# Environmental Monitoring by Remote Sensing in Denmark

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*Danish environmental monitoring of the open sea, coastal waters, lakes, streams, ground water, air and land surfaces is presently based solely on conventional in-situ measurements. This paper discusses the potential for supplementing this programme with remote sensing from space- and aircraft. Three classes of remote sensing applications is identified and discussed: Monitoring of quickly varying parameters, requiring modest spatial resolution, monitoring of slowly varying parameters, requiring high spatial resolution, and 'on-demand' aircraft-based remote sensing of environmental phenomena. The discussion leads to a series of suggestions, concerning the potential operational applications in the short term as well as, demonstration experiments and research with a longer time horizon and implications for the design of future satellite-/sensor-systems.*

Keywords: *Environmental monitoring, remote sensing, Earth observation, satellites.*

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The Danish environmental monitoring system is generally believed to be among the most comprehensive national programmes, involving both national services, such as the 'Forest & Nature Agency' (FNA), the 'Environmental Protection Agency' and the 'National Environmental Research Institute' (NERI), the counties and municipalities. It covers both the air, the sea, lakes and streams, ground water and the terrestrial environment, and it applies a variety of in-situ measurement techniques. Measurements made at individual points or within small areas are often extrapolated to cover the entire Danish sea and land area. Remote sensing techniques, giving much better spatial coverage, have only been used to a relatively limited extent, in spite of the substantial developments within this field during the last two decades.

In late 1992, NERI proposed to initiate a study of how remote sensing from satellites and aircraft could best be applied in Danish environmental monitoring. Based upon a grant from the Danish Space Research Board, a team, comprised by the authors of this paper, was set up with the aim of reviewing the requirements as defined by the various application fields, and the options offered by present and future remote sensing methods and data sources. This paper contains a brief account of the results obtained by the group.

In the following the present Danish environmental monitoring system is briefly introduced, and basic remote sensing principles will be summarized. The subsequent paragraph deals with the present state and future potential of environmental remote sensing applications. It is followed by a discussion of two classes of environmental monitoring themes: 1) Rapidly changing environmental parameters, which require frequent data acquisition, yet do not need to be monitored in great spatial detail, and 2) slowly varying phenomena, which require high spatial resolution. The subsequent paragraph discusses the need for an aircraft facility for observation of transient environmental phenomena such as oil spills. Such a facility may also be of great value as a research tool by allowing for easy and cost-effective in-flight testing and calibration of new or redesigned remote sensing instruments considered for future use in space. Finally, a number of action proposals are put forward, concerning both monitoring applications, ready for implementation in the short term, demonstration experiments and research.

## The Danish environmental monitoring system

The Danish environmental monitoring programme so far is based upon the use of 'conventional' observation techniques. Such a programme requires continuous updating and refinement in order to ensure and improve quality and cost-efficiency. The use of remote sensing methods may only in a few cases replace existing techniques. More often, remotely sensed data and conventionally collected data will be complementary, and in particular remote sensing may provide better spatial coverage and increased observation frequency at a relatively low cost. The comprehensive conventional measurement programme will allow for proper calibration of the remote sensing methods by providing 'ground/sea truth' measurements, whereas remote sensing data will allow for interpolation between and extrapolation of the conventional point measurements in time and space. This applies e.g. to parameters as sea surface temperature, precipitation and evapotranspiration.

Until recently, remote sensing has - with a few, yet important, exceptions - been considered a research area rather than a tool for solving practical environmental monitoring tasks. The field is now so well-developed that it will be worth considering a wider range of practical applications and to point out areas, where further research, development, testing, calibration and demonstration activities should be given priority. As indicated, this paper will discuss candidate methodologies for practical use and for further research within the broad field of environmental monitoring.

In the following, the main elements of the Danish environmental monitoring system will be briefly described under the headings of sea, air and land monitoring.

### *Monitoring of the open sea and coastal waters*

A considerable part of the Danish environmental monitoring has been established as a consequence of the 'Action Plan for the Aquatic Environment', initiated in 1990 in response to the observed severe effects of pollution - and in particular eutrophication - of Danish waters.

As for open sea monitoring, the list of parameters monitored includes physical, chemical and biological variables, and measurements are generally made as depth-profiles. The aim has been to understand the background, physical as well as biological, for the pollution of the Danish marine environment, with an emphasis on the causes and effects of eutrophication. Measurements are carried out along transects and at fixed locations. The frequency and density of measurements made from ships are limited by the high costs involved, and thus the programme does not allow for precise identification of spatial patterns and temporal trends. Limited use of remote sensing is presently made in relation to the detection of oil-spills, using a 'side-looking airborne radar' (SLAR) operated on behalf of the Environmental Protection Agency. And the Danish Meteorological Institute (DMI) has initiated experiments with the use of data from the US NOAA series of satellites for monitoring sea surface temperature, with a view to its use for future operational systems.

The condition of coastal waters is monitored jointly by the counties and NERI. Since eutrophication is particularly serious within fiords and bays, the measurement programme, encompassing more than 600 stations, emphasizes parameters relevant to this problem, including the concentrations of nutrients and oxygen as well as phyto- and zooplankton. Buoys as well as ships are used, and depth profiles are measured in most cases. Measurements are located along lines, allowing for tracking of pollutants from the river outlets to the open sea, thus linking to the open-sea and freshwater monitoring programmes. Again, cost limits the frequency and density of measurements. A special monitoring theme within the coastal zone concerns the bottom vegetation, which may be used as an indicator of the overall biological state of the water-body.

