Analysis of the sedimentary characteristics of the tees estuary using remote sensing and GIS techniques

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Volume One

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Declaration

This thesis is the result of my own work. Data from other authors which are referred to in the thesis are acknowledged at the appropriate point in the text.

Statement of Copyright

To my father

Hubert Xaver Konrad

ERINNERUNG

Willst du immer weiter schweifen ?
Sieh das Gute liegt so nah.
Lerne nur das Glück ergreifen,
Denn das Glück ist immer da.

Johann Wolfgang von Goethe (1749 - 1832)

Abstract

This thesis examines the ability of airborne remotely sensed data to provide quantitative information about the characteristics of intertidal sediments. The research was undertaken on Seal Sands in the Tees estuary, UK, and the airborne imagery was acquired by the Natural Environment Research Council (NERC) using a Daedalus 1268 11 channel scanning radiometer. The research focused upon establishing calibration and correction procedures for the airborne imagery as well as developing GIS techniques to process and analyze the data. A database was produced for the National Nature Reserve of Seal Sands to integrate remotely sensed imagery data, primary data from fieldwork (particle size analysis) and digital map data. Quantitative analysis of the relationship between radiance and particle size characteristics was undertaken. Results show that a multiple regression model is able to predict sand fractions in intertidal sediments and explain over 70% of the variance in radiance data.

GIS techniques have facilitated predictions of the ATM data and particle size analysis of the intertidal sediments, sediment interpolation, and spatial patterns of birds' feeding behaviour. In addition, a digital elevation model (DEM) was established to investigate the relationship of sediment distribution to topography. Although limited to a single study area, the integrated approach employed in this research should be of use in monitoring estuarine environments elsewhere.

Acknowledgments

The past year was in many concerns tough and cost a lot of energy and faith. Firstly I would like to thank my father, who tragedly died in the mid of my studies. Without his believe and support in my studies I would have never reached this point. I also would like to thank the rest of my family, relatives and friends who were and still are a great source of strength during this time.

This research would have not been possible without the help of many people, supporting me with advice, information and practical help. Firstly I would like to thank my first supervisor Dr Ian Evans who supported me very well at the final stage of the thesis. I also would like to thank my second supervisor Dr Christine Dunn who supported me well with GIS advice. Further I would like to thank Mr Robin Ward from the Biological Science Department, who supported me exceptionally well with my field work on Seal Sands; whenever I intended to go, I could count on him. Furthermore I am indebted to Dave Robinson who made the radiometric calibration of the image data possible by his genius programming knowledge. I am also greatly in debt to Prof Michael Tooley for his practical and moral advice. I also want to thank Dr Martin Coy from the University of Tübingen for his support which enabled me to stay in Durham for a second year. Thanks also go to Prof Peter Evans and NERC for supplying the ATM imagery. Furthermore I would like to thank Dr Desmond Murphy from the GKSS in Germany for the material he supplied me with. Additionally I would like to thank my new boss, Prof Dr.-Ing. Hans Peter Bähr from Karlsruhe University, for his final advice in my studies. Last but not least I want to thank greatly the technicians, in the Department of Geography, especially Mrs Stella Henderson, Mr Derek Coates and Mr Derek Hudspeth, as well all my postgraduate colleagues, who gave the department during this research year a very pleasant atmosphere.

Preface

Previous research on mapping intertidal estuarine environments has been carried out at the Department of Geography, University of Durham, using Landsat TM imagery of the Wash and the Tees Estuaries (Donoghue & Shennan, 1987; Donoghue & Zong, 1992). These preliminary analyses have shown that remote sensing techniques, especially when combined with GIS, provide a very useful method for mapping spatial distributions of intertidal ecosystems and their variability through time.

Two runs of ATM Daedalus 1268 images taken on 15th July 1992 ten minutes apart, were analyzed to assess the feasibility of using visible and short wave infrared reflectance and thermal emitted data for mapping tidal sediments in the Tees Estuary. The image data are compared with ground reflectance measurements and particle size analysis in the raster based module of ARC/INFO, called GRID. For the purpose of mapping sediment distribution on Seal Sands in the Tees Estuary, a Digital Elevation Model (DEM) was established, examining the sediment distribution in relation to topography.

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Chapter One - Aims and Methods

Preamble

" Writing a book is an adventure. To begin with, it is a toy and an amusement. Then it becomes a mistress, then it becomes a master, then it becomes a tyrant. The last phase is that just as you are about to be reconciled to your servitude, you kill the monster, and fling him to the public (SIR WINSTON CHURCHILL 1874 - 1965) " .

Introduction

The intertidal zone is the area between land and sea. It is characterised by its daily cyclus of water coverage and tidal exposure. The intertidal zone is a very sensitive environment and all over the world on a dramatic decline. Industrial development of these low lying and easy accessible areas, are the main reason for their gradual decrease. Most of the now-a-days remained European intertidal land are National Nature Reserve areas. The intertidal zone are heavily frequented by a high variety of wildlife, such as fish, mammals and birds. Especially a big variety of birds are dependent on intertidal areas, by using them as feeding and resting grounds. Intertidal land is further important for coastal defence, because of its function as a natural buffer against flooding of the adjacent land. For these reasons there is a high scientific interest to monitor and evaluate changes in the coastal habitat, on a reliable, quick, accurate and repeatable scale.

The aim of this research is to show how remotely sensed airborne data, in combination with additional tools and techniques can be used to produce maps of intertidal surface sediments in an estuarine environment, using the Tees estuary as a study area (Figure

1.1 a - d). Besides the image processing, the project also undertook to integrate ATM[1]-data and aerial photography (Figure 1.1e) with particle size analysis and other digitised data in a Geographical Information System (GIS). This research intends critical to evaluate the techniques used for the purpose of mapping intertidal sediments in the Tees Estuary. Therefore the main focus is on i) the necessary techniques, ii) their interrelation, iii) their accuracy and last but not least iv) their repeatability for future studies.

Conventional mapping of tidal sediments is achieved through direct ground observations and extensive field work. Usually the size of the intertidal land, and the variability over space and time, creates severe logistical problems. Additionally the intertidal land is influenced by daily tidal changes, and is therefore difficult to access. Ground observation of large areas is a time-consuming exercise and sampling is therefore often restricted to a between-year strategy (Doerffer & Murphy 1989). Mapping surface sediments in large intertidal areas by conventional methods involves extensive sampling programmes that are often difficult in practice and expensive in time and personnel. No matter how extensive the conventional programmes are, the accuracy of the resultant maps is limited by the need to extrapolate from sample sites to the whole area, usually by linking similar sites in a series of contours (Yates *et al.* 1993 b). Therefore, precise, high resolution field mapping is possible only for parts of an area and procedures may take months or even years, where major changes can appear through time. Additionally, biological variables and processes such as the distribution and productivity of organisms influence tidal flats, while there may be changes on a seasonal or even daily basis due to heavy storms or ground frosts.

The present study, however, takes a deterministic approach to evaluate the suitability of visible, and short wave infrared radiance, and thermal emittance data for sediment mapping. Besides the image processing, main concentration was paid to an extensive GIS approach, in order to integrate the data gained in the field work with the image processed data from a Terra Mar image processing[2] workstation and the digitised data from maps. The very up to date data base such as the airborne thematic imagery, aerial photographs[3] (Figure

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[1]ATM = Daedalus 1268 Airborne Thematic Mapper

[2]Based on a 386 processor.

[3]Data acquisition in June 1992.

1.1e); the digital map data such as high and low water mark in a scale of 1:25000 and contour line data of one metre; the field work, such as sediment sampling and particle size analysis; as well as the easy accessibility of Teesside from Durham University permitted a comprehensive and interrelational but quite complex study.

As imagery data are in raster format, the use of the 'GRID' module in ARC/INFO enables a direct downloading from the image processing system into the GIS. Conversions between the Terra Mar software and GRID can be performed easily. In addition, existing digitised data from Donoghue and Zong (1992) comprised landcover, tidal range, sampling stations and land classification which could be used directly as it existed in ARC/INFO format. The GIS approach involved further processing of the existing data, but also combining and interrelating the data in a sensible way, as well as checking the ground truth and the reliability of the data. Several attempts to achieve deeper understanding of sedimentary behaviour over space and time were made. Additional information on the processes of the intertidal zone could than be processed with the connection of the field data and the contour line data. Last but not least a prediction model could be created, based on a multiple regression analysis which enables prediction of particle size classes with spectral behaviour of the tidal sediments.

Methodological approach

The research structure is build up as follows (Figure 1.2): The study starts with field work and particle size analysis. Understanding of the sensitive sedimentary environment, such as changes over time and space, are gained in this chapter. At this stage of the research the study continues with an extensive image processing procedure. The necessary pre-processing steps are covered; such as the radiometric calibration, atmospheric correction and geometric correction. After the pre-processing first results for the sedimentary distribution are achieved in an image classification, using the widely used Maximum Likelihood Classifier (MLC). With the arising limitations of the MLC technique, deeper analysis in the feature space of the image data was performed. Especially correlation between particle size analysis and spectral behaviour of corresponding sampling stations in the study area were evaluated. Band combinations with a high explanatory power are examined within this approach. A regression analysis to predict different particle size classes was introduced and optimised within a multiple regression model predicting particle size classes with several band combinations.

The final output is then introduced in the GIS environment. The MLC output comes into further use as a mask to determine sedimentary and none sedimentary picture elements (water, vegetation, clouds and shadow) in the ATM data.Three particle size class maps, i.e. medium sand class, silt & clay and the total sand amount, are created using GIS. Interpolation techniques are introduced additional for filling 'gaps' of information, where remote sensing techniques cannot supply information. The GIS environment is then further used in order to examine sedimentary distribution over Seal Sands in combination of a Digital Elevation Model (DEM). This DEM can also be used to estimate birds' feeding grounds in relation to the tide. Care was taken to ensure that each step of the study is repeatable for future approaches.

The Tees Estuary area near Middlesbrough has been the focus of several intensive studies of the Department of Geography in Durham, both for its social and physical characteristics, for example by Hudson and Sadler (1985) and by Sadler (1986). Ornithological studies have been made by Evans and Pienkowski (1983), investigating the effects of reclamation of intertidal land in the Tees Estuary, on shorebird populations. In 1992 Donoghue and Zong carried out a pre-investigation of tidal sediment mapping in the Tees Estuary, with the help of Landsat TM imagery. Unfortunately at the time of their research there was no useful imagery data available for the purpose of intertidal sediment mapping. The images investigated were either taken during high tide, when the sediments were covered with water, or atmospheric conditions did not allow any detailed sediment mapping to be carried out. Nevertheless, the work of Donoghue and Zong (1992) provides a useful framework for the current research in terms of the techniques used.

Many other attempts have been made to map coastal habitats with remote sensing technology. In the 1970s and '80s, coastal monitoring and mapping was mainly based on aerial photography and on Landsat MSS and TM data (Ehlers & Böker 1989; Donoghue & Shennan 1987). Bartsch (1990) mapped the German Wattenmeer with the help of aerial photography, by introducing a so called "photo-key" in order to systemise the classification of tidal sediments. Dennert-Möller (1983) based her PhD research on the multispectral classification of Landsat MSS scenes in the early eighties. Doerffer and Murphy (1989) mapped the German Wattenmeer with the help of Landsat TM data and explained the different spectral behaviour of the sediments using Factor Analysis, which is based on a Principal Component Analysis (PCA) and which models the proportional contribution of several factors to the reflectance behaviour of the sediments. Kleeberg (1990) also used this technique to map the tidal sediments of the German Wattenmeer, using the database of the GKSS in Germany. Finally Yates *et al.* (1993 b) completed a similar study on the Wash Estuary using Landsat TM data for mapping the distribution of intertidal surface sediments. The image processing method which was used in their study comprised (i) Maximum likelihood classification, (ii) Multiple Regression Modelling, and (iii) Spectral Mixture Modelling.

Landsat MSS and TM, as well as SPOT HRV data have the restriction of the low ground resolution (Landsat TM has 30 x 30 m) which results in problems with the radiance spectrum of a single pixel (picture element). Within a pixel of 30 x 30 m for an intertidal zone, it is very likely that there will be small patches of algae, mussel shells etc., each of which has a different spectral reflectance. Consequently, the spectral information contained in a pixel is a mixture of different surface types which can lead to ambiguous interpolation of the radiance spectrum. This large scale heterogeneity of one pixel leads to the expression *mixel* (mixed pixel). Conventional aerial photography is restricted since, in the case of true or false colour photography, only three rather broad spectral bands within the visible or Near Infrared (NIR) are available.

Therefore, in the present study the Daedalus 1268 Multispectral Scanner (MSS) Airborne Thematic Mapper (ATM) was used as it has the advantage of 11 bands, ranging from the visible, through the NIR and the Short Wave Infrared (SWIR), into the Thermal Infrared. The Airborne Thematic Mapper (ATM) data in this study are similar to the Landsat TM data in terms of the arrangement of the spectral channels. The ATM device measures the amount of light reflected from the ground surface. The resultant imagery is recorded in digital form for manipulation and display by computer. In addition it has a very high spatial resolution; in the case of the ATM-Tees data, the resolution is 5 m. This allows more detailed and precise mapping. This is very important due to the high level of variation of intertidal sediments in terms of space and time. MSS airborne radiometers have, up to now, seldom been used, due mainly to the high costs involved in both operating and processing the data. Nevertheless it is a very useful tool for mapping tidal sediments because of the absence of sharp boundaries as found in purely terrestrial environments, for example, between forests and agricultural land (Doerffer & Murphy, 1989).

Apart from the lack of clear boundaries in the intertidal zone, the radiance spectrum is affected to varying degrees by the surface water content on each surface type. This can result in a modification of the backscattered radiation spectrum. Large parts of the tidal flat surface, and especially those areas which are not adjacent to drains, remain covered by a shallow film of water during most of the low tide. This water film is usually only a few centimetres thick but as a result of the shallow gradient it is unable to run off (Ehlers & Böker 1989). Although high resolution imagery is used in order to be able to map the tidal flats accurately, in cases where a division into a large range of particle size groups or a high accuracy is required, field work in small areas is inevitable in order to verify results of airborne analysis. For this reason, a combination of the remotely sensed data with the digitised map data and the field work has been achieved here within a Coastal Monitoring GIS[4].

For the present study only a part of the intertidal land of the Tees Estuary was used for sediment mapping, namely Seal Sands. Seal Sands forms the main part of the remaining intertidal land of the Tees Estuary, and also shows a high degree of spatial variation of the intertidal sediment distribution. Furthermore, restrictions of time and resources made a more detailed study of one, manageable area the most feasible. Future studies could concentrate however on the other two remaining areas of intertidal land in the Tees Estuary, namely Bran Sands and North Gare Sands, in order to verify the established approach within the same data set (Figure 1.1 d).

Having considered the benefits and constraints of applying remote sensing techniques to support monitoring and mapping programmes for Seal Sands in the Tees Estuary, the specific aims of the present work can be summarised as follows:

[4] The Coastal Monitoring GIS contains the remotely sensed data, field work results and the internally processed data, e.g. digital maps, etc. .

■ An evaluation of the possible use of airborne MSS-systems for mapping intertidal sediments. Several techniques are applied, such as field work and image processing. A combination in order to achieve a high accuracy in mapping the intertidal sediments of Seal Sands is attempted in a GIS environment. The limiting factors of the techniques used are noted and their influencing power evaluated.

■ Production of a base map of the sedimentary environment of the Tees estuary before a tidal barrage is constructed 17 km upstream of the river Tees (near Stockton)[5], in order that any changes over time in the sedimentary environment, resulting from the barrage may be identified. Changes which may relate to the barrage construction, can be then monitored with the same techniques used for this research some time after the construction of the barrage.

■ Intertidal mudflats are of interest to ornithologists because of the correlation between the feeding behaviour of birds and the local sedimentary environment. Part of the aim of the present work is to examine the nature of this relationship in terms of spatial patterns of particle size. Several sediment distribution maps are established such as a classified ATM image, predicted sediment class maps, based on a multiple regression model, and interpolated sediment class maps, based on particle size analysis. The results are processed, incorporated and evaluated in a GIS, and form the basic information for investigating the relationship between tidal sediment distribution and bird feeding behaviour. In addition, information from a detailed, 1 metre contour line map is used to predict feeding grounds according to tidal range.

[5]The barrage is planned to be operational in summer 1994.

Chapter two - The study area, estuaries & birds

Work within the Tees Monitoring Programme

The current research forms part of a monitoring programme for the Teesside Development Corporation (TDC) which was established in 1990 to cover nature conservation concerns arising from the proposed Tees Barrage. The main monitoring programme is designed to detect changes in the ecology of the river Tees attributable to the building of the barrage at Blue House Point (River Tees Barrage and Crossing Act 1990). The programme started in Spring 1990 and covers a continuous period of at least two and a half years before the commissioning of the barrage. It extends over at least three years after the commissioning, investigating all the determined parameters (i.e. water quality, fish and benthic research), and over at least five years to cover invertebrate and bird studies. The mapping of particle size distribution carried out for this research over Seal Sands forms part of the studies on birds and invertebrates.

The monitoring programme is concerned with detecting changes which can be linked to the effects of the barrage, in particular any changes in sedimentation patterns at the Site of Special Scientific Interest, and which can be correlated with invertebrate densities and bird feeding behaviour. The monitoring of the sedimentary environment, invertebrates and birds is being carried out on the Corporation's behalf by the Department of Biological Sciences, University of Durham under the direction of Professor Peter Evans. Besides this work, the monitoring of water quality, fish and benthic animals is being carried out on the Corporation's behalf by the Northumbrian Region of the National Rivers Authority (River Tees Barrage and Crossing Act 1990). The monitoring of sediments, invertebrates and birds has taken place on the intertidal land of Greatham Harbour, Seal Sands, North Gare Sands and Bran Sands. The mapping of the sedimentary environment of the Tees estuary using airborne imagery is undertaken in co-operation with the Department of Biological Sciences.

The Geology of Teesside

The Tees estuary is based on a succession of sedimentary rocks of Triassic and Jurassic age, dipping gently south east (Robson 1980). The formation starts with the *LOWER LIAS SHALES, LOWER JURASSIC*, and continues with *RHAETIC, MERCIA MUDSTONE* (formerly *KEUPER MARL*) and *TRIASSIC SHERWOOD SANDSTONE* (formerly *BUNTER SANDSTONE*). The Geology of the Tees estuary itself consists very little of solid outcrops. At Seaton Carew the Sherwood Sandstone is exposed on the foreshore as the Longscar Rocks. In the intertidal zone at Redcar, there is an exposure of Lower Lias shales and limestones. An exposure of the Mercia Mudstone once visible in the river between high and low water was removed by blasting in order to improve navigation.

Over the rest of the area the solid geology does not outcrop at the surface, and is overlain by unconsolidated deposits of Quaternary age. Borings for engineering works, put through the unconsolidated sediments, reveal the presence of a broad shallow valley in the solid geology. This valley, which has possibly been formed by ice coming from the north, can be seen as the proto-Tees valley. It is covered and filled with glacial tills with a maximum thickness of 30 m.

A typical sequence would be (Agar 1954):

Red Boulder Clay	10 m
Dark Boulder Clay	
Sand and Gravel	2.5 m
Drab Boulder Clay	2.5 m
Sand	4.0 m
Gravel	4.0 m

	23.0 m.
Solid MERCIA MUDSTONE	

Overlying the glacial tills across most of the central part of the area is a late-glacial lacustrine deposit, the Laminated Clays. These clays were probably laid down in freshwater coming from the receding Devensian ice sheet. The deposit consists of thin beds of sand, red clay and blue clay with sharp boundaries between the layers. Agar (1954) describes these as varved sediments. The deposit also includes a number of drop stones, one of which consists of a boulder of Granite. The maximum thickness of the laminated clay is 10 m. The late glacial lake drained following final ice retreat, which allowed the free drainage of the post-glacial river Tees to a contemporary sea level at between -100 m to -150 m O.D. During the process of adjustment to the reduced level, the Tees cut a gorge down to -25 m O.D., through the laminated clay and glacial till and 6 m into the Mercia Mudstone. The following Flandrian Transgression (7000-6000 years B.P.) stopped further incision of the gorge into the solid geology by glacio-eustatic sea-level rise to approximately its present position. Further sea-level rise resulted in the infilling of the gorges (Sproxton 1986). Estuarine deposits have accumulated, partly because of the constriction of the river mouth by sand accumulation from the north at Seaton Sands and from the south by Coatham Sands (Figure 1.1 b). Engineering boring has recorded up to 18 m of grey silt, overlying sand and gravel, in the post-glacial gorge of the Tees estuary. Fossil organic material such as peat layers, has been recorded in some areas of the Teesside region. These peat layers are usually overlain by estuarine clays. Above these, over most of Seal Sands, blast furnace slag has been used, mainly in the 1960s and '70s to reclaim otherwise waterlogged or periodically flooded areas for industrial development.

Industrial development of Teesside

In many parts of the U.K. coastal and estuarine areas have provided sites for industrial and commercial activity together with associated residential development on an increasingly large scale. These areas benefit from easy transport of bulk materials and access to sufficient quantities of cooling water for industry and power generation. In the 18th century the iron and steel industry started to develop in the upper parts of the Tees estuary. With the exhaustion of local supplies of iron ore, the steel works gradually moved further downstream with major new docks and urban areas developing at Middlesbrough in the early part of the 19th century. Even so, in 1850 the estuary remained as a large expanse of intertidal land (Figure 1.1 c, d).

