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COMMITTEE ON THE PEACEFUL USES OF
OUTER SPACE

United Nations/European Space Agency Training Course on the Use of Remote Sensing Systems in Hydrological and Agro-meteorological Applications, held in cooperation with the Regional Centre for Services in Surveying, Mapping and Remote Sensing

(Nairobi, 12-30 October 1992)

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INTRODUCTION

A. Background and objective

1. At its thirty-seventh session, in its resolution 37/90 of 10 December 1982, the General Assembly endorsed the recommendations of the Second United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE 82) and decided that the United Nations Programme on Space Applications should organize training courses on advanced space science applications and new system developments for the benefit of Member States, particularly the developing countries.

2. The United Nations/European Space Agency (ESA) Training Course on the Use of Remote Sensing Systems in Hydrological and Agrometeorological Applications was one of the activities of the Programme on Space Applications for 1992 that were endorsed by the General Assembly in its resolution 46/45 of 9 December 1991. The training course was organized in cooperation with the Regional Centre for Services in Surveying, Mapping and Remote Sensing (RCSSMRS) and hosted by RCSSMRS at Nairobi from 12 to 30 October 1992 for the benefit of participants from the Economic Commission for Africa (ECA) and Economic and Social Commission for Western Asia (ESCWA) regions.

3. The objective of the course was to provide education and practical hands-on experience to participants on various aspects of current and future visible, infrared and microwave remote-sensing systems, including the acquisition, processing, interpretation, applications and archiving of the data generated by such systems as well as on the use of the data in hydrology and agrometeorology.

4. The present report, which covers the background, objective and organization of the course, together with a summary of the lectures presented, has been prepared for the Committee and its Scientific and Technical Subcommittee. The participants will report to the appropriate authorities in their respective countries.

B. Organization and programme

5. The participants were professionals and experts with several years of experience in agronomy, meteorology, hydrology, forestry, agrometeorology and remote sensing. The co-sponsors jointly selected 12 participants and 5 observers from the following 6 countries: Botswana, Jordan, Kenya, Nigeria, Oman and the United Republic of Tanzania. Instruction was provided by experts from Canada, France, the United Kingdom of Great Britain and Northern Ireland, the Food and Agriculture Organization of the United Nations (FAO), ESA, RCSSMRS and the United Nations (Office for Outer Space Affairs).

6. Funds allocated by the United Nations and ESA for the organization of the training course were used to defray the cost of international air travel and daily subsistence allowance for six participants from the ECA and ESCWA

regions. RCSSMRS provided the course's classroom and laboratory facilities and consumable materials.

7. Opening addresses were presented by Mr. Maurizio Fea on behalf of ESA and Mr. Adigun Ade Abiodun on behalf of the United Nations. The keynote address was presented by Mr. Harvey Croze on behalf of the United Nations Environment Programme (UNEP).

I. OVERVIEW OF THE COURSE

A. Introduction and scope of the course

8. Ecological problems throughout the world have become more acute than ever and require urgent action. General awareness of the problem has increased and it is now clear that priorities must be established, because while the problems are numerous and complex, the means of solving them are rather limited. In this context, global ecological trends are of primary importance because they potentially threaten human life. In order to ensure viable and sustainable development, it is necessary to ensure the allocation of essential capabilities, which include, inter alia, the availability of relevant information and data for decision-making, national capacity-building and science for sustainable development.

9. Remote sensing, the science of observing Earth from a distance, will provide much of the necessary information in order to decide what has to be done to protect the environment and to manage the Earth's resources in order to ensure the welfare of future generations. Naturally, satellites will be the main source of information for this. The three main groups of satellites that will play a leading role are the current optical or thermal Earth-observing satellites, and the first of a series of radar satellites, which have recently been launched.

10. Today, mankind has advanced from the deployment of the first generation of passive sensor systems aboard a variety of space platforms to the utilization of high-resolution space cameras and scanners and into microwave sensing in order to monitor the resources of the Earth on a continuing basis. The development of applications for radar data is today one of the highest priorities in the remote-sensing community. Radar brings a new dimension to environmental monitoring and surveillance by satellite, because it guarantees global data collection at predictable, regular intervals.

11. Improvements have been made not only in remote-sensing systems themselves but also in the computer hardware and software used to analyse and extract information from the data that are being acquired by these systems. As the new generation of Earth-observing satellites, particularly the radar satellites, are launched and become operational, an increasing amount and diverse type of data are becoming available. Radar satellites are providing data over frequently cloudy areas that could not be monitored in the past. The use of these microwave data along with data obtained in the visible and

infrared portions of the electromagnetic spectrum in the Geographic Information System (GIS) is becoming a powerful tool to monitor, manage and protect the natural resources and the environment of the Earth.

12. Accordingly, the objective of this training course was to provide the participants with basic knowledge through education and practical training in remote-sensing systems (visible, infrared and microwave), the applications of data generated by such systems and the processing of data for subsequent hydrological and agrometeorological applications, particularly in their respective countries. Attention was focused on fundamental principles of remote sensing, including visible, infrared and radar-imaging systems, current and future Earth observation and meteorological space systems, general principles of Synthetic Aperture Radar (SAR) data acquisition and processing, the formation and interpretation of radar images, digital analysis of satellite data, use of remote-sensing techniques in detecting those processes that are of importance in agrometeorology and hydrology, and practical applications to hydrology, agriculture, forestry and land use.