### *Monitoring of streams, lakes and ground-/freshwater*

The freshwater monitoring programme covers lakes, springs and streams. Springs are monitored since their state indicates trends in ground water quality. Streams are monitored because their state is interesting as such, and because they transport nutrients from the sources to the sea. 37 lakes, representing different types of lakes - in a biological sense - and subjected to different types of pollution, are monitored. The measurement programme covers physical and chemical parameters as well as phyto- and zoo-plankton and fish stocks, in order to gain insight into the function of the lake ecosystems.

### *Monitoring of the leaching of nutrients*

The major source of pollution of the open sea, coastal waters and freshwater areas is the fluvial outlet of nutrients, and in particular nitrogen compounds from agricultural areas. Monitoring this outlet and understanding its relation to agricultural practices is a major challenge. A land monitoring programme has been implemented within six small (5-10 square kilometres) watersheds, each comprising some 35-70 farms. Three of these watersheds are located in areas with sandy soils, and three in heavier soil areas. The leaching of nutrients within these watersheds is studied in detail, and relations to the observed land-use and agricultural practices are established. Regional and national scale assessments of leaching are then made, based on scaled-up results from these six watersheds. Presently, detailed models, developed for describing the leaching for certain crop/soil combinations at the micro level, appear not to be applicable for estimations at the regional and national level.

### *Monitoring of air pollution*

The monitoring of air is - in this context - understood as measurements of concentrations of atmospheric constituents, and in particular pollutants, within the lower few hundred metres of the atmosphere. Such measurements are performed by NERI at 6 locations. In addition, atmospheric deposition is measured in 16 places. Also, pollution levels within urban areas are monitored in 4 major

Danish cities. Atmospheric monitoring related to meteorology and global change research is the responsibility of the DMI and will not be dealt with here. It should be noted, however, that remote sensing plays a significant role in the monitoring of global phenomena, such as the ozone layer depletion.

### *Monitoring of land cover, vegetation and landscapes*

Monitoring of the terrestrial environment is the shared responsibility of several national agencies as well as of county and municipality administrations. At the EU level, mapping of land cover takes place within the CORINE programme, and the Danish part of the work is done by the Department of Land Data (DLD) (Stjernholm, 1992). At the national level, agricultural land use is also monitored by the DLD (Nyholm Poulsen & Borup-Svendsen, 1992), while the monitoring of forest areas is the responsibility of the Forest and Nature Agency (FNA), whereas NERI is in charge of monitoring the landscape and wildlife habitats. General physical planning for the open land and the monitoring of nature types are the responsibilities of the counties, and - on the smaller scale - the municipalities. The monitoring system for the terrestrial environment is rapidly evolving, and no coherent set of methodologies has yet been established. This is in particular true for the monitoring of structural properties of the landscape and of 'nature types'.

Many sources of information are being utilized for monitoring the terrestrial environment, ranging from intensive local scale ground observation of species composition within nature types covering a few square-metres to national scale land cover and land use mapping using Landsat TM satellite images. This diversity reflects the need for information at scales from centimetres to kilometres. Some parameters, especially some related to meteorology and hydrology, are rapidly varying and require very frequent data collection, while others change slowly and require only observations at intervals of years. As mentioned, remote sensing from both satellite and aircraft is used to some extent, both for national-scale activities by the DLD and the FNA and for county level nature type monitoring, yet a coordinated system, utilizing data for a range of monitoring tasks, has not been implemented.

## Remote sensing principles and systems

In this paper 'remote sensing' is understood as the

> collection of spatial data of properties of the Earth's surface or the atmosphere by means of measurement of electromagnetic radiation, reflected from or emitted by the Earth's surface or the atmosphere, using sensors on platforms at a great distance from the object

For an in-depth discussion of the meaning of this definition and how it differs from other widespread definitions, see Tychsen et al (1994).

Remote sensing methods and systems may be categorized according to

- the part of the electromagnetic spectrum utilized, i.e. visual/thermal infrared versus microwave remote sensing,
- whether natural or artificial radiation sources are utilized (passive versus active systems),
- the platform used (airborne versus space-borne),
- spatial resolution
- whether one-dimensional or two-dimensional (image-) data are acquired,
- the object of analysis, i.e. land, sea or atmosphere, and
- whether the system is considered operational or experimental.

The core of remote sensing is the development of methods and models, to derive, from the measured radiation, information about the object studied. This information may either identify the type of object, e.g. the crop species, or consist of values of the parameters describing the object studied, e.g. the sea surface temperature.