Only by the mid- 1970s had the total intertidal area of the Tees estuary been reduced by a succession of land-claims to 470 ha, resulting in an overall reduction of 3,300 ha, and representing 83% of intertidal land in the Tees Estuary since the 18th century (Figure 1.1 c, d). These areas of reclaimed land now support one of the largest industrial and port complexes in Britain, with major petrochemical refineries, stabilisation plants and export jetties, agrochemical plants, a variety of chemical works and chemical storage facilities, steelworks, offshore engineering, as well as cargo port facilities and nuclear power generation (Davidson *et al.* 1991). There has been no further land-claim at Teesmouth since 1974, even though it was planned in the structure plan for this area. In the 1980s, the remaining part of Seal Sands was proposed as a National Nature Reserve.

Coastal Morphological Unit of Hartlepool to Saltburn

Hartlepool Bay and Tees Bay act as sediment traps (Figure 1.1 b). According to Tooley (pers. comm.) there has been much sediment infilling in both bays since the early Holocene (9700 BP) which continues to the present day and is enhanced by the action of man. Some of the coal waste tipped at the coast further north is deposited in both bays, due to the southward trend of the current.

Major changes have been brought about as a result of man's activities in the Tees estuary. The North and South Gares are man-made breakwaters built of blast furnace slag during the 19th century, and dune systems have developed on them (Clark *et al.* 1989). Currently the Tees has the longest tidal reach of all rivers in North East England. Between the Tees entrance and Redcar there is accretion of sand associated with a local reversal of the littoral drift which represents a second, smaller localised northwest drift from Coatham Sands (Figure 1.1 b). Even within the major zone of sand deposition there are localised areas of erosion of current sea defences, e.g. at Hartlepool Headland and at Seaton Carew.

Sedimentary environment of the Tees Estuary

Although there are clear spatial and temporal patterns of erosion and deposition in the estuarine environment, these patterns can vary over a wide range of scales and it is frequently the case that even where a series of direct observations have been made, they are likely to be spatially and temporally very restricted (Shennan & Sproxton 1990). According to a recent Hydraulics Research report (1986) the major longshore drift component comes from the North, where Magnesian Limestone and dumped colliery waste provides the main source of clastic material coming into the Tees estuarine environment (Figure 1.1 b). The most recent changes in the sediment accumulation within the Tees estuary have been due to the construction of breakwaters (South Gare 1863-1888 and North Gare 1882-1891) at the mouth of the river using 4 million tonnes of industrial slag (Figure 2.1), and reclamation of intertidal flats for industrial development from the 1860s to the 1970s (Shennan & Sproxton 1990). One of the major purposes of this study is an evaluation of possible changes in the sedimentary environment which will appear when the new tidal barrier is constructed 17 km upstream of the mouth of the Tees estuary. Furthermore, according to Shennan and Sproxton (1990) wave, tidal and sedimentary factors may well change in the future, along with sea level rise and changing rainfall patterns.

Along the North East coast it must also be taken into account that there is a very large input of sediment to the coastal environment from coal mining activities. Disposal of colliery shale onto the beaches along the coast at places such as Seaham, Hartlepool and Teesside over the last century has added many millions of cubic metres of material to the near-shore system. Dispersal of this material by the grinding action of waves takes place rapidly.

Tides, tidal current and wave environment

The current spring tide range is 4.60 metres, whereas the extreme predicted range could reach a level of 7.24 metres, caused by the additional effect of the fluctuation of atmospheric pressure. The neap tides' range is 2.3 metres. The mean high water of spring tides intersects the coastline at a maximum of +2.75 metres OD (Figure 2.2). Additionally there is an increase of 0.20 metres of mean high water of spring tides upstream within the tidal part of the estuary. Figure 2.2 shows the basic tidal cycle at the Tees Estuary. There are two spring tide and two neap tide series during each month. Typically one spring tide series has larger tidal ranges than the other (Figure 2.3). This means that some of the highest intertidal parts of the shore are covered by tidal water for only short periods on a few days in each month, whereas the lowest intertidal levels are exposed for only brief periods on a few days in the month (Davidson *et al.* 1991). In contrast, mid shore levels undergo twice-daily inundation and exposure. Besides the lunar cycle, there is also an annual cycle. The largest spring tides appear regularly in autumn and in spring. Sometimes, appearance of storm surge tides can cause rapid major changes within estuaries. Furthermore, high water levels will also be affected by freshwater discharge from the Tees catchment. The level of the Tees can change very rapidly due to periods of intense rainfall in the upland catchment areas, although some regulation is now provided by using reservoirs. The formation of currents in the Tees Estuary is dependent not only on the tides, but also on the wind. The wind therefore plays a significant part in the shaping of the tidal flats and islands. Whilst the tide-induced currents are primarily controlled by the configuration of the tidal creeks, the wind is not subject to this limitation and can act areally and undirectionally over the estuarine environment (Ehlers & Böker 1989).

The prevailing winds from the south-west are offshore but high onshore winds occur especially during winter gales. North winds have long fetches across the North Sea and produce a very high wave energy climate from the north and north-east (Hydraulics Research 1986). These promote a net transport of beach material southwards and are assisted by tidal currents. Tidal currents generally flow in a southward direction during the flood following the coastal outline and in a northward direction during the ebb (Figure 1.1 b). In general the movement of material on the open coast is dominated by wave activity, although the maximum flood flow velocity is generally higher than the maximum ebb flow. Therefore there is a southward trend of material in suspension over the sea bed as well as in the littoral zone (Hydraulics Research 1986).

Wave height values along the North East coast have been crudely grouped into four groups (Hydraulics Research 1986):

(i) less than 0.3m for 70% of the time

(ii) between 0.3m and 0.9m for 18% of the time

(iii) between 0.9m and 1.5m for 9% of the time

(iv) greater than 1.5m for 3% of the time.

In summary, tidal current activity undoubtedly affects the movement of sediment within the mouths of estuaries and within large bays such as Hartlepool Bay and Tees Bay. In these situations, currents can attain sufficient speed to enable them to transport fine sands, silts and muds. On the open coast of the North East, however, beach movement is dominated by wave activity (Hydraulics Research 1986). The morphologically most active parts of the system are the tidal inlets. They are influenced twice-daily, both by flood and by ebb current. The large water volumes that are forced through these inlets during short periods cause a strong current to develop, the so-called "tidal jet", which has considerable erosive power (Ehlers & Böker 1989).

The Tees barrage project

In October 1991 the Teesside Development Corporation (TDC) awarded the River Tees Barrage Contract to Tarmac Construction Ltd. The barrage project includes a new road bridge and a new footbridge across the river Tees in the Stockton area (Figure 2.4). The barrage project was started in September 1992, with a contract value of £49 million. This sum is fixed for the contract period of 186 weeks. The barrage is being constructed at Blue House Point, Stockton on Tees which is approximately 17 km upstream of the estuary mouth.

The major structure is the barrage across the existing River Tees, which was required to secure the regeneration of the site known as Teesdale on the south bank of the river opposite Stockton on Tees (Figure 2.4). The barrage substructure comprises a heavy reinforced concrete sill beam below the level of the existing river bed. The barrage is built up of four so-called "fish belly" gates, which are each 13.5 metres long and 8 metres high. The barrage gates can be operated either automatically or manually, in order to control the water flow. A fish ladder is included in the barrage system.

For pleasure-boating a lock will be provided to enable the passage of craft from the restrained water upstream of the barrage. Around the north east site of the barrage, a 350 metres long canoe slalom course will be constructed. The course will be fed from retained water upstream of the barrage. The flow into the canoe slalom course will be around 10 cubic metres per second which, according to the TDC, will form 50 % of the water that will not pass the barrage. The outflow and operation of the course will be dependent on the tidal situation. Further work will be completed for the purpose of recreation and activity, comprising a caravan site, car parks and extensive landscaping.

To enable construction of the Tees barrage, the River Tees has been diverted to the south in a temporarily widened navigation channel, whereas the existing river has been dammed off upstream and downstream of the barrage[6]. The barrage is constructed to maintain the upstream water level at 2.65 metres and the downstream level at 5.0 metres. One purpose of this massive concrete construction is to decrease the pollution problem upstream of the barrage, which will be out of tidal influence. The £49 million project cannot solve the actual pollution problem, it can just restrict the problem to the downstream area, thereby increasing the risk (eg. heavy metals and toxic chemicals) for the remaining part of the intertidal land of Seal Sands and its wildlife.

Further environmental problems are likely to arise, as the barrage acts as an artificial sediment trap, which possibly influences the very sensitive mud and sand flat environment of Seal Sands, in terms of affecting the density of invertebrates in this area and thereby, the feeding behaviour of estuarine birds. The temporary dam for the purpose of diverting the river upstream of the barrage construction has already shown approximately half a metre of sediment accumulation in the short time period of half a year; and has shown therefore the possible future influence of the barrage on the sedimentary environment of Seal Sands.

Physical characteristics of the intertidal zone

Estuaries

Estuaries are wetlands that form the margins between land and sea. These areas are influenced by daily movement of the tide, and the mixing of fresh and salt water. Present day estuaries were formed when rising sea level shallowly flooded the continental shelf after the last ice age, 10000 - 15000 years ago. Estuaries are active morphological systems undergoing continuous change, influenced by a long history of glacial river and marine processes acting upon the coastal geology.

"The continual input, trapping and recycling of sediments and nutrients leads to estuaries being amongst the most fertile and productive ecosystems in the world" (Davidson *et al.* 1991). Estuaries function as a link between marine, freshwater and dry land ecosystems. The relatively sheltered location of estuaries causes a slow down of tidal and

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[6]The temporary dam was constructed in order to allow the building of the barrage in a dry environment.

river currents, so that fine sediments settle out of suspension, forming the characteristic estuarine landform of mudflats. Sedimentation is enhanced in estuaries by salt flocculation: salt water causes fine clay particles to stick together, so increasing their effective particle size and accelerating their settlement (Davidson *et al.* 1991). Higher energy parts of the estuary result in more mobile sand flats. Sedimentation patterns are dependent on topography, sediment loads and currents. This continual catchment and settlement results in a depositional environment consisting largely of fine unconsolidated muds and sands.

Besides sediments, nutrients are also deposited from the sea and rivers, and are taken up by plants and animals. Estuaries are influenced by very variable and unstable conditions, for example, temporal or spatial changes in tides, river floods and storm surges. This uniquely varying set of physical, chemical and biological conditions enables estuaries to support abundant wildlife specially adapted to these conditions and capable of exploiting the nutrient-rich but variable environment. In this case study, particular attention is paid to the shorebird population using the estuarine environment as a feeding place.

Tidal Flats

Variations in tidal and river current, and the large volumes of sediments carried in suspension, result in estuaries being places of active change (Davidson *et al.* 1991). Generally the tidal flats consist mainly of sand. Mud areas are mostly limited to the margins of tidal creeks or inner areas of the estuary, which are the most sheltered places. Coarser sediments are deposited closer to the mouth of the estuary, or on more exposed shores, where higher wave energy and faster tidal currents keep fine sediments in suspension. Intertidal zone sediments are characterised by a dominance of fine sand with variable amounts of medium sand. Coarser fractions occur only in overdeepened sections of tidal inlets and at bottoms of tidal streams eroding into gravel-bearing strata of subcropping Pleistocene deposits (Ehlers 1988).

Sand flat areas (Figure 2.5) generally have a clay and silt content of ≈1%, and are dominated by quartz grains; true mud flats have a clay and silt content of over 50%. Mixed flats have a silt and clay content of 10 % to 50 %. The dominant peak lies in the fine sand, rather than in the clay. There is also a seasonal variation in the intertidal sediment distribution; in the winter time the sediments are coarser, whereas in summer, mainly finer sediments are deposited.

From a distance, sand flats seem to have a smooth surface and appear light coloured on aerial photography. A detailed examination, however, shows that sand flats do not have an absolute plane surface; small ripples and a subdivision of numerous small scale elements form this zone. These small scale features are often detectable on aerial imagery, especially when lower parts are still covered by a water film which is highly reflective. Areas at a higher altitude on the sand flat environment are sculptured mainly by wind action.

Tidal flats provide a substrate within which lives a very large biomass of macrobenthos, notably polychaete worms and gastropod and bivalve mollusca (Figure 2.6). These animals often live in very high densities and provide food for estuarine fish during high tide. During low tide, when tidal flats are exposed, they provide feeding grounds for many bird species of migrant and wintering waterfowl (Davidson *et al.* 1991).

Mudflats

In general, the grain size of the sediments decreases landwards, and mudflat sediments are characterised by a high organic content. The silt and clay fraction in the intertidal environment consists almost exclusively (more than 90 %) of organic matter (Ehlers 1988). In addition, carbonate particles also contribute to the fine fraction, consisting mainly of ground shell fragments. Mudflats which rarely exceed 1 metre in thickness, and which overlie dominantly sandy sediments, are found in areas of decreasing intensity of water movement and increasing influence of organisms on the sediment composition. Halophytic vegetation helps to reduce the current and to stabilise the mudflat (Ehlers 1988). Mudflats often support extensive beds of eel-grass (*Zostera spp.*) and green algae (*Enteromorpha spp.*), especially in nutrient-rich areas (Figure 2.7).

Tidal creek system

The intertidal zone is characterised by a drainage pattern of tidal streams varying in form and length. Tidal creeks on sandflats are distinguished by straight courses, which makes them clearly distinct from mainland streams. The creeks in the sandflat areas are, according to Ehlers (1988), mostly short and straight, whereas the creeks of the mud flats meanders have many branches (Figure 2.8 & 2.9). A number of minor creeks are confluent with the major creeks. The creek density on sandflats is relatively low and rarely branching, whereas mudflats are drained by a dense creek network.

Intertidal landform changes

Small landform on the tidal sandflats (sand waves and bars) undergo rapid replacement and reshaping, in extreme cases even within one tidal cycle. The larger landform (flats and major tidal creeks) undergo only minor alterations and thus the general drainage pattern can be maintained for many decades. Major changes can appear in terms of altering the size of the drainage area or where the course of tidal streams is altered. Nowadays, human interference plays the major role in changes in the intertidal zone. In the case of Seal Sands, changes during the last three years have mainly been caused by the breakdown of the man-made tidal wall at the northern part of Seal Sands.

Ornithological Studies

Birds are the most visible and easily the most intensively studied members of all fauna in the marine environment. They are also viewed as conspicuous indicators of the health of the marine environment and are therefore worthy of consideration. There is a high level of interest in birds, especially in Britain, both at professional scientific level, with organisations such as the Natural Environment Research Council (NERC) and major ornithological societies, such as the British Trust for Ornithology (BTO), and at amateur level, with over a million birdwatchers. One important purpose of the present study is to map a "status quo" of the intertidal sedimentary conditions in the Tees estuary in order to detect changes after the construction of the barrage across the estuary. The shorebirds' feeding behaviour is directly related to the number of invertebrates which, in turn, is related to the sedimentary environment. The tidal barrage may have both negative and positive effects on the shorebird population. Possible disadvantages to the birds could be the reduction of feeding areas, because the lower levels of the shore would be flooded permanently, or less feeding time for birds due to the barrage delaying the ebb tide. A tidal barrage might also be advantageous due to its possible increase in productivity, especially for invertebrates colonizing the remaining inter-tidal flat areas.

Estuarine birds

There are three groups of birds which frequent coastal areas. These are the *seabirds*, the *waders* (or shorebirds) and the *wildfowl*. This grouping is helpful even if to some extent arbitrary, due to the reflection of differences in feeding and nesting habits, and distribution.

Seabirds: Seabirds are birds which obtain at least part of their food from the sea, travelling some distances across it. Typically they nest on offshore islands or at inaccessible coastal sites, especially cliffs. Almost all (98%) of the 274 species breed in colonies (Furness & Monaghan, 1982). There are 34 species of seabird which regularly occur in the North Sea area, involving about 10 million individuals (Webb 1987). The North-East coast of England is an important breeding place for these colonies, particularly in the Farne Islands, Coquet Island, Marsden Cliffs, Flamborough Head and Bempton Cliffs. Many species have succeeded in increasing their numbers during this century by establishing themselves at new breeding sites.

Waders: Waders are typically estuarine species. They belong to the family *Charadrii*. They feed on sand or mud flats and often at the margin of the sea, typically by wading into it. Their number is approximately 1.3 million during winter time (Moser 1987). The waders are the main species affected when changes in the sedimentary environment occur. British waders are of international importance because Britain holds about 40% of the total European population. Most species breed in the Arctic and then overwinter in Britain. They are not under threat during the breeding season but human use of estuaries for industrial and leisure purposes, and the consequent pollution and loss of overwintering habitat, is potentially serious (Clark 1989).

Wildfowl: Wildfowl belong to the family *Anatdae*; the swans, geese and ducks. Most of the species breed in northern latitudes and, like many waders, migrate south to overwinter in warmer zones. An estuarine environment provides good feeding and roosting sites for them. The North Sea coast is an important area for wildfowl, supporting roughly 25% of those breeding in Britain. The number of wildfowl species has been stable over the past 25 years in Britain's estuarine environment.

The birds of the North Sea region are threatened by various factors. Lowland areas especially have been used in the past two centuries for industrial and recreational purposes due to their ideal location for transporting goods, presence of widespread flat areas and their recreational attraction. Feeding and breeding sites decreased drastically during the period of industrialisation in Britain. Threats come from land reclamation at Seal Sands where bird sites are simply built over (Table 2.1).

Approximate number present	**before reclamation**	**after reclamation**	**change observed**
Species	**1972 - 1973**	**1974 - 1976**	**percentage**
Shelduck	1650	1000 to 3000	-40 to +90
Ringed Plover	50	5	-90
Grey Plover	230	80 to 100	-60
Bar-tailed Godwit	1100	60 to 80	-95
Curlew	200	20 to 200	-0 to -90
Redshank	350	180 to 200	-60 to -75
Dunlin	1500	400	-75
Knot	4500	2900 to 3600	-20 to -35

Table 2.1 Comparison of midwinter numbers of shorebirds using Seal Sands before and after partial reclamation (whole table reproduced from Evans & Pienkowski 1984).

Other threats to bird life are sewage effluent, oil and chemical pollution, plastics in the marine environment and man-made changes in food supplies for birds, for example by overfishing. The Tees estuary has suffered severe loss of mud flats (Figure 1.1 c, d); 94.3% of the former intertidal land has been reclaimed (from an original 2500 ha to 655 ha by 1967, and to 149 ha by 1976). The remaining, unreclaimed area of Seal Sands is now protected as one of four Sites of Special Scientific Interest (SSSI) in the Teesmouth which meet the criteria for designation under the terms of E.C. Directive 79/409/EEC on the conservation of wild birds and for inclusion on the list of Wetlands of International Importance under the Ramsar Convention. Seal Sands still maintains rich populations of waders and wildfowl, and also has an internationally important level of Shelduck.

Chapter three - Field Work and Particle Size Analysis

Introduction

Field work was performed for the purpose of correlating the image processing data over the intertidal zone of Seal Sands. This comprised sediment sampling and particle size analysis. The results of the particle size analysis, were used for correlating particle size and reflectance measurements in the visible and near infrared, and emittance in the thermal infrared part of the electromagnetic spectrum (EMS). Further use of the particle size analysis was the verification of results, such as the classification in Chapter four.

Ground sampling and Particle Size Analysis on Seal Sands

During 1990 and 1991 the Department of Biological Sciences, University of Durham collected superficial sediment samples from 80 sites over Seal Sands (Figures 3.1 & 3.2), 70 sites over Bran Sands, 7 sites in Greatham Creek and 31 sites over North Gare (Figure 1.1d). Sediment sampling was performed by pushing 3.5 cm diameter plastic tubes into the tidal sediments to a depth of 2 cm. The samples were then used for particle size analysis in the Department of Geography in Durham (Donoghue & Zong 1992). The BS technique of measuring particle size involved wet sieving of the sediments through a 63 μm sieve in order to wash out the *silt & clay* particles; and re-sieving the dry material on 2mm, 600 μm, 220 μm and 63 μm sieves. The fractions gained from these measurements are *coarse sand* (< 2mm, > 600 μm), *medium sand* (< 600 μm, > 220 μm), *fine sand* (< 220 μm, > 63 μm) and *silt & clay* (< 63 μm). The weight of *silt and clay* was obtained by subtracting the weight of the *coarse*, *medium* and *fine sands* from the 20 grams of the total weight of the dry sample. In winter 1992 for the present research, the first set of ten control samples were selected from Seal Sands at random. The samples were taken from the surface (top 1 cm) and from 2 to 3 cm depth, in order to evaluate change with depth. This method allowed comparison to be made with samples taken in autumn and winter 1990 and 1991. For the first batch of sediment samples in the present study, the very precise but time-consuming BS pipette method[1] was chosen in order to divide the sediments into seven classes, namely *clay* (< 2 μm), *fine silt* (< 6 μm > 2 μm) , *medium silt* (< 20 μm > 6μm), *coarse silt* (< 63 μm > 20 μm), *fine sand*, *medium sand* and *coarse sand,* (the last three categories as previously defined (Figures 3.3 a-j). Visual comparison with the sediment samples taken in 1990/91 showed that four out of ten sites showed significant differences in particle size distribution from the previous analysis (Figure 3.4 a-j). These sites were on the edges of Seal Sands, the most obvious change appearing at sites A3 and G9 (Figure 3.1), close to the point where the tidal sea wall was damaged during the winter of 1990/91. This morphological change resulted in an increased influx of coarse sediments, which resulted in a consolidation of the tidal sediments.

