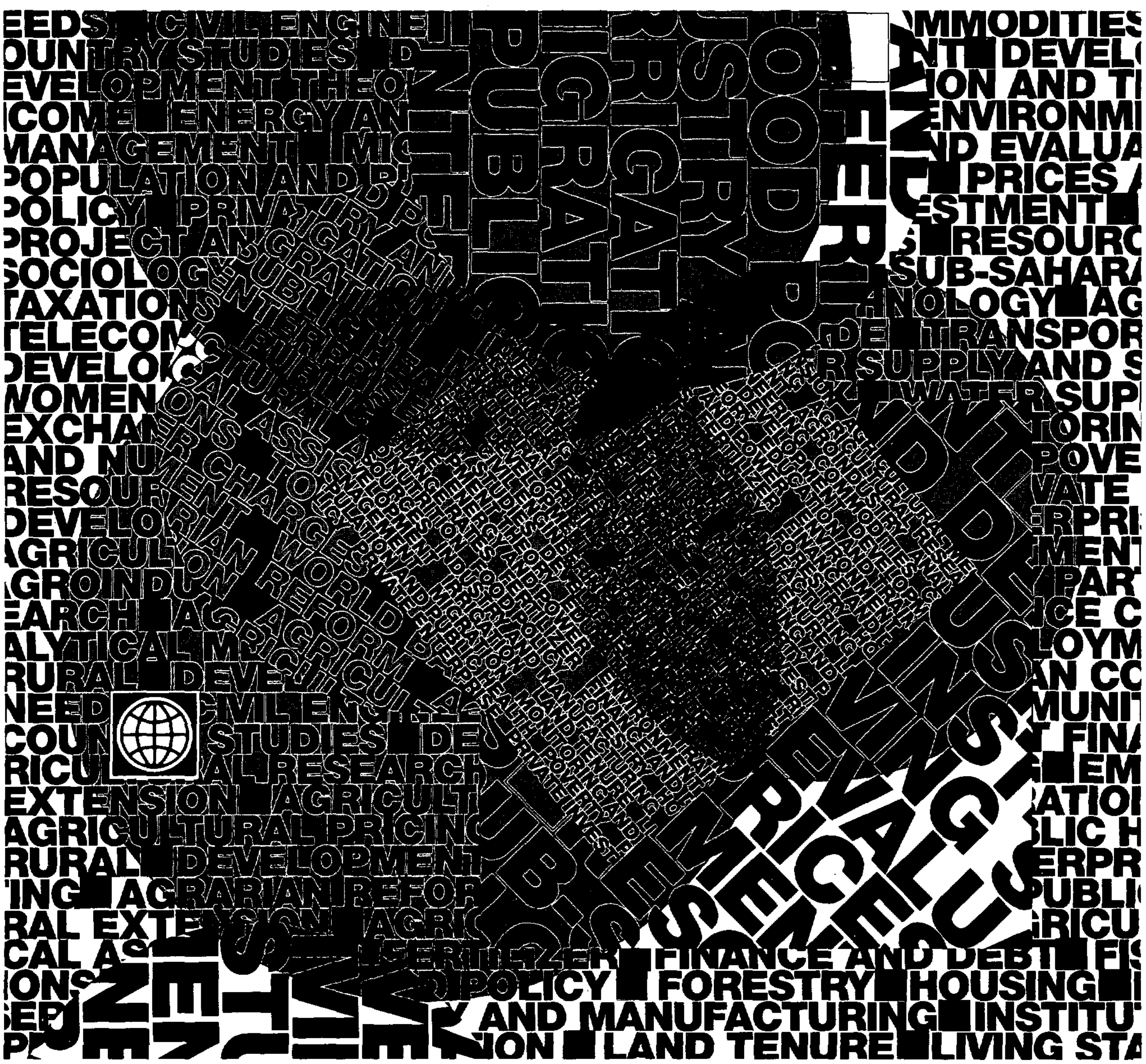
WORLD BANK TECHNICAL PAPER NUMBER 128

Satellite Remote Sensing for Agricultural Projects

J.P. Gastellu-Etchegorry, editor



RECENT WORLD BANK TECHNICAL PAPERS

No. 65 Hegstad and Newport, *Management Contracts: Main Features and Design Issues*

No. 66F Godin, *Préparation des projets urbains d'aménagement*

No. 67 Leach and Gowen, *Household Energy Handbook: An Interim Guide and Reference Manual* (also in French, 67F)

No. 68 Armstrong-Wright and Thiriez, *Bus Services: Reducing Costs, Raising Standards*

No. 69 Prevost, *Corrosion Protection of Pipelines Conveying Water and Wastewater: Guidelines*

No. 70 Falloux and Mukendi, *Desertification Control and Renewable Resource Management in the Sahelian and Sudanian Zones of West Africa* (also in French, 70F)

No. 71 Mahmood, *Reservoir Sedimentation: Impact, Extent, and Mitigation*

No. 72 Jeffcoate and Saravanapavan, *The Reduction and Control of Unaccounted-for Water: Working Guidelines* (also in Spanish, 72S)

No. 73 Palange and Zavala, *Water Pollution Control: Guidelines for Project Planning and Financing* (also in Spanish, 73S)

No. 74 Hoban, *Evaluating Traffic Capacity and Improvements to Road Geometry*

No. 75 Noetstaller, *Small-Scale Mining: A Review of the Issues*

No. 76 Noetstaller, *Industrial Minerals: A Technical Review* (also in French, 76F)

No. 77 Gunnerson, *Wastewater Management for Coastal Cities: The Ocean Disposal Option*

No. 78 Heyneman and Fägerlind, *University Examinations and Standardized Testing: Principles, Experience, and Policy Options*

No. 79 Murphy and Marchant, *Monitoring and Evaluation in Extension Agencies* (also in French, 79F)

No. 80 Cernea, *Involuntary Resettlement in Development Projects: Policy Guidelines in World Bank–Financed Projects* (also in Spanish, 80S, and French, 80F)

No. 81 Barrett, *Urban Transport in West Africa*

No. 82 Vogel, *Cost Recovery in the Health Care Sector: Selected Country Studies in West Africa*

No. 83 Ewing and Chalk, *The Forest Industries Sector: An Operational Strategy for Developing Countries*

No. 84 Vergara and Brown, *The New Face of the World Petrochemical Sector: Implications for Developing Countries*

No. 85 Ernst & Whinney, *Proposals for Monitoring the Performance of Electric Utilities*

No. 86 Munasinghe, *Integrated National Energy Planning and Management: Methodology and Application to Sri Lanka*

No. 87 Baxter, Slade, and Howell, *Aid and Agricultural Extension: Evidence from the World Bank and Other Donors*

No. 88 Vuylsteke, *Techniques of Privatization of State-Owned Enterprises*, vol. I: *Methods and Implementation*

No. 89 Nankani, *Techniques of Privatization of State-Owned Enterprises*, vol. II: *Selected Country Case Studies*

No. 90 Candoy-Sekse, *Techniques of Privatization of State-Owned Enterprises*, vol. III: *Inventory of Country Experience and Reference Materials*

No. 91 Reij, Mulder, and Begemann, *Water Harvesting for Plant Production: A Comprehensive Review of the Literature*

No. 92 The Petroleum Finance Company, Ltd., *World Petroleum Markets: A Framework for Reliable Projection*

No. 93 Batstone, Smith, and Wilson, *The Safe Disposal of Hazardous Wastes: The Special Needs and Problems of Developing Countries*

No. 94 Le Moigne, Barghouti, and Plusquellec, *Technological and Institutional Innovation in Irrigation*

No. 95 Swanson and Wolde-Semait, *Africa's Public Enterprise Sector and Evidence of Reforms*

No. 96 Razavi, *The New Era of Petroleum Trading: Spot Oil, Spot-Related Contracts, and Futures Markets*

(List continues on the inside back cover)

WORLD BANK TECHNICAL PAPER NUMBER 128

Satellite Remote Sensing for Agricultural Projects

J.P. Gastellu-Etchegorry, editor

The World Bank
Washington, D.C.

Technical Papers are published to communicate the results of the Bank's work to the development community with the least possible delay. The typescript of this paper therefore has not been prepared in accordance with the procedures appropriate to formal printed texts, and the World Bank accepts no responsibility for errors.

The findings, interpretations, and conclusions expressed in this paper are entirely those of the author(s) and should not be attributed in any manner to the World Bank, to its affiliated organizations, or to members of its Board of Executive Directors or the countries they represent. The World Bank does not guarantee the accuracy of the data included in this publication and accepts no responsibility whatsoever for any consequence of their use. Any maps that accompany the text have been prepared solely for the convenience of readers; the designations and presentation of material in them do not imply the expression of any opinion whatsoever on the part of the World Bank, its affiliates, or its Board or member countries concerning the legal status of any country, territory, city, or area or of the authorities thereof or concerning the delimitation of its boundaries or its national affiliation.

The complete backlist of publications from the World Bank is shown in the annual *Index of Publications*, which contains an alphabetical title list (with full ordering information) and indexes of subjects, authors, and countries and regions. The latest edition is available free of charge from the Publications Sales Unit, Department F, The World Bank, 1818 H Street, N.W., Washington, D.C. 20433, U.S.A., or from Publications, The World Bank, 66, avenue d'Iéna, 75116 Paris, France.

ISSN: 0253-7494

Library of Congress Cataloging-in-Publication Data

Satellite remote sensing for agricultural projects / J.P. Gastellu
-Etchegorry, editor.
p. cm.—(World Bank technical paper, ISSN 0253-7494 ; no. 128)
Includes bibliographical references.
ISBN 0-8213-1625-7
1. Agriculture—Remote sensing. 2. Agricultural development projects. I. Gastellu-Etchegorry, Jean-Philippe, 1955-
II. International Bank for Reconstruction and Development.
III. Series.
S494.5.R4S27 1990
631—dc20 90-12783
CIP

FOREWORD

Although satellite remote sensing has been used for almost twenty years, the recent development of a series of new satellites and techniques to utilize the information available has opened a new field of data collection and interpretation. In response to World Bank staff who asked for operationally relevant information on remote sensing, on Bank experience with remote sensing and the comparative advantage of the various systems, the Agriculture and Rural Development Department (AGR), in cooperation with the Environment Department (ENV), organized a seminar on remote sensing for agricultural projects which took place March 30-31, 1989.

The seminar brought together a large number of remote sensing experts and practitioners, both from within and outside of the World Bank, who addressed the following main subjects:

- the capabilities and limitations of the various satellite remote sensing systems;
- World bank utilization of satellite remote sensing techniques; and
- case studies in several agricultural subsectors with information on methodologies, achievements, costs and time requirements.

The papers presented at the seminar show the wide spectrum of subjects for which remote sensing can be employed usefully. They also indicate the still evolving nature of remote sensing techniques. The publication of these papers is expected to contribute to a better understanding of how satellite remote sensing can assist in the preparation and monitoring of agricultural projects, within and outside the World Bank.

The organization of the seminar was financially supported by a generous contribution from the Government of France and CNES, the French spatial agency, through which the services of Dr. J. P. Gastellu-Etchegorry of SCOT Conseil were financed. Dr. Gastellu-Etchegorry provided invaluable assistance to AGR and ENV in the preparation of the seminar, the selection of the speakers and editing this volume. Messrs. Küffner of AGR and Hardy of ENV also contributed to the organization of the seminar.

We wish to express our thanks to the organizers and, especially, to the speakers, who shared with us their particular knowledge and experience in this rapidly developing subject.

Guy Le Moigne
Senior Advisor
Agriculture and Rural Dev. Department

D. Jane Pratt
Division Chief
Environment Department

TABLE OF CONTENTS

LIST OF CONTRIBUTORS

Frédéric Achard
GREF (French Agriculture Ministry)

S. Azzali
The Winand Staring Center for Integrated Land, Soil, and Water Research, The Netherlands

E.Barisano
SODETED T.A.I. Remote Sensing Centre
France

F. Blasco
I.C.I.V. (Institute for the International map of Vegetation), France

J.A.A. Berkhout
Department of Physical Geography and Soil Science
University of Amsterdam, The Netherlands

P. Carton
SOGREAH
France

Jean-Claude Cazaux
SCOT CONSEIL
France

J.L. Chambouleyron
Instituto Nacional de Ciencias y Tecnicas
Argentina

François Falloux
Africa Technical Department, The World Bank

J.P. Gastellu-Etchegorry
SCOT CONSEIL/Paul Sabatier University
France

Ray Harris
Software Sciences
United Kingdom

H.M. Hassan
Environmental Operations and Strategy Division
The World Bank

S.M. Howard
TGS Technology, Inc.

J. Huygen
The Winand Staring Center for Integrated Land, Soil, and Water Research, The Netherlands

T.R. Loveland
TGS Technology, Inc.

B. Wayne Luscombe
Environmental Operations and Strategy Division
The World Bank

M. Menenti
The Winand Staring Center for Integrated Land, Soil, and Water Research
The Netherlands

D.G. Moore
U.S. Geological Survey

Glenn Morgan
Environmental Operations and Strategy Division
The World Bank

Thierry Pointet
BRGM
France

Bobby E. Spiers
Foreign Agriculture Service
U.S. Department of Agriculture

Guy Rochon
DIGIM, Inc.
Canada

John D. Sullivan
Science and Technology Department
U.S. Agency for International Development

G.G. Tappan
TGS Technology, Inc.