13. Radars used for remote-sensing purposes may be grouped into three different categories: altimeters, scatterometers and imaging radars. Specialized applications use altimeters to determine the altitude of an object, e.g., a satellite above ground level; their applications are usually to determine land and ocean topography. Scatterometers are used to determine wind speed over a sea surface or as data to assist in the analysis of other radar data. Imaging radar can provide picture-like representations of the observed scene and finds its applications primarily in natural resource surveys and environmental monitoring. The microwave portion of the course focused primarily on imaging radars and on the analysis and interpretation of their data.

B. Fundamentals of remote sensing

14. The development of remote-sensing applications requires a knowledge of the scientific principles underlying remote sensing, including the propagation of electromagnetic radiation through the atmosphere, the interaction of radiation with matter, the detection of radiation by the sensor systems and the generation of images in photographic or computerized form. The sensors themselves are classified as imaging or non-imaging, depending upon whether the sensor data can be converted into a map-like representation of the scene observed. Remote sensing deals primarily with imaging sensors. Sensor systems are also classified as active or passive systems depending upon whether they supply their own source of radiation, as in the case of radar, or use natural radiation, as in the case of photographic systems.

15. Airborne photographic cameras still commonly use remote-sensing systems. The advantages offered by aerial photography include geometric accuracy, stereoscopic relief information, a broad range of image scale and coverage, depending upon the flight altitude and camera focal length, a broad choice of film-filter combinations to select spectral bands, well-established procedures

for acquiring and interpreting images, a large number of experienced photo-interpreters and photogrammetrists and the flexibility of acquiring images at the desired time and place.

16. Photographic systems are sensitive to the visible portion of the electromagnetic spectrum and to portions of the ultraviolet and near infrared regions. Because shorter-wavelength radiation is scattered to a greater extent by the atmosphere, resulting in hazy images, the ultraviolet band is not commonly used for remote-sensing purposes, and blue light is often excluded in favour of near infrared radiation. Thus, the three commonly used bands in colour photography in remote sensing are the green, red and infrared bands. The selection of photographic spectral bands, through the selection of films and filters, is determined by the spectral characteristics of the objects to be studied. Colour infrared film (with filters to eliminate blue light), for example, is used to study vegetation since green leaves are highly reflective in the near infrared and that reflectance is sensitive to vegetation type and condition.

17. The information obtained from aerial or space photography is generally used to create a map or is transferred onto a map. This can be done either by tracing features from the photograph onto a transparent overlay, by visually comparing features of the photograph with corresponding features on a map and transferring information freehand or by using equipment that optically or digitally superimposes the photographic image on the map.

18. Photo-interpretation involves the identification and evaluation of features on a photograph that are considered significant for some applications. The photographic elements on which the identification and evaluation are based are the size, shape, tone and colour, texture, pattern, shadow, site and association of the various features on the photograph.

19. Visual interpretation of satellite imagery is an extension of photo-interpretation of aerial photography, differing mainly in that the large scale of the satellite imagery and the lack of stereoscopy (except in the case of some SPOT data) make features less easily recognizable. While on small-scale aerial photography, an untrained viewer can recognize many common features such as trees, rows of crops, buildings, roads and animals, these features are generally too small to be seen on satellite imagery, and few untrained viewers can reliably interpret the larger features. Information must often be deduced from seemingly abstract textures, patterns and associations. Satellite image interpretation, therefore, tends to be more theoretical and more specialized than photo-interpretation. The repetitive nature of the satellite data is often useful in interpretation since images from different seasons or years will show changes that indicate the nature of the area.

20. The information gathered by a sensor system in each of possibly many spectral bands can be converted digitally into an image form. The image can then be represented in black and white with varying grey tones or in colour with varying colour hues. For each band the intensity of tone or hue is proportional to the amount of radiation that was reflected, emitted or back-

scattered by an object (target) on the surface being observed. When the primary colours (blue, green or red) are assigned arbitrarily to each spectral band and two or three of the bands are superimposed, the resulting composite image will contain a wide range of colours where each colour is the visual effect of superimposing the primary colour hues corresponding to an object on the ground. Knowing the spectral properties of various targets (e.g., water, vegetation, soil) in the spectral bands in which the sensor systems gathered the information, the primary colour that was assigned to each band and the theory of colour, the user would be able, qualitatively, to make a first-level identification of most of the objects that appear in the image. For many applications this accuracy and level of classification is sufficient.

21. Since the tones of grey or the digital values that represent an image are a measure of the radiation received by the sensor, a user can perform either a qualitative or a quantitative radiometric analysis or perhaps both. For accurate image analysis and interpretation it is essential that the user have a thorough understanding of the physical processes involved in the creation of an image. This implies being familiar with the two basic principles of radiometry, which are: (a) the validity of the principle of superposition for wavelike phenomena; and (b) the linearity of sensor response to radiation coming in its band of operation.

22. One of the limiting factors in using remote sensing on an operational basis has been the lack of data in time periods that are most adequate for optimal discrimination of features particular to a specific application. Because of cloudy conditions, a multi-temporal approach to land use also suffers from limitations of data availability. To some extent the off-nadir viewing capability of SPOT and the combined use of its data with Landsat's Thematic Mapper (TM) data have alleviated these limitations. However, in tropical areas which have excessive cloud cover, the capability of microwave radiation to penetrate clouds and light rain showers could make radar imagery of particular value to developing countries.

23. Microwave remote sensing provides the capability for day or night observations and under clear-sky or cloudy conditions. This is possible because most microwave sensor systems provide their own source of radiation (i.e., independent of the sun) and because microwave radiation, which is in the 0.3 GHz (in terms of wavelength, between 1m and 1mm) portion of the EM spectrum, can penetrate through clouds and light rainfall.