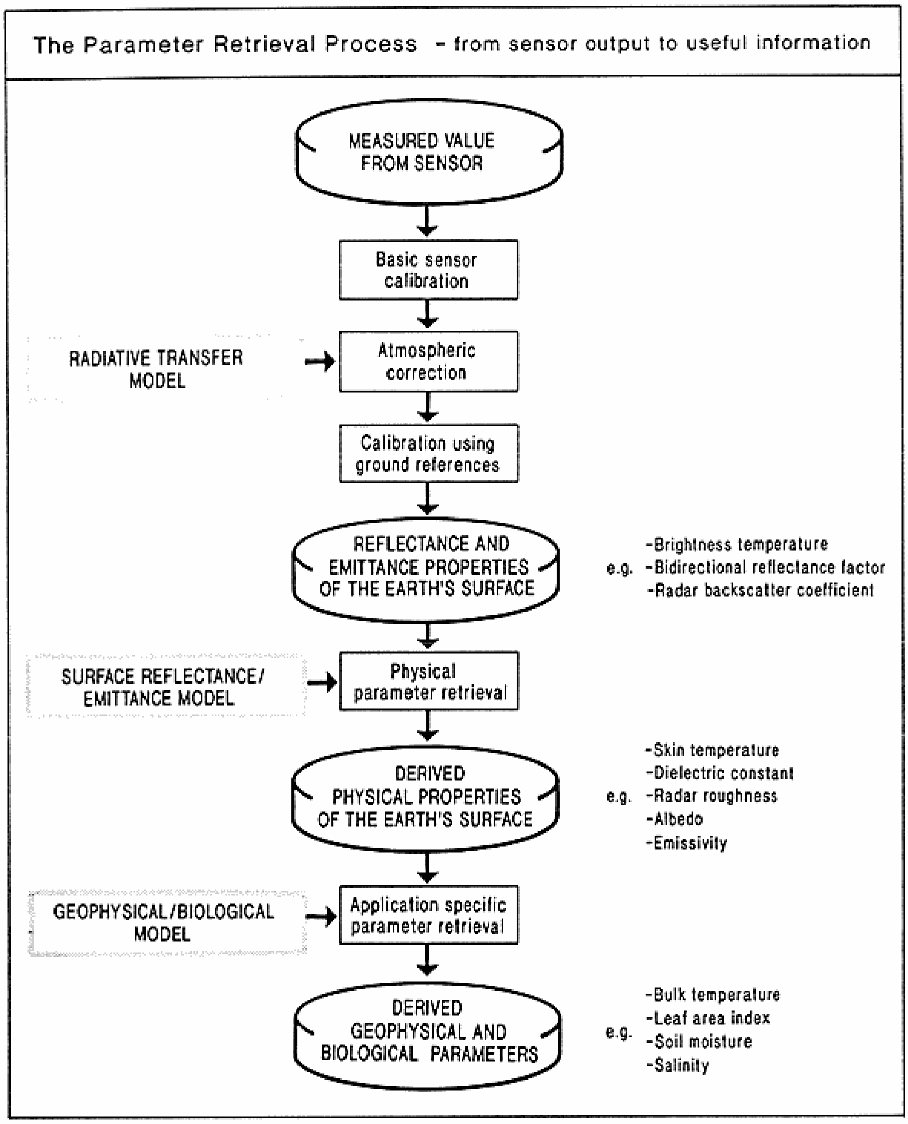
Remote sensing measurements are often influenced by the atmosphere between the sensor and the target, and therefore derivation of valid information on the properties of the target may require compensation for such effects. Clouds may hinder optical remote sensing of the Earth's surface entirely, while remote sensing within the microwave part of the spectrum may be relatively unaffected, depending on the frequency (wavelength) utilized.

The parameters which may be determined directly from remote sensing data, e.g. optical properties such as 'spectral reflectance' ('colour'), temperature, structural properties, such as roughness, or electrical properties, may not be those of greatest importance to environmental monitoring, therefore models, relating these parameters to more application-relevant ones are required. Such 'indirect' estimation of parameters, utilizing a 'series' of models, is sketched in Figure 1.

Satellite/sensor-systems may be subdivided into two main categories according to their spatial and temporal resolution. This is illustrated in Figure 2.

In the following these two groups will be referred to as 'high resolution' and 'low resolution' systems, and they have quite different applications, though they may often

Figure 1. Chart, illustrating the processes and models for the retrieval of geophysical and biological parameters from "raw" sensor data. Rectangular boxes show processes ("algorithms") performed upon the data, while rounded, "disc/drum-symbol", boxes represents data at various stages of transformation.




complement each other. The distinction between optical and microwave remote sensing is important, since the physics and technologies involved differ substantially. Optical remote sensing systems measuring electromagnetic radiation within the wavelength interval 0.3-15 $\mu$m are mostly passive, relying on reflected sunlight or emitted thermal radiation. Microwave systems may be either passive or active. Passive systems may be used in the wavelength range of 1 mm to 50 cm whereas active systems may, for technical reasons, currently operate only within the range of cm to 50 cm. Passive systems measure the thermal radiation from the area observed, whereas active systems detect the reflection from the surface of an emitted signal, as in the case of radar. Generally, the passive microwave systems have low spatial resolution, determined by the size of the aperture of the receiving antenna measured in wavelength units of the radiation. In contrast, the active systems in the form of a synthetic aperture radar may have a very fine resolution, in the order of metres, due to the use of special signal processing methods. The physical properties of surfaces, determining the reflection of a radar signal, e.g. surface structure and water content, are different from those relevant within the optical domain, implying that the combined use of optical and microwave methods may yield new information. In addition, microwave methods are often