D.J. Tyler
TGS Technology, Inc.

T. Visser
The Winand Staring Center for Integrated Land, Soil, and Water Research
The Netherlands

Donald R. Wiesnet, Consultant
Vienna, Virginia

William Wigton
Environmental Operations and Strategy Division
The World Bank

REMOTE SENSING ACTIVITIES IN THE WORLD BANK : A REVIEW OF EXPERIENCES AND CURRENT TECHNICAL CAPABILITIES

Glenn Morgan

INTRODUCTION

This paper reviews the Bank's experience to date with remote sensing technology (specifically satellite remote sensing) and describes the context in which remote sensing is used in the Bank's operations. The paper considers the steps the Bank has taken in response to the challenge of incorporating this technology into its lending operations and reviews a number of operational constraints that hinder successful application of this technology. The paper concludes by providing an overview of current in-house capabilities and suggests ways in which to improve the contribution of this technology to Bank operations.

BACKGROUND

To varying degrees the Bank has been involved with satellite remote sensing technology for close to 15 years. As early as 1974, in its Rural Development Sector Policy Paper, the World Bank acknowledged the potential contribution of remote sensing technology. The paper stressed that :

> It is important to have more information about the resources available for exploitation by the rural poor and others. To this end the Bank will finance resource inventory and evaluation work based on field surveys; the use of ERTS (Landsat) imagery and aerial photography; and sectoral and regional studies to discover additional growth centers and rural urban linkages.

Because of the long-term implications of project and policy initiatives on a country's natural resources, concern is growing that national, state, and local governments are adequately prepared to design, evaluate, implement, and supervise large-scale development projects inways that fully account for natural resource and environmental consequences. It is not unusual for long-term resource allocation decisions to be made in a resource information "vacuum"

Comments made by David Simonett of the University of California several years ago still ring true today:

> Decisions on capital investment and resource development are made in an atmosphere of greater or lesser uncertainty the uncertainty is almost always greater in the developing than the developed world because of the weaker information base. As a result many projects in the developing world have unexpected and sometimes undesirable outcomes economically, socially, and environmentally. Since the major bases for economic development in the developing nations lie in their natural resources, improved information on these resources will reduce some of the uncertainty in decision making.

Information on the nature, extent, and productive potential of natural resources in developing countries is typically incomplete or out of date. There is an unquestionable need for better management of natural resources and ecologically sensitive areas: improving management will almost certainly entail improving the quality and availability of basic information in many situations. Remote sensing technology is seen as one technique for facilitating this goal.

OPERATIONAL EXPERIENCES WITH REMOTE SENSING

Since 1974 the Bank has used remote sensing technology in a wide range of applications. Typically, remote sensing activities have been small components of larger Bank projects. During the 1970s and early 1980s remote sensing activity was centered primarily in Agriculture and Rural Development Department (AGR) and maintained a strong project-by-project focus. Over the years the Bank has funded numerous air photo missions and has utilized most forms of satellite imagery, including Landsat, SPOT, and AVHRR. About 100 projects have utilized satellite remote sensing technology to a greater or lesser extent since the mid-1970s. The number of annual requests for remote sensing applications assistance projects has risen since the availability of SPOT imagery.

One of the Bank's main applications of satellite imagery during the late 1970s and early 1980s was on the preparation of satellite image base-maps, usually a small, scale (1:250,000) national map series relying primarily on the use of Landsat (Multispectral Scanner and Thematic Mapper imagery). Such planimetric map series were completed, for example, for Nepal, Peru, Bangladesh, and the Indian State of Orissa, among others. Extensive use of remote sensing technology, both photographic and nonphotographic imaging systems, has been made for large-scale survey and base-mapping programs in Brazil and Indonesia.

In addition, imagery has been used for numerous specific project activities including rangeland assessments, deforestation studies, soil surveys, land-use inventories, and groundwater hydrology studies, to name a few. Due to the resolution of the imagery available during the 1970s and early 1980s, the principal applications were in the area of regional planning. Little was done, for example, in the area of urban planning or site-specific studies. Regional planning remains the primary application of the technology today.

In general, the imagery has been used for preproject feasibility analysis or for the collection of data relevant to project planning and implementation. In a few cases the imagery has been used for project supervision activities. Though not as common as specific project applications, the Bank has attempted in a few cases to build in-country technical capacities in this field through the provision of technical assistance, equipment, and staff training to selected counterpart organizations.

REMOTE SENSING IN THE ENVIRONMENT DEPARTMENT

Since the Bank's reorganization in 1987, the functional responsibility for remote sensing activities has been formally established within PPR's[1)] Environmental Operations and Strategy Division (ENVOS). The ENVOS program is broadly based, focusing on cost-effective techniques and methodologies for natural resource surveys, environmental baseline studies, and resource inventories Remote sensing technology plays an important, although by no means exclusive, role in this program.

To address resource survey and inventory issues, ENVOS has established technical specialists in the fields of natural resource survey and inventory design, geographic information systems technology, remote sensing, digital image processing, resource assessments, and regional land-use planning. ENVOS staff are available to provide direct operational assistance to project staff as needed in these various fields. Typically, ENVOS staff provide such services as defining

---

[1)] Policy, Planning & Research Staff

consultant terms of reference, reviewing technical proposals for application of remote sensing, preparing bid specifications for project components focusing on survey and inventory work, and participating in field missions.

While remote sensing activity in ENVOS continues to have a strong operational focus, ENVOS has expanded the Bank's role in remote sensing to include the development of collaborative programs with other international organizations, public interest groups, non-governmental organizations, scientific bodies, and the private sector; provision of technical assistance to member governments in the development of remote sensing applications; provision of remote sensing training for Bank staff; provision of advice on appropriate consultants for survey applications (ENVOS maintains an extensive consultant roster in the resource survey field); and development of research programs into various aspects of remote sensing applications.

To assist in the implementation of Geographic Information System (GIS) and remote sensing technology, ENVOS has now established a permanent computer facility for image processing and geographic information system applications based on IBM-PC level technology. Currently, ENVOS has three PC-based GIS workstations. One of the systems also has complete digital image processing capabilities to facilitate the computer handling of satellite imagery. The idea of the computer capabilities is not to establish a full-blown production facility in the Bank but rather to establish an easily accessible facility where project staff can learn about the use of satellite imagery and GIS through real-world applications. ENVOS staff currently conduct about ten specialized case studies yearly.

ENVOS also acts as the custodian of a large collection of satellite imagery that has been collected over the years. Currently there are about 800 satellite tapes in the ENVOS collection, some dating back to 1974. The tapes are available for in-house use and can be used to generate hard-copy paper or film prints if necessary. ENVOS maintains a database search facility for on-line queries of available imagery. In addition ENVOS has borrowing privileges with numerous agencies that have also collected imagery for many years. On-line search facilities are also available for some of these agencies. At the present time, ENVOS does not have a separate budget for the purchase of new imagery for project applications.

The Bank's interest in remote sensing technology has been paralleled in other international development agencies and multilateral development banks. Virtually every bilateral development assistance program has expertise in the field of natural resource survey and inventory methodologies. Many, such as FAO and UNEP, have established permanent remote sensing and

GIS units. Many of the Bank's developing member governments have also supported remote sensing programs. Countries such as India and Thailand, for example, have extensive remote sensing technical expertise. India has launched its own remote sensing satellite, IRS-1A, with functional capabilities similar to Landsat-TM and MSS sensors. Other countries have yet to use the technology in any meaningful way.

EVALUATION OF REMOTE SENSING

The reaction of Bank staff to remote sensing technology has been mixed, ranging from strong skepticism to cautious endorsement. Most individuals who have utilized the technology have indicated that the use of satellite imagery has not met all of their operational expectations. There have even been some operational staff who have described remote sensing technology as a "cure looking for an illness." In far too many cases, the critics maintain, remote sensing has been applied as a result of a "technology push" rather than serving an articulated user need. Many regional and national remote sensing organizations have rarely been self-sustaining, and in some situations they have not achieved their operational mandates.

The disappointment with the use of satellite imagery stems from a number of interrelated problems. Some of the problems are related directly to the technology itself, but many more are related to the "institutional aspects" of using the imagery. The more commonly cited problems Bank staff have encountered with the use of satellite imagery have been :

- The resolution of the imagery has not lent itself well to site-specific applications. This has been a typical problem where land holdings are small or where very detailed information is required.
- The operational difficulties related to procurement and acquisition of imagery (delivery times, costs, cloud cover, etc.) often do not justify the incremental information content of the images. For example, timely delivery of multidate satellite data, an often cited advantage of satellite data, has been extremely difficult to achieve in practice.
- There is a perception that satellite imagery only provides a marginal contribution to the understanding of resource management problems compared with field surveys or more traditional sources such as air photos.

- Lack of trained staff and equipment in counterpart agencies to actually accomplish anything with the imagery once it is procured has made it difficult to show how remote sensing data can make a long-term contribution to resource management problems.

Many remote sensing applications have not met expectations because the mapping activities were poorly designed or the technology was used for an inappropriate purpose. One of the most frequent errors is failing to provide for adequate ground truthing procedures. Another common error is not linking a survey and mapping program closely enough to a planning problem. Many projects have been rather imprecise about how the resulting data will be used or how the information is expected to make a difference. As a consequence the results of image analysis, such as statistical summaries and cartographic products, are frequently underutilized in the planning process.

Traditionally, one of the greatest constraints to the widespread use of imagery for project identification, preparation, and supervision has been the lack of funding for ad hoc purchases of imagery. Rarely are funds earmarked for image procurement in advance and many potential contributions of imagery have not materialized due to lack of funds.

FUTURE OF REMOTE SENSING IN THE BANK

With the introduction of SPOT imagery there will be a renewed interest in satellite remote sensing in the Bank. The higher resolution imagery, coupled with rapidly decreasing requirements for capital investment in digital image processing, has given remote sensing a new life. Operational satellite systems utilizing cloud, penetrating radar will soon be available for commercial use and aircraft, mounted multispectral scanners also seem to be overcoming some of their operational problems. All of these developments indicate more flexible systems and lower costs to the user.

In the short run this will mean an increased demand for technical assistance services, for execution of proof-of-concept case studies, and for survey and mapping project components that are based on SPOT as a primary data source. As the Bank begins to view the environmental impacts of large development programs, we will need more reliable, more timely information. Satellite imagery must surely play an expanded role in delivering that information.

With the availability of higher resolution SPOT imagery, many new applications are likely to emerge. In the field of urban planning, SPOT imagery will have a much greater impact than its

Landsat predecessors. Within the Bank several case studies are currently being prepared that will evaluate SPOT as a data source for urban surveying and mapping.

Remote sensing technology, however, is only one piece of the natural resource information management issue. The Bank will begin to deal not only with the technical aspects of remote sensing or GIS technology but also should begin to pay greater attention to the need to support national mapping programs in member countries. Remote sensing technology must not be viewed as an end in itself, but must be seen as fitting into broadly based natural resource information management programs.

If this can be accomplished, the demand for assistance will likely shift away from the "nuts and bolts" of remote sensing toward the management and organizational aspects of national, regional, and local survey and mapping programs. The Bank will be required to provide more direct guidance in the areas of staff training, prioritizing data-base development programs, and guiding primary data acquisition. In addition, the Bank should strive to make the use of the imagery more operationally relevant by supporting remote sensing and data-base development programs within those agencies that have a direct, day-to-day mandate for natural resource management.

APPENDIX 1
ENVOS STAFF CONTACTS IN REMOTE SENSING APPLICATIONS

ENVOS currently has four regular staff with extensive experience in the application of remote sensing and geographical information system (GIS) technology to natural resource and environmental management problems. They are available to provide direct operational Bank project design, implementation, and supervision activities.

Wayne Luscombe
Room S-5109
(202) 473-3456

Felipe Villagran
Room S-5111
(202) 473-3290

Hassan Hassan
Room S-5105
(202) 473-1376

Glenn Morgan
Room S-5107
(202) 473-3455

Ernie Hardy (Consultant)
Room S-5105
(202) 473-3291

Jennifer Allen (Consultant)
Room S-5101
(202) 473-3294

APPENDIX 2

RECENT PAPERS BY ENVOS STAFF RELATED TO REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS

Allen, J., 1988. Review of monitoring and assessment of forest resources in Asia,

Dannett-Pace, L., 1988. A comparative evaluation of remotely sensed forestry data for forest inventory applications,

Luscombe, W., G. Morgan and F. Villagran, 1988. Guidelines for the selection of automated mapping and land information management systems,

Luscombe, W. and E. Hardy, 1988. Real world applications of remote sensing,

Luscombe, W. and G. Morgan, 1986. Thailand: A geographical information system for land policy analysis,

Morgan, G., 1987. Natural resource surveys: An overview of concepts, principles, and practice,

Morgan, G., 1989. Geographic information systems in development planning: A World Bank perspective,

Mori, H., 1988. Forest infestation detection using remote sensing technology: The case of the spruce bark beetle,

Villagran, F. and W Luscombe, 1987. Geo-based information systems for developing countries, 1987.