24. Although radar systems are usually defined by the frequency interval in which they operate, they are sometimes designated by their wavelength of operation. This is done because newcomers to radar technology are usually more familiar with the concept of wavelength of the EM radiation. However, frequency is the more fundamental property of EM radiation since its frequency remains constant when it passes through media of different densities while its wavelength and velocity change. To transmit information, a carrier wave of a particular frequency can be modulated by varying the amplitude of the wave (AM modulation). An alternative way is to modulate the frequency (FM modulation); this is less subject to interference and is the one commonly used to transmit high-quality signals.

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25. Microwave sensors can be classified into passive and active systems. Passive systems measure microwave radiation emitted by the ground features or by the sun and reflected by the surface. Active systems "illuminate" the area under observation and measure the strength, phase and time delay of the radiation reflected by the ground features.

26. The interaction of microwave radiation with objects on the surface of the Earth depends strongly upon the electrical properties of the objects and the surface roughness relative to the wavelength of the incident radiation. The electrical properties of matter are determined by its dielectric coefficient, which is highly sensitive to water content. An analysis of the returned signal can therefore provide information on the nature of the objects, their relative size, distribution and moisture content.

27. Radar images can be obtained from either an aircraft or a satellite. In both cases, the images are obtained by transmitting microwave pulses at an angle to the vertical and measuring the intensity and time delay of each return pulse. The first return pulse corresponds to the object whose projected distance in the direction of the sensor system is the smallest. In general this pulse corresponds to the object closest to the flight path. Because of the geometry between the incident pulse and the height of objects, the projected distance in the direction of the sensor system of the upper part of an object is smaller than the distance of its corresponding ground-point projection. This effect is known as foreshortening and makes terrain of high relief appear in the image as falling towards the radar. On the images, foreshortening causes the slopes to become extended and to appear darker. This effect can be corrected with reference to a digital terrain map.

28. The foreshortening effect can become very severe so that the top of a mountain appears to be closer to the flight path than the foot of the mountain. This effect is called layover and cannot be corrected. Other image degradations include a speckle effect, which appears as noise on the image and is related to the frequency coherence of the system, as well as several effects due to the motion of an object with respect either to the sensor system or to other objects in the field of view of the radar.

29. Because the difference in distance between objects directly beneath an aircraft or a satellite is very small, the corresponding return signals often cannot be electronically discriminated. For this reason airborne radars have been designed to scan objects at some distance to one of the sides of the aircraft and are called side-looking airborne radars (SLARs).

30. The spatial resolution attainable from a radar system is independent of the altitude of the sensor platform and increases with the length of the antenna that transmits and receives the microwave pulses. A technique known as Synthetic Aperture Radar (SAR), which applies a linear frequency modulation to a transmitted long pulse in order to simulate a train of short pulses, has been developed in order to keep satellite antennas reasonably small. The technique uses the Doppler shift of the reflected pulse due to the motion of the platform and a modified data processing to simulate a much longer

antenna. The result is a higher resolution which is only limited by the power that the antenna is capable of transmitting.

31. The microwave spectrum is subdivided into various bands, each of which is referred to by a single letter and is determined by a specific range of frequencies, as follows:

Band name	Band limits (GHz)	Band name	Band limits (GHz)
P-band	0.225-0.390	K-band	10.90-36.00
L-band	0.390-1.550	Q-band	36.00-46.00
S-band	1.550-4.200	V-band	46.00-56.00
C-band	4.200-5.750	W-band	56.00-100.0
X-band	5.750-10.90		

For airborne radar missions, which account for the bulk of the microwave data gathered world wide to date, the most used bands have been in the X-band. For the satellite radar systems of the 1990s, the predominant frequency will be the C-band.

C. Radar concepts

32. For most imaging radar systems, the geometric configuration is such that a microwave beam is radiated from the side of the platform, at an angle to the surface and perpendicular to the flight direction. The radar beam is wide in the vertical dimension and narrow in the horizontal dimension. A two-dimensional imaging plane is produced by the motion of the radar platform which periodically transmits pulses. Thus, continuous strips of the Earth's surface may be "viewed" parallel and oblique to the flight direction. The scanning concept of the imaging radar is, therefore, quite different from that used by scanners that operate in the visible and infrared regions of the EM spectrum. The latter build an image on a line-by-line basis, their viewing geometry is downward-looking and the spatial resolution of the images depends upon the angular resolution of the sensor system and platform altitude and degrades away from the nadir track.

33. Imaging radars do not depend on angular resolution; instead, their across-track resolution range is determined by measuring the time delays between the reflected signals due to the transmitted pulses. The range resolution depends upon the length of the radiated pulse which determines the distance by which two objects must be separated in order to be discriminated. This resolution increases as the radiated pulses become shorter. The azimuth along-track resolution is determined by the width of the microwave beam, which is in turn determined by the length of the antenna. The azimuth resolution increases with the length of the antenna.

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34. For SAR instruments, the limiting factor for their range resolution is shortening the transmitted pulse while maintaining sufficient power to detect the reflected signal. This is accomplished by coding the transmitted pulse through a linear frequency modulation, the so-called "chirped pulse". The range components of the return signal must be processed to obtain the corresponding resolution. Azimuth-related components of the same signal must similarly be processed to obtain the along-track resolution. Thus, the acquisition of SAR imagery requires a processing system that can operate on a two-dimensional array of signal data.

