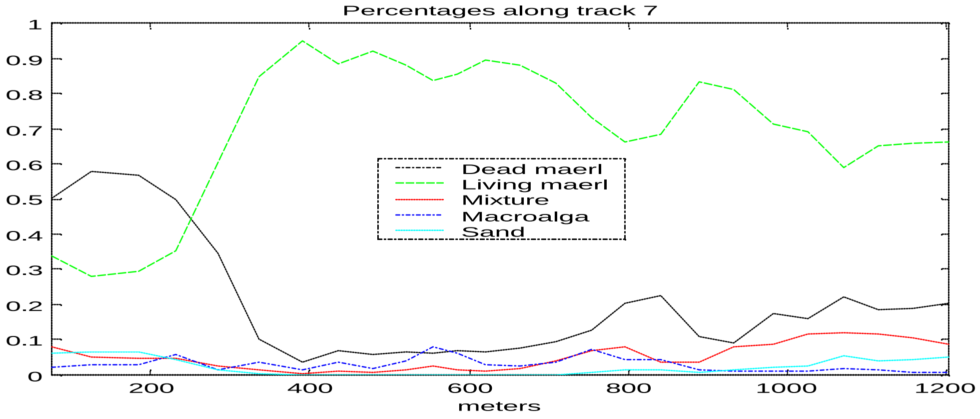
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0.7
0.6
0.5
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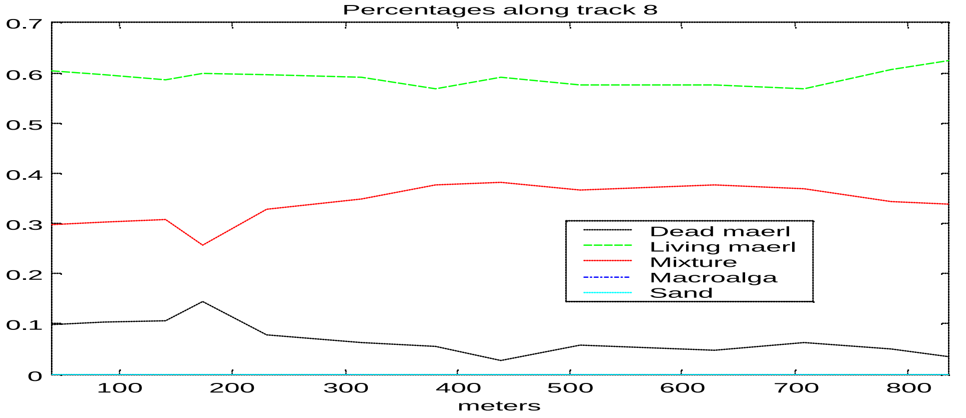
1000
1200
meters
Dead maerl
Living maerl
Mixture
Macroalga
Sand


Percentages along track 8
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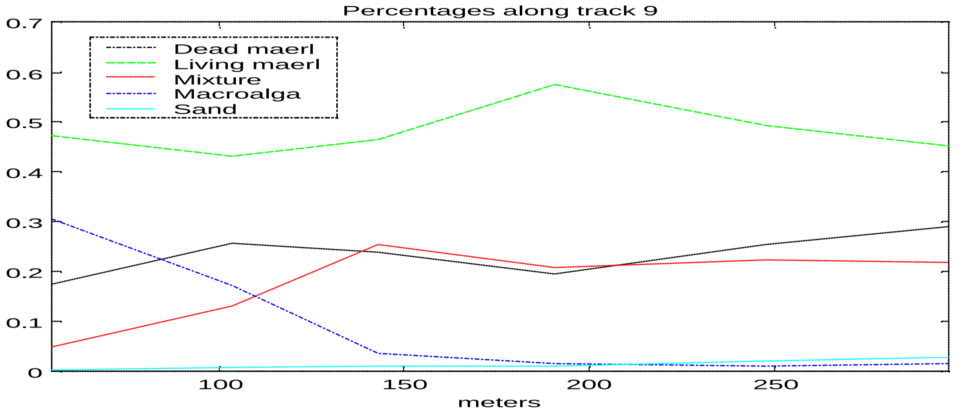
0.5
0.4
0.3
0.2
0.1
0
100
200
300
400
500
600
700
800
meters
Dead maerl
Living maerl
Mixture
Macroalga
Sand