- 2 -

SATELLITE REMOTE SENSING

Ray Harris

INTRODUCTION: BENEFIT STRUCTURES

Satellite remote sensing

Satellite remote sensing is now in a phase of transition. Transitions are always characterized by uncertainty, and for satellite remote sensing the uncertainty is that while the potential of the technology has been clearly demonstrated there is still some progress to be made in converting the potential into practical reality. A further aspect of transition is variability, and in satellite remote sensing that variability can be seen in the differing stages of maturity of different satellite systems: products from meteorological satellite data are used operationally around the world, often by users who are not aware of their origin, while imaging radar data are still used primarily in the research community.

It is in the context of transition that this paper provides an overview of four satellite remote sensing systems. The four systems are NOAA-AVHRR, Landsat, SPOT, and radar. This overview discusses the background to the satellite systems, the acquisition of data from them, the limitations of using the data, the applications, and the economic benefits to be gained from satellite remote sensing.Before the overview begins in detail, this introductory section discusses the categories of economic benefits that users of satellite remote sensing seek.

Economic benefits

In operational, rather than research, applications of satellite remote sensing, the users will be seeking benefits in some way. Commonly these can be written as economic benefits, and these are categorized below.

Lower direct costs

The use of satellite remote sensing can lead to lower direct costs in performing existing tasks. SPOT imagery can be used for cartographic purposes at scales from 1:25,000 to 1:100,000 and smaller. The SPOT images can be acquired at much lower cost than an airborne or ground survey, and the mapping task can be achieved more rapidly.

Shorter timescales

The timescales of ground-based regional resource surveys are normally measured in months or years. Satellite remote sensing can provide resource survey--information for example for route planning--in weeks and so speed up decisionmaking processes.

Higher productivity

Imagery from Landsat and SPOT have been used successfully for oil and mineral exploration and for forestry inventory. Because of the lower direct costs and the shorter timescales, this means that higher productivity can be achieved, which, in a commercial environment, translates into higher profitability. Profit in its broadest sense is also embedded in noncommercial projects because of the financial and nonfinancial benefits that accrue to the applications project itself and to the funding authority.

New activities

The three topics above describe old wine in new bottles: that is, existing capabilities met by new satellite remote sensing data. However, there are also many new activities that would not be feasible whithout satellite remote sensing. For example, biomass surveys using NOAA-AVHRR data (Millington et al. 1987), identification of mineral resources in semiarid and arid regions using the longer wavelengths of the Landsat Thematic Mapper sensor, and the abilitiy of imaging radar to penetrate hyperarid surfaces all mean that satellite remote sensing offers the opportunity to create new wine from new vineyards.

Cost structures and value chains

An alternative way to view the economic benefits of satellite remote sensing is to consider the implications on the cost structures of economic activitiy. Costs can be divided into direct costs (labor and data), overheads, equipment, and margin (direct profit or some other measure of tangible economic benefit). An example of cost structure is shown in Figure 2-1.

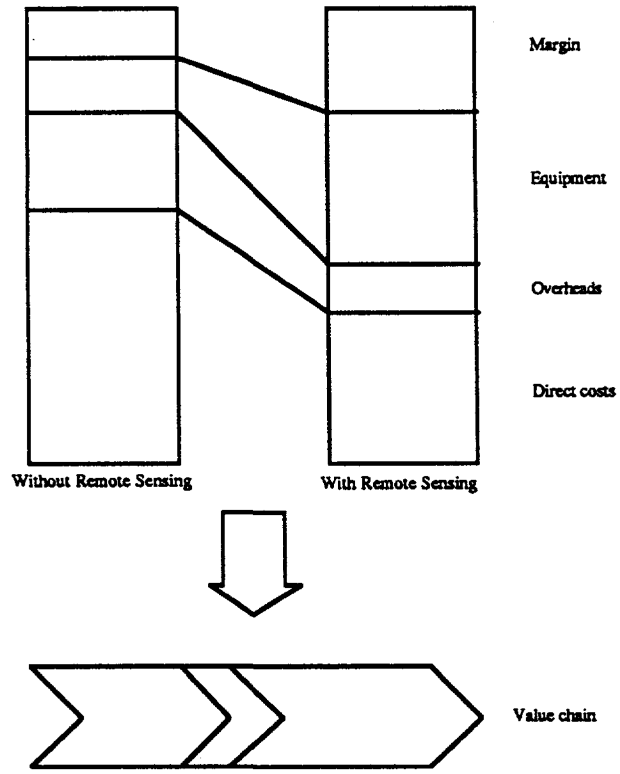


Figure 2-1. Cost and Value Chains of Remote Sensing Applications

The impact of satellite remote sensing on the cost structure of a project is likely to be as follows:

Direct Costs: Reduction because of lower labor costs, shorter timescales, and lower data charges.

Overheads: Reduction because they are normally associated with direct costs.

Equipment: The investment in equipment is likely to be higher, particularly if satellite data reception and advanced image processing are involved.

Margin: Higher because of reductions elsewhere.

The impacts discussed here are related to the use of satellite remote sensing for particular applications. However, any such use will normally represent a part of a larger activity, so it is important to see the use of the data as one component of a value chain (Figure 2-1). Therefore the overall impact of satellite remote sensing will depend upon the proportion of the value chain occupied by the use of satellite data. For example, for projects involving the construction of new irrigation schemes the total role of satellite remote sensing may be limited, whereas the value chain for forest inventories may be dominated by the role of satellite remote sensing.

Definition and limitation

The discussion of value chains is concerned with adding value, be that for cartography, renewable resources survey, or famine early warning (EOSAT 1988). Therein lies the fundamental limitation of satellite remote sensing: it is all about adding value to physical data concerning the Earth and its atmosphere. Short (1982) gives a definition of remote sensing as

> the acquisition of data and derivative information about objects or materials (targets) located at the Earth's surface or in its atmosphere by using sensors mounted on platforms located at a distance from the targets to make measurements of interactions between the targets and electromagnetic radiation.

The key part of the definition is "the acquisition of data and derivative information," because while it is possible to collect data on surface reflectance, emission, or backscatter, this information must be converted into some other form in order to have economic value. Accordingly, much of the work with satellite remote sensing for practical applications is concerned with adding value to geophysical data.

THE SATELLITE SYSTEMS

This section of the paper briefly describes four systems for satellite remote sensing: NOAA-AVHRR,Landsat SPOT, and radar.

NOAA-AVHRR

The National Oceanic and Atmospheric Administration (NOAA) is responsible for the operation of the civilian meteorological satellites. The satellite type is termed Tiros-N, and each satellite has a number and is called NOAA 8, 9, 10, etc. One of the main sensors on the NOAA satellites is the Advanced Very High Resolution Radiometer (AVHRR). The channels of the AVHRR are shown in Table 2-1. The AVHRR is a five-channel sensor operating in the visible, near infrared, short-wave infrared, and thermal infrared regions of the spectrum, and it has a wide variety of uses for atmosphere, land, ice, and oceanographic applications.

Table 2-1. Wavebands of the NOAA Advanced Very High Resolution Radiometer (AVHRR)

Channel	Waveband (μm)
1	0.58 - 0.68
2	0.725 -1.10
3	3.55 - 3.93
4	10.3 - 11.3
5	11.5 - 12.5

Source : Harris (1987).

The NOAA satellite has a global coverage each day because it has a near-polar orbit, with swaths wide enough (2,400 kilometers) that each point on the Earth is covered twice each day: once during the day and once at night. There are three methods of data availability, and these are discussed below.

- High Resolution Picture Transmission (HRPT), which is available when the satellite is in line of sight of a ground receiving station. The coverage by a ground station is local and is constrained by the horizon view of the satellite.

- Local Area Coverage (LAC). In each orbit, up to ten minutes of full resolution data are recorded on board the satellite on a tape recorder. When the satellite is in line of sight of a ground station the tape recorder can be commanded to replay the data for reception at the ground station.

- Global Area Coverage (GAC). The full resolution data are sampled to allow the construction of a global image at low resolution.

NOAA-AVHRR data are best suited to applications that examine relatively large areas. They have been traditionally used in meteorology and oceanography for the analysis of cloud patterns and sea surface temperatures. More recently the data have been used for monitoring biomass over large land areas. Global vegetation monitoring is described by Justice et al. (1985), seasonal changes and classification of vegetation for the African continent are presented by Tucker et el. (1985), and Nelson and Holben (1986) use AVHRR data to identify deforestation in Brazil. A special isssue of the *International Journal of Remote Sensing* (vol. 7[11], 1986) is devoted to the use of AVHRR for monitoring the grasslands of semiarid Africa. The key to this use of AVHRR data is the vegetation index, which is calculated as:

$$\frac{\text{Visible - Near infrared}}{\text{Visible + Near infrared}}$$

Because vegetation has a low visible reflectance and a high near infrared reflectance, by using this equation high vegetation amounts are distinguishable from bare areas and areas of low vegetation. NOAA produces a weekly composite map of the vegetation index.

Landsat

Landsat satellites have carried three principal sensor packages:

- Return Beam Vidicon (RBV)
- Multispectral Scanner (MSS)
- Thematic Mapper (TM).

It is the TM that is now most widely used. The TM has a high resolution with 30 meters pixels and operates in seven wavebands (see Table 2-2) in the visible, near infrared, short-wave infrared, and thermal infrared regions. The primary emphasis of Landsat is on land applications, and it has been widely used for geology, forestry, agriculture, and hydrology. The coverage by Landsat is global, either by direct transmission to one of the many ground receiving stations (Figure 2-2), or by using data routing through the Tracking and Data Relay Satellite System (TDRSS).

Table 2-2. Wavebands of the Landsat Thematic Mapper (TM)

Band	Wavelength range (μm)	Application
1	0.45 - 0.52	Coastal water mapping Soil/vegetation differentiation
2	0.52 - 0.60	Green reflectance by healthy vegetation
3	0.63 - 0.69	Chlorophyll absorption
4	0.76 - 0.90	Biomass survey
5	1.55 - 1.75	Vegetation moisture. Snow/cloud discrimination
6	10.4 - 11.7	Thermal mapping
7	2.08 - 2.35	Geological mapping

Source : Harris (1987)

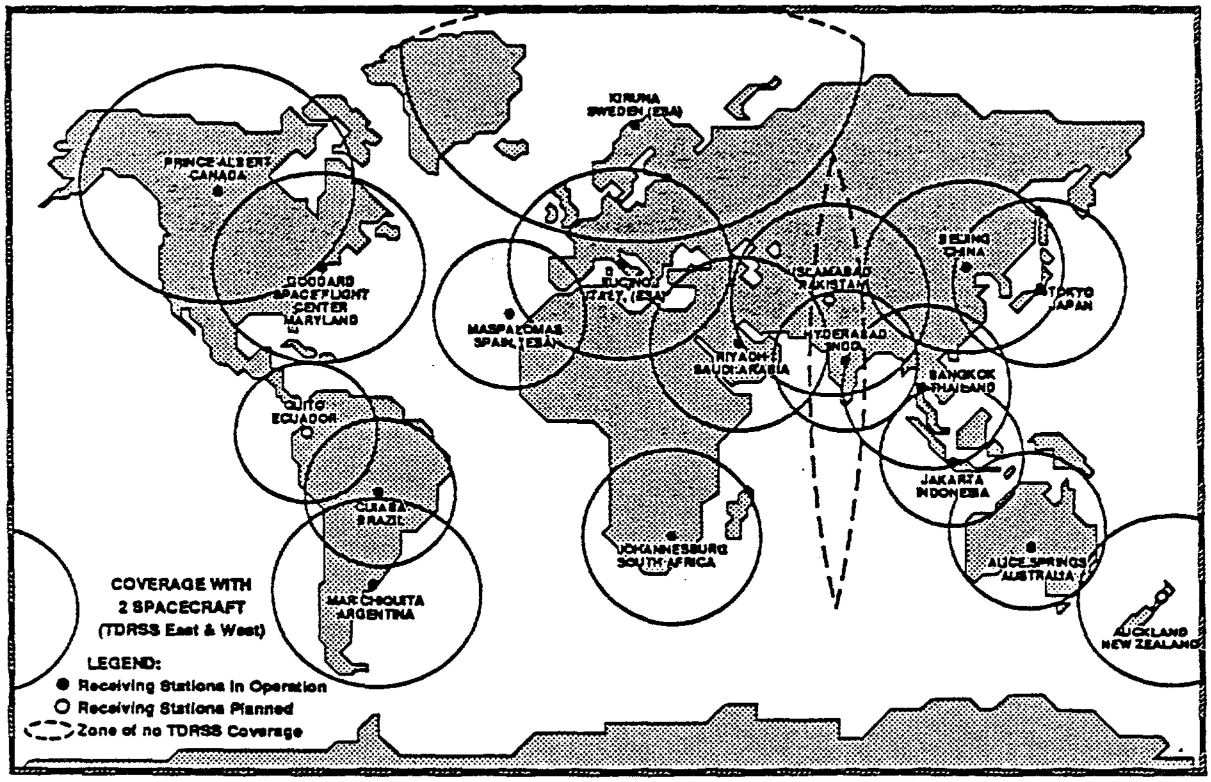


Figure 2-2. Landsat Receiving Stations
Source: Landsat Data Users Notes, December 1988

SPOT

The French Satellite Probatoire d'Observation de la Terre (SPOT) has been in operation since 1986. It carries a high resolution visible (HRV) sensor with two modes. First, a three-band mode (see Table 2-3) with a pixel size of 20 meters, and, second, a broad panchromatic mode with a pixel size of 10 meters. SPOT data are designed for mapping applications, including stereoscopic coverage. It achieves this by employing a steerable sensor that can view off-nadir up to 27°. This means that the same area can be viewed on successive days, which is useful both for topographic mapping and for acquiring images for high-priority areas. However, the normal imaging interval for SPOT is 26 days.