The first set of control measurements showed that the splitting up of silt and clay did not result in an increase of information as shown by the frequency distribution of the particle size analysis because there is a fairly even spread between the four classes of silt and clay (linear trend in Figures 3.3 a-j). This justifies keeping silt and clay together in one group. The analyses of the differences of the sediment samples at the surface and 2 to 3 centimetre depth, shows an overall correspondence in the samples. However there appears to be a relationship of higher amounts of silt and clay in samples taken from the surface in mainly sand-dominated areas, such as at stations A3, C6, G9 and H9, (Figure 3.1 & Figure 3.3 a-j). Further investigations of whether this relationship is stable could not be performed due to the limit of time during this research.

Particle size analysis of the resampled stations showed that changes in the particle size distribution occurred mainly at the border areas of Seal Sands[2]. Therefore, a wider

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[1]see BS 1377 : 1967

[2]After comparison with the sediment samples of 1990/91.

sampling spread was designed, including the sampling stations which showed major differences in their particle size distribution, such as at stations A3, G6, G9 and M2, along with their neighbouring sampling stations. This larger network of resampled stations was concentrated particularly on the borders of Seal Sands, where the main changes occurred.

For the second and third sample attempt, 25 stations were resampled and only superficial sediment samples were taken (Figures 3.1, 3.5 a-r & 3.6 a-m). In addition, six samples were taken at the same time from a site which appeared to be stable at the first time of resampling (O1), and six samples were taken at a supposedly unstable site (G9) in order to investigate the differences in the particle size distribution at one site (Figure 3.7 a, b). The result of this investigation was that the maximum differentiation of the six samples at both stations was up to nearly 20% in their particle size composition (Figure 3.7a, b). The changes in the particle size distribution appeared to be in both the fine sand and the silt & clay classes. These results suggest that the fine sand class and the silt & clay class are the most sensitive classes, subject to temporal and spatial changes. Further studies should investigate this phenomenon. The apparent changes at a sampling station imply variability in deposition and erosion in a short time interval or over short distances within a sampling station. These rapid geomorphological changes appear especially at the shoals of so-called "ebb tidal deltas" which form the seaward border of the tidal inlets. They are re-modelled and displaced within short periods of time and space (Ehlers & Böker 1989).

Such unpredictable changes within the tidal sediments of Seal Sands are very important since the ultimate aim of the study is to establish a model to allow tidal sediments to be mapped with the help of airborne multispectral data. For the purpose of relating spectral behaviour of the intertidal sediments to specific particle size classes, the individual sediment classes must not be too narrowly defined, allowing changes within the sampling stations in a defined border over space and time. Furthermore, a successful distinction of tidal sediments must be based on a safe and relatively easy method of relating tidal sediment classes to spectral features. For this purpose a 4-stepped gradation is proposed, based on the work of Bartsch (1990), in order to classify the tidal sediments. The gradation, which is based on the texture analysis of the tidal sediments, comprises sandflat, mixed sandflat, siltflat and mudflat (Table 3.1). The analysis of the changes that have appeared over time and space within the sampling stations show a very interesting result. Apart from one station

(A5) changes have always appeared in the silt & clay fraction and/or in the fine sand fraction, whereas the medium sand and the coarse sand class showed strong stability over time (Table 3.2). This also relates very well with the previously described experiment, when two sampling stations have been sampled six times each in order to investigate differences of particle size composition within a site. Changes there, also appeared in the silt & clay and the fine sand classes. These results strengthen the assumption that fine sand and silt & clay are the 'sensitive' particle size fractions within the intertidal sediments.

Nevertheless some uncertainty in comparing particle size analysis of the intertidal sediments must be reported. The sampling which was performed in 1990/91 by the Biological Sciences, was not carried out absolutely according to the British Standard. The sample amount was too small (approximately 20 grammes for each station) and the method by pushing 3.5 cm diameter plastic tubes into the tidal sediments was not quite adequate. Within a grain size distribution to up to 2 mm a rule of thumb is 250 to 300 grammes of wet sample material. The sampling should also be performed over a few sub-stations in each sampling station, in order to make the sample representative for each station (because of detected differences within one sampling station). This is an unfortunate site effect in this study. Its quantitative influence on the particle size analysis is difficult to evaluate. Therefore the reader may keep in mind that the particle size analysis from 1990/91 is not 100% comparable with the one of 1992/93.

Sediment class definition	**Percent of sand** (> 63 μm)
Sandflat	> 90%
Mixed Sandflat	50 - 90%
Siltflat	20 - 50%
Mudflat	< 20%

Table 3.1 Chosen classification of tidal sediments.

The intertidal zone is subject to so many influencing factors that a higher number of classes could not be justified. The simplification of the distinction of tidal sediments allows variations to take place to a certain extent, within pre-defined sediment classes. Because of the unquantifiable, changing variables it was not found possible to define more classes than the ones chosen in Table 3.1. This has the advantage that many time dependent changes like re-deposition, erosion and sedimentation, for example through increased biological activity during the summer months, will remain within the defined limits. Accordingly the sediment maps will be valuable for a longer time, enabling distinction of main sediment types. In order to be able to compare the particle size analysis taken in 1990/91 and 1992/93, with the imagery data taken in summer 1992, the boundaries between the sediment classes must not be too narrow; otherwise sensible comparison of these two different data types cannot be performed. This section aims to show variations in the sedimentary environment of Seal Sands between the two sample intervals, in order to detect changes over time (Table 3.2). The most stable areas appeared to be the ones with vegetation coverage (*Enteromorpha spp.*) and the areas towards the mainland.

It must be considered that in general, according to Reineck (1978), sediment redistribution is based upon the sediments of the tidal flat itself: only to a small extent do changes appear resulting from the river or sea influx. Future work should therefore consider establishing a current analysis over Seal Sands in order to trace the sediment accumulation. A current analysis could be used to trace where each particle size class tends to accumulate, in relation to the tidal energy pattern. With the building of the tidal barrage in the river Tees, an approach, whether the changes appear within the intertidal zone or whether they are implied from outside, would be important to consider.

Table 3.2 Percentage changes of sampling stations over Seal Sands (resampled in winter 1992/93, comparison to sampling in 1990/91).[3]

Station	Change in %[4]	Station	Change in %
A3	12% fs	G3	10% sc
A4	15% fs	G5	30% sc & 17% fs
A5	15% ms	G6	15% sc
B2	14% sc	G7	25% sc
B5	no change	G8	20% sc
B6	no change	G9	15% sc
B7	no change	H7	no change
C6	10% sc	H9	no change
D1	no change	I4	no change
D2	no change	I6	no change
E5	no change	I8	22% sc & 32% fs
E6	no change	J8	no change
E7	10% sc	M1	no change
E8	30%sc[5]	M2	18% fs
E9	10% sc	M3	20% sc & 22% fs
E10	14% sc	N1	13% sc
F2	10% fs	N2	24% sc
G1	40% sc & 20% fs[6]	O1	no change

[3]Abbreviations: ms = Medium Sand, fs = Fine Sand, sc = Silt & Clay.

[4]Changes of over 10 % within one of the four particle size classes (coarse sand, medium sand, fine sand and silt & clay).

[5]High change is probably based on particle size analysis error.

[6] see footnote No.5

Chapter four - Image Processing

Introduction

For the purpose of sediment mapping of the intertidal areas of Teesside two digital images from an Airborne Thematic Mapper (ATM) Daedalus 1268 were taken on 17th June 1992. The ATM image data correspond to the Landsat TM data in the coverage of the electromagnetic range, although the spectral and spatial resolution of ATM is higher. Remote sensing scanners measure reflected radiation from surfaces in specific wavebands which are particularly sensitive to environmental materials, such as vegetation, water, and sediments. This study evaluates the use of high resolution remote sensing tools for the purpose of mapping the intertidal zone. Consideration has been given to the pre-processing of the image data, in order to transform the data to a 'usable' format, as well as for the evaluation of each spectral band for mapping features of the intertidal zone.

Reflectance characteristics of tidal sediments

The spectral behaviour of tidal sediments is influenced by a number of factors. There are constant factors such as mineral content and particle size, which influence the soil matrix, and iron oxide combinations and organic matter, influencing the surface pigments. Secondly, there are variable factors, such as moisture content, and structure and roughness of the tidal sediments. Both constant and variable factors are interrelated (Figure 4.1). For example, moisture content is directly dependent upon the organic matter and particle size. High organic matter corresponds, in general, to a high moisture content and therefore a high level of absorption at radiance. Similarly, small particle size results in an increased moisture content and absorption rate.

The main factors influencing the spectral characteristics of tidal sediments are moisture content, the amount of organic matter, the amount of iron oxide, the relative percentages of clay, silt and sand, and surface roughness (Swain & Davis 1978). These factors are, in turn, influenced by variable, external factors, such as meterological factors like tide and wind conditions (Ehlers 1988). The topography or elevation of the area is assumed to be the dominating internal influencing factor because it dictates the period of water coverage during a tidal cycle, the water content in the sediment, and other physicochemical variables such as temperature or the oxygen content of the sediment. The increased absorption rate of moist sediments is the result of different refraction indices at the border line of air, soil particle and water[1]. Dry soils, where the pores are filled with air, have a higher refraction index than pores filled with water. This results in dry sediments being recorded with a higher reflectance (Irons *et al.* 1989).

One concern of the present work is on the relation between particle size distribution and elevation, which mainly influences moisture content and surface roughness, and the different reflection behaviours of the tidal sediments. For this task, steps are taken towards assessing the topography, which can be used to explain the particle size distribution within a so-called digital elevation model (DEM). The DEM will contain factors like relief and elevation (chapter six).

The main problem one has to handle when dealing with image processed data of the intertidal zone, is the problem of spectral mixture. The intertidal zone tends to vary at a small spatial scale and homogenous features are seldom found in these areas. The intertidal zone can consist of a variety of different features over only a few square metres. Water coverage, shells, tidal vegetation (*Enteromorpha spp.*) and intertidal sediments distributed over a small scale, are a typical succession (Figures 2.6 & 2.7). This spectral variation or mixture over space is a restriction of remote sensing, which the user wishing to map tidal sediments must face.

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[1] See also later in this chapter Figure 4.11, showing the water absorption bands in 1.4, 1.9, and 2.7μm of the EMS.

Multispectral Scanning

A multispectral scanner measures the radiance of the Earth's surface along a scan line perpendicular to the line of the aircraft flight. As the aircraft moves forward, repeated measurements of radiance enable a two-dimensional image to be built up (Figure 4.2). This sort of scanner has been available since the mid-1960s and consists of a collecting section, a detecting section and a recording section (Curran 1985).

The advantages of using a multispectral scanner are threefold. First, multispectral scanner data have high radiometric and spatial resolution in narrow and simultaneously recorded wavebands. Secondly, these wavebands span a relatively large portion of the Electromagnetic Spectrum (EMS) from visible wavelengths (0.4μm) to thermal infrared wavelengths (14μm). Usually, the digital image data gets stored in a 8 bit format. This results in a data spread from 0 to 255, whereas 0 stands for black and 255 for white (no reflection and high reflection). Thirdly, these data can be stored in digital form for correction and quantitative analysis. Disadvantages relate to the limited sensor availability[2] and the high costs of the multispectral airborne thematic mapper data (MSS ATM-data).

The ATM device consists of a collector and detector of electromagnetic radiation (EMR) (Figure 4.2). Radiation from the Earth's surface passes through a telescope, to be focused onto a rotating mirror, which reflects the sets of radiation onto a set of optics, where it is passed to a dichroic grid, to be split into reflected and emitted radiation. The emitted radiation goes straight to the thermal infrared recorders and pre-amplifiers. The reflected radiation is divided into its spectral components using a prism and is detected and amplified by the detectors and pre-amplifiers. All the information is in electronic form and is controlled by the electronic control console, into which can be plugged one or several recording devices (Curran 1985).

The type of recorder is dependent upon the make and model of the multispectral scanner. Usually multispectral scanners have a cathode ray tube which enables the operator to observe the data as they are recorded. Other recording methods are either a film recorder, where the electrical impulses are recorded directly onto film, or a so-called analogue tape

[2]Only in recent years has ATM image data been more widely used for image processing techniques.

recorder, where the electrical data are stored on magnetic tape. The new scanners tend to use analogue to digital converters to produce a digital output which is recorded on high density digital tape (HDDT) in a digital tape recorder (Figure 4.2). On the ground this high density digital tape can be read onto low density computer compatible tapes (CCTs) for digital image processing (Curran 1985).

Characteristics of multispectral scanner images

Signal to noise in ATM-data

There are three different factors causing "noise" or unwanted signals to the imagery data. First, there is a modulation in the average signal strength due to the fact that the radiation arrives at the sensor in bunches known as quanta and not as a continuous beam. This affects mainly longer wavelengths where less energy and fewer quanta are available for detection. Secondly, the signal level varies even when the radiation flow is constant because the probability of an electronic signal being caused by radiation hitting a detector is stochastic (Curran 1985). The third effect is caused by vibrations of the aeroplane, thereby causing distortion of the recording of the imagery signal.

As all scanners have a certain amount of this described noise, it is advisable to maximise the signal strength, in order to maximise the signal to noise ratio (S/N). This routine has already be done automatically in the case of the Teesside airborne data by NERC, while recording the two runs with different gain-settings for each band in order to vary the sensitivity of the spectral data in certain recorded bands. The operator has nevertheless to bear in mind that by improving the signal to noise ratio, the spatial and spectral resolution decreases and the geometric distortion increases.

Scanning geometry

Multispectral scanner images are distorted both laterally and in the direction of flight. Lateral distortion is introduced while the scanner is looking sideways from the centre line of the flight which appears to be at an angle of around 45°. This accordingly affects the resultant data in three ways (Curran 1985). First, the area of the ground sampling elements (pixels) is larger for off-vertical view angles thus squashing the terrain on the image edge. Secondly, objects are displaced laterally outwards; such displacement reduces overall geometric accuracy. The third effect of lateral distortion is the change of reflectance and emittance properties of non-Lambertian[3] surfaces. For example, during crop classification, even if fields have identical surfaces, their reflectance shows a difference by looking sidewards onto the ground. Directional distortion appears when the scanner moves from one side of the swath to the other and the aircraft moves forward at the same time. This sort of distortion is under control by using very fast scans and automatic correction of this effect.

Daedalus 1268 airborne thematic mapper data (Table 4.1)

The Daedalus AADS 1268 is an 11-channel digital airborne scanner recording in the 0.42 to 13.00μm region of the electromagnetic spectrum. There are five bands in the visible part of the spectrum (0.4 to 0.68μm),three bands in the Near Infrared Region of the spectrum (0.69 to 1.05μm), two bands in the Short Wave Infrared Region of the spectrum (1.55 to 2.35μm) and two bands in the Thermal Infrared Region of the spectrum. Although channels 11 and 12 have the same wavelength (8.5 to 13μm), channel 12 has its gain setting set to 0.5. This can be of particular use when the data in channel 11 are saturated.

[3]Objects which appear to be equally rough from all the angles of observation are called Lambertian surfaces. As the majority of objects on the Earth's surface are non-Lambertian their angle of observation must be specified (Curran, P.J., 1985, p.22).

Table 4.1 Comparison of ATM Daedalus 1268, Landsat5 TM and MMR data.				
ATM 1268 channel	**Landsat5 channel**	**MMR Radiometer**	**Wavelength in μm**	**Description**
1			0.42 - 0.45	"blue"
2	1		0.45 - 0.52	"blue/green"
3	2	1	0.52 - 0.60	"green"
4			0.605 - 0.625	"red"
5	3	2	0.63 - 0.69	"red"
6			0.695 - 0.75	"Near-Infrared (NIR)"
7	4	3	0.76 - 0.90	"NIR"
8			0.91 - 1.05	"NIR"
9	5	4	1.55 - 1.75	"Short Wave Infrared (SWIR)"
10	7		2.08 - 2.35	"SWIR"
11/12	6		8.50 - 13.00/ TM 10.4 - 12.5	"Thermal-Infrared"

The data are recorded on the tape in standard band interleaved by line (BIL) format. The file header is 512 bytes long and contains ASCII informative data. In Table 4.2 several possible ATM channel combinations for the detection of different surface types are demonstrated. Especially the NIR and SWIR wavebands are well known in literature for the possible differentiation of different soil types, due to their iron and water content (Irons *et al.* 1989).

The user should however keep in mind that more sophisticated image processing can be carried out by using image enhancement methods such as Band Ratio Analysis or Principal Component Analysis (PCA).

Table 4.2 Sensor specification for feature detection in remote sensing[4]

	ATM-Channels										
Feature detection	1	2	3	4	5	6	7	8	9	10	11/12
Vegetation examination											
-vitality examination	x	x	x	x	x						x
-green peak			x								
-chlorophyll absorbtion boundary	x			x							
-maximum reflection values						x	x	x			
-water content									x	x	
Differentiation of soils			x	x	x	x	x	x			
-water content									x	x	
Separation of land and water						x	x	x	x	x	x
Distinction of plankton suspensions	x	x	x	x	x						
Division of snow and clouds									x		
Land cover classification	x	x	x	x	x	x	x	x			
Geological & mineralogical examinations									x	x	
Division of vegetation & soils				x	x	x	x	x			
Thermal mapping											x
Aerosol determination/ Atmospheric correction									x	x	

Figures 4.3 and 4.4 show the relation of the ATM channels over eleven spectral bands along the 80 sampling stations on Seal Sands. Four spectral groups can be identified within the eleven channels. There is a high correlation within the five visible channels, and within

[4]Modified after Kleeberg 1990.

the three NIR channels. The SWIR and the Thermal Infrared form a separate class. The high correlation of the ATM channels indicates the necessity for image processing enhancement techniques like Ratio imagery. This is discussed later in this chapter.

Image-Processing Overview

Image-processing methods may be grouped into three functional categories: Pre-processing, image enhancement and classification (Sabins 1987). Roughly speaking, these involve respectively the removal of systematic errors in the data; increasing their intelligibility as a representation of the sensed object; and extracting meaningful patterns from the data, (Rees 1990). The distinctions between these steps are not always clear-cut.

The first routine involved in image processing is the *image restoration* which compensates for data errors, noise and geometric distortions. These inaccuracies appear during the scanning, recording, and playback operations.

Inaccuracies include:

- restoring periodic line dropouts
- restoring periodic line striping
- radiometric calibration of the imagery data
- correcting for atmospheric scattering
- correcting geometric distortions

The second routine is the *image enhancement* or spectral enhancement which alters the visual impact that the image has on the interpreter, resulting in an improvement of the information content of the image.

Image enhancement includes:

- Contrast enhancement
- Intensity, hue and saturation transformations
- Density slicing
- Edge enhancement
- Ratio-images

The final step is *information extraction* utilizing the decision-making capability of the computer, using in the present case the Terra Mar image processing software for recognising and classifying pixels on the basis of their digital signatures.

These routines are now discussed further in the context of the ATM-Teesside data.

Pre-processing techniques

Pre-processing is preliminary to the main analysis. There is no definitive list of "standard" pre-processing steps because each project requires individual attention. Furthermore, the quality of image data varies greatly, some data sets requiring more attention (pre-processing) than others. Pre-processing changes data[5] (Figure 4.5). It is assumed that such changes are beneficial, but the analyst should remember that pre-processing may influence primary analysis in ways that are not immediately obvious. The operator should use only those pre-processing operations that are essential and beneficial to achieve a given purpose. Therefore, it is essential for the operator to understand the format of the data as well as inter-band relationships.

Radiometric Calibration

Introduction

It is now 22 years since the first Landsat satellite (7/1972) was launched. Since that time a large amount of image data has been collected and these data can be used for studies of long-term changes in the terrestrial land surface. Unitemporal statistical classification and mapping of ground features rely on internally consistent differences within a scene, and may not require radiometric correction (Hill & Sturm 1991). But in the case of making direct comparison with other imagery data, or where the study relies on proper inter-band relationships, an absolute physical radiance value needs to be derived. The aim is to achieve radiance values normalized to a standard set of conditions.

The acquired data may be separated by years and obtained by markedly different

[5]The pixel DN-value (digital number) and its relative location are changed during pre-processing operations.

sensors. Therefore, a consideration of atmospheric effects, illumination (variations in sun angle), ground reflectance and sensor differences between data acquisition needs to be made. A radiometric calibration involves the conversion of raw DN-values into absolute physical numbers (radiance units) or relative surface reflectance values. Several transformation techniques to minimize atmospheric effects on remotely sensed data have been developed, but significant levels of image-to-image variability remain (Hall *et al.* 1991).

Atmospheric properties are defined as the vertical profiles of atmospheric water vapour, aerosols and molecular composition (e.g. CO_2 or O_3). This kind of data is difficult to acquire, even when planned, and is usually not available for historical satellite images. A direct comparison of Landsat 2-5 MSS data shows that these sensors agree within only about 12%[6], showing that a radiometric calibration is absolutely essential for multi-data studies (Hall *et al.* 1991). Radiometric calibration is therefore a necessary first step for quantitative data analysis, and needs to be achieved before implementation of more advanced radiometric corrections such as removal of atmospheric distortions.