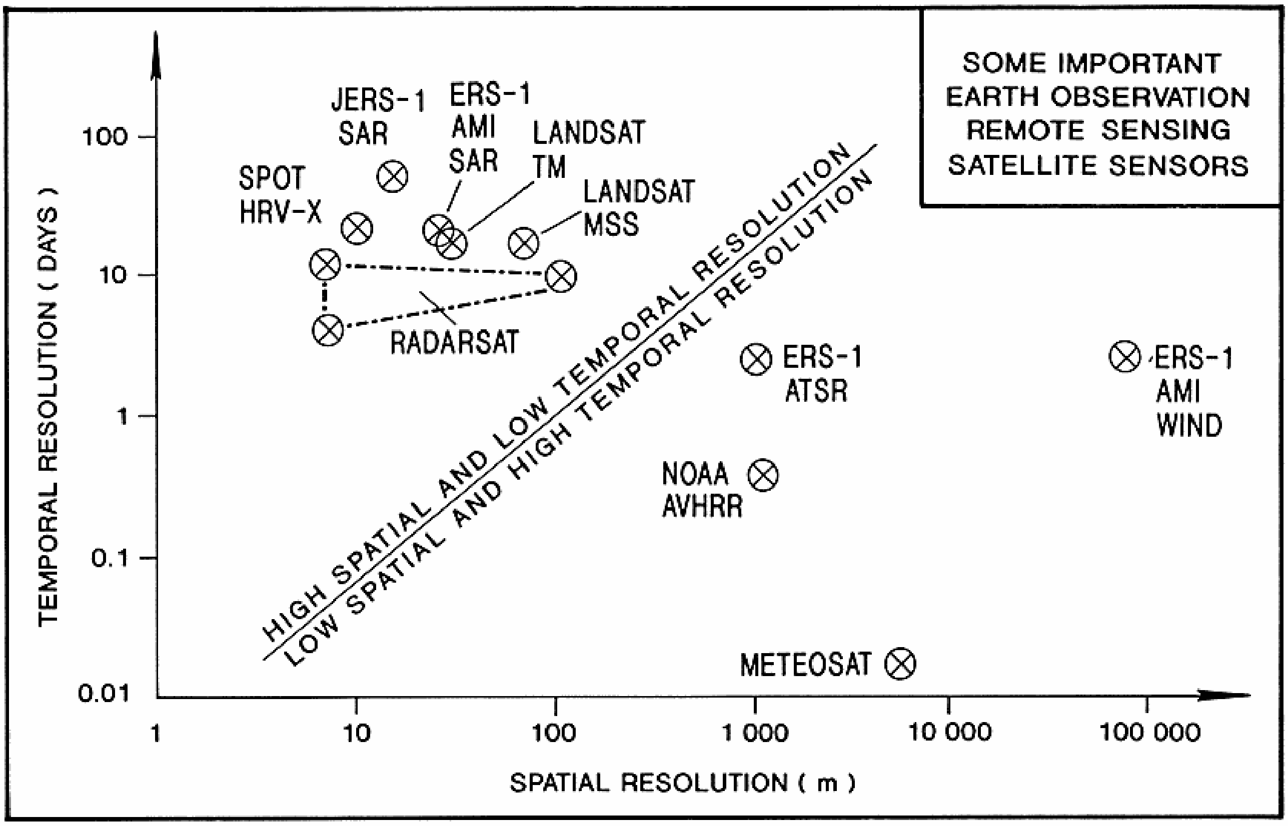



Figure 2. Spatial and temporal resolutions of selected current and future satellite remote sensing systems. For NOAA and Meteosat the spatial resolution at nadir is applied, and for SARs, 3-look data are assumed. By 'temporal resolution' is meant the approximate average time interval between two observations of a given point in Denmark. For ERS-1, a 35-day repeat cycle is assumed. For Radarsat, the area shown depicts the various options planned for this system. The off-nadir viewing capability of SPOT is not accounted for.

independent of atmospheric conditions, (cloud cover etc.) at the time of acquisition and of the solar angle as well. High power requirements may, however, impose operational limitations on radar systems, in that the instruments may often only be operated during a fraction of each satellite orbit.

Airborne sensors differ only little from space-based systems, technically speaking, yet more advanced sensors will often be tested from aircraft years before they are orbited in space. Parameters such as spatial and temporal resolution depend upon the flying altitude and mission planning. Also the selection of 'spectral bands' and 'field of view' may be changed according to the purpose of the data collection.

## The present state and future potential of environmental remote sensing applications

In a European and a worldwide context, remote sensing is envisaged to contribute substantially to future environmental monitoring. This has been strongly emphasized at the political level by the decision of the European Space Agency (ESA) to give high priority to remote sensing activities, and likewise the EU has expressed its interest in using remote sensing as a tool for future union level environmental monitoring systems, probably within the framework of the 'European Environmental Agency', which is being established. Three recent EU reports, named after Rovsing (1991 and 1994) and Gibson (1992), recommend that the EU should give priority to environmental remote sensing applications. Furthermore, the establishment of an EU 'Centre for Earth Observation' aims at increasing the interaction between users - including environmental protection agencies at the national and European level - and ESA.