There is global coverage available for SPOT (Figure 2-3), either through local receiving stations or by retransmission of tape recorded data to the main ground station at Toulouse.

From its outset it was envisaged that SPOT would have a commercial basis, so a company called SPOT Image was established to market the SPOT data.

Radar

The emphasis in imaging radar from space has been on synthetic aperture radar (SAR) to achieve a high spatial resolution of about 25 meters SAR is quite different from the previous three satellite systems because it operates at microwave wavelenghts rather than the visible and infrared wavelengths of NOAA, Landsat, and SPOT. Thus far spaceborne SAR has been experimental, with three missions. The Seasat satellite flew a SAR in 1978 and the mission lasted 106 days. This was followed by the shuttle imaging radar (SIR) flown on the NASA space shuttle in 1981 and 1984 (SIR-A and SIR-B).

One key characterisitic of SAR is its ability to see through clouds, because at its operating wavelenghts (5-25 centimeters) the radiation in not affected by cloud particles. This means that it is possible to collect data on the land and ocean surfaces in all weather conditions. In addition the SAR can operate day and night. The initial use of SAR has been for oceanographic applications because of its ability to reveal surface and subsurface ocean structures, but it also has application in ice and land studies because of its all-weather capability. SAR has particular capabilities in measuring soimoisture and in penetrating hyperarid regions.

Table 2-3. Wavebands of the SPOT High Resolution Visible (HRV) Sensor

Band	Wavelength Range (μm)
1	0.50 - 0.59
2	0.61 - 0.68
3	0.79 - 0.89
The panchromatic mode has a waveband of 0.51-0.73 μm	

Source : Harris (1987)

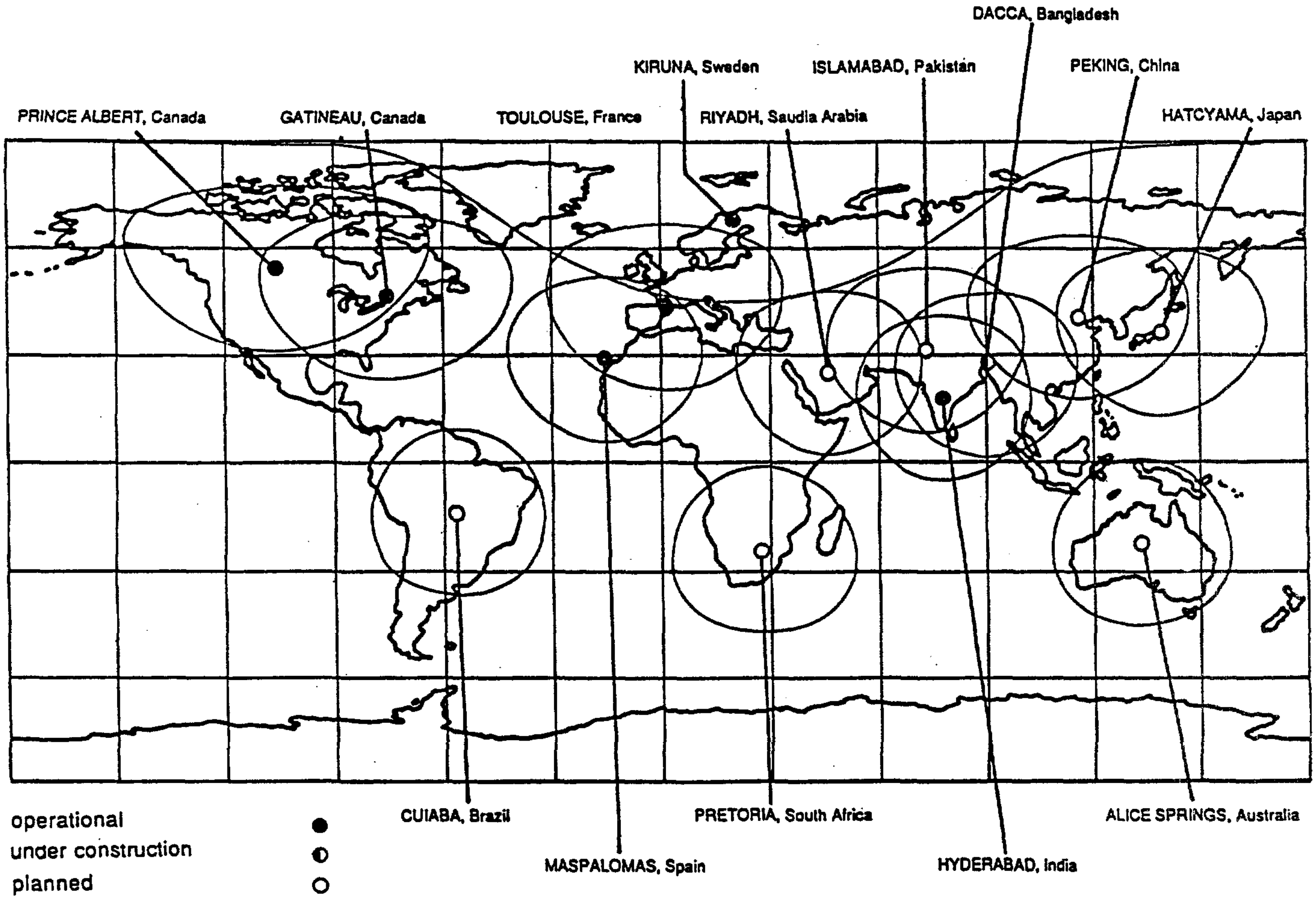


Figure 2-3 : SPOT Receiving Stations
Source: U.K. National Remote Sensing Center

Because it is experimental, the coverage by spaceborne SAR is patchy and confined to orbital strips around the globe (Ford et al. 1982).

Acquiring the data

This section of the paper has briefly described the key characteristics of four satellite systems. One outstanding question is the process of acquiring the data, and that subject is addressed here.

Locations

As indicated earlier, NOAA-HRPT data are recorded locally by ground receiving stations built for the purpose: an example of one such station is at the University of Dundee, Dundee, Scotland. The LAC and the GAC data are available through the NOAA, whose HQ is at Room 100, World Weather Building, Washington, D.C., 20233, U.S.A. Landsat data are recorded by many receiving stations throughout the globe, and in the appendix the addresses of the international Lansdsat distribution centers are listed. For central information the contact is EOSAT, 4300 Forbes Boulevard, Lanham, Maryland, 20706, U.S.A. Information on SPOT data is available from SPOT Image, 16 bis avenue Edouard Belin, 31055, Toulouse Cedex, France. The primary contact for the Shuttle Imaging Radar and for Seasat is the Jet Propulsion Laboratory, Pasadena, California (Ford et al. 1982, Pravdo et al. 1983).

Price

The prices of satellite remote sensing data depend on whether the products are in digital form or photographic form; if they are in photographic form, then the price depends on the scale and the type of medium. Table 2-4 gives the prices of some representative products for NOAA-AVHRR, Landsat, and SPOT. The information on the prices was taken from EOSAT (*Landsat Data Users Notes* vol. 3[3] December 1988) and the U.K. National Remote Sensing Centre (NRSC), with figures converted to U.S.dollars where appropriate.

The prices shown in Table 2-4 will vary from one source to another depending on their policy over onward sales. One element which is fixed is the copyright payment on SPOT data, which means that at each sale of the data a copyright fee is paid which is the commission to SPOT Image. The figures for SPOT data given in Table 2-4 are the prices at the U.K. NRSC. In the case of multi-project use by World Bank staff of the same set of data, a copyright fee of 25 percent rather than the normal 30 percent is charged.

Table 2-4. Representative Prices for NOAA AVHRR, Landsat and SPOT Data (in US$)

NOAA-AVHRR	
Black-and-white print (500 mm x 500 mm)	$65
Color print (500 mm x 500 mm)	$110
Digital computer compatible tape (CCT)	$150
Landsat-TM	
Black-and -white prints	Production suspended
Color prints (1:500,000 scale)	$700
Standard digital scene	$3600
Geocoded digital scene	$4900
Floppy disk of 512 x 512 pixels	$600
SPOT	
Black-and-white HRV print (1:250,000 scale)	$135
Black-and-white panchromatic print (1:250,000 scale)	$240
Color print (1:250,000 scale)	$300
Digital scene	$1400

Sources: EOSAT, UK National Remote Sensing Centre

Delivery times

The position on delivery times (Table 2-5) depends on a number of factors. First, if the data are received directly, and used locally then delivery is in near real time. Second, if data are ordered from an archive then the time delay depends upon access to that archive. And third, if special acquisitions are requested, then there is a dependence upon other scheduling demands on the satellite.

Typical delivery times from an archive are two to four weeks, and for special acquisitions one week or more. For example, SPOT has a programming ability, but the response time depends upon other programming requests already scheduled.

For specific application programs the delivery times can be improved. For example, the Agrispine experiment in Europe was able to place Landsat data with agricultural scientists 24 hours after receipt.

LIMITATIONS

General

Much has been written on the uses of satellite remote sensing, but often the limitations of using the data are implicit rather than explicit. This section of the paper discusses some of those limitations. One limitation common to the visible and infrared satellite sensors (NOAA, Landsat, and SPOT) is cloud cover. Where cloud cover exists the surface is obscured. Areas of the world with continuous cloud cover (for example, parts of the tropics) have never been imaged, and, in areas with high cloud cover (for example, Northern Europe) cloud-free conditions may not coincide with Landsat or SPOT overflights. One serious problem is that no remote sensing satellite data can be guaranteed where cloud-free data are required.

Table 2-5. Delivery Times for Satellite Data

NOAA-AVHRR	
HRPT	Near real time
Local Area Coverage (LAC)	Three weeks
Global Area Coverage (GAC)	Three weeks
LANDSAT-TM	
Archive requests	Two - four weeks
Special acquisitions	Three weeks +
SPOT	
Archive requests	Three - four weeks
Special acquisitions	One week +

NOAA AVHRR

The principal limitation of NOAA-AVHRR is spatial resolution. The pixel size of 1.1 kilometers is relatively large for land applications, so the data are best suited to regional or continental applications. Set against this limitation, because the coverage is global twice a day, the probability of obtaining cloud-free coverage is high. There is thus a tradeoff between resolution and repetition.

Landsat

One limitation of Landsat-MSS and TM data is the limited regional coverage, particularly for cloudy regions. For example, most of Britain is covered by Landsat only two or three times a year. Much work has been undertaken on classification of Landsat data, but there are no universally recognized models available and each study has to determine its own supervised or unsupervised classification model parameters. The improvement in spatial resolution from the MSS (79 meters) to the TM (30 meters) initially caused a deterioration in classification because the smaller pixels identified more detail in what are often functionally homogeneous regions. Finally, one present limitation on Landsat is its continued funding. Since the Land Remote Sensing Commercialization Act of 1984 was passed by the U.S. Congress there have been ambitious plans for Landsats 6 and 7 to follow the first five launched into orbit, but each year there has been uncertainty in the funding position, and as of March 1989 the financial future of Landsats 6 and 7 was not yet confirmed.

SPOT

As with Landsat, one limitation of SPOT is its regional coverage. With a standard repeat cycle of 26 days the chance to obtain cloud-free imagery is smaller. SPOT has a stereoscopic capability, but this is not true stereo because the data are collected on different orbits and normally with different viewing geometries. SPOT does not have the range of wavelengths offered by Landsat-TM (see Tables 2-2 and 2-3), so it cannot detect the subtler spectral differences of vegetation and mineral changes. A useful combination is Landsat TM and SPOT-HRV together. This provides high spatial resolution with good spectral features. A good example of this is showncombination for Munich in the *Earth Observation Quarterly* (no. 23/24, December 1988) published by the European Space Agency.

Radar

The key limitation of spaceborne radar is its availability. The missions thus far have been experimental, which means that the spatial coverage is restricted and that the geophysical meaning of the data is not clear. The backscatter of radar is related to soil moisture and to surface roughness, but because of the complexity of the models and the limited availability of data there is not yet a consistent understanding of the radar data. In particular, the volume scattering models are in their infancy, which means that estimation of vegetation volumes (for example, forestry) is not yet near an operational phase.

APPLICATIONS AND BENEFITS

Progression

The data from NOAA, Landsat, and SPOT satellites are being increasingly used for semi-operational purposes. In some cases this is taking the applications demonstrated by research programs into an operational phase, while in others the applications are more potential than realised.