Radiometric calibration of the ATM AADS 1268 sensor is performed by NERC before and after each airborne campaign. The calibration is based on laboratory measurements, employing calibrated sources and spectral filters. Several sets of calibration data are available for each year; the set closest to the time of the data acquisition should be applied. This calibration method is called *preflight calibration.*

Preflight Calibration

Several calculations have to be carried out before the actual preflight calibration procedure of the imagery may start (Figure 4.6 and Tables 4.4 a - e). The first value is the so-called Panel Radiance which is provided by a black anodised rectangular box with a top aperture for the scanner (Daedalus AB532A Calibration Fixture). Inside the box are two 200 Watt calibrated tungsten lamps, illuminating a barium sulphate ($BaSO_4$) panel. The average radiance of the illuminated panel in $mWsr^{-1}m^{-2}nm^{-1}$ for each scanner band is a known factor. The obtained values provide the calibration source radiance values. The scanner is installed

[6]Because of the different scanning optics of the systems and mechanical changes over time.

on the calibration fixture, viewing the $BaSO_4$ panel to get a so-called flat field reflectance or solar curve without any atmospheric interference, and operates at each of the five possible gain-settings (Figure 4.6). The peak of the solar curve is in the green part of the visible spectrum.

The scanner receives the analog signal in each channel and records it firstly with the illuminated panel to gain the Vcal radiance-value for each gain-setting in each band. The procedure is repeated with the lamps off, to provide the dark level signal or V0 voltage. Missing values for Vcal indicate a saturation of the signal (value is higher than Vcalmax = 4000mV) - which makes it unrecordable, and therefore not available for later conversion of the imagery data into radiance units. Missing values for Vcal in the ATM data for Teesside appeared for the gain-setting of 4 in band 10 and for a gain-setting of 8 in bands 9 and 10. The next step is the scaling of Vcal and V0 in the range of the DN values from 0 to 255 (Table 4.3). Having obtained the DN lamp on/off values, the following step is to acquire both the Gain value, which is the average panel radiance divided by the difference of DN lamp on, and DN lamp off (Table 4.3), and the Base value which is DN lamp off.

When all the described values are available, the final step is then to calculate the *Radiance = (rawDN of each pixel - Base) * Gain* (Table 4.3). With this last step the raw DN-number has now been converted into an absolute physical number.

Table 4.3 Equations for the radiometric calibration.

N ***Average panel radiance in*** $mWsr^{-1}m^{-2}nm^{-1}$

Vcal ***Sensor voltage from calibration source Mv DC (Max 4000mV)***

V0 ***Sensor voltage from calibration source Mv DC (Min 0mV)***

DN lamp on = (Vcal*256)/4000 ***DN value for calibration source***

DN lamp off = (V0*256)/4000 ***DN value for zero input source***

Gain = N / (DNon-DNoff)

Base = Dnoff

Radiance = (DN - Base) * Gain ***in*** $Mwsr^{-1}m^{-2}nm^{-1}$.

Having completed the *preflight* calibration, the next step is the so called *inflight* calibration. It employs the preflight calibration on every pixel of the gained video data and simultaneously the reflectance of the target is measured by ground spectrometers in order to have a second means of control.

Gain-settings

The gain-settings of the Daedalus 1268 scanner can be preset independently for each wavelength to one of five gain-settings (0.5, 1, 2, 4, 8) in order to achieve maximum sensitivity under the prevailing viewing conditions of the flight (Tables 4.4 a - e & Figure 4.6). The use of these independently set gain-settings without radiometric conversion can lead to incorrect interpretations of the data, and of results from commonly used techniques such as PCA or Ratio Analysis.

Calibration Method for the ATM Tees data

The present research aims to investigate the possibility of establishing a model of relating particle size information to the different reflectance properties of tidal sediments, which is easy to follow and repeatable in subsequent research for different data sets and different intertidal areas. Therefore, a model needs to be built up, to be able to compare the data with ground measurements, data from different sensors and different dates, and different research areas along an intertidal environment. Usually, digital data arrives with a radiometric calibration (such as Landsat TM data). In this case study, however for the better data understanding (such as data format and band relations), the radiometric calibration was performed within this research project. Even though the labour input was very high, a valuable data awareness was the beneficial result.

Format of the ATM data

Each band/channel contains 750 bytes of data. The band format is Band Interleaved by Line (BIL) which means that each scanline contains 9000 bytes for 12 channels. Bands 11 and 12 are in the Thermal Infrared and will not be considered for the radiometric calibration (Figure 4.7 & 4.8). The 750 bytes of data for each channel are divided up as follows: bytes 1-23 as line header, the so-called housekeeping data, bytes 24-739 as video data and bytes 740-750 as line trailer, the second part of the housekeeping data (Figure 4.7). Full details of the contents of the housekeeping data can be obtained from Huntings (1985).

The first step in calibrating the ATM-data is to extract the gain-setting values for each channel, which are kept in the housekeeping data in each scanline. For Run I of the Teesside data the gain-setting for band 1-10 is 8, band 11 has a gain-setting of 1 and band 12 has 0.5. This results in the double sensitivity of band 11 compared to band 12 in the Thermal-Infrared region (8.5 to 13.00 μm). Run II has a gain-setting of 8 for band 1-4, a gain-setting of 4 for band 5-6, band 7 has a gain-setting of 2, band 8-10 have a gain-setting of 4, and in the Thermal-Infrared no change appears compared to Run I (Tables 4.4 a-e). The next step is to obtain the Gain and Base values of the preflight calibration for each band, associated with the different gain-settings appropriate to the data of the flight time (Tables 4.4 a-e).

Technical approach for Radiometric Calibration

A computer program needed to be written to carry out the radiometric rectification of the video data (Appendix I). The 'C language' was chosen for this operation as it is sufficiently powerful and fast[7]. The video data of the uncalibrated image is written in machine readable binary-code. Before the program is able to run, a description of the format of the imagery needs to be obtained. This information is held in the header file (512 bytes). The operator needs to input the data format which can be either Band Interleaved (BIL) or Band Sequential (BSQ). The following step is then the input of the number of lines of the imagery data, as well as the number of bytes in each band (Figure 4.7). These details, along with the header size need to be pre-defined at the beginning of the program. If the operator wants to extract only a subscene out of the whole image for the calibration in order to speed up the operation, it should be noted that the data format changes from BIL to BSQ format and that there may not be any band header or trailer. In the case of the ATM Teesside imagery, a nearly cloud free subscene of Seal Sands was extracted, meaning that the DN-spread is not very likely to reach the maximum of 255 because of the extraction of cloud

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[7] The radiometric calibration was run on a 486 dx processor and took approximately 10 minutes to correct a sub-scene of the ATM-Tees data.

covered areas in the image which could affect the calibration due to saturation at a value of 255, and make comparison with ground measurements unreliable[8].

The program asks for the minimum and maximum raw DN-values for each band. If they are not available the program calculates them internally by browsing through the image dataset. After having calculated the minimum and maximum raw DN-values, the program will calculate lookup tables for each band considering the different panel radiance and gain-settings for each raw DN-value. The final step is to read in every pixel (expressed by one byte), and convert its raw DN-value into the radiance value (absolute surface reflectance), by looking at the pre-calculated lookup table and setting the converted pixel back into the data set. When the operation is finished, the program reports how many lines it read in and how many it wrote back. Input and output must consist of the same size, apart from the missing file header of 512 bytes which the program had to skip before the operation started. After the successful calibration, a new ASCII-file header of 512 bytes needs to be appended onto the calibrated video data. Then the converted image is ready to be displayed using the Terra-Mar Microimage software. The image data is now converted into an absolute physical value format (Figures 4.8 & 4.9 a,b).

Technical problems with radiometric correction of ATM data

Run I of the ATM-data has a gain setting of 8 for band 1-10, which results in missing values for Vcal in band 9 and 10, and which consequently does not allow the raw DN-values of the Short Wave Infrared (SWIR) to be converted to radiance values (Table 4.4 a - e). The SWIR has a high sensitivity for clay minerals, which is very helpful for the distinction of the tidal mudflats (Table 4.2). Another, probably major problem for Run I, was faced by recognising that due to this high gain-setting the maximum DN-value in each band is at a maximum of 255. This means that the data may have been compressed into the 255 range. A calibration of the whole image of Run I is therefore not very meaningful due to data saturation in most of the bands. The data would be more suitable for mapping a water environment than intertidal sediments. To resolve this problem, a small area of the ATM-data

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[8]Clouded areas show a very high reflection and tend to be over the 255 DN limit, if not compressed into the range from 0 to 255. This could result in an over-saturation of the image data and therefore falsify the image calibration.

for Teesside was extracted for Seal Sands which is the major study area. Fortunately this area, on both runs, is nearly cloud free.

Run II has a similar problem with band 10 where there is still a saturation for a gain-setting 4, and therefore no calibration of band 10 is possible (Table 4.4 a - e). A further problem is that on the day of the airborne data acquisition, it was not possible to obtain ground reflectance measurements due to a lack of arrangement with the company who took the imagery[9]. This would have enabled a second means of control over the inflight calibration and therefore a better comparison with the preflight calibration. These problems are an unfortunate limitation of the Daedalus AADS 1268 ATM-Scanner in this study, which could be minimized by better arrangement with the company in charge of taking the image.

Unless a radiometric correction is carried out, much of the digital data cannot be used for quantitative analysis. Radiometric calibration is the first step in the image restoration, by removing atmospherical interference effects. The data are "restored" to their (hypothetical) correct condition (Figure 4.7), although we can of course never know what the correct values might be and must always remember that attempts to correct values may themselves introduce errors. However, the analyst must decide if the errors removed are likely to be greater than those that might be introduced, by comparing the ground information of the uncalibrated data set with the calibrated data set. A radiometric calibration of the imagery is consequently the first step in order to assess an intertidal sediment distribution model with the use of remotely sensed spectral data.

[9] The company acquired the ATM image data from Teesside two days earlier than expected.

Table 4.4 a Values for the Radiance value calculation for Gain-setting of 8.

Gain-setting 8						
Band	Panel Radiance	Vcal	V0	DN on	DN off	Gain
1	5.96	403	251	25.79	16.06	0.61
2	11.36	848	492	54.27	31.49	0.50
3	21.55	1273	618	81.47	39.55	0.51
4	28.79	1025	522	65.60	33.41	0.89
5	35.11	1897	606	121.41	38.78	0.42
6	41.64	2096	595	134.14	38.08	0.43
7	48.12	3900	648	249.60	41.47	0.23
8	49.93	3179	598	203.46	38.27	0.30
9	22.00	-	472	-	30.21	-
10	9.34	-	621	-	39.74	-

Table 4.4 b Values for the Radiance value calculation for Gain-setting of 4.

Gain-setting 4						
Band	Panel Radiance	Vcal	V0	Dn on	Dn off	Gain
1	5.96	197	118	12.61	7.55	1.18
2	11.36	425	247	27.20	15.81	1.00
3	21.55	640	312	40.96	19.97	1.03
4	28.79	511	260	32.70	16.64	1.79
5	35.11	949	302	60.74	19.33	0.85
6	41.64	1053	302	67.39	19.33	0.87
7	48.12	1956	326	125.18	20.86	0.46
8	49.93	1591	299	101.82	19.14	0.60
9	22.00	2432	237	155.65	15.17	0.16
10	9.34	-	315	-	20.16	-

Table 4.4 c Values for the Radiance value calculation for Gain-setting of 2.

Gain-setting 2						
Band	Panel Radiance	Vcal	V0	DN on	DN off	Gain
1	5.96	100	60	6.40	3.84	2.33
2	11.36	214	124	13.70	7.94	1.97
3	21.55	325	160	20.80	10.24	2.04
4	28.79	257	130	16.45	8.32	3.54
5	35.11	476	150	30.46	9.60	1.68
6	41.64	534	156	34.18	9.98	1.72
7	48.12	981	164	62.78	10.50	0.92
8	49.93	799	151	51.14	9.66	1.20
9	22.00	1222	120	78.21	7.68	0.31
10	9.34	2246	162	143.74	10.37	0.07

Table 4.4 d Values for the Radiance value calculation for Gain-setting of 1.

Gain-setting 1						
Band	Panel Radiance	Vcal	V0	DN on	DN off	Gain
1	5.96	52	31	3.33	1.98	4.43
2	11.36	108	63	6.91	4.03	3.94
3	21.55	167	84	10.69	5.38	4.06
4	28.79	128	64	8.19	4.10	7.03
5	35.11	237	74	15.17	4.74	3.37
6	41.64	273	83	17.47	5.31	3.42
7	48.12	497	84	31.81	5.38	1.82
8	49.93	401	76	25.66	4.86	2.40
9	22.00	616	61	39.42	3.90	0.62
10	9.34	1132	86	72.45	5.50	0.14

Table 4.4 e Values for the Radiance value calculation for Gain-setting of 0.5.

Gain-setting 0.5						
Bands	Panel Radiance	Vcal	V0	DN on	DN off	Gain
1	5.96	27	16	1.73	1.02	8.47
2	11.36	53	31	3.39	1.98	8.07
3	21.55	86	45	5.50	2.88	8.21
4	28.79	62	32	3.97	2.05	14.99
5	35.11	115	35	7.36	2.24	6.86
6	41.64	140	46	8.96	2.94	6.92
7	48.12	246	43	15.74	2.75	3.70
8	49.93	198	38	12.67	2.43	4.88
9	22.00	303	31	19.39	1.98	1.26
10	9.34	561	46	35.90	2.94	0.28

Transition from radiometric calibration to atmospheric correction

Radiometric pre-processing corrects for instrument settings. Any sensor observing the Earth's surface using visible or short wave infrared radiation will record a mixture of two kinds of radiation: i) firstly, radiance reflected from the earth's surface, which is of interest for remote sensing, and ii) secondly radiance due to the earth's atmosphere itself which absorbs, emits and scatters energy. An atmospheric correction is therefore the next necessary step.

Atmospheric Correction

Correcting Atmospheric Scattering

Effects on Aerial Imagery:

Scattered light that enters the scanner is a source of illumination which results in low image contrast and contains no information about the terrain. This extra illumination reduces the contrast ratio of the scene, thereby reducing the spatial resolution and detectability of the photograph (Sabins 1987). For MSS images the EMR-region[10] of 0.5 to 0.6 μm has the highest component of scattered light. In contrast, the NIR (0.8 to 1.1 μm) has the least component of scattered light. The aim is therefore to correct this effect in order to improve the contrast ratio of an image.

Atmospheric scattering consists of *selective scattering* and *nonselective scattering*. It is the result of multiple interaction between light rays and the gases and particles of the atmosphere (Sabins 1987). In selective scattering, shorter wavelengths like UV and blue light are more affected than red light and IR-energy. Selective scattering is caused by smoke, fumes and gases such as NO_x, CO_2, O_2, O_3, CH_4 and H_20. In nonselective scattering, all wavelengths of light are equally scattered. This is caused by dust, clouds and fog in which the particles are much smaller than the wavelength of light. Due to this effect clouds are white by scattering all wavelengths equally.

Atmospheric scattering is therefore the result of a combination of selective and nonselective processes. The range of atmospheric scattering is shown in Figure 4.10. The lower curve represents scattering in a clear atmosphere, whereas the higher part shows scattering in a hazy atmosphere. Typical atmospheres have their scattering characteristics somewhere in between these two extremes. The important point to remember for aerial imagery is that the earth's atmosphere scatters UV and blue wavelengths at least twice as strongly as red light (Sabins 1987). Therefore, an interpretation of the EMR in the blue spectrum is very hard due to the difficulty in predicting the amount of interference of the Earth's atmosphere.

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[10] Electro Magnetic Radiation

Atmospheric Correction of ATM data

Atmospheric correction is based upon examination of reflectance from an object of known, or assumed brightness recorded by multispectral imagery. From basic principles of atmospheric scattering it is known that the amount of scattering is related in part to the wavelength of the energy. If the target is observed using a set of MSS measurements, the relationship between values in the separate bands can help to assess the effect of the atmosphere upon the data (Campbell 1987).

In the 400 to 2500 nm spectrum, the recorded signal depends on the reflectance of the earth's surface and on atmospheric variables. To restore the inherent object spectral radiance (target radiance) from the measured total radiance, it is necessary to evaluate and remove the atmospheric influence (Figure 4.5).

Atmospheric effects

The atmosphere modifies the reflectance of the earth's surface in several ways (Richter 1992):

- it contributes a signal independent of the ground (path radiance)
- it absorbs some fraction of the ground reflected radiance
- atmospheric scattering (Rayleigh & aerosol) modifies the radiances of adjacent fields of different reflectance (adjacency effect). This means that dark areas surrounded by bright areas appear to have a higher reflectance than the original inherent reflectance.

In the 400 to 700 nm spectral region the reflectance difference of natural targets is usually in the range 5 - 20 % (Richter 1992), and the adjacency effect is not very strong. By contrast in the Near Infrared Region (NIR), the 750 to 900 μm range, there are very large reflectance differences between water (typical reflectance 1 - 3 %) and vegetation (reflectance range 30 - 60 %). Finally in the 1.5 to 2.5 μm region, the scattering efficiency strongly decreases and the adjacency effect can usually be neglected (Richter 1992).

The relative contribution of the target radiance to the total measured radiance is an important parameter which can be used as a measure of importance of atmospheric correction. For example, bright objects like sand, observed from aircraft, show that most of the received radiance is radiance from the target, while for water the atmospheric path radiance prevails (Sturm 1992). In this case study, reflectance differences of tidal sediments will be dependent mainly on differences in moisture content of the sediments (Irons *et al.* 1989). Consequently, atmospheric correction is of major importance in the study of water signatures in remote sensing, while in terrestrial applications of remote sensing it may be less important.

Ideally atmospheric correction should be performed by using ground control measurements, of targets of a consistent natural or man-made feature that can be observed, with both airborne and ground-based instruments, at the time of the image acquisition. Unfortunately, in the case of the Teesside imagery, it was not possible to make ground reflectance measurements on the same day as the airborne data acquisition; this would have allowed an evaluation of atmospheric effects on the image data on this specific day[11]. The reason for this lack of simultaneous measurement was the uncertainty of the weather conditions on the day of the data acquisition, as well as lack of arrangement with the company in charge of taking the image.

The idea behind selecting the targets of different surface types is to extract pixels of the ATM-data of dark objects, like a large clear water body, asphalt or shadowed areas. In a clear atmosphere the reflection should be low, near zero. If bright values appear, it can be concluded that the additional brightness is contributed by the effects of atmospheric scattering. Therefore ideally, control measurements need to be taken with the field spectrometer for the same areas. The field spectrometer data can then be treated as absolute reflectance values. Moreover, the operator needs to keep in mind that the added value caused by the atmosphere differs from band to band. The highest contribution appears usually in the NIR-region (0.76 to 0.9 μm). The additional values are then subtracted from all digital values for the image and specific band. This rather simple operation is also called the "histogram

[11] Field Spectrometer Measurements are not influenced by atmospherical effects. They record absolute physical numbers.

minimum method" (HMM). Nevertheless, the operator needs to consider that atmospheric effects change not only the position of the histogram on the axis, but also its shape.

Atmospherically corrected data have certain advantages. Having corrected the raw imagery data it is possible to compare them with ground reflectance measurements, or with measurements of other sensors and different sites and dates. The accuracy of classification of multispectral images is improved due to the removal of falsifying effects. The reflectance differences in multi-temporal scenes are caused by actual changes in the ground reflectance, while changes in the raw data might be caused by the different atmospheric and illumination conditions. For quantitative data analysis the video data need to pass this correction method for the purpose of establishing a kind of "photo-key" (Bartsch 1990), being able to classify tidal sediments on a quantitative basis. In the case of the ATM data, the atmospheric correction also enables us to obtain meaningful spectras, i.e. spectras which show already known spectral behaviour, e.g. of a vegetation spectrum, the green peak in band 3 and the high reflectance in the NIR.

Atmospheric correction using the Flat Field correction method

The Flat Field method corrects only for wavelength-dependent effects without allowing for topography or other location-dependent factors. The aim is to find a spectrally flat location; an area where no significant absorption occurs within the wavelength range of the examined data (Figure 4.11). The Flat-Field operation is achieved by dividing the whole data set by the mean value of an area within the scene, which is spectrally flat, and homogeneous. Thus, the absorption features caused by atmospheric influence and the "solar curve" effect, as well as system induced effects, are eliminated (Rast *et al.* 1991).

Each image spectrum is divided by the flat field value to produce a normalized image. The result should be an overall spectral curve that is truly flat, except for significant features caused by ground absorption (Figure 4.11 & 4.12). The obvious problem with this technique is that it requires field work in order to verify the spectral response of an area selected as flat field calibration target. Unfortunately it was not possible to find an area in Run I for gaining a meaningful atmospheric correction of the image.

Mathematically, the technique is defined by the following equation:

$$R_{s\lambda} = k * S_{s\lambda} / F_{\lambda}$$

where

$R_{s\lambda}$ **= reflectance in band λ at pixel s;**
k **= scaling factor;**
$S_{s\lambda}$ **= radiance in band λ at pixel s;**
F_{λ} **= flat-field radiance in band λ.**

In practice, a scaling factor is applied to scale the result back into a suitable range[12]. For every pixel s, the computed reflectance $R_{s\lambda}$ in band λ is divided by the flat-field radiance F_{λ}.

Technical approach for Flat Field correction

In order to obtain a flat field spectrum, the extracted and calibrated image of Run II was loaded into the imaging spectrometry software called T-Spectra Version 1.1[13]. Using T-Spectra it is possible to take spectral curves of an image. With this option it was possible to find a spectrally flat region in the calibrated image. In the case of the ATM Teesside data, a white, clouded area from the northern part of Run II was chosen, which came close to being a spectral flat area (Figure 4.12). Before the Flat Field correction of an image starts, T-Spectra requires that a statistics file be pre-processed, containing means, maxima, minima and log-pixel means. For this operation the Flat Field correction in T-Spectra needs the band means calculated in the *Pre-Process* option. Each image spectrum is divided by the spectra of the chosen pixel, to produce a normalized image within the T-Spectra software package (Donoghue & Robinson 1991).