Potential applications of remote sensing for environmental monitoring in Denmark may be grouped under the following three headings:

(1) Monitoring of rapidly varying parameters (mostly but not exclusively related to the open sea and coastal zones) using satellite-based sensors providing high temporal but low spatial resolution.
(2) Mapping of surface cover types and monitoring of slowly varying surface parameters - in particular land cover types - using a combination of satellite-based and airborne sensors with high spatial resolution.
(3) Monitoring of phenomena requiring exact timing of data acquisition, coverage of specific areas, relatively high spatial resolution and the use of selected sensor designs. This will be termed 'on-demand remote sensing'. These requirements are often very similar to those of research applications.

Category 1 and 2 correspond well to the pattern seen in Figure 2, showing spatial and temporal resolutions of a number of satellite-/sensor-systems. The third category includes themes such as the detection and monitoring of oil spills, algae blooms and detection of the spread of plant diseases. The distinction made between the three categories does not imply that they may not be combined. On the contrary, this may be very relevant in several cases, e.g. in crop/vegetation and marine salinity monitoring. All three categories involve optical as well as microwave methods, and in most cases these may be combined with advantage, as mentioned above.

## Low resolution monitoring of rapidly varying environmental parameters

A range of environmental applications of satellite remote sensing uses data from the so-called meteorological and marine observation satellites, presently encompassing the NOAA-, MOS- and Meteosat/GOES-series, and from low resolution sensors onboard 'Earth observation' satellites, such as ATSR on the ERS-1. Several satellite-/sensor-systems with similar combinations of high repetivity and low resolution are planned for the future, including the SeaWIFS and the 'second generation Meteosat'.

These systems will allow for the estimation of parameters relevant to Danish environmental monitoring such as:

Open sea/coastal waters:

* Sea surface temperature, indicating the spatial distribution of water masses
* Optical properties (colour), turbidity, concentration of algae in the uppermost water layer, sediment load etc.
* Wave heights, wind

Land:

* Surface radiation and energy balance, surface temperature

* Regional water balance, in particular evapotranspiration

* Soil water content

* Regional photosynthetic activity

Measurement of constituents of the lower part of the atmosphere has recently attracted much interest. Airborne systems have been implemented and advanced systems for satellites are being developed. Presently, it may be characterized as a field of research, and only airborne systems are able to retrieve data at heights lower than 5 km. Measurement from satellites of rainfall amounts and intensities over land is also being studied but seems to present great problems, at least under Danish conditions. Data may only be obtained from ground-based radars.

Acquisition and analysis in near real-time of data from the presently available systems - such as the NOAA AVHRR - present few technical problems, due to the fairly limited volume of data involved. Nation-wide coverage may be obtained at low cost. NOAA reception facilities in Denmark are presently operated, and the costs of such facilities are so modest that duplication is likely to occur.

For some of the parameters listed above, methods are ready for operational application. This is true for sea surface temperature (Hansen et al, 1992) and regional photosynthetic activity (using the 'vegetation index-approach') (Tucker & Sellers, 1986). The main technical obstacles to the implementation of more operational applications in Denmark are (1) the remaining scientific problems of verifying the parameter estimation methods, and (2) the lack of a suitable framework for integrating remotely sensed and conventionally measured data.

Some of the future satellite-/sensor-systems will produce more data per coverage than present ones, because optical multi-channel systems and wide-swath radars will be operated. Yet, in view of the foreseen rate of growth in computer systems capacity, this is not likely to present major problems or require any huge investments into equipment. Whether the reception of future low-resolution data will still be possible by use of low-cost receiving facilities, as in the case of NOAA and Meteosat data today, will depend upon the data policies adopted, in that a trend towards "encoded reception" pay-systems is currently observable.

Research will be required, involving substantial sea and ground truth measurements, if full use is to be made of future multi-channel systems. Few studies have included sufficiently detailed measurements to allow for development of models, relating relevant physical and biological parameters to the finer details of the spectral reflectance and emittance patterns now becoming available.

## High resolution monitoring of slowly varying environmental parameters

Monitoring of the terrestrial environment includes identification and characterization of a substantial number of land cover types. So far, optical remote sensing methods, relying mainly upon aerial photos, Landsat and SPOT data, have dominated this application field. Recently, ERS-1 SAR data have become available and the use of an airborne SAR (EMISAR) has been demonstrated. Due to the cloud penetration ability of the SAR, these data sources have attracted great interest. Many future practical applications are thus likely to combine optical and SAR data, and research into combined applications is ongoing and should be further encouraged.

The main land cover types studied will be (1) crops, (2) forests, (3) meadows, heathlands, fallow areas and (4) other 'nature types'. The monitoring often comprises identification of these land cover elements and recording of their change in size and location over time. In addition, high resolution data will be a relevant data source for studies of soil moisture as well as water quality of lakes and coastal waters, and for studies of bottom vegetation in the coastal zone.

Requirements with respect to the spatial resolution of the images to be used vary between these four categories: Agricultural fields are relatively homogeneous and have typical sizes of several hectares. Forests are less homogeneous, and identifiable 'forest stands' are smaller. Categories (3) and (4) are most often inhomogeneous, contain few distinct boundaries and may have quite limited sizes. Consequently, satellite data may be applicable in certain agricultural and forestry application, whereas airborne methods, yielding spatial resolutions in the order of magnitude of 0.5 - 10 m, will be needed to monitor certain 'nature types'. The advantage of large spatial coverage, simple geometry and consistent spectral properties of objects, associated with satellite images, and the advantage of greater spatial detail of airborne remote sensing data may be combined. This is believed to be the optimal solution for many terrestrial applications. Further research and development activities, aiming at easing the integration of data acquired on different scales and resolutions, are recommended. It should be noted that terrain variations have significant effects upon the geometry of images acquired from low altitude and/or at high off-nadir viewing angles. This calls for the use of digital elevation models in the geometrical registration of images from airborne and off-nadir viewing spaceborne sensors.