Instrumentation

35. A basic imaging radar system consists of a transmitter, a receiver, an antenna designed to transmit and receive microwave energy and a data-processing and recording unit. The transmitter generates a short microwave pulse with a duration of microseconds. This signal is transmitted by the antenna. The antenna directs a narrow beam into the range direction and receives the returned portion of this pulse. The design and form of the antenna determines the beam width of the "illuminated" ground surface.

36. The receiver measures the strength of the returned portion of the transmitted signal and relates the receiving time to the transmitting time in order to determine the range distance of the reflecting object relative to the radar. The receiver converts the signal waveform from a frequency band suitable for radiation to an equivalent one that is suitable for recording. This requires a correlation process between the transmitter and the receiver. The recorder and processor units turn the raw data either into an optical record (e.g., on film) or into a digital record using high-density digital tapes (HDDTs). Further processing of the radar return signals is necessary by means of correlating signal film or HDDT data to produce radar imagery or computer-compatible tapes respectively. The latter may then be used for digital display, image manipulation and analysis.

Microwave polarization

37. An electromagnetic wave consists of coupled electric and magnetic fields which oscillate at right angles to each other in a regular wavelike manner. The polarization of a waveform describes the orientation of the electric field sector at a given point in space during one period of oscillation. In the simplest case, each field oscillates only in one plane: the wave is plane-polarized. When the electric field oscillates in a vertical (horizontal) plane, the wave is vertically (horizontally) polarized. Most imaging radars use an antenna that transmits horizontally polarized radiation. Upon incidence on a ground object, a portion of the return energy retains the same polarization as the transmitted pulse while the remainder of this energy is randomly polarized (i.e., depolarized).

38. Sophisticated radar systems can transmit horizontally and vertically polarized energy. A switching mechanism in the antenna allows it to receive both the horizontal and vertical components of the return signal.

Designations such as "HH" and "VV" stand for "horizontal transmit and horizontal receive" and "vertical transmit and vertical receive" respectively. Similarly, "HV" represents "horizontal transmit and vertical receive"; this is known as cross-polarized return. Polarization of the incident radiation is an important discriminating element since ground surfaces and other targets reflect differently each of the two components mentioned. For example, a simplified model of a vegetation canopy composed of vertically linear leaves (scatterers) would provide a strong reflected signal for vertically polarized incoming radiation but a very weak signal if the radiation were polarized horizontally. Thus, the return signal can provide information on the structure of the objects being viewed.

D. Sources of radar data for remote sensing

39. Launched in July 1991, ERS-1 is a low-orbit Earth observation satellite with several microwave sensors on board. The primary mission of ERS-1 is to increase the understanding of ocean processes, to monitor the polar regions and to contribute to the World Climatology Research Programme. However, an increasing number of land-oriented applications will soon result as the international research community gains access to the data. The primary instrument on board ERS-1 is the Active Microwave Instrument (AMI), which can provide high-resolution images (C-band), wind speed through ocean wave spectra analyses and the length and direction of ocean waves. Operating in the imaging mode, AMI covers a swath of 80 to 100 kilometres, with initially assessed resolution of 27 metres in range and 29 metres in azimuth. Assessment through October 1992 also shows high precision and replicability of the data acquired by ERS-1.

40. Operating in the wind mode, AMI covers a swath of 400-500 km over the ocean with resolution cells of 50 km and measures wind speed in the range of 4-24 m/s with an accuracy of 0.5-2 m/s. Wind speed and direction are determined by measuring the strength of the back-scattered signal of each resolution element from three directions: obliquely ahead, to the side and obliquely behind the satellite path. The intensity of the three signals provides the wind speed, and the differences between them indicate the wind direction with an accuracy of 20 degrees. In wave mode operation, AMI determines the length and direction of ocean waves in 5 x 5 km cells for segments of 200-300 km along the satellite path. Ocean wavelengths of 100-1,000 m can be measured to an accuracy of 25 per cent and their direction to an accuracy of 20 degrees.

41. In addition to AMI, ERS-1 carries a Radar Altimeter (RA) that operates at a wavelength of 2 cm. This altimeter looks vertically downward to measure average wave height and wind speed and to determine the meso-scale ocean topography. Data from this altimeter will be used to determine ice type and topography as well as the water-ice boundaries. ERS-1 also carries an Along Track Scanning Radiometer (ATSR) that operates in three bands in the thermal infrared region; these bands are centred around 3.7, 11 and 12 micrometres. ATSR looks through the atmosphere at the surface of the ocean from two

directions, downward vertically and at an incidence angle of 50 degrees. The difference between the oblique and vertical measurements provides information on atmospheric absorption while the differences between measurements at the three wavelengths are used to determine atmospheric water vapour content.

42. ERS-1 data is received by ESA's network of ground stations, which include Maspalomas, Spain; Kiruna, Sweden; Fucino, Italy; and Gatineau and Prince Albert, Canada; as well as by a number of ground stations located in the industrialized and developing countries. User requests for acquisition of ERS-1 data over a particular area of the Earth or requests for specific products of ERS-1 data already acquired are channelled through ESA's Earthnet Central Facility (EECF), located in Frascati, Italy. It is the user gateway to the ERS-1 system, and performs cataloguing, handling of user requests, payload operation planning, scheduling of data processing and dissemination, quality control of data products and sensor performance monitoring.

43. The Mission Management and Control Centre (MMCC) is at the European Space Operations Centre (ESOC) at Darmstadt, Germany. It controls the satellite and schedules the instruments, communicating with the spacecraft via the Kiruna ground station. This station is used because its northerly latitude allows it to see the satellite on 10 out of the 14 daily orbits. ESA ground stations at Kiruna, Fucino, Gatineau and Maspalomas form the main network for data acquisition and the processing and dissemination of fast-delivery products.