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[12] It is usually a range from 0 to 255

[13] T-Spectra was developed by Donoghue and Robinson, in the Department of Geography at the University of Durham, 1991.

Log-Residual correction method[14]

The Log-Residual method was applied to the ATM Teesside image in order to have a second means of control of the atmospheric correction of the image data. It is a useful alternative to the flat field correction, especially in situations where a flat field spectrum can not be derived in the image data. This technique removes the so-called solar radiance drop off, atmospheric effects and topographic effects in the data set. The Log-Residual method applies two major corrections. The first method divides the radiance values for a pixel by the mean over all bands for that same pixel. This normalizes the spectra for all pixels to the same average level, in order to eliminate effects (e.g. slope & shadows) that are different for each location, but independent of wavelength. The second correction divides the radiance value for a band by the mean over all pixels (the scene average) for that band. This converts the overall continuum shape of each spectrum to a horizontal line, correcting for effects (atmospheric absorption and scattering, sun spectrum) that depend on wavelength but not on location. Finally, a constant factor, the mean of all pixels over all bands, is applied to produce a normalized, dimensionless number that could be usefully compared with results from other data (Donoghue & Robinson 1991).
Mathematically, the technique is defined by the following equation:

$$lnR_{s\lambda} = lnS_{s\lambda} - (1 / (N\Sigma_s lns_{s\lambda})) - (1 / (M\Sigma_\lambda lns_{s\lambda})) + (1 / (NM\Sigma_s \Sigma_\lambda lns_{s\lambda}))$$

where
$R_{s\lambda}$ = ***residual reflectance at pixel s (location) in band (wavelength)*** λ;
$S_{s\lambda}$ = ***radiance at pixel s in band*** λ;
N = ***number of pixels;***
M = ***number of bands;***
Σ_s = ***sum over all pixels;***
Σ_λ = ***sum over all bands.***

[14]Logarithmic Residual method

Technical approach for Log-Residual correction

The same extracted and calibrated image was used for the Log-Residual transformation, as was used for the Flat Field correction. This has the advantage that the statistics file described for the Flat Field correction can be now used again for the Log-Residual transformation. Additionally both images can be directly compared after the correction due to the exact overlap of their locations. The Log-Residual correction uses the log-pixels means, calculated in the preprocessed statistics file. The output of the Log-Residuals process, originally in floating-point numbers, is scaled into an appropriate range to be represented by the same data type as that of the current image (from 0 to 255).

A direct correlation of the Log-Residual correction with the Flat Field correction method is possible. Figure 4.13 shows that the spectra taken of both images at exactly the same location have similar shapes. Differences occur for the sand and grass spectras in the example, but the main differences are the overall higher values of the Log-Residual corrected image, which is simply a matter of scaling and does not interfere with the shape or the absolute values of the data.

Restriction of Log-Residual correction

The Log-Residual method does not correct for additive effects such as energy scattered by the atmosphere as already described. This atmospheric scattering significantly influences shorter wavelengths. Therefore, this technique is best used in the near-infrared and short wave infrared of the spectrum. Typically, it is used most effectively on short-wave infrared data.

The ATM-Teesside data do not seem to be badly affected by atmospheric scattering. Therefore the atmospheric correction of Run I was completed with the Log-Residual method due to the lack of any suitable spectrum for a flat-field correction.

Source of errors during Atmospheric Correction

Whilst carrying out an atmospheric correction, the operator needs to keep in mind that dominant cover types, which may be important, are likely to be removed or even suppressed in the corrected image data. Another problem is the creation of "spectral artifacts" which could be interpreted as real cover - absorption features and/or spectral peaks. Finally, there is the problem of apparent suppression of more subtle mineral absorption features in the 2.2μm wavelength region when vegetation is present (Mackin *et al.* 1987). The atmospheric correction for the present data set was, however, necessary for the purpose of making the image data comparable with other remotely sensed data and for obtaining typical spectral features of different surface types. Both the Flat Field and the Log-Residual method worked successfully on the ATM data set (Figure 4.13).

However, for the purpose of further processing and analysis, the rest of the text refers to the Flat Field corrected data only. The decision is based on the fact that the Log-Residual method is less effective for atmospheric correction of shorter wavelengths. Therefore the chosen Flat Field correction method presents the best of the available correction methods for the present study.

Geometric correction

A geometric correction needs to be carried out because each image includes geometric (locational) errors, caused by the perspective of the sensor optics, motion of scanning optics, terrain relief and earth curvature (Campbell 1987). The ATM MSS data are influenced in particular by geometric distortion because the data are collected in a continuous fashion; they lack the consistent relative orientation of points found on a photograph. These geometric or locational errors need to be removed in order subsequently to overlay the ATM-image with locational data, like sampling stations, high and low water marks (HWM & LWM) or the topographic lines of the intertidal zone, using GIS. The geometric correction is therefore a pre-processing step for the combination of the image data with the digitised data.

In order to perform the geometric correction, the digital image needs to be registered to a map base. Therefore, the image is simply treated as an array of values that needs to be manipulated to create another array with the desired geometry. This operation is essentially done by interpolating the uncorrected input image with a superimposed geometrically "true" image (output image). The output pixels are derived from locational information provided by so-called *Ground Control Points* (GCPs). These are locations on the input image which can be precisely located on the ground and on a geometrically correct map. The location of these points helps to establish the geometry of the output image and its relationship to the input image. The first step is therefore to find GCPs which can be clearly identified on the input image and on a map. In the following the point coordinates shall be defined as :

i)	raw, not referenced image:	(x1, y1)
ii)	referenced image:	(x2, y2)
iii)	reference map:	(u,v)

In order to transform the distorted, not referenced image (x1, y1) into the referenced output (x2, y2), where the transformation function is unknown, a polynom equation (of n degrees) is set as approximate solution. In the praxis, polynoms of 1st to 3rd order are sufficient to achieve an accuracy of $\leq$ 2 pixels (Bähr & Vögtle 1991).

$$x1=\sum_{j=0}^{n}\sum_{i=0}^{j} a_{ij}x2^{j-i}y2^{i} \qquad n = 1,2,3$$

$$y1=\sum_{j=0}^{n}\sum_{i=0}^{j} b_{ij}x2^{j-i}y2^{i}$$

x1,y1 =	*coordinates of the geometric distorted image*
x2,y2 =	*coordinates of the geometric corrected image*
a_{ij} =	*polynom coefficients in X-direction*
b_{ij} =	*polynom coefficients in Y-direction*
n =	*order of the polynom*

For the solution of the polynom equation and the calculation of the unknown polynom coefficient (*aij, bij*), GCPs are needed, taken from a different reference system (*u, v*).

To calculate the unknown polynom coefficients (*aij, bij*), at least 3 GCPs are needed for the 1st order polynom transformation.

$[(u_i, v_i)) <\!\!-\!\!-\!\!> (x1_i, y1_i), i = 1,2,3)]$ $\qquad$ *i = number of GCPs*

When taking the coordinates (*x1, y1*); (*u, v*) into the polynom equation, the result are two linear equation systems in the following:

$u_i = a0 + a1\ x_i + a2\ y_i$
$vi = b0 + b1\ x_i + b2\ y_i \qquad i = 1,2,3$

This linear affine transformation accounts for the following errors:

- geographical shift
- rotation
- scaling differences

When using polynom transformation of 2nd or 3rd order, the number of GCPs increases to 6 or 12; and 12 or 24 unknown polynom coefficients need to be calculated. The quality and accuracy of the referencing equation is highly dependent on the accuracy and number of the GCPs. The quality of the rectification can be checked by calculating the distance of a point from the position it should have, and the position it has in reality (Bähr & Vögtle 1991).

The next step is to estimate the values at pixels in the corrected image, based upon information in the uncorrected image. The simplest method is the so-called nearest neighbour correction. This sets the output value equal to the brightness level of the pixel closest to the resample location. This method has the advantage that the DN values of the image stay unaltered, however it lacks in positional accuracy. The second geometric correction method is the bilinear interpolation method, where a value for each output pixel is calculated, based upon a weighted average of the four nearest input pixels. The output is a geometrically accurate and smooth image. The interpolation, however, creates new pixel values, which may result in a change of the brightness values in the output image from those in the input image. An additional negative effect is a decrease of spatial resolution, caused by the averaging over areas. Finally the most sophisticated, most complex, and widely used method is the cubic convolution method. This method uses a weighted average of values within a neighbourhood of some 25 adjacent pixels.

Technical approach of Geometric Correction of ATM-Teesside data

It was originally intended to perform the geometric correction within Terra Mar, by using a digital line graph file (DLG file), extracted from ARC/INFO, from a digitised 1:25000 Ordnance Survey map of Teesside (Pathfinder 591). Because of hard and software limitations with the available Terra Mar image processing workstation[15], it was decided to carry out the geometric correction in ARC/INFO. A precise geometric correction was required in this study due to the need to locate the sampling stations over Seal Sands accurately. The image data are registered to a master reference system, using the REGISTER command in ARC/INFO. In this case the reference system comprises coordinates from the 1:25000 Ordnance Survey map of Teesside. The system allows the user interactively to collect GCP pairs by prompting the user to enter the (*x2, y2*) coordinates of a point in the base map, and then selecting the corresponding point on the image (*x1, y1*). The *x2* and *y2* coordinates in the Ordnance Survey map needed to be defined by digitising the exact

[15] The display screen of the workstation was corrupted, and problems with importing ARC/INFO line coverages occurred.

geographical locations in the ARC/INFO environment ARCPLOT.

In the case of the ATM image data, seven GCPs have been specified. The GCP collection was a very difficult operation, because of the very high resolution of the image data. Usually street junctions, bridges, etc. are easily distinguishable ground features within satellite scenes, but with the high resolution of the ATM data, e.g. a cross point of a street is normally made up by a cluster of several pixels. This means that absolute decision making, as to which pixel represents the map coordinates, presents severe problems. Unfortunately the 1:25000 map of Teesside was the most detailed map available. Several attempts had to be made in order to achieve a good result. Some of the originally chosen pixels had to be erased because of the not satisfying result. Seven GCPs were finally chosen for the geometric correction of the ATM image, (Figure 4.14 a and Table 4.5). In order to get good rectification results over the whole image the GCPs are widely distributed over the raw image. A limitation with determining GCP's appeared within the intertidal land of Seal Sands, because it is subject to changes over time, and therefore ground features can not be traced reliably on the Ordnance Survey map. The best points to take are artificial features which have not changed over time, such as street junctions. The unrectified image consists of 914 rows (X) and 366 columns (Y). A measure of accuracy is the Root Mean Square (RMS) Error.

The RMS Error is :

$$\sqrt{\frac{\sum_{i=1}^{n} d_i^2}{2n}}$$

Where d is the root of the sum of squared X and Y residuals ($d^2 = X^2 + Y^2$), n is the number of GCPs, and i a numerator (Table 4.5).

The rectification of the ATM image was processed with a 2nd order polynom transformation.

GCP[16] No.	NGs[17] X-Coord.	Ngs Y-Coord.	Image X-Coord.	Image Y-Coord.	Residual X in Pixel	Residual Y in Pixel	Distance (d)
6	453520	525440	615.5	341.7	1.38	-1.38	1.95
8	453910	525960	838.3	268.3	-1.57	-0.30	1.60
17	451750	525700	50.9	114.9	-1.16	-0.31	1.20
14	454180	525770	899.2	336.9	-0.29	1.09	1.13
12	452590	525350	280.4	273.1	0.65	0.80	1.03
10	452920	526750	638.4	1.4	0.91	-0.46	1.01
9	452300	526410	365.1	15.7	0.09	0.56	0.57
				RMS Error in Pixel	**1.33**	**1.05**	**1.70**

Table 4.5 Ground Control Points for the Geometric Correction

For the image rectification the Nearest Neighbourhood method was selected as the simplest approach. This rectifies the image in a less accurate way than the two previously described methods would do, but still to a satisfactory quality. The Nearest Neighbourhood Method has the advantage that it sets the output value equal to the brightness level of the pixel closest to the resample location, and therefore does not change the DN-values of the image. Otherwise all effort which was put into the calibration and atmospheric correction of the imagery data could be questioned again at this point. The rectification was also done in ARC/INFO using the RECTIFY command. The rectification requires the Upper left and the Lower right coordinates of the area.

After rectification, the image can be overlaid with the digitised map and the digitised sampling stations in ARC/INFO or Terra Mar (Figure 4.14 b). Although geometric correction is inevitable for overlaying the image with digitised data, the operator must keep in mind that

[16] GCPs are ordered from worst to best residuals. The numbers are not in a logical order because some of the GCPs had to be erased and newly defined.

[17] Coordinates are in the National Grid System (NGs).

the resampling of data elements results in spectral degradation.

After the Geometric Correction, the image contains 600 rows (X) and 380 (Y) columns (Figure 4.14b). The upper left point has the National Grid Coordinates of Northing = 451400 and Easting = 526900. The raw image was rotated by 36.553 degrees. In order to check whether the geometric correction worked correctly, the rectified image is overlain with the digital high and low water mark (HWM & LWM) from the 1:25000 Ordnance Survey Map of Teesside and the 80 sampling stations of the intertidal zone of Seal Sands (Figure 4.14 b). The rectified image fits very well within the boundaries of the digital map of Seal Sands. Only at the boundary to the sea, does some overlap appear, which can be explained by the averaged features of the 1:25000 map, and by changes of tidal water cover of the intertidal land of Seal Sands. The RMS error of 1.70 pixels is a good achievement. It however shows a limitation of the ATM image data for mapping the intertidal zone, because of its small locational error. Especially crucial is the fact that no GCPs could be defined within the intertidal zone of Seal Sands, because it is subject to temporal and spatial changes. Future work should consider a method to define some artificial points with known location over Seal Sands, which later can be identified in the scanned image data. The exact position of these points could be defined e.g. by a Global Positioning System (GPS)[18].

The geometric correction will allow direct correlation of the particle size analysis with the spectral behaviour of the tidal sediments. This approach will be introduced in chapter five. In the meantime the classical method of mapping surface features via scanned images can now be presented. With the geometric correction of the image data the last pre-processing step is achieved and the image classification can start.

[18] Satellite based positioning system.

Image Classification

Having completed the pre-processing of the image data, the next step is the spectral pattern recognition or classification of the intertidal zone image data (Figure 4.5). The pattern recognition is based on three aspects; firstly on the detection of different kinds of surface material, secondly the discrimination of distinctive shapes and thirdly the recognition of changes in areas in time (Drury 1987).

In this thesis classification of intertidal sediments is undertaken in three separate ways. i) Visual enhancement and interpretation of spectral data using band ratios.
ii) Statistical separation of the imagery using a supervised method based on training data.
iii) Deterministic modelling of particle size from regression analysis of multi-band reflectance data (Chapters five and six).

Classification is based on the spectral properties of the surface. Classification is a statistical analysis, based on the algorithms in n-dimensions (n=number of channels) based on spectral reflection curves of one pixel. The aim of the classification is to reduce the high amount of information, by creating classes in order to simplify and generalize the complexity of the imagery. Figure 4.15(a, b) shows that some surface types display contrasted reflectance at different wavelengths.

The classification is computer based and works on a simple 'yes' or 'no' decision as to whether the pixel is part of the class or not. In order to classify the image, so-called *training areas* need to be selected during field work. The simplest technique is called parallelepiped classification, which defines rectangular boxes around the chosen training areas (Figure 4.16 b). Each pixel is tested to determine if it falls within one box or not, which decides whether it is classified within that class or whether it stays unclassified. This technique has the disadvantage that it classifies in a quite crude way, especially on the borders of the classes.

A favoured method in science is the use of the Maximum Likelihood Classification (MLC). The basic idea of this classifier is that a multispectral dataset with n channels can be described by a n-dimensional vector, defining the spectral feature space. The coordinates of a feature vector are totally independent from the position of the pixel coordinates in the image data. Picture elements of an object class (e.g. siltflat as a landcover type) are characterised by similar features, and their feature vectors build a characteristic cluster in the feature space. These clusters are statistically described by *n*-dimensional density equations. These density equations are usually unknown, and therefore determined through training data (training areas), which are in the case of digital remote sensing, picture elements with known assignments to a certain class. The n-dimensional density equation is approximated through the density of a Gaussian distribution: a Gaussian distribution in the data set is assumed (Günther &Rieckerts 1992).

The representation of the object classes, or in other words the description of the feature space is done with the help of the training data. The classification procedure is trained on the satellite data and its classes. It relies on the operator making decisions about the areas on the ground which are most representative of the surface categories of interest. For that reason it is called supervised classification, and corresponds to the more dimensional density function for the class ω_i of the Gaussian distribution:

$$p(X|\omega_i) = \frac{1}{(2\Pi)^{\frac{n}{2}} |\Sigma_i|^{\frac{1}{2}}} \exp\left(-\frac{1}{2}(X-\mu_i)^T \Sigma_i^{-1} (X-\mu_i)\right)$$

Whereas $|\Sigma_i|$ presents the determinant of the covariance matrix Σ_i of the class ω_i , Σ_i^{-1} the inverse covariance matrix, X the feature vector, μ_i the mean value vector of the class ω_i, and $(X - \mu_i)^T$ the transponent of the vector $(X - \mu_i)$.

With this equation the most likely assignment to a class can be determined for a given feature vector X. The class ω_i is chosen for which $p(\omega_i | X)$ has its maximal value. This is the technique upon which the Maximum-Likelihood-Method is based.

Maximum likelihood classification (MLC), in which the training areas are defined as elliptical 'clouds' is therefore a more sophisticated classification method (Figures 4.16 e, f & 4.17). Each 'cloud' can be contoured to show how the probability decreases away from the mean point.

Another, less sophisticated method is the *unsupervised classification*, which allows the computer to examine the image data and to sort out and class particular correlations amongst the data. Unsupervised classification is based purely on spectral properties. This technique is useful for a pre-classification of unknown areas, providing the operator with a means of identifying spectrally different kinds of terrain (Drury 1987).

In order to achieve good classification results, the operator has to be aware of the close correlation in the 0.4 to 2.5 μm range (Figure 4.3 & 4.4). Spectral differences of intertidal sediments can be gained mainly from ATM bands from the NIR, the SWIR and the Thermal Infrared region of the ATM-data. These bands are the main means of discriminating clay content (particle size) and moisture content. Therefore, a good classification is not necessarily based on a large number of bands, due to the possibility of a strong interband relationship diluting the classification accuracy. Therefore, a strategy needs to be devised to use only those bands which give the best enhancement of intertidal features.

Image Enhancement using Ratio Imagery

For the purpose of classifying in an accurate and effective way, the user should try to enhance the spectral features of the image data. A very useful and popular image enhancement method is the division of the DN of a pixel in one band by that in another band, giving so-called ratio imagery. In order to enhance spectral features of the imagery data, ratios are most effective when two bands which have a negative correlation with each other are divided by each other. In this case good results can be achieved by dividing, for example, between band 3 and band 5, and band 9 and band 5 of the ATM data, which results in an enhancement of differences of intertidal zone sediments. In the intertidal zone band 3 and band 9 have a high reflection rate whereas band 5 has a high absorption rate . A division of these bands therefore results in strong enhancement of the intertidal sediment surface. Problems with band ratioing can appear if band-specific random noise arises either in the numerator or denominator, producing extreme values. Various contributions from atmospheric effects also tend to accentuate the degradation of images (Drury 1987). This effect is minimised by using calibrated and atmospherically corrected ATM data.

Classification of the intertidal zone of Seal Sands

For the image classification a mask for Seal Sands was created in ARC/INFO in order to extract only the intertidal zone of Seal Sands. This step is necessary in order to eliminate the industrial area and the grass land around Seal Sands. This surface would otherwise distort the classification[19] of the ATM-image. For this purpose a single polygon, containing the intertidal land of Seal Sands has been digitised from the 1:25000 Ordnance Survey map of Teesside. Both the polygon and the geometrically correct ATM-image were imported into ARC/INFO. ARC/INFO provides, for the extraction method, a command called LATTICECLIP. Before this command can be applied, however, the image needs to be converted into GRID-ARC/INFO format, using the IMAGEGRID command. LATTICECLIP simply 'clips' the area outside the polygon away. The result of this operation is the extraction of the intertidal zone of Seal Sands. The image at this stage is ready for further processing, such as classification.

The next step is the classification of the intertidal zone of Seal Sands, performed by using the ratio enhancement image data. For classification the maximum likelihood method was chosen, this method providing the highest accuracy (Drury 1987). Maximum likelihood classification is based on a deterministic model, a regression estimation. This complements the rest of the present thesis which is based on a deterministic approach. Table 4.6 shows statistics for the training areas determined over the intertidal zone of Seal Sands. The classification of the intertidal surface sediments is based on the gradation introduced in Chapter three. Eight spectral classes have been chosen for both classifications, containing: *Clouds, shadow, water, tidal vegetation, pure sand, sandflat, siltflat and mudflat* (Table 4.6, Figure 4.18). Best results could be achieved with the ratio enhancement technique. A colour composite of band 2, band 7 and ratio of band 3 to band 5 has been chosen for its high enhancement of spectral features of the tidal sediments, especially moisture content which enables a high distinction between silt & clay, and water. Additionally this combination allowed a clear distinction of vegetation, clouds and shadow. (Figure 4.18, and Table 4.6 & 4.7) . The analysis intended originally to include an analysis of the feature space of the

[19] Industrial land reflects in this case very similarly to the mixed sandflat, which falsifies the classification of intertidal sediments.

training areas, in order to detect whether the chosen training areas overlap each other, or whether they are clearly distinguishable (similar to Figure 4.17). The available Terra Mar package however did not allow this step, and a technical solution to this problem was not available during this research. A clear analysis of the reliability of the feature space could therefore not fully be made. This is an unfortunate limitation of the introduced technique for mapping the intertidal zone of Seal Sands.