Analysis of data sets on the terrestrial environment will often require the use of additional existing information on soils, terrain etc, stored within 'Geographical Information Systems' (GIS). Thus, any practical system for the utilization of remotely sensed data for monitoring the environment should be made consistent with the current implementation of 'Environmental GIS' within national agencies and at the county and municipal levels. Considerable efforts are still required in order to allow for flexible, combined use of environmental data in vector format and remote sensing data, which are in raster format, and often have different spatial resolution.

Within the field of general land use, land cover, crop and forest monitoring, a number of Danish research projects have been carried out during the last decade. The main conclusions arrived at are as follows:

(1) Proper identification of a sufficiently large number of land cover classes requires the use of several optical satellite images from carefully selected periods during the growing season (Niels-Christiansen & Rasmussen, 1984, and Nyholm Poulsen & Borup-Svendsen, 1992). These may not be available due to cloud cover, and a recent project (Fog et al, 1993) aims at demonstrating how scarce optical data may be combined with time series of ERS-1 SAR images in order to obtain higher accuracy and probability of coverage.

(2) Classification of individual 'pixels' within a single or a multitemporal set of satellite images will often yield unsatisfactory results. Use of spatial (textural, structural and contextual) information is necessary (Møller-Jensen, 1990), yet it is not known whether a satisfactory segmentation into homogeneous entities, such as fields or forest stands, will be possible based on automatic analysis of the satellite data alone, or whether other data sources and/or visual/manual interpretation techniques will be needed.

(3) Integration with spatial data bases (GIS-systems) will be required. The contents of these data bases may be updated based on the results of the satellite image analysis, and information from the data bases may be used as input to the classification process.

With respect to 'nature types', a term which has a precise definition within Danish environmental legislation, the use of satellite data will have to be combined with airborne remote sensing techniques. This combination has not been tested thoroughly in Denmark, neither in the optical nor in the microwave-/SAR-field, and substantial research, development and demonstration efforts will be needed. At present, county administrations base their work mainly on (colour) aerial photos, and some of them experiment with the digitizing of such photos. There seems to be a strong need for collecting and unifying the experiences gained from these decentralized activities and to develop a coherent approach, in order to ensure consistent results.

It is proposed that a 'digital satellite image base-map', covering the entire land area of Denmark, is produced annually, to serve as a common base for a wide range of land use, land cover, forestry and nature type monitoring activities. It should be co-registered with existing spatial data bases, and will allow for extrapolation of results from more detailed mapping and monitoring efforts, using airborne remote sensing techniques. The base-map should be available to all interested public-sector users, together with the hardware and software needed to handle and extract useful information from it. Standards concerning formats for distribution and interchange of such data will have to be decided upon soon. Assuming a pixel size of 20 m for this base-map, the Danish land area will correspond to approximately 125 million pixels, and the total amount of data involved is 5-10 Gbytes, to be processed (including geometrical correction) over a period of a few months. This may be accomplished without huge investments in equipment.

## On-demand remote sensing

The desire for an on-demand airborne remote sensing facility comes from the need for carrying out remote sensing of a given phenomenon at a given place and time, using a specific combination of sensors, a given flight altitude/direction, and spatial resolution. This need may arise in relation to phenomena such as oil spills from ships or off-shore installations, algae blooms and rapid spread of crop diseases and pests. In addition, such a facility will be able to supply high-resolution data for use in terrestrial environmental monitoring, as described above. As for research, it will also ease the development of methods for retrieving parameters, by allowing for data acquisition at selected places and times, to be coordinated with ground/sea measurements and satellite passes. Finally, work in preparation for the use of data from future satellite-/sensor-systems will be facilitated.

Aircraft may be equipped with a wide range of sensors, including cameras, optical scanners, SLAR, SAR and microwave radiometers, yet the optimum combination of sensors will vary according to the task. It should be noted that requirements with regard to flight altitude, stability, power supply etc. may vary substantially between sensors, and the use of just a single aircraft may not be the optimum solution.

Since the purchase of sensors and having an aircraft on stand-by is costly, a careful analysis of costs and benefits will be required. It is suggested that a series of demonstration experiments are performed in order to test the practical usefulness of airborne data for selected applications. As for 1994, the "Danish Multi-Sensor Airborne Campaign" (DANMAC) and the "European Multi-Sensor Airborne Campaign" (EMAC) experiments will serve this purpose. In order to reduce costs, cooperation with the Royal Danish Air Force should be considered. This has been done in the case of the Electromagnetics Institute airborne SAR (EMISAR), yet most other sensors will have to be operated at a lower flying altitude in order to obtain the high spatial resolutions often required.