44. Both real-time instruments and onboard recorded data are acquired by Kiruna, with the raw data being stored on high-density digital tapes. Fast-delivery processing facilities comprise two chains devoted to the SAR (image and wave mode), and one devoted to the processing of the data from other instruments. The Fucino station is used primarily for the acquisition of SAR image data and real-time low-bit rate data over the Mediterranean Sea. The stations at Gatineau and Maspalomas are used for the acquisition of recorded low-bit rate data.

45. To date, most of the radar data collected world wide have been obtained by airborne radar systems. Even with the arrival of radar satellite systems, aerial systems will continue to provide data to meet specific use-determined acquisition parameters, particularly flight direction, viewing angle and high spatial resolution. Although the bulk of the satellite radar data that will be acquired over at least the next 10 years will be obtained in the C-band, most of the experience developed to date has been with radar operating in the X-, L- and K-bands. Airborne radar such as the C/X-SAR can also be used to investigate the use of C-band radar in monitoring the Earth.

E. Digital image processing and analysis

46. The capability to digitally process large volumes of data with uniform criteria, and often data that have been enhanced or which include new bands as a result of linear transformations of the original ones, allows the routine monitoring of large areas and the attainment of a finer discrimination between classes in the scene.

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47. Satellite image data as provided to the users does not generally represent the surface of the Earth with the geometric fidelity necessary for topographic maps and does not usually fit into existing standard map projections. This is due to effects that are introduced by changes in attitude, altitude and spacecraft velocity, non-linearities in the sensor scan process, unequal sensor response, effects of the Earth's curvature and rotation and elevation of the satellite over the Earth's surface. Most of these effects (the systematic ones) can be compensated for during the preprocessing geometric and radiometric correction stage; this is done more efficiently using a digital process.

48. Digital image enhancement improves the visual presentation of the information content of the image. These techniques assist in a visual interpretation or in reducing the amount of digital data to be processed but do not create any new or additional information. Common techniques include the following: contrast enhancement, spatial filtering, linear band combinations and principal component transformation. Since in any image the full dynamic range of values that the pixels could take (typically from 0 to 255) is not utilized, the contrast of the entire image can be digitally improved. A typical range of values in an image is of the order of 80, so that the contrast can be improved visually by a factor of 3. Low-pass and high-pass filters are used to smooth out the local variations of radiance values or to enhance reflectance differences, particularly at borders between two classes of objects. Principal component transformations are a way of reducing the number of data of a set of images while retaining the most significant information. Linear band combinations include generating a new band from the ratio of two bands or the ratio of the difference of two bands to the sum of the same bands; these transformations, and many others that might be performed, enhance features of interest to the interpreter.

49. The final output of the evaluation of remote-sensing data is a thematic image (or map) of the scene analysed depending upon the specific interest of the interpreter. The process of achieving this through digital processing is called "classification". Two different approaches to digital image classification have been developed: supervised and unsupervised classification. The first approach requires that the interpreter identify areas representative of the classes to be included in the thematic output in order that the classification algorithm may use statistical parameters to classify each pixel in the image into one of the classes requested. Unsupervised classifiers require little interaction by the user and are based entirely on statistical methods. The rationale behind the latter approach was to make the classifications independent of the skill of the user. However, experience has shown that the quality of the supervised classification is usually better, since the experience accumulated by the user is more fully utilized.

F. Remote-sensing applications

50. Water, which used to be taken for granted and was thought of as existing in practically infinite abundance, has become one of our most precious natural resources. Hence hydrological and water management problems represent key areas of applied science in current world-wide economic and ecological conditions. Furthermore, hydrological properties are strongly interlinked with processes at the surface of the Earth and in the atmosphere, influencing environment and climate. Water shortages or excesses may have disastrous consequences. Droughts in one region may coincide with heavy rains and floods in others. Equally essential is a continuous survey of the water quality and pollution of all major water bodies.

51. Accordingly, the need to access and forecast water supplies has increased rapidly. Satellite remote-sensing technologies have been used increasingly to satisfy these urgent requirements for information. No other method is capable of providing the necessary data in near real time, in regular temporal sequences and on a regional, continental or global scale in order to measure, monitor and model the complex hydrological processes in the environment. Most elements such as rainfall, snow, run-off, evaporation, soil moisture, sediment load and discharge, pollution, temperature, etc., show characteristic temporal and areal variations.

52. Remote-sensing applications in hydrology include inventories of water resources, measurement of land cover and assessment of wetland areas. There is limited use of remote sensing in hydrologic modelling because of dissimilarity in time and space averages. Key parameters include soil moisture, evaporation, impervious areas, land cover, extent of snow cover, water equivalent of snow cover and precipitation. Various rainfall run-off models currently used for hydrologic modelling were developed before the advent of remote sensing and are based upon the use of topographic maps.

53. The difficulty in determining the soil moisture is related to the fact that most data gathered by space-borne sensors are limited to the uppermost layers of the soil. Soil moisture can be defined as the temporary storage of precipitation within a shallow layer of the Earth that is generally limited to the zone of aeration or root zone.

54. The passive microwave region (particularly around 21 cm wavelength) has been exploited the most so far. It has been established that the moisture content can be measured to a depth of about 5 cm (perhaps as much as 10 cm) with a relative accuracy of 10-15 per cent. These measurements can be made under all-weather conditions and through light to moderate vegetation cover. Soil moisture at lower levels cannot be detected directly if covered by a dry layer.