The following steps in the MLC procedure would ideally have been to perform a detailed examination of the feature space of the classes, creation of Gaussian distributed sub-classes, tracing the location of the sub-classes, and the evaluation of the Mahalonobis distances of the classes (Segl 1990).

Table 4.6 Statistics of the training areas for the classification of the ATM data

	Band2 min	Band2 max	Band2 mean	Band7 min	Band7 max	Band7 mean	Band3/5 min	Band3/5 max	Band3/5 mean
Clouds	72	240	138.46	60	172	105.23	153	161	156.93
Shadow	48	64	56.35	32	48	36.83	157	165	161.04
Water	62	68	65.51	26	44	26.91	161	169	167.57
Tidal vegetation	54	70	59.73	42	94	66.82	157	164	159.55
Pure Sand	68	100	78.62	42	100	69.92	149	162	155.46
Sandflat	60	84	70.70	42	80	61.50	153	160	156.54
Siltflat	60	76	67.02	42	62	50.51	155	161	158.09
Mudflat	58	68	62.36	42	52	43.45	155	162	158.70

Table 4.7 Classification using ratio image data			
Surface type	**Pixel count**	**Percentage**	**Hectares**
Clouds	10261	10.14 %	14.6
Shadow	4360	4.31 %	6.2
Water	989	0.98 %	1.4
Tidal Vegetation	11900	11.76 %	16.9
Pure Sand	11076	10.94 %	15.7
Sandflat	19496	19.26 %	27.7
Siltflat	31467	31.09 %	44.7
Mudflat	6395	6.32 %	9.1
Unclassified	5279	5.22 %	7.4
total	101223	100 %	143.7

Accuracy check of the classified ATM image

The classification results of the ATM image (Figure 4.18) needs to be evaluated on its accuracy. Firstly by visual examination of the classification results. Big errors could however not be found immediately in the classification of the intertidal sediments. The overall pattern of the intertidal sediment distribution is in the expected frame. A more sophisticated approach is however based on the 80 sampling stations over the intertidal zone of Seal Sands. The results of the particle size analysis for each station can be used to verify the classification. For this operation the digital sampling stations need to be overlaid with the classified image, which is best done in a GIS environment. Firstly it needs to be examined whether the sampling station covers a tidal sediment cover class. Table 4.8 shows the stations covering surface types, such as vegetation, water, shadow and clouds.

Table 4.8 Sampling stations with non-sedimentary cover type		
Sampling stations	**Image information**	**Sediment type**[20]
A3	Cloud cover	Sandflat
A4	Cloud cover	Sandflat
A5	Cloud cover	Sand mix flat
B3	Cloud cover	Sandflat
B4	Cloud cover	Sandflat
B5	Cloud cover	Sand mix flat
B6	Cloud cover	Sand mix flat
C3	Tidal vegetation	Sandflat
C5	Tidal vegetation	Sand mix flat
C8	Tidal vegetation	Sand mix flat
D3	Tidal vegetation	Sand mix flat
D4	Tidal vegetation	Siltflat
D5	Tidal vegetation	Sand mix flat
D6	Tidal vegetation	Sand mix flat
D8	Tidal vegetation	Sand mix flat
E1	Tidal vegetation	Sandflat
E6	Tidal vegetation	Sand mix flat
E7	Tidal vegetation	Siltflat
E9	Tidal vegetation	Sand mix flat
E10	Tidal vegetation	Siltflat
F6	Tidal vegetation	Sand mix flat
G8	Tidal vegetation	Siltflat
G9	Tidal vegetation	Sand mix flat
J5	Cloud cover	Sand mix flat
N1	Tidal vegetation	Sand mix flat

After excluding the 25 stations with non-sedimentary surface, named in Table 4.8, the verification of the classified ATM image with the particle size analysis can start. Figure 4.19 shows the sampling stations over the intertidal zone and as grouped into one of the four sampled particle size classes. Each station is labelled whether they are in the expected class or not.

The classification worked best for the non-sedimentary image information. The tidal sediment classification, however, did not give satisfactory results. After subtracting the sampling stations named in Table 4.8 only 23 of the remained 55 sampling stations could be

[20] Sediment classing is based on the particle size analysis.

related to the 'right class' (41.8 %), according to the particle size analysis (combination of 1990/91 and 92/93). Further improvement with the MLC could not be achieved, because of the previously mentioned limitation of the Terra Mar software. The reason for this high misclassification probably partly lies in the fact that the tidal sediments of Seal Sands do not react as in laboratory conditions, i.e. that coarse sediments dry out quicker than fine sediments.

It appeared also to be very problematic to detect appropriate training areas for the tidal sediment classes, because of so-called 'mixed areas', where the boundaries in the image could not clearly be distinguished. Furthermore the problem arose that clearly distinguishable differences in moisture content in the infrared wavebands, were misinterpreted as different sediment classes, because of the different reflectance characteristics influenced by the moisture content. This problem is already well known and described in Dennert-Möller (1983).

Yates *et al.* (1993 b) have already mentioned similar phenomena in the Wash estuary. They state that coarse sediments are often more wet than fine sediments and that laboratory conditions are not always fulfilled. Sandflats seem to facilitate tidal pools in a 'unpredictable pattern' over the intertidal zone, whereas mudflats are well drained, especially through the high number of creeks in these areas. Possibly influencing factors such as the micro relief and surface roughness come into action. For further mapping of tidal sediment types, concentration will be focused on the fundamental relationship of the reflectance of the tidal sediments at each sampling station, in order to correlate the particle size analysis and the reflectance in the ATM channels. Additionally band 11, which could not properly be used in the MLC due to the similar spectral response of tidal sediments and vegetation processed. The output of the MLC will nevertheless be of further use, particularly for the discrimination of non-sediment areas, such as water, tidal vegetation, clouds and shadow (mask of non-sedimentary image information). Discrimination is very straightforward and reliable when based on the MLC model. With restrictions the classified ATM image of the sediment surface will also be of use for comparison with further results.

Chapter five - Reflectance Analysis of Seal Sands

Introduction

At this stage of the work, deeper understanding of the reflectance behaviour of tidal sediments was planned to be gained, by using a field radiometer in a laboratory environment. Spectral reflectance measurements were taken using a Milton Multiband Radiometer (MMR). This is a portable device for taking spectral reflectance measurements in the field (Figure 5.1). The instrument has a spectral range from 0.4 to 1.75 μm in 4 bands (green, red, NIR and SWIR). The band passes are designed to allow comparison with Landsat and ATM data, with the radiometer measurements (Table 3.1). The instrument is not calibrated in absolute units, and is intended only for the measurement of spectral radiance relative to a reflectance panel. In this study a Kodak grey card was used as the reference panel. The MMR consists of two devices; a sensor unit and an output unit. The sensor unit contains filters, detectors and pre-amplifiers, which convert radiant energy into a voltage, which is then displayed on the output unit.

This can be expressed by the following formula:

$$\boldsymbol{BRF_\lambda = L^t / L^c}$$

where

$\boldsymbol{BRF}$	=	bidirectional reflectance factor at wavelength λ.
$\boldsymbol{L^t}$	=	reflected flux from target surface at wavelength λ.
$\boldsymbol{L^c}$	=	reflected flux from perfectly diffuse, completely reflected panel at wavelength λ.

The instrument was used for an extensive experimental measurement programme to investigate the reflectance of several particle size classes, such as medium sand, fine sand

and the total sand amount. Different moisture condition levels were established, such as levels between saturation with water and absolute dryness. Correlations between the MMR bands and the moisture content of the classes were performed. Further an analysis of variance was performed, in order to test whether differences in the reflectance of the particle size classes are related to a the particle size class itself, or whether other factors such as time do have the main influence to the reflectance.

A big data set was set up and analyzed. Later in my studies, it was found that the radiometer device did not work properly, in other words the device was not calibrated sufficiently by NERC. This was a very unfortunate case, especially since the device had just arrived from servicing by NERC before I used it. This means that a whole set of experimental laboratory measurements, as described above, could not be presented in this thesis. In consultation with my supervisor, I left the data set out[1].

The information would have been a nice addition as background information for the spectral characteristics of tidal sediments. It is however not an absolute necessity for further analysis, which may be based on further interpretation of the ATM image data. Additional information of the spectral behaviour of sediments under laboratory conditions could be mainly gained from Irons *et al.* (1989).

Results of the ATM data analysis

For the purpose of predicting particle size distribution by spectral reflectance characteristics of the intertidal zone of Seal Sands, the ATM Tees data have been overlaid on the 80 sampling stations used for particle size analysis and invertebrate counting (Figure 3.1). Spectral reflectance curves over the nine radiometric corrected channels of the ATM data and the thermal infrared channel, have been taken from each sampling station.

An investigation of the sampling stations and their locations had to be carried out, to identify outliers in the data. As already discussed in Chapter four, 24 of the 80 sampling stations (Table 4.8) had to be eliminated before any statistical analysis could start. The reasons for the elimination are related to atmospheric effects, i.e. cloud and shadow cover,

[1]Repetition of the measurements was not possible due to my urgent return to Germany and the shortage in time.

as well as being surface type-related, mainly due to tidal vegetation (*Enteromorpha spp.*), or unrepresentative geographic positions, i.e. tidal creeks and the tidal wall (at the boundary between the sea and intertidal land in the north of Seal Sands) . These locations had to be eliminated because they do not represent intertidal sediment sites, or even the ground situation. This reduction of data had to be performed in order to concentrate on meaningful and undisturbed data for the intertidal zone. A sampling station covered, for example, by clouds or shadows does not portray its typically tidal zone reflectance. The elimination of sampling stations for statistical processing is however, a limitation of the image processing techniques for the mapping of the intertidal zone. Further analysis of the image data showed the need to drop another eight sampling stations. These outliers are C7, E2, F3, H2, H7, I8, I9 and J6. The identification of these positions showed that C7, E2, F3 and I9 were mislocated in tidal creeks, whereas H7 and J6 showed vegetation patches. The outliers I8 and H2 could not be related to any particular surface feature type or location.

Table 5.1 Interband relationship, correlation of particle size and ATM channels. n = 48

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band11	Coarse Sand	Medium Sand	Fine Sand	Silt & Clay	Total Sand
Band1	1.000														
Band2	0.358	1.000													
Band3	0.354	0.873	1.000												
Band4	0.236	0.728	0.918	1.000											
Band5	0.262	0.717	0.921	0.968	1.000										
Band6	0.32	0.434	0.623	0.595	0.662	1.000									
Band7	0.355	0.385	0.591	0.579	0.632	0.972	1.000								
Band8	0.270	0.385	0.624	0.657	0.7	0.903	0.943	1.000							
Band9	0.097	0.507	0.65	0.677	0.682	0.634	0.641	0.734	1.000						
Band11	-0.13	-0.15	-0.34	-0.35	-0.38	-0.59	-0.58	-0.49	-0.4	1.000					
Coarse Sand	0.006	0.091	0.161	0.153	0.137	0.467	0.46	0.395	0.292	-0.51	1.000				
Medium Sand	0.057	0.127	0.299	0.286	0.331	0.646	0.613	0.53	0.456	-0.8	0.51	1.000			
Fine Sand	0.0	-0.05	-0.12	-0.18	-0.22	-0.25	-0.26	-0.34	-0.24	0.003	-0.17	-0.29	1.000		
Silt & Clay	-0.05	-0.1	-0.23	-0.17	-0.19	-0.5	-0.45	-0.33	-0.31	0.796	-0.44	-0.82	-0.32	1.000	
Total Sand	0.045	0.1	0.228	0.17	0.19	0.481	0.44	0.317	0.316	-0.79	0.407	0.814	0.322	-1	1.000

Table 5.1 shows the computed correlations between the ten spectral bands, and the particle size classes. As already noted for the MMR data the visible part of the EMS correlates only weakly with particle size (Figures 5.2 a - f). Band 5, the red part of the visible part of the EMS is worthy of mention for its slight increase of correlation (e.g. with the medium sand class) compared to other bands in the visible part of the EMS; even though it is weakly related to the percentage of medium sand (0.331). Band 6, the transitional band from the red into the NIR, shows for all particle size classes, excluding the fine sand class, a fairly strong positive correlation, especially with medium sand (0.646): the other two particle size classes are around 0.5 correlation coefficient. Band 7, 8 (NIR) and 9 (SWIR) follow this trend, but the correlation between reflectance and particle size decreases with increase in band number. Medium sand gives the strongest correlation in all spectral bands. Band 8 shows a weak negative correlation between fine sand and reflectance (-0.34).

Finally band 11 gives the best correlations between particle size and spectral reflectance. Medium sand (-0.802) and total sand amount (-0.788) especially show a strong negative relationship; whereas silt & clay (0.796) shows a strong positive correlation with spectral reflectance (Figures 5.2 a - f and Table 5.1). This is a rather surprising result; that with the increase of coarser sediments the thermal energy emitted decreases, whereas with an increase of fine sediments, i.e. silt & clay, the thermal response increases. The explanation for this unexpected spectral behaviour probably lies in the reason that the bright coarse sediments, represented by medium sand and total sand amount, emit electromagnetic energy more effectively than sediment types with a high amount of silt & clay, which absorb more energy, due to their darker tone. It might also be that the higher moisture content in tidal sediments, corresponding with higher amounts of silt & clay, results in a higher thermal heat capacity compared with coarser tidal sediment types, which have a lower density because pores are filled with air, rather than water. This could have a cooling effect and therefore lessen the radiometric radiant energy flux. The intertidal zone of Seal Sands is also characterised by a high amount of colliery waste, which was detected during the particle size analysis. The high amount of coal in the sediments may well interact with the heat capacity of the intertidal sediments, due to their black colour and therefore high absorption rate. Future work should study this effect at different estuarine environments, in order to verify the results of the ATM Tees data. At this stage of the work it can however be clearly stated that the relationship of radiance and sediment types is indirect, i.e. very likely based onto the colour of the tidal sediments.

With the knowledge of the spectral behaviour of the intertidal sediments already gained, more sophisticated analysis can be performed. Therefore a multiple regression model has been established in order to predict particle size groups with the help of spectral ATM channels. The multiple regression analysis started by including all 10 wavebands[2] of the radiometric-calibrated and atmospheric-corrected image data, including visible, NIR, SWIR and thermal infrared, for the medium sand class, for the total sand amount and silt and clay. As already shown, the coarse sand class of the intertidal sediments over Seal Sands was in a very narrow range and the fine sand class did not show any strong relation with reflectance. The maximum R-square value which could be gained for predicting the total sand amount was 0.72. Most of the spectral bands, however, had a very low proportion of explanatory value, because of the strong interband relationships (Figure 4.3 & 4.4). Therefore attention was concentrated on band 6 (NIR), band 8 (NIR) and thermal band 11 for the prediction of the total sand amount and silt & clay. The medium sand class, for example, could be predicted most effectively with channel 6 and channel 11 (Table 5.2).

Table 5.2 Regression analysis of particle size classes predicted with the ATM image data

48 observations	Variables	R-square	t
Total Sand	band 11	0.62	- 8.6
	band 11, band 8 and band 6	0.66	band 6, t= 2; band 8, t= -2.2; band11, t= -6.7
Medium Sand	band 11	0.63	-9
	band 11 and band 6	0.69	band 6, t= 2.6; band 11, t= -6.2
Silt & Clay	band 11	0.63	8.8
	band 11, band 8 and band 6	0.68	band 6, t= -2.2; band 8, t= 2.4; band 11, t= 6.8

[2]Channel 10 in the SWIR spectrum had to be missed out due to the saturation problem for a gain-setting of 4 (Table 4.4b).

As already stated, the t-value can be used to show the degree of significance of the relationship. The regression was run by first using only thermal band 11, and then additional bands were included, in order to increase the explanatory value of the image data.

The form of the regression for the different particle size classes is:

$$Ps = Rx_I + b.$$

where *Ps* is the particle size class (weight percentage), *R* is the reflectance of one of the 11 ATM channels and *b* is constant, fitted by least squares.

In all cases, thermal band 11 had the highest degree of explanation. Regression analysis without band 11 are very weak and do not give a suitable prediction of any of the three particle size classes. The high explanatory power of band 11 greatly increases the value of the scanned image data in order to predict particle size classes. Scatter plots of band 11 & band 6 and band 11 & band 8 show that both band combinations result in an increase of information. It is a 'mixed scatter plot', represented by a cloud. Band 6 & band 8 correspond to each other very well which can be seen in a nearly linear relation (Figures 4.4 and Figures 5.3 a-c).

The equations predicting total sand amount, medium sand class and silt and clay are as follows:

i) Total Sand Amount = 619.6 + 5.35 * band6 - 4.1 * band8 - 4.0 * band11

ii) Medium Sand Class = 412.3 + 3 * band6 - 3.4 * band11

iii) Silt & Clay Class = - 517.6 - 5.8 * band6 + 4.3 band8 + 4 * band11

These formulae could be used further in order to predict the three particle size groups over the whole intertidal sediment zone of Seal Sands for each pixel of the multispectral ATM data. The resulting steps for that operation will be presented in Chapter six, due to the necessity to further pre-process the image data in a GIS environment.

Chapter six - Data Analysis with GIS techniques

Introduction

In order fully to determine the intertidal sediment distribution of Seal Sands, many sources of information need to be considered. Primary data from field work (particle size analysis, image processed data (e.g. classified image from the intertidal zone of Seal Sands), and digitised data (e.g. contour lines or high & low water mark of Teesside), need to be considered and brought together in a common database, for the purpose of relating, overlaying and further processing the data. The final aim is to present particle size distribution maps over the intertidal land of Seal Sands and relate them to birds' feeding places. Integration of the remotely sensed ATM data into a GIS is therefore the next step. A so-called Integrated Geographical Information System (IGIS) needs to be developed. A GIS is an information system for spatial data that are referenced by geographical coordinates (Ehlers *et al.* 1991). It is designed to acquire, store, retrieve, manipulate, analyze and display this information according to user-defined specifications.

According to Marble (1990) all GIS systems contain common components:

- A data input subsystem collecting spatial data from various sources.
- A data storage/retrieval subsystem organising spatial data in a quickly retrievable form for update/correction and subsequent analysis.
- Data manipulation and analysis subsystem.
- Data reporting subsystem capable of displaying all or part of the original database and manipulating data and output in tabular or map form.

Basically all geographical data can be reduced to three topological concepts - the point, the line and the area. Every geographical phenomenon can in principle be represented by a point, line, area or volume plus a label saying what it is (Burrough 1986). Thus a sampling station could be represented by a point, consisting of a single X, Y coordinate pair and a number as a label; a part of the high water mark could be represented by a line entity consisting of a starting X, Y coordinate and an end X, Y coordinate; similarly an area or a polygon is defined where start and end X, Y coordinates are the same. Three dimensional coverages have an additional Z coordinate. Conceptually, information can be considered to reside in a GIS as a series of spatially co-registered layers, with each layer relating to a particular theme; for example, particle size distribution, topography, bird feeding places and so on. Most of this information is derived from digitized maps, which were themselves manually compiled from analogue data (Trotter 1991).

GIS data can be stored and displayed in either raster or vector format. A raster structure means that, for example, a feature is built up from a set of points on a grid or raster. Each element is located by its specific number of row and column. Remotely sensed data is made up of pixels, in a raster format. For interactive work between the Remote Sensing System and the GIS, the raster data structure is the most common and convenient to use. Vector data, however, is the format in which data are usually retrieved from existing maps, by digitising or scanning the data. Vector data make use of a set of lines, defined by starting and end points and some form of connectivity. Basic differences between vector and raster data are i) the storage of the data; vector data require fewer numbers for representation, implying fewer storage spaces. ii) Graphical high quality output can be more easily performed with vector than with raster based format, due to the high resolution required for high quality raster output. iii) Modifications can be performed more quickly and easily in the raster environment. Every update in the vector system brings an updating of the coordinates and a rebuilding of the connections. iv) Lastly, high spatial variations, as they appear in photographs or more generally speaking in image processed data, can best be managed in the grid environment. This highly complex data would not be manageable in a vector system. The aim of the coastal monitoring GIS is to integrate the raster or pixel based information from the image processing tool within the GIS. Therefore, a hybrid system like the workstation version of ARC/INFO (Version 6.1.1) with its raster based module called GRID, was chosen as a flexible data storage, analysis and processing system. GRID allows, via the shared ARC display device ARCPLOT, the display of raster and vector based data interactively. The field work and the digitised data existing in vector format can easily be overlain with the raster based image processed data. Geometric or overlay operations are easier to perform in the raster based system, whereas network analysis or topological operations are more suited to the vector domain (Ehlers *et al.* 1989). An important use of remotely sensed data is in change detection studies. In this study context, remote sensing offers greatly enhanced capabilities over GIS in updating map information on a regular basis. The spectral reflectance, as determined with remote sensing, can be used to check and update both thematic and geometric descriptions of objects that are stored in a GIS (Molenaar & Janssen 1992).