An airborne remote sensing facility - as outlined above - will produce ample amounts of data per time unit of data acquisition. The exact figures will, of course, depend upon the selection of sensors. With regard to the EMISAR, a real-time processor has been developed by the Electromagnetics Institute at the Danish Technical University (EMI), and EMI intends to be able to deliver fully geometrically corrected SAR images within the next two years, employing the interferometric capabilities of the EMISAR or a user-supplied 'Digital Elevation Model'. Optical multi-channel scanners also produce large quantities of data, and due to problems associated with the geometry of such data their processing is complex and demanding with respect to methodology, hardware and software. This should be taken into account when defining the airborne remote sensing facility.

The greatest benefits from airborne remote sensing will be gained if integration with satellite-based remote sensing is ensured. A close link between those institutions carrying out preprocessing (including geometrical correction) of satellite data, as suggested in the preceding section, and those involved in the preprocessing of data from the airborne remote sensing facility, should therefore be established, ensuring comparability and co-registration of the data sets. If this is ensured, the satellite data - which typically have a wider spatial coverage - may be used for extrapolation of the airborne monitoring results.

## Conclusions

The study here has resulted in a number of suggestions for action, either in the form of initiation of operational applications, demonstration experiments or research ac-

tivities in the short, middle and long term. In brief, these suggestions include:

1) Operational monitoring of sea surface temperature of all Danish waters on a near-real-time basis, employing data from the NOAA AVHRR sensor and, if possible, the ERS-1 ATSR. It is essential that the implementation ensures the integration of conventionally (in situ) collected and remotely sensed temperature and wind data.
2) Production of an annual 'satellite image base map', based on one or more Landsat TM and/or SPOT coverages. This product should serve as a common reference, providing a uniform and consistent basis for a wide range of applications. The failure of Landsat 6 presently rules out the use of TM images, leaving SPOT as the only alternative, which makes the operation somewhat more costly. With the advent of upcoming satellite systems such as ENVISAT, EOS etc., this is likely to change in the near future, however.
3) Initiation of 'demonstration experiments', providing a basis for future operational applications. Such experiments, the 'European Multi-Sensor Airborne Campaign' and the 'Danish Multi-Sensor Airborne Campaign', were carried out in the summer of 1994 in Denmark, involving most Danish research institutions within the field. They address many of the themes discussed above, including both marine monitoring and various agricultural and environmental land applications of remote sensing data. In addition to EMISAR, a multispectral scanner and a video system are operated on a dedicated aircraft. But more campaigns like these will be needed soon.
4) A number of promising areas for future research are identified, including:
   * Measurement and modelling of optical/radar signatures with a view to the enhancement of future systems for environmental monitoring. Preparation will be needed for future satellite-based optical systems with a high number of very narrow bands as well as for advanced radar systems and scatterometers with multiple frequencies and polarimetric and interferometric capabilities.
   * Integration of multi-sensor and multi-scale remote sensing data, including data from optical and microwave systems.
   * Development, validation and use of invertible reflectance models for estimation of plant canopy, soil and surface roughness parameters from optical and microwave data.
   * Estimation of components of the energy and water balances of the Earths surface using data from several optical and microwave low resolution data sources.

These recommendations reflect the general opinion that environmental remote sensing should be seen in a broader context than before : remote sensing data will supplement conventional data and will be used as input into a variety of models, and all geo-referenced environmental data will have to be integrated into 'geographical information systems' (GIS).

So far, 'users' have defined requirements to be met in order for remote sensing data to be used as input to models. Existing models operating in the spatial domain, such as 'distributed hydrological models', have, however, been designed without considering the potential of input from remote sensing data sources. The true potential of remotely sensed information may not be realized until the models have been redesigned with this in mind. This is also true for models in many other fields, including climatological, hydrographical and plant production models. Redesigning models with the use of remote sensing data in mind will require close interaction between 'model builders' and scientists working with remote sensing techniques.

Integrated use of remotely sensed and conventional data, organized in a GIS and used as input to models, implies that remote sensing will become a tool to be utilized by a much broader group than the 'remote sensing specialists' dominating the field today. This broader group of professionals will need to understand the potential and - not the least - the limitations of remote sensing techniques, which in turn creates the need for a considerable amount of training activities.

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1) Operational monitoring of sea surface temperature of all Danish waters on a near-real-time basis, employing data from the NOAA AVHRR sensor and, if possible, the ERS-1 ATSR. It is essential that the implementation ensures the integration of conventionally (in situ) collected and remotely sensed temperature and wind data.
2) Production of an annual 'satellite image base map', based on one or more Landsat TM and/or SPOT coverages. This product should serve as a common reference, providing a uniform and consistent basis for a wide range of applications. The failure of Landsat 6 presently rules out the use of TM images, leaving SPOT as the only alternative, which makes the operation somewhat more costly. With the advent of upcoming satellite systems such as ENVISAT, EOS etc., this is likely to change in the near future, however.
3) Initiation of 'demonstration experiments', providing a basis for future operational applications. Such experiments, the 'European Multi-Sensor Airborne Campaign' and the 'Danish Multi-Sensor Airborne Campaign', were carried out in the summer of 1994 in Denmark, involving most Danish research institutions within the field. They address many of the themes discussed above, including both marine monitoring and various agricultural and environmental land applications of remote sensing data. In addition to EMISAR, a multispectral scanner and a video system are operated on a dedicated aircraft. But more campaigns like these will be needed soon.
4) A number of promising areas for future research are identified, including:
   * Measurement and modelling of optical/radar signatures with a view to the enhancement of future systems for environmental monitoring. Preparation will be needed for future satellite-based optical systems with a high number of very narrow bands as well as for advanced radar systems and scatterometers with multiple frequencies and polarimetric and interferometric capabilities.
   * Integration of multi-sensor and multi-scale remote sensing data, including data from optical and microwave systems.
   * Development, validation and use of invertible reflectance models for estimation of plant canopy, soil and surface roughness parameters from optical and microwave data.
   * Estimation of components of the energy and water balances of the Earths surface using data from several optical and microwave low resolution data sources.