55. SAR measurements at C-band and L-band frequencies are also sensitive to the presence of water in the topsoil layer and provide sufficient spatial resolution to separate areas of uniform land use and vegetation cover for moisture mapping. Determination of volumetric soil moisture from SAR data is

complicated by additional factors, such as vegetation cover and surface roughness, which influence back-scattering. Some of these difficulties can be overcome by multi-temporal analyses, which enable the detection of temporal changes in soil moisture content as demonstrated by means of airborne C-band scatterometer measurements.

56. Soil moisture affects the thermal properties of the soil. If vegetation is present, its appearance may be used as an indication of the water available in the root zones, provided that it is the plant's growing season. Since no straightforward remote-sensing method is available for accessing soil moisture, it is necessary to combine various measuring techniques with hydrological models. Extensive research is needed with both active microwave and thermal infrared in this field.

57. The all-weather capability of imaging radar offers considerable benefits of agricultural applications because there is a strong requirement for frequent and reliably timed images. For instance, crop inventories require the collection of data at various times during the crop growing season when there are marked differences in the appearance of each type of crop. The timing requirements are more stringent for yield prediction, when crop growth needs to be monitored at specific times during the growing season.

58. Radar has therefore aroused world-wide interest, and many experimenters have used and analysed Seasat, SIR-A and SIR-B imagery. Although the potential of SAR observations has been demonstrated by such analysis, a proper evaluation of the use of SAR as a source of information in agriculture has not been possible. There are at least two reasons for this. The first is that the L-band radars used in these space-borne missions were not optimized for applications in agriculture, and the second is that no multi-temporal imagery was available. Over the past decade a number of investigations have been carried out which are intended to fill these gaps.

59. The potential for crop identification is related to the fact that crops have different growth cycles through which their back-scatter responses follow particular temporal sequences. With a single-frequency radar (especially X-band), a combination of images taken on different selected dates can produce a good crop classification. Apart from the multi-date observation capability, for most SAR systems that have single frequency, multi-polarized data appear to be promising. For vegetation, on the basis of both models and field experiments, multi-polarized data are expected to be sensitive to differences in plane morphology. In addition, for a single-frequency radar, the use of different incidence angles appears to help crop identification. The relative contribution of the vegetation to the radar back-scatter is higher at high incidence (>40"), whereas at lower incidence the underlying soil surface may make a significant contribution.

60. Besides measuring temporal variations in crop spectral properties for identification and monitoring purposes, radar may provide useful information on canopy structure and biomass. Since the radar back-scattering coefficient can be affected by the amount of water contained in the canopy of a given

structure, as well as the underlying soil moisture and soil surface roughness, to retrieve a given crop parameter from the radar measurement requires an optimum choice of radar parameters to minimize the other effects.

G. Image analysis hardware and software

61. The aim of the image analysis hardware and software presentation was to provide insight into how to choose hardware/software configurations for image analysis, emphasis being placed on aspects that may determine the final choice of system. Where necessary, the appropriate warnings were given, particularly where technical jargon and sales or media-intensive publicity promotion serve to obscure the real merits, or demerits, of particular system configurations.

62. The following hardware systems were analysed in retrospect and according to their purpose: low-cost budget systems based on the IBM PC family of personal computers; and general-purpose workstations based on Reduced Instruction Set Computer (RISC) processors and the UNIX operating system. Particular emphasis was placed upon the graphic display subsystems available for all these systems, as well as the suitability of these graphic display subsystems for image analysis. Recommendations were made regarding suitable systems configurations for image analysis applications, and guidelines were given regarding the balance of investment to be made in the display subsystem against other system components such as raw processor speed and the provision of disk storage.

63. Software systems were considered from the perspective of the software interface, general functionality and specific remote-sensing functionality. Discussion of the software interface included a historical overview of the evolution of image analysis environments, from the traditional sub-routine libraries to the modern point-and-click approach, and the use of icons and functional diagrams to define the desired operations. More than general functionality, attention was drawn to those requirements of image analysis software which are important for remote-sensing applications but which are sometimes overlooked or neglected in general-purpose image processing systems. Consideration was also given to features of software systems that may influence the choice of one particular system before another, and mention was made of some of the image analysis software available in the public domain. A small range of PC-based image analysis software packages were made available to participants for their personal use and evaluation.

H. Geographic Information Systems

64. Geographic Information System (GIS) technology has emerged as a new and powerful tool for the analysis of geographic, environmental and statistical data in the common spatial framework. The concept of GIS aiding the environmental planning process has gained considerable attention throughout the world in recent years. Conventional databases have been commonly used by environmental planners for information storage and retrieval. This

information, however, lacks a visual, spatial context. More often, environmentalist planners need information to be displayed and related in its true geographical context (e.g., a map) in order to arrive at concrete solutions. There are many instances where environmental problems, in addition, require interpretation by superimposing or overlaying more than one thematic map on the base map of the area under study. Manually, this process is very tedious and suffers from many drawbacks.

65. A computer-based system, on the other hand, is an excellent tool that is not only speedy but also relatively free from most drawbacks. GISs are computer systems designed to store, retrieve, manipulate and analyse spatially referenced or geo-coded data. A computerized GIS allows managers to perform complex analysis by "overlaying" and displaying large volumes of spatial and non-spatial data. The interfacing of remote sensing and GIS has attracted considerable attention in the past few years.

66. Technical issues such as raster-to-vector conversions have obstructed the ready use of remote sensing information with GIS in the past. However, significant breakthroughs have been made recently to remove the bottleneck in integrating remotely sensed information with GIS. The advances in GIS technology that have enhanced its value to managers are the following:

(i) New hardware and software for digitalizing and managing data and interpreting and reproducing maps, making these tools more powerful and easier to use;

(ii) Desk-top workstations, with increased data-processing speed and data storage capabilities;

(iii) Inexpensive plotters, lowering the cost and improving the quality of producing maps, charts and tables.