Up to now spaceborne radars have been experimental, which means that no operational programs have been or can be constructed to use these data, so the benefits accruing to their use remain be potential, albeit built on a firm base of experimental missions.

NOAA-AVHRR

Because of the spatial resolution of the AVHRR, the most appropriate applications of the data are at a regional or continental scale. This is clearly the case with meteorology, where AVHRR data are in regular use for weather forecasting, and the data are also appropriate for regional estimates of land vegetation properties. The measurements of photosynthetically active radiation from AVHRR data are useful both for qualitative indications of vegetation boundaries and for quantitative assessments of biomass. Biomass estimates can be of direct economic benefit by monitoring woody fuel resources in developing countries.

Direct benefits using AVHRR data include improved identification of fishing ground locations in the Pacific Ocean, faster ship crossings of the Atlantic Ocean, and extensions of the time periods of useful weather forecasts (Harris 1987). All of these applications have direct and measurable economic benefits, in part because the applications fit well the scale of the data.

Landsat

The range of applications of Landsat data are very great. Much work has been undertaken on crop and land use classification, in particular the Large Area Crop Inventory Experiment (LACIE) and its successor Agristars (Erickson 1984). The LACIE project used Landsat data, together with meteorological and other conventional data sources, to estimate wheat production in parts of the U.S.A., Canada, U.S.S.R., India, China, Australia, Argentina, and Brazil among other countries. One goal of LACIE was to achieve 90/90 accuracy; that is, to estimate at least 90 percent of total production 90 percent of the time. This was achieved for the U.S. Great Plains for winter wheat, and for the U.S.S.R. wheat growing regions. Similar projects, although not on so grand a scale, have been undertaken for many of the world's agricultural regions.

A second common application of Landsat data is in rangeland analysis. At image scales of 1:500,000 or 1:250,000, for instance, large areas of land can be analyzed speedily to produce regional land use maps. One such study is the use of Landsat imagery in support of the White Oryx Project in the Sultanate of Oman (Harris 1987). Landsat imagery, backed up by field transects, was used to prepare maps of vegetation, geomorphology, and key location features for an area of some 60,000 square kilometers of the desert area in central Oman. The purpose of the work was to provide information on food sources for the White Oryx, which were reintroduced into the region in 1980. The data and travel costs associated with this work were approximately US $ 3000, and the project was completed in six months. The use of satellite remote sensing enabled a task to be undertaken that would not have been financially viable using other technologies.

SPOT

A major advantage of SPOT data is their possible application in topographic mapping. SPOT-XS data, when corrected using ground control points, can meet the recognized standards for topographic mapping at 1:100,000 scale. SPOT panchromatic data can be used for mapping at 1:50,000 scale, and several projects have combined SPOT panchromatic and Landsat-TM data together in order to produce image maps with high spatial resolution and a varied range of spectral information.

As with Landsat data, SPOT data have been widely used for agricultural, rangeland, and hydrological projects in many parts of the world. This was encouraged in the early days of the SPOT program by PEPS, a preparatory demonstration program of the applications of SPOT data.

Radar

As indicated earlier, the applications of radar data have been based thus far on experimental missions, so only an indication of their value can be given. One key feature of radar is its ability to produce a regular supply of data because of its all-weather capability. This means that once operational radar programs do develop in the 1990s, the users will be able to rely on a regular supply of data, irrespective of weather conditions.

Satellite radar data will also have applications in vegetation measurement, by using three-dimensional scattering models; in cartography; and in geology, because of its ability to show topographic structures through its oblique illumination. Radar backscatter is related to soil moisture, so radar data can be used for agricultural work and for water supply studies.

CONCLUSIONS

This paper has reviewed the position of satellite remote sensing for four satellite systems in the late 1980s. The next decade will see the launch of several new satellites, culminating in the space station era. In 1990 the European Space Agency (ESA) will launch its first Earth observation satellite, ERS-1. The satellite will carry four main sensor packages, as listed below.

- Active Microwave Instrument (AMI). This instrument has three modes: synthetic aperture radar; wind mode; and wave mode.
- Along Track Scanning Radiometer (ATSR). This is a thermal infrared system comparable to the thermal channels of the NOAA-AVHRR.
- Radar Altimeter (RA).
- Precise Range and Range-Rate Experiment (PRARE).

ERS-1 marks a new phase in satellite remote sensing. This phase will provide better geophysical understanding of the Earth; combined with data from optical systems such as SPOT and Landsat, the data bases will be powerful tools for monitoring the Earth at a wide variety of scales.

APPENDIX
LOCATIONS OF LANDSAT DISTRIBUTION CENTRES

United States of America
EOSAT
4300 Forbes Blvd,
Lanham, MD 20706

Tel: (301) 552-0500; Tlx: 277685

Brazil
Instituto de Pesquisas Espaciais (INPE)
Departamento de Producao de Imagens
ATUS-Banco de Imagens Terrestres
Rodovia Presidente Dutra, Km210
Cachoeira Paulista-CEPT 12.630
Sao Paulo, Brazil

Tel: (0125) 611507; PBX : (0125) 611377
Tlx (0122) 160 INPE BR

Canada
Canada Centre for Remote Sensing (CCRS)
User Assistance and Marketing Unit
717 Belfast Road
Ottawa, Ontario K1A 0Y7, Canada

Tel: 613 995-1210; Tlx : 053-3777

Europe
Earthnet User Services
Via Galileo Galilei
100 44 Frascati, Italy

Tel: 39-6-9401360 or 39-6-9401216
Tlx : 611295 or 610637

Japan
Remote Sensing Technology Center of Japan
Uni-Roppongi Bldg, 7-15-17 Roppongi
Minato-ku, Tokyo 106, Japan

Tel: Tokyo 3-403-1761; Tlx:02426780

India
National Remote Sensing Agency
Balanager, Hyderabad-500 037
Andhra Pradesh, India

Tel: 262572 Ext. 67; Tlx: 0155-522

Argentina
Comision Nacional de Investigaciones Espaciales (CNIE)
Centro de Procesamiento Dorrego 4010
(1425) Buenos Aires, Argentina

Tel: 772 5108; Tlx: 17511

South Africa
National Institute for Telecommunications Research
ATTN : Satellite Remote Sensing Centre
PO Box 3718
Johannesburg 200, South Africa

Tel: 27-12-26-5271; Tlx: 3-21005

Thailand
Remote Sensing Division
National Research Council
196 Phahonyothin Road
Bangkok 10900, Thailand

Tel: 579-0117; Tlx: 82213
Cable: NRC Bangkok

China
Academica Sinica
Landsat Ground Station
Beijing, People's Republic of China

Tel: 284861 (Beijing, China); Tlx: 2102222

Indonesia
Chairman
Indonesian National Institute of Aeronautics and Space
JLN Pemuda Persil NO. 1; PO Box 3048
Djakarta, Indonesia

Tlx: 49175

Saudi Arabia
King Abdulaziz City for Science and Technology
PO Box 6986
Riyad 11442, Saudi Arabia

Tel: 01-478-8000; Tlx 201590

REFERENCES

EOSAT, 1988. Landsat Data Users Notes, Vol. 3 (1).

Erickson, J. D., 1984. The LACIE experiment in satellite aided monitoring of global crop production, in G.M. Woodwell, ed., *The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing* pp 191-217, Chichester, U.K.: John Wiley and Sons.

Ford, J. P., J. B. Cimino, and C. Elachi, 1982. *Space Shuttle Columbia Views the World with Imaging Radar: the SIR-A Experiment,* JPL Publication 82-95, Jet Propulsion Laboratory, California.

Harris, R., 1987. *Satellite Remote Sensing. An Introduction.* London: Routledge.

Justice, C. O., J. R. G. Townshend, B. N. Holben, and C. J. Tucker, 1985. Analysis of the phenology of global vegetation using meteorological satellite data. *International Journal of Remote Sensing* 6: 1271-318.

Millington, A. C., R. J. Saull, P. Kennedy, J. R. G. Townshend, R. Madams, and S. D. Prince, 1987. Biomass energy appraisal in Southern Africa -the role of remote sensing, in *Advances in Digital Image Processing*, pp. 134-44 Nottingham U.K.: Remote Sensing Society.

Nelson, R. and B. Holben, 1986. Identifying deforestation in Brazil using multiresolution satellite data. *International Journal of Remote Sensing* 7: 429-48.

Pravdo, S. H., B. Huneycutt, B. M. Holt, and D. N. Held, 1983. *Seasat Synthetic-Aperture Radar Data User's Manual*, JPL Publication 82-90, Jet Propulsion Laboratory, California.

Short N., 1982. *The Landsat Tutorial Workbook*, NASA Reference Publication 1078, Washington D.C.

Tucker, C. J., J. R. G. Townshend, and T. E. GOFF, 1985. African land cover classification using satellite data. *Science* 227: 369-75.

LAND USE MAPPING IN THE PHILIPPINES USING SPOT SATELLITE IMAGERY

B. Wayne Luscombe

INTRODUCTION

An important and evolving application of remote sensing technology is the identification and mapping of natural resources for sustainable land use development. This paper discusses an example of where SPOT satellite imagery was used to develop national, regional, and provincial statistics on land use and natural resources and to prepare land use classification and satellite image maps for an entire country. It identifies the objectives of the project, how it was implemented, what results were achieved, and what limitations and constraints were realized. It also addresses the issues of the cost and time required to undertake such a program of data collection and analysis.

BACKGROUND

The Philippines is an archipelago of more than 7,000 islands. It encompasses approximately 30 million hectares of land area, 1.1 million hectares of coastal wetlands, and 26.6 million hectares of coastal waters. It has a tropical island geography with a very diverse environment, supporting a range of terrestrial and marine ecosystems. Because of increasing population pressures, many of these ecosystems are being degraded at alarming rates. Over 50 percent of the total land mass is mountainous, with slopes in excess of 18 percent and thus is susceptible to erosion when the forest cover is indiscriminately removed.

In developing its lending strategy, the World Bank recognized the need for more current and accurate resource information about the Philippines in order to identify a set of interventions that would lead to improved management for sustainable use of the land and water resources. As part of its regular economic and sector work, the Bank undertook a study to identify and address significant natural resource management issues in the country. This study became known as ffARM--Forestry, Fisheries, and Agricultural Resource Management Study. In support of this activity, the Bank attempted to develop a basis of information from which it could prepare development strategies. By the very nature of the study, up-to-date information about resources and land use was required within a relatively short time frame. Conventional approaches and techniques for resource and land use surveys are typically very time consuming and costly. An alternative approach was sought that could provide the data quickly and inexpensively.

LAND USE MAPPING IN THE PHILIPPINES

With funding from the Swedish Agency for International Technical and Economic Co-Operation (BITS), the Bank, in agreement with the Philippine Department of Environment and Natural Resources (DENR), executed a land use study using SPOT satellite imagery. The Swedish Space Corporation (SSC), part owners of the SPOT program, was contracted by the Bank to carry out the technical work and the image interpretation and analysis. The land cover classification and mapping activity cost approximately US$ 1.7 million. The SPOT study primarily used visual interpretation of the imagery, with some digital classification being used to demonstrate how additional information could be gleaned to refine the classification system.

Earth observations collected by the SPOT satellite have a spatial resolution of 20 meters on the ground surface in its multispectral scanning mode. This means that it can identify features on the ground as small as 20 meters by 20 meters and records digital information about these areas in each of three portions, or "bands", of the electromagnetic spectrum. It has an even higher spatial resolution (i.e., 10 meters by 10 meters) on a second sensor on the satellite, but this only records information in one band of the spectrum and is less useful for discriminating differences in vegetative land cover.

PROJECT DESCRIPTION

Because the Philippines is located in a tropical area, cloud cover is a major concern for collecting satellite imagery. Open windows during which imagery can be collected are heavily dependent on the seasons. For this study, the SPOT satellite was programmed to acquire information in a systematic manner to achieve total coverage of the country. Even before the final contract was negotiated, the satellite was programmed to receive images in order to take advantage of the short cloud-free period. The first images were received by SSC at their receiving station in Esrange, Sweden on March 26, 1987. To obtain a maximum number of scenes before the rainy season arrived, the satellite was programmed to acquire multiple views with each overhead pass. In addition, the side-looking capabilities of the sensors on board the satellite were used to acquire imagery over the land areas during those passes when the orbit took the instrument over water. The project was one of the first large national mapping activities to use SPOT satellite imagery and was therefore given high priority in the programming of scene acquisitions.

Fortunately, the cloud-free period extended until nearly mid-July in 1987 and SPOT was able to cover 102 of the approximately 190 scenes required to cover the area of interest in the country. New scene acquisitions were terminated in mid-July because of unacceptable image quality. The satellite was reprogrammed to begin data acquisition in mid-September, 1987, to cover the remaining areas region by region, taking into consideration the periods during which individual regions were likely to be affected by cloud cover. Because of the vastness of the country, there are tremendous differences in the climatic regimes of regions in the north compared with regions in the central and southern parts of the country. To meet the delivery dates of the contract, the last scene was acquired at Esrange on February 26, 1988, nearly 11 months after the start of the collection process.