These recommendations reflect the general opinion that environmental remote sensing should be seen in a broader context than before : remote sensing data will supplement conventional data and will be used as input into a variety of models, and all geo-referenced environmental data will have to be integrated into 'geographical information systems' (GIS).

So far, 'users' have defined requirements to be met in order for remote sensing data to be used as input to models. Existing models operating in the spatial domain, such as 'distributed hydrological models', have, however, been designed without considering the potential of input from remote sensing data sources. The true potential of remotely sensed information may not be realized until the models have been redesigned with this in mind. This is also true for models in many other fields, including climatological, hydrographical and plant production models. Redesigning models with the use of remote sensing data in mind will require close interaction between 'model builders' and scientists working with remote sensing techniques.

Integrated use of remotely sensed and conventional data, organized in a GIS and used as input to models, implies that remote sensing will become a tool to be utilized by a much broader group than the 'remote sensing specialists' dominating the field today. This broader group of professionals will need to understand the potential and - not the least - the limitations of remote sensing techniques, which in turn creates the need for a considerable amount of training activities.

## Acknowledgements

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# Assessing the Land Cover Change of Accra Using Landsat-TM Data

Lasse Møller-Jensen & Poul Yankson

Lasse Møller-Jensen & Poul Yankson: Assessing the Land Cover Change of Accra Using Landsat-TM data. Geografisk Tidsskrift, Danish Journal of Geography 94:xx-xx. Copenhagen, Dec. 1994.

*The objective of the current study is to produce a land cover map of Accra, Ghana, showing the recent spatial growth in order to assess the nature of this growth and the current spatial development trends. A second purpose is to test the adequacy of Landsat-TM images for urban change detection studies. Comments are made on the rationale for land cover mapping based on digital satellite images. The applied image processing method includes a texture-based classification method, pixel to vector conversion and post processing in a vector-based geographical information system.*

Keywords: *Urban land cover, mapping, remote sensing, geographical information systems, Accra, Ghana*

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Most third world cities have witnessed very rapid urbanization since the middle of this century. The rapid growth of urban population has been translated into land use – the extension of urban land uses into the surrounding rural agricultural land. In most cases this process occurs so fast that it almost always overtakes the capacity of planning authorities to deal with what is happening and how to control urban growth so as to avoid the misuse of the scarce land-based resources and environmental degradation.

A major problem or factor in this respect has been a severe lack of up-to-date data or information on land use to guide planning and decision-making. Existing maps are usually old, outdated and, therefore, they cannot be used as an effective information base for planning. Various methods including windshield surveys, census data and aerial photography have traditionally been used for collecting land use and land cover information depending on the degree of details required. Most contemporary urban maps have been developed using large scale aerial photographs. Though there is much merit in this method, aerial photographs have several drawbacks: they are relatively expensive per unit of area; they are produced rather infrequently and they have to be interpreted manually, which for large metropolitan areas is a task of considerable size involving the work of a group of persons for several days or weeks. In recent years the use of satellite imagery for urban land cover studies has become quite popular. The

tivities in the short, middle and long term. In brief, these suggestions include:

1) Operational monitoring of sea surface temperature of all Danish waters on a near-real-time basis, employing data from the NOAA AVHRR sensor and, if possible, the ERS-1 ATSR. It is essential that the implementation ensures the integration of conventionally (in situ) collected and remotely sensed temperature and wind data.
2) Production of an annual 'satellite image base map', based on one or more Landsat TM and/or SPOT coverages. This product should serve as a common reference, providing a uniform and consistent basis for a wide range of applications. The failure of Landsat 6 presently rules out the use of TM images, leaving SPOT as the only alternative, which makes the operation somewhat more costly. With the advent of upcoming satellite systems such as ENVISAT, EOS etc., this is likely to change in the near future, however.
3) Initiation of 'demonstration experiments', providing a basis for future operational applications. Such experiments, the 'European Multi-Sensor Airborne Campaign' and the 'Danish Multi-Sensor Airborne Campaign', were carried out in the summer of 1994 in Denmark, involving most Danish research institutions within the field. They address many of the themes discussed above, including both marine monitoring and various agricultural and environmental land applications of remote sensing data. In addition to EMISAR, a multispectral scanner and a video system are operated on a dedicated aircraft. But more campaigns like these will be needed soon.
4) A number of promising areas for future research are identified, including:
   * Measurement and modelling of optical/radar signatures with a view to the enhancement of future systems for environmental monitoring. Preparation will be needed for future satellite-based optical systems with a high number of very narrow bands as well as for advanced radar systems and scatterometers with multiple frequencies and polarimetric and interferometric capabilities.
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