Preprocessing in GIS

As with the image processing, various pre-processing operations need to be performed in a GIS in order to transform data into a compatible format. The first step, as already described, is the geometric correction of the image data using Ground Control Points, identified on the 1:25000 Ordnance Survey map of Teesside. The biggest and most time-consuming operation was to import the very detailed and accurate contour line data for Teesside, which already existed in MOSS and AUTOCAD-DXF formats, into ARC/INFO. The data were converted from DXF format to an ARC coverage, by using the ARC commands DXFARC for the actual data conversion and DXFINFO for obtaining internal information about the layer. Before the coverage could be used for further processing, it was necessary to CLEAN and BUILD it; these processes generate a coverage with corrected polygon topology, edit and correct geometric coordinate errors, assemble arcs into polygons, and create and update so-called feature attribute information for each polygon, line or point in a so-called feature attribute table[1]. Data pertaining to the area of interest were subsequently extracted by using the ARC command CLIP, which extracts only the area inside a predefined polygon. This polygon was created by digitizing a single polygon comprising

[1]PAT for Polygon Attribute Table and Point Attribute Table, AAT for Arc Attribute Table.

the intertidal land of Seal Sands from the 1:25000 Ordnance Survey Map of Teesside (see also Chapter four; Classification). The contour lines' individual arcs, each carrying a different identifier, not related to the actual height of the contour lines, were UNSPLIT where necessary and pseudo nodes deleted using ARCEDIT. This reduced the total number of arcs from 230 to 127. The final step was to label the contour lines with an attribute for altitude at 1 metre intervals, using large scale maps of Seal Sands, since this was not present in the original DXF file. This step was performed in dBASE, by manually updating the values of the AAT file[2] of the contour coverage. This very labour intensive procedure was completed for every arc, and enables the contour height values to be plotted onto the relevant contour line.

Another necessary pre-processing step is to bring the image processed data into a format GRID will understand. The TerraMar image processing workstation gives the option to export images into ERDAS file format, which is basically Band Interleaved by Line (BIL) format, together with a file header of 128 bytes. GRID expects an ASCII image description file to accompany the image, indicating the size and format of the image data. Having created both files, the remotely sensed image is converted into an ARC/INFO readable format by using the IMAGEGRID command. The converted image can then be displayed by using ARCPLOT display commands such as IMAGE, GRIDSHADES or GRIDPAINT. The final pre-processing step is to shift the imported data into the correct geographical location, so that overlay and processing operations with other digital data of the same geographical location can be performed. This is necessary because the image is not yet registered to a coordinate system. GRID performs this operation with the SHIFT command, during which the raster image gets shifted into the geographically correct position by registering the lower left corner of the image[3]. It is then possible to overlay and process the digitised data, data gained from the fieldwork and the image processed data (Chapters three, four & five).

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[2] AAT = Arc Attribute Table.

[3] Optionally the cell size can be changed additionally within the SHIFT command.

Modelling and processing in the Coastal Monitoring GIS

Predicting Particle Size Classes in the intertidal zone

The multiple regression analysis based on field sites (Chapter five) can now be applied to predict particle size classes via the ATM image data. Good R-square values were achieved for predicting the **total sand amount**, the **medium sand** class and the **silt and clay** class. The main explanatory power was found in the thermal channel 11. Channels 6 and 8 in the NIR were less strong (Chapter five). The aim is now to produce three maps, predicting intertidal sediment classes (total sand amount, medium sand and silt & clay). Before the formula introduced in Chapter five can be applied for each pixel of the ATM data covering the intertidal sediments of Seal Sands, cover types such as tidal vegetation, water, as well as clouds and shadow need to be eliminated, because they do not represent intertidal sediments and would therefore falsify the prediction. For this purpose the classified image introduced in Chapter four needs to be resampled in the GIS environment. The vegetation, water, clouds and shadow cover types values are set to NODATA via a remap table in GRID, and the four sediment classes are put together and set to a value of 1. This is a straightforward operation, and no problems appear with the discrimination of tidal sediments, because they all stay in one class together, whereas vegetation, water, clouds and shadow can easily be distinguished due to their spectral characteristics (Figure 4.18). The command for this operation in GRID is RESAMPLE. The former areas of tidal vegetation, water, clouds and shadow appear now as 'NODATA wholes'. This new grid can now be used as a mask for multiplying the image data channels which need to be used for predicting intertidal sediment classes over Seal Sands[4]. All areas with no tidal sediment cover are clipped out (masked out). They are simply set to NODATA, whereas the tidal sediment areas retain their values in the respective bands, because they were multiplied by 1, which does not change their value. This has the advantage that the operation is only based on the reliable classification of the intertidal zone of Seal Sands, as presented in Chapter four. The sediments themselves are just taken as one sediment group at this stage of the work.

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[4] i.e. band 11, 8 and 6 for predicting the total sand amount and silt & clay, and band 11 and 6 for predicting medium sand.

Each retained pixel can now be predicted applying the formula described in Chapter five with the help of the chosen bands (6, 8 and 11) (Figures 6.1 a - c). In order to present differences in the sediment composition, six classes have been defined. The boundaries are created from the mean minus three standard deviations, and plus three standard deviations of the respective classes (Figures 6.2 a - c). This operation was performed in GRID. This is a possible illustration, because the image data of the tidal sediments over Seal Sands showed a higher spread of DN-values than appeared for the reflectance values in the respective bands over the 48 sampling stations, analyzed in Chapter five. A few extreme outliers are present (Figure 6.3). Therefore presentation on a 0 to 100 % scale of each predicted particle size class was not possible.

The elimination of clouds and shadows show however a big reduction of the data spread for high DN-values. The data spread of low DN-values got decreased by the elimination of the tidal vegetation and the water pixles. The decrease of data can be investigated by comparing Figure 5.3 a-c and Figure 6.3. Nevertheless the output does provide good maps of the sedimentary environment and this technique is easy applicable and repeatable for future research on Seal Sands.

As expected the prediction maps of silt & clay are a mirror image to those of total sand amount and the medium sand prediction (Figures 6.1 a-c & 6.2 a-c). As previously mentioned an absolute quantitative verification of the prediction models is not possible because their range exceed the 0 to 100 % scale. However, the very detailed output can be compared with the particle size analysis over the respective sampling stations. Also the detailed field knowledge of the intertidal zone of Seal Sands can be used for the interpretation of the results. The very sandy areas in the east, south and north-west of Seal Sands are very well located. Also changes in these sandy areas are well detectable and, from knowledge of the field well located (Figures 6.1 a, b and 6.2 a, b). Another remarkable result is the preservation and possible distinction of the tidal creek pattern over Seal Sands. Figures 6.1 a-c show that these areas are mainly dominated by coarse sediments, such as medium sand, whereas the fine sediments such as silt and clay are not situated in these areas. Even in the west, which is highly dominated by silt & clay, Figures 6.1 c and 6.2 c show a line shaped distribution of sandy sediments along the tidal creek pattern. This coincides with the field knowledge because these areas are the only ones traversable along the tidal creek system, due to their consolidation by coarser sediment types.

The output is an overall very satisfying result, even though further improvements are possible for future work. Especially, an optimisation of the location of the sampling station should be achieved; i.e. sampling stations should be not positioned within tidal vegetation areas because their spectral reflectance cannot be used for sediment prediction (see Chapter four & five). Further improvement could come from establishing the exact X and Y coordinates of the sampling stations. The use of a GCP system for exactly locating the sampling stations, as already mentioned in Chapter four (geometric correction), would be a useful tool for future work on Seal Sands.

Surface modelling with TIN

Further GIS processing shall now include the height data over Seal Sands. The use of the height data in this case study is twofold. Firstly the height data shall be used as an additional source of information for explaining particle size distribution over the intertidal land of Seal Sands, in direct dependency to the topography. Secondly can the height data over Seal Sands be used for better prediction of birds' feeding grounds.

In terms of representing attributes of a landscape other than altitude, the term digital terrain model (DTM) is commonly used, whereas the term DEM (digital elevation model) is preferred for models containing only elevation data (Burrough 1986). DEMs have a wide range of possible uses: they can be used for simple storage of digital elevation data for digital topographic maps; their continuous features can bridge the gap between 'no data' points through interpolation, and three-dimensional display/modelling of landforms in direct relation to the real world features; and they give the user the choice of different viewpoints. Furthermore, DEMs are used for statistical analysis and comparison of different kinds of terrain, and for computing slope and aspect maps, which can be used to prepare shaded relief maps. DEMs can also be used as a background for displaying thematic information or for combining relief data with thematic data such as sediment distribution. Lastly, when replacing altitude by any other continuously varying attribute (e.g. % of medium sand), a DEM or DTM can be used to create surfaces of continuous thematic features (Burrough 1986).

The 1 meter contour line coverage over the intertidal land of Seal Sands and the spot height data, derived from the AUTOCAD DXF file, was used to create a Digital Elevation Model (DEM), representing the continuous variation of relief over space. A GIS supports, in general, two kinds of features. There are the discrete features which are discontinuous, with definite feature boundaries such as the classified two-dimensional area over Seal Sands. These feature types are easily represented on maps by sets of points, lines or areas. Attributes can easily be assigned to the map features. The second type of features are the continuous features, which are not spatially discrete. For example, although a simple contour line feature showing the change in topography can be seen as a discrete feature, elevation does exist at every location on the map surface. Typically this would be calculated by interpolation between the contours. The main limitation of using continuous map data is the storage requirements of the data. To achieve spatial precision, a dense interpolation of data points needs to be carried out. Interpolation can be performed either by using equally spaced sample points (lattice), or as a series of lines of equal surface values.

In order efficiently to represent the surface elevation based on the contour lines over Seal Sands, a triangulated irregular network (TIN) was created. A TIN is a set of adjacent, non-overlapping triangles whose nodes correspond to the irregularly spaced points on the surface. The triangles are computed from irregularly spaced points with X and Y coordinates, and Z-values (Figure 6.4). The TIN data structure is therefore based on two fundamental elements: points with X, Y and Z values, and a series of edges joining these points to form triangles. Such points on the Earth's surface correspond to ridges, channels, mountaintops and passes. The TIN model is a vector topological structure similar in concept to the fully topologically defined structures for representing polygon networks, with the exception that the TIN does not have provisions for features such as "islands or holes", due to its continuous feature structure. According to ESRI (1992), each triangle represents a facet of a surface. A TIN needs to consist of a database containing information defining each of these triangles as a set of nodes and the triangle's adjacency to other triangles from the topological structure of TIN. For each triangle, a triangle number needs to be recorded, a list of three nodes defining the triangle, the X, Y coordinates of each node, the surface (or Z) value of each node, and a list of each triangle's three adjacent triangles. These requirements consequently generate very large datasets for TIN models.

A TIN can be used to represent continuous data, such as elevation. Continuous data can therefore be illustrated as a continuous surface, generally without sharp or abrupt changes. ARC/INFO creates the TIN with the so-called CREATETIN command. ARC/INFO provides two methods for interpolating line features; the linear and the bivariate quintic method. In linear interpolation, the surface value to be interpolated is calculated based solely on the Z-values for the nodes of the triangle within which the point lies. In the present study the more complex bivariate quintic interpolation method was chosen, which uses not only the nodes of the triangle, but also the slope information at the nodes. The interpolated value is evaluated at the X, Y coordinates of the point for that fifth-order polynomial. The bivariate quintic interpolation produces more realistic results from sparse sampling data sets, such as the contour lines over Seal Sands, whereas the linear interpolation tends to produce discontinuous output at triangle edges.

The extracted intertidal area of contour lines over Seal Sands contains information from -2 metres to +4 metres. The created TIN-model can be seen in Figure 6.4. The model's weak areas are the areas where the triangulation used long distances between the connecting nodes. In the case of Seal Sands this mainly occurred in the middle southern part of the intertidal zone, where only limited topographic information is available. The TIN-model's bivariate quintic interpolation technique nevertheless reproduced the surface in a very authentic way. This can be observed by creating a 3-dimensional fishnet block diagram out of the TIN-model (Figure 6.5). The 3-D model can be created in the SURFACE environment of ARCPLOT, by using the commands SURFACE, SURFACEDEFAULTS and SURFACEDRAPE. The ARCPLOT command SURFACEINFO shows the possible interactions for the user as well the SURFACE commands[5]. By using the ARC command TINCONTOUR, an interpolated contour line coverage over Seal Sands can be created, where the user must specify the *z-value* difference between adjacent contours, as well as the base contour from which the interpolation should begin (Figure 6.6). In this case the newly created contour lines over Seal Sands give a more complex impression of the elevation of the study area, and can be used for a first direct comparison with the particle size distribution by overlaying the classified ATM-image with the contour coverage (Figure 6.7), or by using the

[5]SURFACEINFO shows the current geographic location of the operator, possible z-factor multiplied to the data, the SURFACE boundary, the SURFACE z-range, the SURFACE number of points and the SURFACE resolution.

interpolated particle size analysis of the 80 sampling stations over Seal Sands.

This technique in itself demonstrates an association between particle size distribution and topography. Two main patterns can be recognized. First, there is a definite distribution of coarser sediments towards the low lying borders towards the sea in the northern part of Seal Sands where the tidal energy is at its highest level and where only coarser sediments can accumulate. Furthermore, coarse sediments are distributed at the more elevated areas, especially in the eastern, and middle-southern part of the intertidal zone. The siltflats appear at a neutral elevation of around 0 metres. Finally, the mudflats appear to be situated in sheltered and low lying positions over Seal Sands mainly in the direct neighbourhood of tidal creeks. The ARC/INFO GIS package however provides more sophisticated and powerful modelling operations, used here to represent particle size distribution, and to explain changes within sites. These are discussed below.

The TIN-model can be seen as the basic input for the intertidal zone modelling. For more sophisticated analysis the TIN-model can be converted into a lattice by using the TINLATTICE command in ARC. A lattice is a raster coverage, instead of the vectorised line coverage or the TIN-model. The first result one can get out of the conversion from TIN into LATTICE is the mapping of the intertidal zone by introducing a so-called remap table, showing six different classes of elevation. Class **one** shows the area -2 to -1 metres, class **two** -1 to 0 metres, class **three** 0 to 1 metres, class **four** 1 to 2 metres, class **five** 2 to 3 metres, and class **six** 3 to 4 metres (Table 6.1). This simple elevation model can be displayed in ARCPLOT by using the GRIDPAINT command and can be used in combination with the tide time table to predict birds' feeding grounds (Figure 6.8). The ZONALAREA command in GRID calculates the average area exposed to the six tide levels described. There are two cycles of high and low tide each day; Spring and Neap tides also need to be differentiated. The Spring tide at the river Tees entrance has its Mean High Water Mark (MHWM) at +3.03 metre OD and its Mean Low Water Mark (MLWM) at -1.57 metre OD, whereas the MHWM for the Neap tide is at +1.83 metre and the MLWM at -0.47 metre OD[6]. The coverage of water during the tidal cycle can be calculated. Further processing of the TIN contour data included an Aspect and a Slope map, for the purpose of explaining further the particle size

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[6]The Mean range for Spring tides is 4.6 metre and for Neap tides it is 2.3 metre.

distribution. A representation and discussion of the results would however over-extend this thesis. Future work could however investigate the beneficial use of these possibilities.

Table 6.1 Exposed area of intertidal land over Seal Sands in relation to the tidal range

Height OD	No of pixels	Area in %
-2 to -1 m	377	1.35 %
-1 to 0 m	3019	10.81 %
0 to 1 m	20276	72.63 %
1 to 2 m	3984	14.27 %
2 to 3 m	255	0.91 %
> 3 m	8	0.03 %
total height change	**total count**	**total %**
5 m	27919	100 %

Spatial Interpolation from sampling points

As an additional source of information, the particle size analysis of the 80 sampling stations over Seal Sands are used to create a continuous surface, by interpolating them. This source of information is especially helpful when dealing with cloud and shadow cover in the ATM data itself, and with tidal vegetation cover over the tidal sediments of Seal Sands. Furthermore, as previously presented, the fine sand distribution could not be predicted using the ATM data. Therefore the following interpolation techniques are a necessary substitute for the previously presented remote sensing techniques, to map intertidal zone surface sediments spatially. Spatial interpolation simply fills the 'gap' of information for mapping the entire intertidal zone.

In order to analyze point data distributions spatially, it is useful to interpolate these to produce a continuous surface. In the case of the Coastal Monitoring GIS for Seal Sands, the percentage of particle size classes (medium sand, fine sand and silt & clay), counted at each station were used to be interpolated to surfaces, covering the whole intertidal area. The points of observation can be arranged either at random, or on a regular lattice as is the case for the intertidal land of Seal Sands. The 80 sampling stations over the study area are spaced in a regular 100 m grid (Figure 3.1). This operation shall be seen as a possibility to present the spatial distribution of tidal sediments in the intertidal zone. However this technique is limited in its applicability and its meaningfulness, which will be discussed later in this Chapter.

The operator needs to keep in mind that the interpolation is based on a mathematical operation and does not always reflect the real distribution of the data in the field. Nevertheless, the interpolation of points allows the examination of spatial variations in an area, which effectively enables recognition of spatial patterns. Interpolation enables us to make more precise statements about the nature of properties of interest at unvisited sites (Burrough 1986). The rationale behind spatial interpolation is the common observation that, on average, points that are close together in space are more likely to have similar values of a property than points further apart. Most interpolation methods embody a model of continuous change that can be described by a smooth, mathematically defined surface. This includes techniques such as Trend Surface Analysis (TREND in ARC/INFO), Spline functions (SPLINE) and Kriging (KRIGING). According to Burrough (1986), these techniques may be divided into global (universal) and local fitting techniques. With global techniques, a model is constructed from all observations of the property of interest at all points in the study area (i.e. sampling stations). Local fitting techniques, however, such as spline, are based on moving averages and estimate values from the neighbouring points only. Such techniques allow an emphasis on local anomalies without affecting the value of interpolation at other points on the surface.

After examination of the output of the TREND analysis, which gives a generalised view of the distribution of different particle sizes, it was decided to apply the more sophisticated Kriging interpolation method. Trend surface analysis is criticised for losing detail because of powerful smoothing; for instability, caused by outlier or observational errors; and for variation in one part of the region affecting the fit of the surface everywhere. Additionally, none of the conventional interpolation methods provides the user with any estimates of the errors of estimation. The nature of Kriging is based on a model of stochastic spatial variation that fits well with reality, while other methods of interpolation are mathematical only (Oliver & Webster 1990). In other words, it is a set of methods for local estimation. The method rests on the recognition that the spatial variation of any property such as height or percentage sediment type, known as a regionalized variable, is too irregular to be accurately modelled by a smooth mathematical function, but can be described better by a stochastic surface (Burrough 1986).

The model assumes that the variation from place to place is usually so erratic that no simple mathematical expression can describe it. Most properties seem to behave as essentially random variables rather than as mathematical ones. However, the variation is not totally unpredictable; there is some spatial structure, i.e. spatial dependence. So-called regionalized variable theory allows these different aspects of spatial properties to be taken into account by a stochastic approach. The interpolation proceeds by first exploring and then modelling the stochastic aspects of the regionalized variable. In its simplest applications the theory assumes a constant local mean and a stationary variance of the differences between places separated by a given distance and direction (Oliver & Webster 1990), which was used for this work. The variance of the differences, usually denoted by γ, is the semi-variance: it is half the expected squared difference between two values.

Formally

$var\,[z(x) - z(x+h)] = E[\{z(x) - z(x+h)\}^2] = 2\gamma(h)$ (reproduced from Oliver &Webster 1990)

where $z(x)$ is the value of some property z at position x and $z(x+h)$ is the value at $(x+h)$. The semi-variance depends on the *lag* or separation h, a vector, in both distance and direction, and not on the actual positions. The weights are based on modelling the pattern of spatial dependence in the data. This in turn is characterised by the semi-variogram, which portrays the mean squared difference in the data values over successive *lags* (distances between observations). Successful *Kriging* depends on the extent to which an adequate theoretical model characterises the experimental variogram (Vincent & Gatrell 1991). The function that relates γ to h is the variogram (Oliver & Webster 1990). The variogram summarizes the general form of variation (Figure 6.9), its magnitude and spatial scale. The variogram may be used to compare variation of properties within a region. The most important use of the variogram is for optimal interpolation. Kriging is assumed to be less arbitrary than other methods, since the Kriging weights are determined by the variogram and the configuration of the data. The estimation variances can be determined and mapped like the estimates, and used for calculating the confidence we can place in the estimates. Comparisons of interpolation methods have shown that Kriging gives quantitatively better results, although it takes more computing time (Oliver & Webster 1990).

Kriging has been used here for the particle size analysis, for the digital elevation model over Seal Sands, and for the interpolation of invertebrate density by using the ARC command KRIGING. In order to run the KRIGING operation, each point needs to have a *z value* item, containing the spatial property on which the interpolation is to be performed; such as percentage values of medium and fine sand and silt & clay or spot height data. The *z value* for the described data can easily be added to the existing X and Y location of the 80 sampling stations by defining a new item in the ARC environment TABLES, where the spatial values can be added by using the ADD command. In ARC the item can then be joined together with the Point Attribute file (PAT) of the point coverage containing the sampling stations, by using the JOINITEM command. At that stage, the point coverage is ready for interpolation using *Kriging*. KRIGING in ARC/INFO optionally produces an out-variance lattice containing the predicted variance at each mesh point of the created coverage.

Results of the Interpolation of spatial features for the intertidal land of Seal Sands

Interpolation of the sampling stations, using the Particle Size Analysis

For the purpose of comparing the predicted particle size map with data gained from the particle size analysis, as well as for producing particle size distribution maps for particle size classes which could not be predicted, or for such areas where the tidal sediments could not be detected on the ATM image; i.e. cloud, shadow, water and vegetation coverage, a spatial interpolation of the results of the particle size analysis over the 80 sampling stations is used. Maps based on interpolation from the field data show generalised patterns of sediment variation. They form a basis, against which the extra spatial detail provided by remotely sensed data can be appreciated.