Percentages along track 9
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
150
200
250
meters
Dead maerl
Living maerl
Mixture
Macroalga
Sand

Appendix B: Modelisation of dead-Maerl patches as Random Closed Sets

Estimates of maerl percentages along the tracks provides information about large scale distributions but do not indicate small scale distributions in terms of freqency and size of individual Maerl patches. One of the contributions of the SUMARE project is to consider the occurrence of a specific type of material as a realisation of a stochastic process, generically denoted as a Random Closed Set (RCS). The visual data indicate that in particular dead maerl patches seem to be realisations of such a RCS, since they seem to be randomly scattered on the seafloor. This phenomenon has already been illustrated by Figure 4. In order to analyse their small-scale distribution we considered the family of Boolean models.

Boolean models

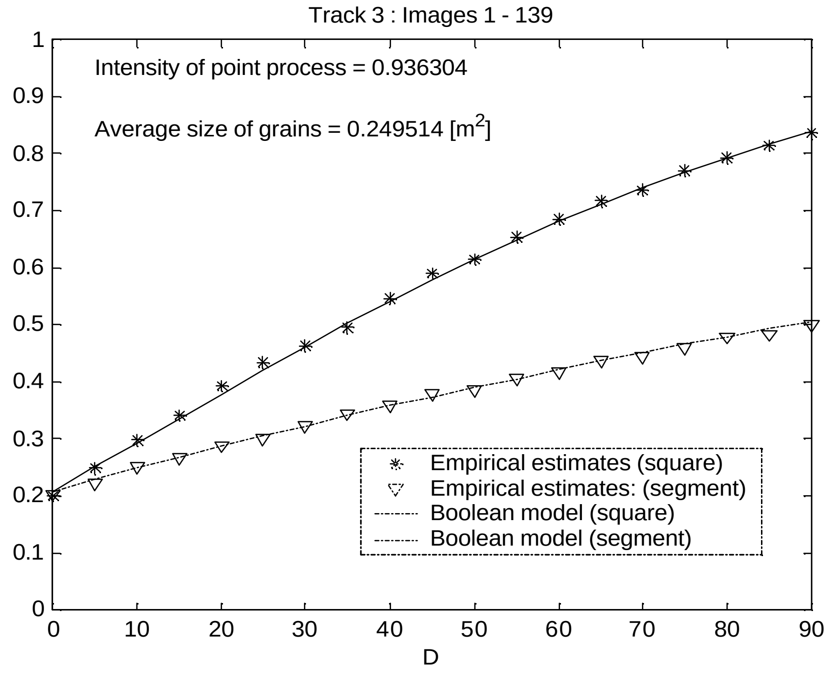
A Boolean model is a doubly stochastic process. The first process, a Poisson point process, determines the locations of the individual grains. Note that a maerl patch can be considered as a set of overlapping grains. The second process determines the shape and size of the grains for each location. The grains are assumed to be identically and independently distributed. The Poisson point process is determined by an intensity parameter l . To modelise the shape process it is often assumed that the grains belong to families of elementary shapes such as circle and ellipses. For dead maerl patches this seems to be a very coarse. However it is possible to determine averages such as the average size E_A and average perimeter E_U of the grains. A simple Boolean model is thus given by the parameter vector $q=\{l,E_A,E_U\}$.

Hitting capacities

It is in general not possible to directly assess the parameter vector q . In this case we use empirical estimates of hitting capacities for a set of structuring elements. A hitting capacity corresponds to the probability that a structuring element (e.g. a compact disc), when placed at some location in the segmented image, hits or not the random field (the union of dead maerl patches). For Boolean models analytical expressions relate these hitting capacities to the parameter vector q (Rolfes 2002).