It is not possible to do a land use classification from satellite imagery without the use of additional collaborative data from other sources. Ground truth information and other data from primary and secondary sources were collected between April 27 and June 12, 1987, to assist in the interpretation. This additional information included seven ground surveys, a large number of low-level oblique aerial photos taken from 19 reconnaissance over-flights, expert interpretations from in-country resource specialists, older Landsat imagery, and a large number of topographic and thematic maps.

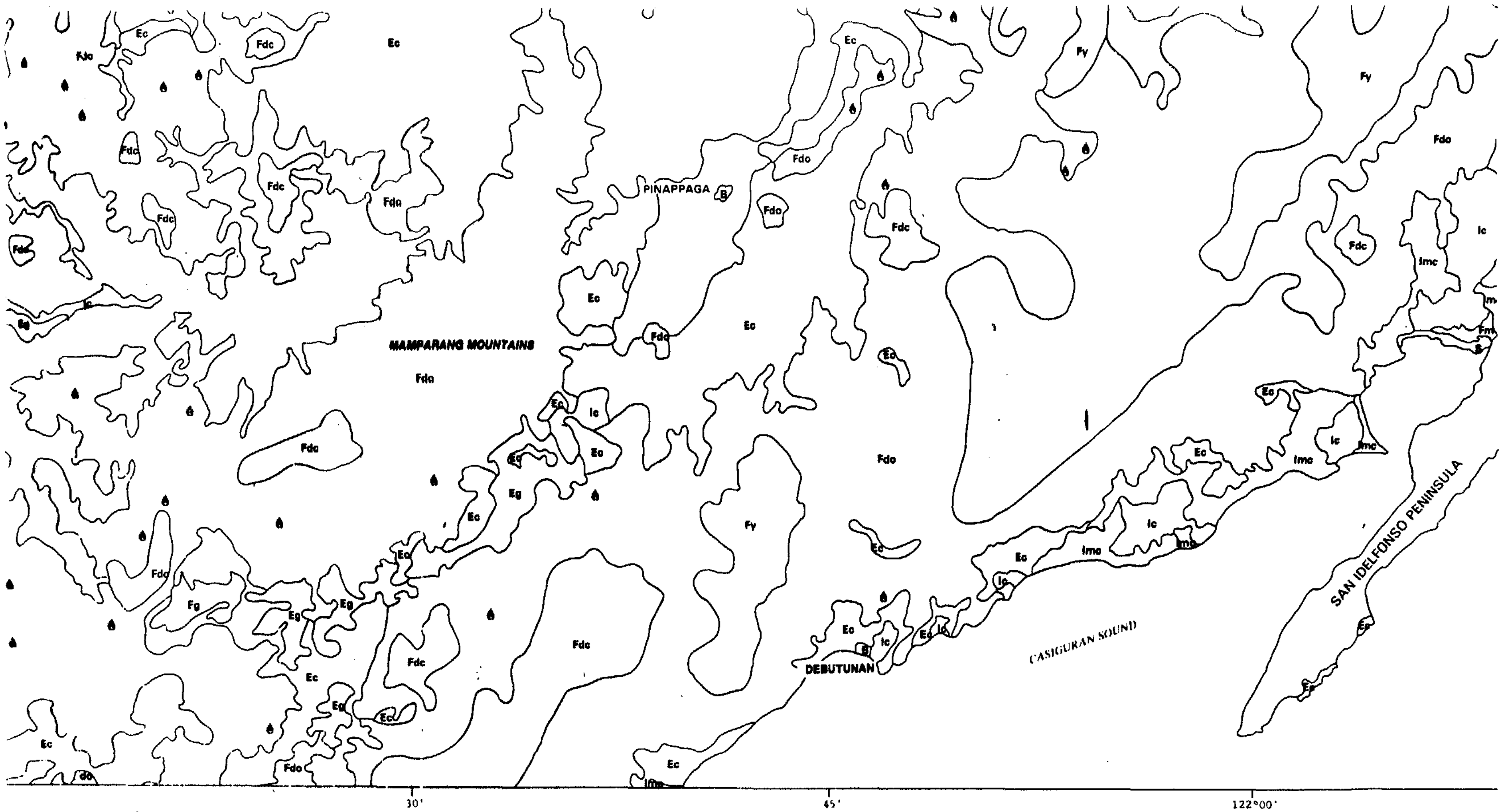
Using the scenes that had been studied during ground and air reconnaissance, the analyst teams developed a classification system and a procedural manual to be used in the visual interpretation of the satellite data. The 190 SPOT scenes were analyzed and classified in Sweden at SSC facilities using the established procedures for visual classification. The images were also geometrically and radiometrically corrected and mosaicked into map sheets corresponding to the Philippine's 1:250,000 map series. This work was done by SSC staff with the assistance of several DENR personnel from the Philippines. To illustrate the magnitude of the task, the classification and interpretation work employed 18 persons, with an additional 10 to 15 persons contributing at various times to the precision correction, image processing, and photo laboratory work.

The legend for the interpretation of data was based on four groups of land cover classes: forest, extensive land use, intensive land use, and nonvegetated land and other areas. The original project design proposed to identify 13 classes of land use; however, following the initial ground truthing exercise, and detailed discussions with resource planners in the country, it was agreed to modify the proposed classes and to add new ones that would better meet the needs of the land use and resource planners. The high resolution of SPOT data made it possible to identify some of these additional classes. The initial field work also demonstrated that some of the proposed classes were impossible to distinguish from other classes. For example, it was found that Imperata grasslands could not be distinguished from other grasslands, and that coconut could not be distinguished from other tree species, particularly when mixed with forest. The revised classification included 22 land cover classes and two marine classes, identifying coral reefs and silted waters. These classes, together with total areas, are described in Appendix 1.

The imagery was produced in hard copy form at a scale of 1:100,000 to facilitate visual interpretation of the land use classes. The interpretation was performed by placing transparent overlays on the imagery and demarcating boundaries between land use classes. The images and the resulting land use maps, at scales of 1:100,000, were photographically reduced to a scale of 1:250,000 and mosaicked into map sheets, corresponding to the existing 1:250,000 national map series, for presentation and publication. This resulted in 43 map sheets; each map sheet area was represented by three standard, visual products:

- a color satellite image map formed by mosaicking the individual SPOT scenes,
- a line-based land cover map on transparent overlays (Figure 3-1), and
- a land cover map printed on photographic paper showing each class in a different shading pattern (Figure 3-2).

The maps and the overlays were compiled into a two-volume atlas. The overlays and the maps on photographic paper contain exactly the same information, but they serve different purposes. The maps are an independent source of land cover information in which the land cover classes appear in different shades, and the transparent overlays are meant to be superimposed on the satellite image maps and on the existing topographic maps for comparison.



LEGEND

F — FOREST
forest trees and reproduction brush
< 10 % cultivated and other open areas
Fp — pine forest
Fy — mossy forest
Fd — dipterocarp and/or other broad-leaved forest
Fdc — closed canopy, mature trees covering > 50 %
Fdo — open canopy, mature trees covering < 50 %
Fm — mangrove vegetation

E — EXTENSIVE LAND USE
populated areas in uplands and grasslands
> 10 % cultivated and other open areas
< 70 % cultivated area
(symbol) — cultivated and other open areas in forest, each symbol representing 50 hectares
Ec — cultivated area mixed with brushland and grassland
Eg — grassland, grass covering > 70 %

I — INTENSIVE LAND USE
crop lands, plantations and fishponds
> 70 % cultivated area
Ip — plantations larger than 100 hectares
Ipc — coconut plantations
Ipo — other plantations
Ic — arable land, crops mainly cereals and sugar
Im — mixed intensive cultivation (crop land and plantations less than 100 hectares)
Imc — crop land mixed with coconut plantations
Imo — crop land mixed with other plantations
If — fishponds
Ifm — fishponds derived from mangrove
Ifo — other fishponds

N — NON-VEGETATED LAND
Ne — eroded area
• — symbol for minor eroded spot
Nr — riverbeds
Nq — quarry
q — symbol for minor quarry
No — other barren land

B — BUILT-UP AREA

M — MARSHY AREA AND SWAMP

L — LAKE

S — SILTATION PATTERN IN LAKE OR ALONG THE COAST

C — CORAL REEF

SPOT Scene location diagram: Sc

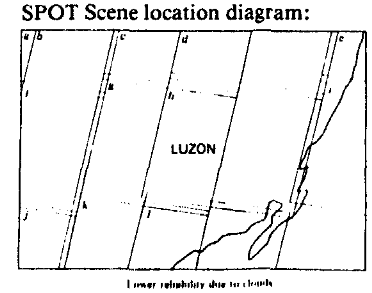


Figure 3-1. An Example of a Line-based Land Cover Map on Transparent Overlay. Represented here as a Paper Print (reduced from original scale).

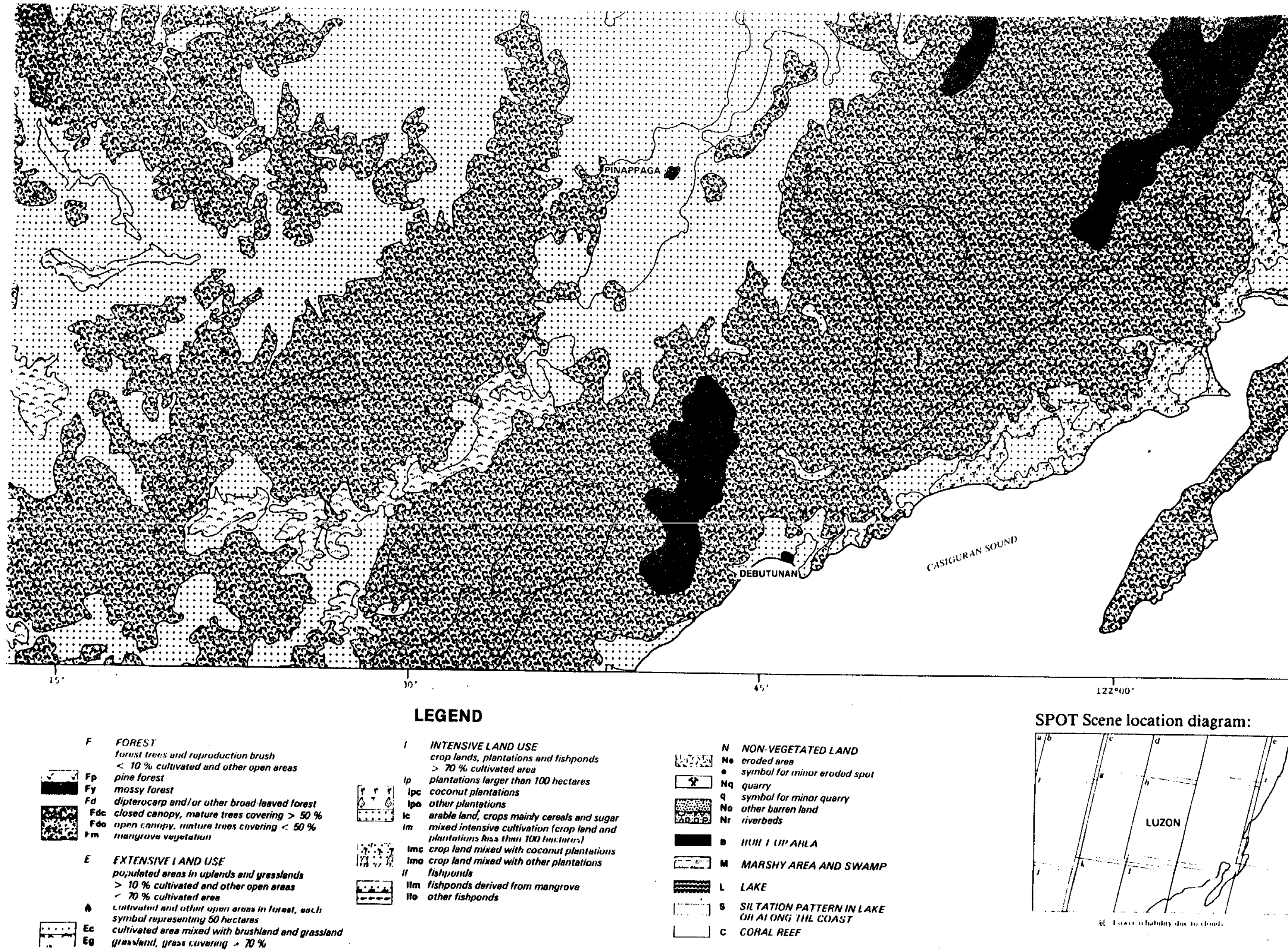


Figure 3-2. An Example of a Land Cover Map Showing Each Class in a Different Shading Pattern (reduced from original scale).

Area calculations on a region-by-region basis for each of the classes were accomplished by digitally scanning the land cover maps, together with the regional and provincial boundaries, and automatically calculating the respective areas. National statistics were then generated by summing the individual statistics for each of the 43 map sheets.