Six point coverages were created, containing the percentage values of the particle size analysis. An item containing the z value (percentage of particle size class) was added to the X and Y coordinates of each coverage, using the JOINITEM command, as already described. Each coverage contains only a single particle size class. There are three coverages, containing the percentage value of *medium sand*, the percentage of *fine sand* and the percentage of *silt & clay* (Figures 6.10 a-c), for each of the 80 sampling stations (Figure 3.1) for a sampling time of autumn and winter 1990/91. A second series contains the updated particle size analysis, based on the resampling data from late autumn and winter 1992/93 (percentage of *medium sand*, *fine sand* and *silt & clay*) (Figures 6.11 a-c). The point data needed to be interpolated in order to produce a surface showing the particle size distribution over the whole intertidal area of Seal Sands. Although Kriging is a very powerful and reliable interpolation technique, there is a limit up to which the interpolation is meaningful. The north-western part of the intertidal zone of Seal Sands, for example, contains a sparse net of sampling stations. Therefore, the estimation error is higher in these areas than in the rest of Seal Sands. Furthermore, the user has to be aware that the Kriging interpolation method is limited in areas with high spatial dynamics, such as near tidal creeks. The sampling density of 100m doe not come any near the high resolution of 5m of the ATM data. However could a continuous surface over the whole study area only be provided with the presented interpolation method, due to the above named influencing factors, such as clouds, shadows, water and vegetation cover.

The overall particle size distribution over the years between the first sampling in autumn and winter 1990/91 and the resampling in winter 1992/93, has not changed dramatically for the medium sand class and fine sand, although the silt & clay distribution not surprisingly shows high positive as well as negative variations. The reasons for these changes have already been pointed out in Chapter three. Besides changes related to the topography of the intertidal land, one must keep in mind that the intertidal zone is an area very susceptible to changes, both seasonal and daily in origin.

Spatial and temporal distributions of particle size are discussed below with reference to Figures 6.10 a - c and 6.11 a - c. Figures 6.12 a - c show the changes of the two sampling attempts, in percentage values.

- The *medium sand* distribution (Figures 6.10 a & 6.11 a) is concentrated on the exposed parts of Seal Sands; mainly the eastern part and a sand bank in the central part of Seal Sands. The eastern part of the study area has a high amount of *medium sand* due to its elevation (> + 1 metre OD), whereas the central sand bank is related to the tidal environment of Seal Sands. The tide comes first to this north western part of the study area. The transport energy in this part of the intertidal zone is still quite high, which means that mainly coarse sediment types accumulate, whereas the fine sediments stay in suspension and get transported further. The elevated eastern part of Seal Sands is rarely flooded for long, with the main coverage appearing at Spring tides. As a result, only coarse sediment types are able to accumulate in this high tidal energy area. Additionally the eastern area is exposed to wind erosion. The dunes surrounding Seal Sands supply these areas with sand. In general the positive changes are in the high lying areas whereas the negative changes are mainly distributed in low lying areas. Changes in the *medium sand* distribution have occurred in the north east part of Seal Sands, mainly caused by the damage to the tidal wall, which resulted in an increase of coarse sediments and a consolidation of the eastern part (Figure 6.12 a). Explaining further changes in the medium sand distribution would be speculative at this stage of the research. Field work in past years has shown that consolidation of the intertidal sediments of Seal Sands is taking place (pers. comm. Ward[7] 1993). There should be further investigations whether this trend continues in the future with the construction of the tidal barrage in the river Tees.

- The *fine sand* distribution (Figures 6.10 b & 6.11 b) is mainly based in the northern part of Seal Sands, and extends into the centre part. It is dominantly situated in the - 1 to 0 metre OD elevation of Seal Sands, having its highest level in the northern part of the tidal channel, where the tidal energy is still relatively high. Comparing the *fine sand* distribution with the *medium sand* distribution, it appears that the *fine sand* map is, to a large extent, an inverse image of the *medium sand* map. High concentrations of *medium sand* correlate with

[7] Robin Ward, Research Assistant in the Biological Sciences, Durham University.

low concentrations of *fine sand*, and *vice versa*. The *medium sand* distribution appears to be associated with areas of high tidal energy, whereas the *fine sand* is distributed in the medium class energy parts of the intertidal zone, where transport energy is not sufficient to hold the *fine sand* load, but still strong enough to hold *silt & clay* in suspension. The high concentration of *fine sand* stands probably in direct correlation to the tidal wall at this part of Seal Sands. The early tide comes in the north east were the tidal wall is broken and in the north west through Seaton Channel (Figure 1.1 d). The north of Seal Sands, however, is covered later by the tide influenced by a lower tidal energy budget. The accumulation of *fine sand* therefore starts in the northern part of Seal Sands and gradually decreases towards the centre of the area. High *fine sand* distribution also appears to be associated with smooth areas, where the slope distribution is scarce. Comparing the first particle size analysis of *fine sand* with the resampling, it appears that spatial distribution of *fine sand* becomes more regularly defined. The *fine sand* map from autumn/winter 1990/91 shows a patchy irregular surface. Absolute changes however are not very strong (+/- 5%) (Figure 6.12 b).

The sensitive fine sand class appears to have two major areas of increase over Seal Sands: in the North East of Seal Sands (broken tidal wall), and in the West of Seal Sands along a tidal creek, where a decrease of medium sand could be noted. The decrease of percentage of fine sand is however more widely spread over a large area of Seal Sands. The low lying and vegetated areas are most affected by this change over time (Figure 6.12 b). This is very likely to be due to seasonal changes, because of temporary changes of the energy budget in this area. The concentration of *fine sand* also appears to correlate with the tidal vegetation (*Enteromorpha spp.*) in the intertidal zone. This occurrence has already been described in Dennert-Möller (1983). The 50 % isoline of the resampled *fine sand* map appears to match roughly the border of the vegetation. This correlation will be worth tracing in future particle size analysis for this area. Field work in 1993 showed that the tidal vegetation had greatly increased since 1992.

■ The *silt & clay* distribution (Figures 6.10 c & 6.11 c) again fits into the overall shape of the sediment distribution on Seal Sands. Areas with low amounts of *medium sand* and *fine sand* tend to have a high amount of *silt & clay*. *Silt & clay*-sized particles are concentrated mainly in the south western part, and in a 'corridor' traversing from the north west through to the south east of the study area. *Silt & clay* is found along tidal creeks and in areas where the transport energy of the tidal range is at its lowest level: the *silt & clay*, which stays mainly in suspension, is able to accumulate in these quiet areas.

The *silt & clay* distribution occurs mainly in low-lying areas on Seal Sands. But besides the requirement for a low altitude, the area also needs to be situated in a sheltered environment, where erosion forces are very low. Therefore, areas adjacent to the tidal channel are not ideal places for *silt & clay* accumulation, due to the high level of tidal energy. Overall there are only rarely zones with pure mud flats (*silt & clay* content > 80%). This shows that the general transport and erosion energy budget in the unreclaimed land of Seal Sands is not at a very low level, for a period, long enough to allow higher amounts of accumulation of the finest particles. Comparison of the two sampling attempts for *silt & clay* shows that the overall area with high amounts of *silt & clay* decreased between the first and second sampling attempts (Figures 3.4 a-j, 3.5 a-r & 3.6 a-m). This implies that the intertidal surface over Seal Sands became more consolidated during the time of resampling, as already mentioned. This also correlates with the fact that some areas are accessible now but were not in the past. As expected the *silt & clay* class is the most sensitive of the three classes in this examination; it tends to change over large areas in high values, positively and negatively. The increase in *silt & clay* appears mainly to be situated in low lying areas, where a decrease of medium sand and partially fine sands could be noted. Negative changes correlate with elevated areas and the border regions of the intertidal zone (Figure 6.12 c).

Reflections on the techniques used for the intertidal sediment mapping

After having presented two possibilities for spatially mapping the intertidal sediments of Seal Sands, a comparison of the results may be made. First of all, the user has to keep in mind that a remotely sensed prediction for the fine sediment class could not be achieved, because of the lack of correlation of reflectance and the fine sand class in the ATM bands. As seen in Chapter five, the fine sand class is more subject to temporal and spatial changes. Therefore an interpolation method, based on particle size distribution as shown above, is the only possibility for spatially presenting the fine sand class distribution. A further restriction of the ATM data is the missing information in areas where the cover type represents nontidal sediments, i.e. tidal vegetation, water, clouds and shadow. In these areas again, interpolation is the only method capable of mapping sediment components. However these restrictions only limit the quality of mapping the intertidal zone sediments via the prediction model to a small extent . As described in Chapter five, the main power lies within thermal channel 11. One has to keep in mind that the interpolated particle size class maps are based on 80 sampling stations in a 100 metre grid over the study area. This is a very crude spatial resolution, and therefore results in a very general pattern, where differences between the sampling stations cannot be presented. The ATM image data, however, has a resolution of 5 metres, and therefore results in a much higher spatial information potential. A visual comparison of both methods results in a much more detailed and precise information content, i.e. the medium sand class, and silt and clay class. This method also has the advantage that it still allows tracing of intertidal-zone features, such as the tidal creek network, over Seal Sands.

The prediction model of the total sand amount class (Figures 6.1 a-c & 6.2 a-c) and the output using the maximum likelihood classifier (MLC) (Figures 4.18 & 4.19), correlate acceptably with each other. The main features such as the distribution of high amounts of sand in the north east and the north west of Seal Sands do correspond quite well. Furthermore the east and the south of Seal Sands with its high amount of sand are well presented in both map outputs. The areas with a high amount of sand are therefore relatively well presented in the map classified with the Maximum Likelihood Classifier (MLC).

However, the pattern of the MLC output is too general and does not allow small scale variations, especially when compared with the grey scale map (Figures 6.1 a-c), of the predicted model. In particular, areas classified as Mixed Sandflat, Siltflat and Mudflat, do not show small scale features, such as distinction of sedimentary patterns related to tidal creeks or to elevation. The MLC method is based on the selection of training areas. The spectral characteristics of the defined training areas shall be representative for the whole image. It appears that similar tidal sediment compositions show different spectral reflectance behaviour over the intertidal zone of Seal Sands. Factors such as moisture content, elevation, surface roughness, and organic matter (Figure 4.1) interact here. A definite assignment of spectral behaviour to special training areas is therefore not possible with the MLC method. For this reason, reliable and accurate mapping of intertidal sediments using the MLC method, is not possible. The MLC output could possibly be improved by using a widely used technique, such as a majority filter on a 3 x 3 or 5 x 5 basis, in order to generalise the output, and to clean off single, isolated and confused pixels. However this technique was found to be a risky operation because of the elimination of small scale differences, which are characteristical for the intertidal zone. Futural work should rather take care that sample sites are located in homogenous areas - more than 10 m from any clear boundary.

For future work, the prediction model should be used to provide a base map in order to estimate and explain further changes in the sedimentary environment of Seal Sands (Figures 6.1 a-c & 6.2 a-c). Certain restrictions of the prediction model have appeared, such as the difficulty of making a quantitative association of particle size classes in a 0 to 100 % scale to their reflectance. It is however a suitable, high resolution tool, which is now accessible and repeatable for future work on Seal Sands.

Chapter seven - Conclusions and recommendations

Analysis of the sedimentary characteristics of the Tees Estuary has been performed using remote sensing, field and GIS techniques. This study evaluated the use of remote sensing techniques in combination with field data and GIS techniques. The approach was designed to be repeatable and easy to follow for future studies with different image data and for different intertidal zone areas. The Airborne Thematic Mapper (ATM) image data has been classified in order to produce a 'snapshot' of the contemporary sediment distribution of the intertidal land of Seal Sands (Figure 4.18). Further analysis involved the combination of particle size analysis and reflectance data of the ATM survey over Seal Sands. A model was created via multiple regression analysis, predicting particle size classes (Figures 6.1 a-c & 6.2 a-c). Additionally an interpolated surface using GIS techniques was produced showing various classes of sediment distribution. The information gathered from the intertidal zone may be of use to ecologists studying the feeding behaviour of birds on Seal Sands (Figure 6.8).

Information collected from field work, and remotely sensed data has been incorporated together with previously existing digital data, in a Coastal Monitoring GIS framework for Seal Sands. Pre-processing involved the resampling of 36 out of 80 sampling stations on the intertidal land (Figures 3.3 - 3.7), including sediment particle size analysis. Furthermore, image processing, comprising radiometric calibration (Figure 4.6), atmospheric correction (Figure 4.13), geometric correction (Figure 4.14 a, b) and classification of the ATM Teesside data has been completed (Figure 4.18).

Furthermore the relationship of particle size analysis and the reflectance of tidal sediments was investigated. Correlations of the reflectance and the particle size analysis at the sampling stations over Seal Sands were estimated. Good results could be monitored on the large scale ATM image data set over Seal Sands. A multiple regression model was developed in order to predict particle size classes, such as medium sand, silt & clay and the total sand amount. The main explanatory power was based on thermal band 11. Models predicting nearly 70 % of variation in the intertidal zone sediments could be achieved. The multiple regression equations were applied in Chapter six to the whole intertidal zone of Seal Sands, excluding areas with vegetation, water, clouds and shadow. This prediction model is seen to be the main achievement of this research. It has a high explanatory power, is easy to understand and repeat, and uses the high ATM resolution data set for a pixel by pixel prediction.

Finally, digital map data of Seal Sands forms the basis of a Coastal Monitoring GIS which integrates particle size analysis (Chapter three) and remotely sensed data (Chapter four). The GIS input is based on vector format for the digitised features, as well as on raster format for the image processed and surface features. ARC/INFO 6.1.1 has been found to be effective in handling, organising and processing such data.

The combination of the high resolution Airborne Thematic Mapper (ATM) data and field work was shown to be a very efficient and successful way of mapping the intertidal zone of a small study area, such as Seal Sands. In particular, inaccessible areas benefit from mapping based on remote techniques. The incorporation of field work into the Coastal Monitoring GIS proved to be very fruitful in verification of the remotely sensed data set by using data from the particle size analysis. The high spatial resolution (5 metre) makes the ATM data much more precise than the comparable field work based on a 100 metre raster of sampling stations (Figure 3.1). The *fine sand* is the only particle size class which does not show any strong correlation with the reflectance of the sediments in the ATM data set. Unfortunately, there are only a few previous studies using the thermal infrared wavelength for intertidal zone mapping, with which the results found in this case study can be compared. This is mainly because most previous studies of the intertidal zone have used satellite imagery, where the thermal channel has a low spatial resolution[1]. Future studies should therefore try to verify the very strong correlation between the thermal infrared reflectance pattern and the particle size distribution.

Three pre-processing steps needed to be performed to the ATM data before the actual correlation of the remotely sensed data and the particle size analysis. Each step was necessary

[1] Landsat TM 5 has a resolution of 120 metre in band 6 (thermal infrared).

for multitemporal comparison of two or more data sets. Great care was taken in order to achieve meaningful results. Nevertheless, each attempted 'correction' of the ATM data will also result in some unpredictable degradation of the radiance data. The reflectance[2] of the tidal sediments appeared to be strongly dependent on the moisture content of the sediments. However does it remain doubtful whether certain particle size classes can be characterised by a distinct moisture content level. In this case study, as well as in previous case studies, such as Yates *et al.* (1993), it appeared that areas dominated by sands, tend to facilitate extensive tidal pools or a thin surface water film. The reflectance signal of such areas, was therefore, not very surprisingly, low and could not be related to a definite particle size class. The main explanatory power therefore lies independently to the moisture on the thermal emittance of the tidal sediments, which was recorded by band 11, the thermal infrared band of the ATM data. A relationship between grain size and colour of the tidal sediments could be investigated. Small grain size correlated to a dark sedimentary appearance (high emittance), whereas bright colours correlate to coarser sediments (low emittance).

The classification of the remotely sensed data was based on an image enhancement method using Band ratios. The gradation of sediment types for the purpose of classification was taken, in a slightly verified form, from Bartsch (1990) and Donoghue & Zong (1992). Within the bounds of this research it was not possible to justify a new sediment gradation which would better suit the needs of ornithologists, to explain birds' feeding behaviour in relation to different sediment types. Future studies should, however, evaluate whether a gradation based on the percentage of total sand present, should be replaced with for example a gradation of percentage of medium sand or percentage of silt & clay, due to the fact that these two particle size classes could more efficiently be used for relating particle size to reflectance. The combination with thermal infrared wavelength, which correlated very highly with medium sand and silt & clay (≈ 0.8) seems especially to be a very promising tool for the future (Figures 5.2 a - f). The fine sand component appeared to present no consistent pattern of spectral behaviour for the ATM data.

Therefore, for the purpose of presenting a spatial distribution map of the fine sand class, only the interpolation technique using Kriging, as presented in Chapter six, produces

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[2] Reflectance in the visible, near infrared and short wave infrared of the electro magnetic spectrum (EMS).

useful results. Moreover this technique can also be helpfully applied where spectral information is lacking in some areas, where the sediments are covered with vegetation, water, clouds or shadow. The steps could be well processed in the GIS environment, by handling raster, line and point data. Accuracy conflicts do however appear in areas around creeks, where a high dynamic of tidal sediment distribution appears.

The combination of image processing with GIS techniques proved to be a very useful tool for monitoring the sediments in the intertidal zone of Seal Sands. The additional use of contour data to create a digital elevation model (DEM) was beneficial in explaining the tidal sediment distribution patterns. One must however keep in might that the tidal sediment distribution can not simply be correlated to the elevation of the area. Low lying areas which are positioned in the direct neighbourhood to the sea (where strong currents appear), facilitate coarser sediments than low lying and sheltered areas in the intertidal land itself.

The DEM could be further used to estimate birds' feeding areas. Not only the particle size distribution, but also the elevation of the intertidal zone plays an important role for determining feeding areas. Low lying areas, with maybe ideal sediment composition and high invertebrate density, are not necessarily ideal bird feeding areas because of the short term exposure by the tide.

The degree of success of using remote sensing techniques as a useful monitoring tool for intertidal sediment distribution can be severely limited by various factors. The use of remote sensing techniques combined with particle size analysis and field radiometry involves a particularly high degree of preparation and organisation. Various uncertainties could not be avoided in this case study. It is important to be aware of the possible factors involved in mapping the intertidal zone with remote sensing tools. Influencing factors can come from within and outside the intertidal system. Factors like particle size distribution or organic matter influence the spectral behaviour directly within the system, whereas atmospheric conditions operate outside the system. As already mentioned the intertidal zone is a very dynamic environment. Therefore, the sediment sampling, as well as the field radiometer measurements, should be undertaken on the same day as the ATM data acquisition, in order to achieve reliable and comparable results. Furthermore, great care needs to be taken with the atmospheric conditions of the day of the data acquisition because coastal and industrial areas such as this study area tend especially to be affected by clouds and haze in the atmosphere.

These effects can degrade the value of the image data. In order to locate the sampling stations more exactly over Seal Sands, further studies should use a Global Positioning System (GPS). This system will allow high accuracy mapping and be easily repeatable. More sampling stations should be positioned in the sediment areas over Seal Sands, rather than in tidal pools or vegetated areas. This should permit a broader spread of the feature space within the regression analysis, which would result in a better scaling of the predicted particle distribution map.

Last but not least, the user of these coastal monitoring tools should keep in mind that the model created is a temporary and limited picture of the surface of the intertidal zone. Temporal and spatial changes imply that mapping and monitoring need to be repeated regularly.

Although the detailed nature of the dynamics of intertidal environments remains uncertain, the techniques and methodology described in this thesis provide a framework for future research. The present techniques showed that high resolution remotely sensed data is a very useful tool for mapping intertidal surface sediments, especially when used in combination with GIS techniques. Remote Sensing based on an aerial platform must be seen as a data source providing information for other sciences and investigation purposes. In this case study ornithologists will benefit greatly from the very up to date data set, its high resolution and its spatial accuracy. This research shall be seen as a contribution for monitoring the very complex ecosystem of the intertidal zone. Techniques introduced in this research should be repeated and improved during further research. The aim in the future must be, to establish a monitoring system, in order to map the intertidal land of Seal Sands on a regular basis. Further efforts should be put into the automation of the techniques presented.

For futural work of monitoring the intertidal zone in a regular scale, attention should also be paid towards radar image data. Radar imagery has the great advantage that influencing factors, such as day time and atmosphere do not need to be considered. In contrary to optical sensors, such as Daedalus, Landsat TM or SPOT HRV, are radar data not disturbed by these factors. Therefore radar imagery presents a useful source to monitor the dynamics of the intertidal land. Similar to the above presented method could this also be used to discriminate stable areas from unstable areas over time. Due to its data acquisition, such as ERS1 every 35 days, a high reliability in monitoring sedimentary changes in a regular scale could be gained. Radar data comprises three typical information types. They are mainly i) the surface roughness, ii) the water content of a cover type and lastly iii) an electricity constant of the measured cover type.

The very interesting aspect of radar image data is that one direct information of radar data is the surface roughness. In former studies such as in Bartsch (1990), surface roughness in dependency to the surface type was already monitored in aerial photographs. Correlations of surface roughness and particle size distribution in a coastal habitat have also be done in recent research using ERS1 data (Krämer & Sasse 1994). Even though this technique is not fully developed yet, it presents high potential for futural monitoring of the intertidal zone.

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