Model estimation

We determined the Boolean models (the parameter vector q) for several image sequences of tracks 3 and 6a as well as the pattern experiment E21. The images are segmented and classified in order to determine the areas that are covered by dead maerl. This procedure results is a binary image (or mosaic) such as the one shown in the figure. The hitting capacities are then estimated based on the binary images for a set of structuring elements. We have chosen elements that belong to the family of squares and line segments. The parameters of the Boolean model are then obtained using a Minimum contrast method, (least squares) that fits the empirical estimates to the model parameter. Figure 5 shows the quality of the fit for an image sequence of track 3 and track 6a and demonstrates (but does not prove) that Boolean models are appropriate models for dead maerl. This is valid for all sites that have been analysed. The set of parameters (intensity, average size and average perimeter) are indicated in the tables below. The last column of the tables indicates the deviation of the shapes from a perfect circle. Values that are close to 0 indicate a rather elongated shape (1 corresponds to a circle).



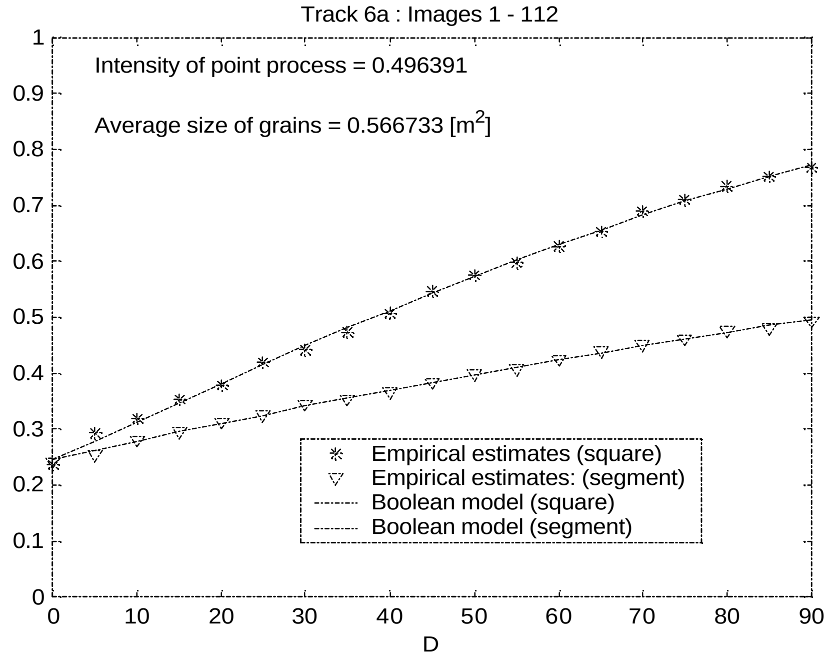


Figure 5) Empirical estimates of hitting capacities for two sets of structuring elements (squares and line segments) of varying length or size D fitted to a Boolean model.

Boolean models for Track 3:

Mosaic	Intensity	Average size $[m^2]$	Average perimeter $[m]$	Ratio: $[\frac{width}{length}]$
139	0.936304	0.249514	1.89593	0.807403
271	0.571203	0.381067	2.4802	0.653415
394	0.669357	0.399452	2.17302	??
527	0.550278	0.44801	2.48245	0.854166
660	0.639319	0.42886	2.43975	0.854166
785	0.690756	0.373284	2.24041	0.912086
907	0.939036	0.295728	2.04977	0.845484
1026	0.685699	0.400522	2.24339	??
1175	0.792336	0.393772	2.38732	0.795465
1307	1.28709	0.253367	1.71785	??
1429	0.689744	0.430525	2.80378	0.560728

Boolean models for Pattern E21:

Images	Intensity	Average size $[m^2]$	Average perimeter $[m]$	Ratio: $[\frac{width}{length}]$
1-200	2.06807	0.084528	1.25343	0.539478
201-400	2.22931	0.0876666	1.24048	0.576638
401-600	2.25027	0.106341	1.36498	0.595979
601-800	2.0826	0.0937719	1.31853	0.55025
801-1000	2.04118	0.099103	1.40558	0.493052

Boolean models for Track 6a:

Mosaic	Intensity	Average size $[m^2]$	Average perimeter $[m]$	Ratio: $[\frac{width}{length}]$
112	0.496391	0.566733	2.87354	0.771689
201	0.550204	0.558451	2.7676	0.872284
305	0.785704	0.349158	1.96986	??
407	0.617053	0.471815	2.48695	0.929032
502	0.693533	0.397441	2.19791	??
603	0.944223	0.319682	1.99432	??

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