The 1:250,000 scale does not reflect limitations with the raw data, which can be used for mapping at scales up to at least 1:50,000, but was chosen because of its appropriateness for national and regional level planning and because of the extra time and cost that would have resulted from mapping at larger scales. In addition to the "hard copy" map products, complete sets of multispectral, digital tapes representing the mosaicked images for each map sheet were produced. Although this digital information was resampled to 40-meter resolution (from the original 20-meter multi-spectral data), it allows for further independent analysis at scales larger than those presented on the published maps.

Nearly all of the land use classification work was done through visual interpretation of the images; however, digital multispectral classification was performed on three selected SPOT scenes. The three scenes represented areas with different geographic characteristics, one representing a mountainous pine forest area, the second representing a lowland coastal area, and the third representing an area of large plantations and intensively cultivated land. The objective of this activity was to demonstrate the full capabilities of the technology and to compare the results with those from a strictly visual interpretation.

It is beyond the scope of this paper to examine the specific details of the results of the classification approaches, but it is important to note that the use of digital classification did--in some cases and for some areas--allow for subclassification in the visually interpreted classes. For example, the definition of forest used in the visual interpretation excluded pine areas with sparse crown cover; but, with the assistance of digital classification techniques, it was possible to delineate pine forests with coverage down to 30 percent.

The digital classification of information on an image is almost entirely dependent on the spectral reflectance of each individual picture element and does not take into consideration other factors that would normally be considered when using visual interpretation, such as surface texture and context, for example, proximity to transportation, or known relationships with other land covers.

Because it does deal with individual picture elements, digital classification can define smaller areas than would be possible using only visual techniques. It also helps to eliminate classification errors resulting from subjective differences among different interpreters. The comparison of the two classification techniques, visual and digital, in this study concluded that "with the techniques currently available, visual interpretation is recommended when a study encompasses the entire investigation area. The advantages of digital classification are best utilized in mapping of defined objects."

DATA ACCURACY CONCERNS

The accuracy of the results of the land cover analysis using SPOT imagery has generated considerable discussion. A national forest resource inventory (NFRI), undertaken in the Philippines recently with German bilateral support, has produced, at first glance, quite different results from those obtained in the SPOT analysis. This resource survey is based on aerial photography and extensive ground studies. Appendix 2 compares the statistics for forest cover, region by region, derived in the two independent studies. Although the national level statistics are comparable, one finds significant differences at the regional level and even greater differences at the provincial level (not reported in Appendix 2).

A close examination of the interpreted data from the two studies suggests, however, that the discrepancies may not be as significant as indicated at first glance. The differences seem to arise from several sources of error. First, all measurements and calculations in the NFRI have been done manually, which has produced some identifiable errors. Area calculations from the SPOT study were all performed by a computer and therefore have eliminated that source of human error. Second, some of the SPOT images have considerable cloud cover, which makes classification much more difficult. In these cases, other sources of information (older aerial photographs, Landsat imagery, etc.) were used when available to make a best judgment about the land cover beneath the cloud cover. Third, differences in the classification criteria between the two studies account for substantial amounts of the discrepancy. For example, dense shrub areas were included more often as forest in the SPOT study than in the NFRI. Considerable work is being done in the Philippines at present to resolve these discrepancies and as the two sets of information are examined more closely by both the German-funded NFRI project and SSC, much of the difference appears to be identifiable and explainable.

POTENTIAL USES FOR SPOT DATA

The usefulness of the information from the SPOT survey has been criticized on the grounds that it is unable to distinguish between important classes of land cover. For example, official government statistics in the Philippines include three categories of forest--primary, residual (or secondary), and reproductive brush, but SPOT has a technological limitation in not being able to distinguish among different sorts of forest cover. The reproductive brush may only be seedlings mixed with brush and grass, and satellite imagery cannot discriminate between this type of cover and a brush or grass cover. Also, it is not able to distinguish between primary and secondary forests, only whether or not the canopy is closed. The study also found that if pine forests are not very dense, crown cover appears low because of the shape of trees and the fineness of needles, causing them to be classified into nonforest categories. The magnitude of this problem is illustrated by comparing the results of the SPOT study, which reported 810 square kilometers of pine forest, with that of the German NFRI, which reported 2390 square kilometers. Further analysis of the SPOT results indicates that it did not accurately differentiate between closed dipterocarp and mossy forests, or between normal and stunted trees. The result is that the extent of mossy forest has been underestimated and that of closed canopy dipterocarp forest correspondingly overestimated. The final report on the ffARM project concludes that "if the commercial potential of a forest needs to be accurately assessed, then satellite reconnaissance must be supplemented by a ground inventory."

In identifying other potential uses of the SPOT land cover survey, the ffARM final report (p. 112) suggests that:

> SPOT land use classifications and the resulting maps and statistics may have utility in devising a better sampling frame (for taking agricultural censuses). Although the SPOT survey did not take identification of cultivated area as an objective, it is possible to estimate this by applying to the land use statistics rough estimates of the proportion of each category of land used in cultivation. Since the category "extensive cultivation" is mainly co-extensive with farming on steeply sloped land, it is also possible to roughly estimate the area cultivated in the uplands.

TECHNOLOGY TRANSFER ISSUES

A complete set of all hard-copy maps and digital tapes that were produced by this study exist in the ENVOS Division in the Bank. A second complete set of all information has been provided to the National Mapping and Resource Information Authority (NAMRIA) in the Philippines. At present, NAMRIA has limited capabilities to make full use of the digital data but with the support of several bilateral donor agencies, it will be developing fully operational image processing capabilities. During the execution of the SPOT land cover project, several staff from NAMRIA were provided with hands-on training in the interpretation and analysis of satellite imagery.

When undertaking a study such as the SPOT land cover survey in the Philippines, in which satellite resource-based information is collected and analyzed, it is extremely important to consider issues associated with the transfer of the technology to the country. Some of these issues include:

- Identification of an effective agency within the country to assist with the collection, analysis, and management of the resource information;
- Provision of technical training to agency staff;
- Provision of an appropriate level of technology to enable full use of the information;
- Adequate long-term support for remote sensing data acquisition to enable monitoring changes in resource bases over time.

SUMMARY

The SPOT land cover study of the Philippines demonstrates that current information about the natural resources and land use patterns of a country can be obtained quickly and inexpensively. This study, which produced national, regional, and provincial land use statistics, as well as complete mapping for the country at a scale of 1:250,000, was completed within one year, from April 1987 to April 1988, and cost approximately US$1,7 million.

The study also demonstrated some of the problems associated with such an activity. It is often difficult to obtain complete satellite image coverage of acceptable quality for a large area, especially in tropical regions because of excessive cloud cover. Also, the technology still has major limitations concerning its ability to discriminate among certain types of vegetation cover.

In some cases, such discrimination is vital for effective land use planning or for developing commercial forest policies. Last, transferring the technology and the information to a country requires that an appropriate institution and infrastructure be developed to make use of the data and to be able to apply the information technology effectively in sustainable resource development.

APPENDIX 1.

PHILIPPINES LAND COVER STUDY USING SPOT IMAGERY

Class Code	Land Cover Category	Total Area in km^2
Fp	Pine forest	812
Fy	Mossy forest	2,455
Fdc	Dipterocarp forest, closed canopy	24,345
Fdo	Dipterocarp forest, open canopy	41,940
Fm	Mangrove vegetation	1,494
Es	Cultivated and other open areas in forest	304
Eg	Grassland	18,129
Ec	Cultivated area mixed with brushland	101,143
Epc	Coconut plantations	11,326
Ipo	Other plantations	908
Ic	Arable land, crops mainly cereals and sugar	43,923
Imc	Cropland mixed with coconut plantations	37,478
Imo	Cropland mixed with other plantations	3,652
Ifm	Fishponds derived from mangrove	1,952
Ifo	Other fishponds	101
Ne	Eroded areas	7
Nq	Quarries	86
Nr	Riverbeds	818
No	Other barren land	103
B	Built-up areas	1,314
M	Marshy areas	1,035
L	Lakes	2,054
	Total Classified Land Area	**295,379**
	(unclassified land area	5,462)
S	Siltation patterns in lakes or along the coast	284
C	Coral reefs	3,527
	Total Classified Area	**299,191**

APPENDIX 2

A COMPARISON OF FOREST COVER BY REGION

REGION	SPOT (percent)	NFRI (percent)
I	14	20
II	42	43
III	16	13
IV	30	25
V	7	4
VI	7	5
VII	3	3
VIII	26	17
IX	20	14
X	37	34
XI	31	27
XII	24	17
Philippines	24	22

MAPPING FROM SPACE

Guy Rochon

INTRODUCTION

This paper deals with the potential and limitations of using satellite imagery to produce base maps, and discusses recent experiences in various countries and environments throughout the world.

There is an acute need for basic geographic information to better manage land and natural resources and to understand the impact of human activities on the environment. Base maps constitute a major contribution to the establishment of this basic information. As their name implies, base maps are the basic layer of information to which more specific layers of information are added.

Since base mapping is as old as civilization itself, over the years the practice has been progressively regulated by scientific and technical societies. In addition, a number of standards have been established on the form such maps should take, which are obviously linked to the technology available to cartographers. In the case of base maps, most of the technologies involved (photographic, aircraft piloting and navigation, photogrammetric, and printing techniques) were developed after World War I.

Since then, a complete set of new techniques has evolved, including electronic sensors, spaceborne platforms, digital image processing, computer and electronic map editing and printing, and electronic data and information storage and transmission, which leads to two essential questions :

- Can the new technologies provide maps that meet the existing standards more efficiently? (This implies that these standards still satisfy the human needs for which they were established.)
- Should we develop new standards to take advantage of the additional capabilities of the new technologies and to meet the additional existing needs of our modern societies? (This implies that base maps and base map production methods do not entirely meet the needs of our modern world.)

The second question is more controversial since it throws doubt on the well-established international scientific culture. It is, nonetheless, a challenging issue for all cartographers and base-map users. As no clear indication of future trends has emerged from the discussions held in international societies and forums (ISPRS 1988, CISM 1987, CISM 1987 etc.), this paper will limit itself mainly to the first question.

The prevailing standards also concern themselves with classes of land maps (cf. NATO 1978), or quality classes. But time is of no importance in these standards. What is the intrinsic value (or class) of a 30-year-old map created with the most rigorous standards? Is a new one with less rigorous standards better? As can be seen, our assessment of the capabilities of SPOT uses very different perspectives.

After an overview of the advantages and disadvantages of the present and emerging technologies, the paper focuses on SPOT, since it is the first civilian remote sensing satellite to offer functional stereo capabilities.

The various approaches to SPOT imagery information extraction are described in brief, as well as a qualitative evaluation of the advantages and disadvantages of each approach. The CARTOSPOT system, which was developed by Digim for the Canadian government, is then outlined.

Published results of mapping projects are used to compare the performance of present systems with those using conventional photogrammetric techniques. The accuracy, type of products derived, delivery schedule, cost, and overall performance of the various systems are compared and discussed. The evolution of this technology in the coming years and the related performance of new systems are also evaluated.

Finally, conclusions are drawn on this new opportunity for building the primary layer of national data bases for future Geographic Information Systems (GIS) rapidly and at a lower cost. This will help meet the growing requirements of developing countries for improved strategies in land and natural resource management and more reliable and efficient techniques of information management.

THE NEED FOR TOPOGRAPHIC MAPS

For scales smaller than 1:250 000, most of the land areas of the world have already been mapped. Because a significant portion of these maps are more than 20 years old, the major need is for map revision (United Nations 1985, Brandenberger et al. 1980). Figure 4-1 shows the coverage of the earth at various scales as a function of time (United Nations 1985).

For scales between 1:25,000 and 1:150,000, approximately 50 percent of the earth remains to be mapped. Map revision is also progressing very slowly in this area and the same report estimates that the annual rate of revision for maps of these scales is below 3 percent of the earth coverage. Current mapping activities are already monopolizing extensive human and equipment resources, even if they do not meet the present needs. To meet the minimum requirements established by the United Nations using photogrammetric techniques would require tremendous human and financial resources.