67. GIS can be defined as consisting of the following three basic elements:

(i) A large amount of data which have spatial or locational characteristics;

(ii) An integrated set of programmes which distinguishes the GIS from a series of unrelated individual programmes;

(iii) A common set of subcomponents which perform such operations as data storage, retrieval and display.

From the user's point of view a GIS is a relational type of database, spatially indexed in such a way that new information can either come from external sources or be created from existing information.

68. Analyses conducted with a GIS can provide decision-makers with information in a form more readily adapted to their needs. GIS maps can be easier to work with and more readily updated than standard maps. A GIS can be

used to highlight areas on maps where action is required or where data are questionable. For example, a GIS can be used to generate maps which depict the status of a resource in a given area. Furthermore, a GIS can be used to visualize alternative scenarios so that they may be easily compared. A GIS can be used to combine different types of maps and display them in a three-dimensional form, and the scale and the features highlighted can be changed quickly.

69. Whether a GIS should be used in any given situation can be determined only by weighing the costs and benefits of performing the required analysis. The benefits are determined by the degree of complexity, integration and sophistication the GIS analysis offers over manual analysis, and the value of this information to the manager in terms of enhancing resource quality, reducing environmental degradation, saving lives, preventing costly management mistakes and increasing economic revenues. Setting up a GIS project involves the consideration of many constraints: high investment costs, additional qualified human resources, and so on.

I. Characteristics of meteorological satellites and applications in early warning for food security and environmental monitoring

70. Operational meteorological satellites provide visible and infrared data useful for meteorological analysis and weather forecasting. These meteorological forecasts are of considerable importance to agricultural applications. In addition, however, there are forms of data and products of meteorological remote-sensing satellites that are of specific interest to agrometeorology, crop output assessment and drought monitoring.

71. The characteristics of both geostationary and polar orbiting satellite systems designed for meteorological observation of the Earth were introduced, in particular, those of Meteosat (in view of its importance for rainfall estimation over Africa) and the NOAA Tiros series of satellites (useful for vegetation monitoring over extensive areas). The relative advantage of high temporal resolution, as opposed to high spatial resolution, for environmental monitoring and rainfall estimation was also discussed.

72. The FAO project at RCSSMRS, which provides the remote-sensing component to the early warning system for food security in East African countries, was briefly outlined at the training course. The project concentrates, for example, on developing methods to utilize meteorological satellite data in early warning systems for food security, the training of national staff from the East Africa region who are involved in early warning, and the distribution of imagery and value-added products to national and regional organizations similarly involved. The project also investigates conventional and electronic mechanisms to communicate remote-sensing data of the type needed for early warning to cooperating users in the region.

73. Sensor characteristics in the visible and thermal infrared regions of the spectrum were presented, along with the nature of the scanner used by Meteosat. Details of the relative importance of convective systems in the total rainfall in the equatorial belt were given, and this concept was related to the cloud characteristics inferred from Meteosat observations. For example, the duration of particular threshold temperatures at the top of storm clouds is strongly related to rainfall amounts received at the Earth's surface. Meteosat is able to monitor cloud top temperatures every 30 minutes throughout both day and night, thus enabling the near continuous estimation of rainfall amounts and distribution over continental Africa from space. Details of calibration experiments currently under way in the Inter-Governmental Authority on Drought and Development (IGADD) subregion were described to underline how the precision of satellite rainfall estimates from cold-cloud-duration (CCD) information could be improved in the future.

74. Cumulative cold-cloud-duration images compiled by accumulating values of individual CCD images for each 10-day period over East Africa during recent rainy seasons were shown to indicate the usefulness of this type of information in highlighting the current drought situation in the region.

75. The characteristics of the NOAA Advanced Very High Resolution Radiometer (AVHRR) on board the satellite were discussed in relation to the spectral characteristics of vegetation reflectance at the Earth's surface, for example, how NOAA satellites sense information in the visible and near infrared portions of the spectrum. An explanation was also given as to the nature of near infrared energy which lies just outside the visible region of human vision, but is strongly reflected by healthy and vigorous green-leaf vegetation. A summary of the research in recent decades was presented, and showed that remote sensors capable of measuring the relative amounts of visible and near infrared light reflected from vegetation can be used to monitor the development of green-leaf vegetation. It was explained that the NOAA satellites contain the necessary sensing devices which enable the monitoring of vegetation behaviour on Earth from space.

76. An index of vegetation vigour, the Normalized Difference Vegetation Index (NDVI), was explained and its use was described in measuring the relative condition of vegetation and soil moisture availability at the Earth's surface from one monitoring period to another. Composite images of vegetation generated from 10 days of data, selecting the "greenest" data to minimize the effects of cloud masking of the Earth's surface, were demonstrated to the participants along with examples of operational NOAA products for early warning which are distributed every 10 days by the FAO project to users in the region.

77. Images of this type are not without limitations, and some of the more important problems were discussed with the participants. The eruption of Mount Pinatubo in the Philippines, for example, in June 1991, caused considerable amounts of volcanic dust to enter the Earth's stratosphere. This in turn caused interference in the radiation sensed by the NOAA satellites and reduced the reliability of the information used to monitor vegetation from June 1991 up to the present time.

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II. EVALUATION OF THE COURSE

78. After completing the course, the participants were requested to complete a questionnaire on various organizational aspects of the course, the time allotted to each of the subjects and practical exercises as well as the applicability of the course to their current and future activities.

79. The completed questionnaires, having been analysed, reveal that participants were satisfied with the organization and planning of the course; they noted, in particular, the high quality of the presentations. Two thirds of the participants were in favour of longer periods for practical exercises in digital image analysis. Depending upon their field of expertise, some participants felt that more time should have been allocated to various applications. The majority of participants indicated that the level and content of the training course were appropriate for the specific needs of their work. They were unanimous in expressing their appreciation to the United Nations, the European Space Agency and the Regional Centre for Services in Surveying, Mapping and Remote Sensing for having organized and sponsored the course.

Annex

PROGRAMME OF THE COURSE

Date	Time	Subject	Speaker
Monday 12 October	9-10 a.m.	Registration	
	10-10.45 a.m.	Opening ceremony	United Nations/ UNDP/ESA/RCSSMRS
	11-11.45 a.m.	Keynote address: "Environmental management: devising strategies for development without damaging the Earth's Biosphere"	H. Croze (UNEP)
	11.45 a.m.- 12.30 p.m.	Overview of remote sensing	L. Isavwa (RCSSMRS)
	2-5 p.m.	Fundamentals of radiometry	J. Baraza (RCSSMRS)
Tuesday 13 October	9-10.30 a.m.	Characteristics of satellite Earth observation systems	A. Abiodun (United Nations)
	10.45 a.m.- 12.15 p.m.	Characteristics of meteorological satellite systems (geostationary and polar)	B. Henricksen (FAO)
	2-3.30 p.m.	Principles of image formation (data acquisition, digital/ analogue representation, display techniques)	J. Baraza (RCSSMRS)
	3.30-5 p.m.	Spectral, spatial and temporal image resolution	M. Fea (ESA)
Wednesday 14 October	9-10.30 a.m.	Practical exercises on images	J. Baraza (RCSSMRS)
	10.45 a.m.- 12.15 p.m.	ERS-1 mission: objective, space and ground segment, coverage of the Earth	M. Fea (ESA)
	2-3.30 p.m.	ERS-1 instruments, data acquisition and specifications	M. Fea (ESA)

Date	Time	Subject	Speaker
	3-5 p.m.	Evaluation of ERS-1 results obtained to date	M. Fea (ESA)
	5-6.30 p.m.	Visit to RCSSMRS facilities	RCSSMRS
Thursday 15 October	9-10.30 a.m.	Principles of radar imaging, processing and analysis of ERS-1 data sets	M. Fea (ESA)
	10.45 a.m.-12.15 p.m.	Practical exercises on ERS-1, specific application (oceanography)	M. Fea (ESA)
	2-5 p.m.	Practical exercises on ERS-1, specific application (forestry/geology)	M. Fea (ESA)
Friday 16 October	9-10.30 a.m.	Estimation of rainfall and run-off	M. Fea (ESA)
	10.45 a.m.-12.15 p.m.	Applications of remote sensing to agrometeorology	M. Fea (ESA)
	2-5 p.m.	Practical exercises related to the morning session	M. Fea (ESA)
Monday 19 October	9 a.m.-12.15 p.m.	Digital image formation and diagnostics	T. Alfoldi (CCRS)
	2-3.30 p.m.	Digital image formation and diagnostics	T. Alfoldi (CCRS)
	3.45-5 p.m.	Digital image pre-processing and corrections	T. Alfoldi (CCRS)
Tuesday 20 October	9 a.m.-12.15 p.m.	Principles of digital image analysis - enhancement and classification	T. Alfoldi (CCRS)
	2-5 p.m.	Practical exercises on digital images	T. Alfoldi (CCRS)
Wednesday 21 October		Image analysis and software systems	L. Hayes (University of Dundee)

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Date	Time	Subject	Speaker
Thursday 22 October	9-10.30 a.m.	Introduction to radar remote sensing	T. Alfoldi (CCRS)
	10.45 a.m.-12.15 p.m.	Radar imaging geometry	T. Alfoldi (CCRS)
	2-3.30 p.m.	Radar target interaction	T. Alfoldi (CCRS)
	3.45-5 p.m.	Radar image characteristics	T. Alfoldi (CCRS)
Friday 23 October	9-10.30 a.m.	Radar applications in geology and oceanography	T. Alfoldi (CCRS)
	10.45 a.m.-12.15 p.m.	Radar applications in hydrology and agriculture	T. Alfoldi (CCRS)
	2-3.30 p.m.	Radar applications in forestry	T. Alfoldi (CCRS)
	3.45-5 p.m.	Practical exercise on radar interpretation	T. Alfoldi (CCRS)
Monday 26 October	9 a.m.-5 p.m.	Technical visit	RCSSMRS
Tuesday 27 October	9 a.m.-12.15 p.m.	Principles of Geographic Information Systems (GIS)	G. Pierre (SCOT CONSEIL)
	2-5 p.m.	General strategy for setting up a GIS project	G. Pierre (SCOT CONSEIL)
Wednesday 28 October	9-10.30 a.m.	Case study: implementation of a regional geographic server	G. Pierre (SCOT CONSEIL)
	10.45 a.m.-12.15 p.m.	Panorama of GIS products, trends	G. Pierre (SCOT CONSEIL)
	2-5 p.m.	Pre-field trip preparation	RCSSMRS
Thursday 29 October	9 a.m.-5 p.m.	Field trip	RCSSMRS
Friday 30 October	9 a.m.-5 p.m.	Post-field trip analysis	RCSSMRS
	2-4 p.m.	Closing ceremony	