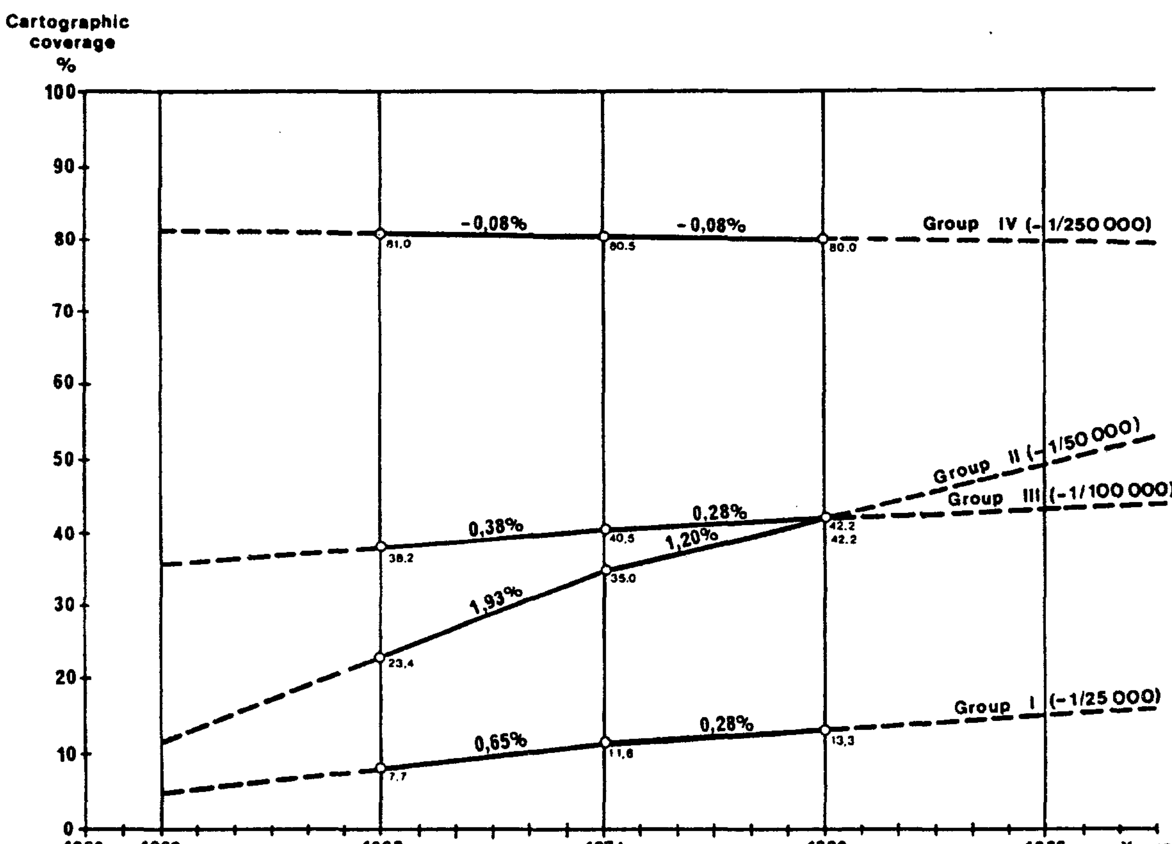


Figure 4-1. Evolution of Cartographic Coverage of the Earth (Source United Nations 1985)

SOURCES OF DATA AVAILABLE

Table 4-1 presents a list of the various sources of data to fulfill these needs.

Table 4-1. Sources of Data Available for Base Mapping

SOURCE	ADVANTAGE	DISADVANTAGE
Aerial photography	High resolution/accuracy Well established technology Simplicity of processing	High costs and delays Heavy logistic Intensive ground control needed Low automation possibilities
Space photography	Low costs and delays Low established technology Simplicity of processing	Low to medium resolution Low automation possibilities Small B/H
Airborne radar	No cloud problems Vegetation penetration possibilities Fast coverage	Low resolution Speckle (Noise) High costs Complexity of altimetric restitution Not operational
Airborne scanner	High resolution possibilities High information content High automation capabilities Other map products available simultaneously	High costs Complexity of sensor/processing Not operational
Spaceborne scanner	Analog or digital processing Low logistic/reduction of controls High automation capabilities Low costs and delays	Low to medium resolution Throughput sensible to cloud cover Small details not visible Not well known

Except in some tropical areas where cloud cover has restricted the possibility of using aerial photography, remote sensing and space technology are still in their infancy. Although these techniques offer a number of interesting possibilities, many of the technologies on which they are based are still under development or not commonly used. Space photography, for example, which has been used in the U.S.S.R. with satellites, should be employed more intensively in the future, even if the base-to-height ratio is quite small (B/H = 0,12 for KFA-1000; Piskulin 1989).

Airborne radar appears to have a bright future for topographic mapping in cloudy areas. However, reliable techniques in extracting precise altimetric data from stereoscopic SAR (Synthetic Aperture Radar) data combined with on-board inertial and GPS (Global Positioning System) data are still in the development phase. The precision of existing techniques restricts the production of radar-made maps to small scales.

Many projects have been announced to build a complete cartographic package for large- and medium-scale maps using an airborne scanner. Yet, no such package exists at this moment, even if prototype systems have been developed (CFS & SMRS 1988) combining push-broom scanners and sophisticated airborne positioning systems. The processing of this type of data is similar to the CARTOSPOT system described herewith. The cost effectiveness of this new technique compared with aerial photography and photogrammetry has yet to be demonstrated, even if preliminary studies have been positive. It will be only a matter of years, however, before this technology replaces aerial photography in large- to medium-scale base mapping. Commercial systems should be available within the next five years.

Finally, the only civilian space airborne scanner capable of producing acceptable topographic maps is SPOT, the French satellite that was first launched in February 1986.

THE SPOT SYSTEM

With its steerable mirror, SPOT can move its ground trace sideways along its orbital path from +27° to -27° in relation to the vertical. This allows two images to be acquired at different times under opposite viewing angles, resulting in a B/H over 1, which makes this satellite very attractive for height measurements.

These characteristics, combined with the satellite's 10 meters pixel in panchromatic mode and 20 meters pixel in multispectral mode, allow SPOT to provide the relative position of an identifiable object in a stereo pair with a root mean square (RMS) error of less than 4 meters (Begni and Henry 1988), a figure now generally accepted by most investigators around the world. As a result, SPOT has a great deal of potential for topographic mapping. How well this potential can be translated into standard cartographic products and to what extent SPOT has an advantage over existing techniques are the next questions to be raised.

MAPPING FROM SPOT

Two different processes are involved in the creation of a topographic map.

- Planimetric compilation, or the identification of the type of land cover and features (forest, road, village, etc.). This is done mostly by visual interpretation, although automated techniques can be used for a few broad classes of land cover (surface water, forest cover, etc.) using digital multispectral data and computer-assisted classification techniques.

- Altimetric compilation, or the localization in space of the ground cover. Except where vegetation or buildings interfere, this process is not dependent on the nature of the land cover (even if altimetric corrections are made, mostly for aesthetic purposes, to ensure that the surface of a lake is at the same altitude, the rivers flow on downward slopes, etc.).

Planimetric compilation

No fully automated techniques are commercially available to extract planimetric details from SPOT stereoscopic images. The operator, or photointerpreter, is always the main instrument of this process. Consequently, even if the quality of the interpretation could be related to the instrument used to support the interpretation, the quality of the input images or photographs and the experience of the operator are often the prime factors.

SPOT images have a better radiometric quality than the panchromatic film normally used in conventional mapmaking, particularly if the images are enhanced with digital techniques. The mean intensity and the contrast of dark forested areas, however, are unfortunately quite low because the gain setting of the SPOT sensors are always set to a low value.

Nonetheless, the resolution of SPOT is not as good as that of large- and medium-scale aerial film. Small features (creeks, field paths, buildings, etc.) are barely visible on SPOT images.(Konecny et al. 1988) "Any specification which requires the depiction of isolated settlements or small tracks is unlikely to be met by SPOT panchromatic data" (Dowman and Peacegood 1988).

Nevertheless, the SPOT resolution may be sufficient for map revision at small and medium scales, particularly for areas with few manmade features. Canada is undertaking a very extensive program of 1:250,000-map revision using Landsat-MSS data at a considerably reduced cost (Gauthier 1987). More than five million square kilometers have already been covered with this source. SPOT data is also being used in this program, for the revision of 1:50,000-scale maps.

This unique experiment on the capabilities of satellite imagery in map revision has demonstrated the technical and economic feasibility of the following activities (Moore 1988):

- 1:100,000- to 1:1,000,000-scale map revision in all parts of Canada;
- 1:20,000- to 1:50,000-scale revision for parts of Canada with minimal man-made features (point-feature limitation);

- 1:10,000- to 1:1,000,000-scale change detection for all parts of Canada (point-feature limitation).

Altimetric compilation

The extraction of altimetric information requires a certain amount of computation, including:

- establishment of a relationship between the geometry of a satellite image and the earth surface;
- establishment of a relationship between the difference in relative positions in a stereopair for the same object point on the ground and the height of this object relative to a known reference.

Computers are thus unavoidable in this process. With the additional development of efficient image-matching software to identify and locate homologous points in the stereopair, it is not surprising that commercial image-processing systems are becoming available to automatically extract altimetric data from digital stereo SPOT images.

The input SPOT images may come in various forms -- on a photographic support (film or print) or in digital form. Satellite data may be provided without preprocessing (except for radiometric calibration) or with different types of geometric transformations. Obviously, each transformation will modify or destroy some of the information contained in the input data, regardless of the quantity. The use of digital data ensures that this quantity will be minimal if not null.

Table 4-2 gives an overview of the various methods of altimetric information extraction, with brief comments on their respective advantages and disadvantages. Each method provides slightly different output products and qualities. The experience of the operator is still important in this process, but the system that supports the process is more important in the overall performance.

Using digital techniques, it is possible to simultaneously acquire a variety of by-products:

- DEM (digital elevation model): a matrix of numbers representing the altitude on a grid pattern, spaced as close as 10 meters apart. The DEM may be viewed in image form using different techniques (shaded relief images, perspective views, color coded, etc.);
- DTM (digital terrain model): a similar matrix giving derived terrain values for parameters such as slope, terrain orientation, slope length, runoff direction, the portion of sky visible at each point, etc.;
- orthoimages: satellite images corrected for distortions caused by relief;

- spatiomaps: orthoimages on which some of the features of the topographic maps have been overlaid;
- perspective views: the earth, with or without superimposed map features, as seen from a simulated point of view defined by the user.

Table 4-2. Existing Methods for Mapping from SPOT

Data type	Information extraction	Type of equipment technique	Processing technique	Advantage	Disadvantage
Film	Visual	Analytical plotter		Simplicity Reliability	Need of an operator for contour mapping
Digital	Visual	Micro-computer		Simplicity Reliability	Need of an operator for contour mapping
Digital	Semiautomated	Image analysis system	Edge matching	Automatic DEM generation	Not suitable forested areas Slow
			Image correlation	Automatic DEM generation Speed and reliability	Need of an operator for more reliability
			Least-squares correlation	Automatic DEM generation	Less efficient

THE CARTOSPOT SYSTEM

The CARTOSPOT system is a good example of a high-performance automated system. It was developed for the Department of Energy, Mines and Resources of Canada by Digim (Rochon et al. 1987, Leclerc 1988). Figure 4-2 gives a breakdown of the various steps involved in the creation of the various map products mentioned above.

Table 4-3 shows the geometric accuracy of the results for a test site in Canada (Simard et al. 1988). The precision of the system is dependent on the quality of the input images and the B/H of the stereopair.

Altimetric errors of less than 7 meters RMS have been achieved for DEM in favorable conditions. Typical errors are less than 10 meters RMS, which should be suitable for 1:50,000-scale maps in most countries around the world.

Table 4-3: Geometric Accuracy of SPOT over a Canadian Test Site

Point type	N	RMS Residuals (meters)		
		in X	in Y	in Z
GCPs	3	0,8	1,5	0,2
Homologous	19	0,5	2,4	-
Check	36	4,5	5,7	6,1

Source : Simard and Leclerc 1988.

This system and ones like it allow a drastic reduction in control points compared with conventional systems. A faster production cycle is also possible. Nevertheless, the planimetric interpretation requires more control and many point-features are missing.

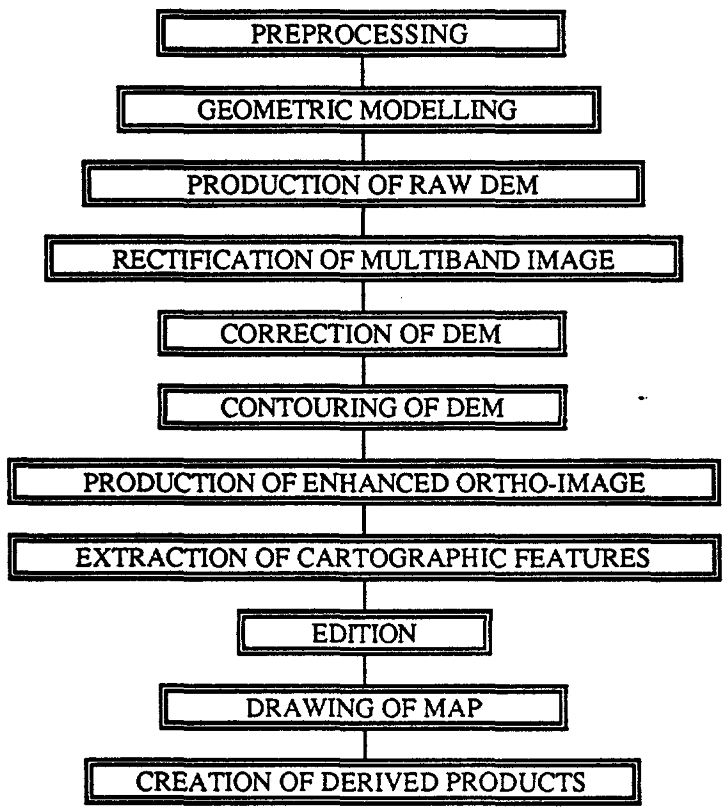


Figure 4-2. Main Processing Steps for Creating a Topographic Map from SPOT Images

A portion of a line map produced over Malaysia is shown in Figure 4-3, while Figure 4-4 presents an example of a shaded relief image for the area covered by the entire map.

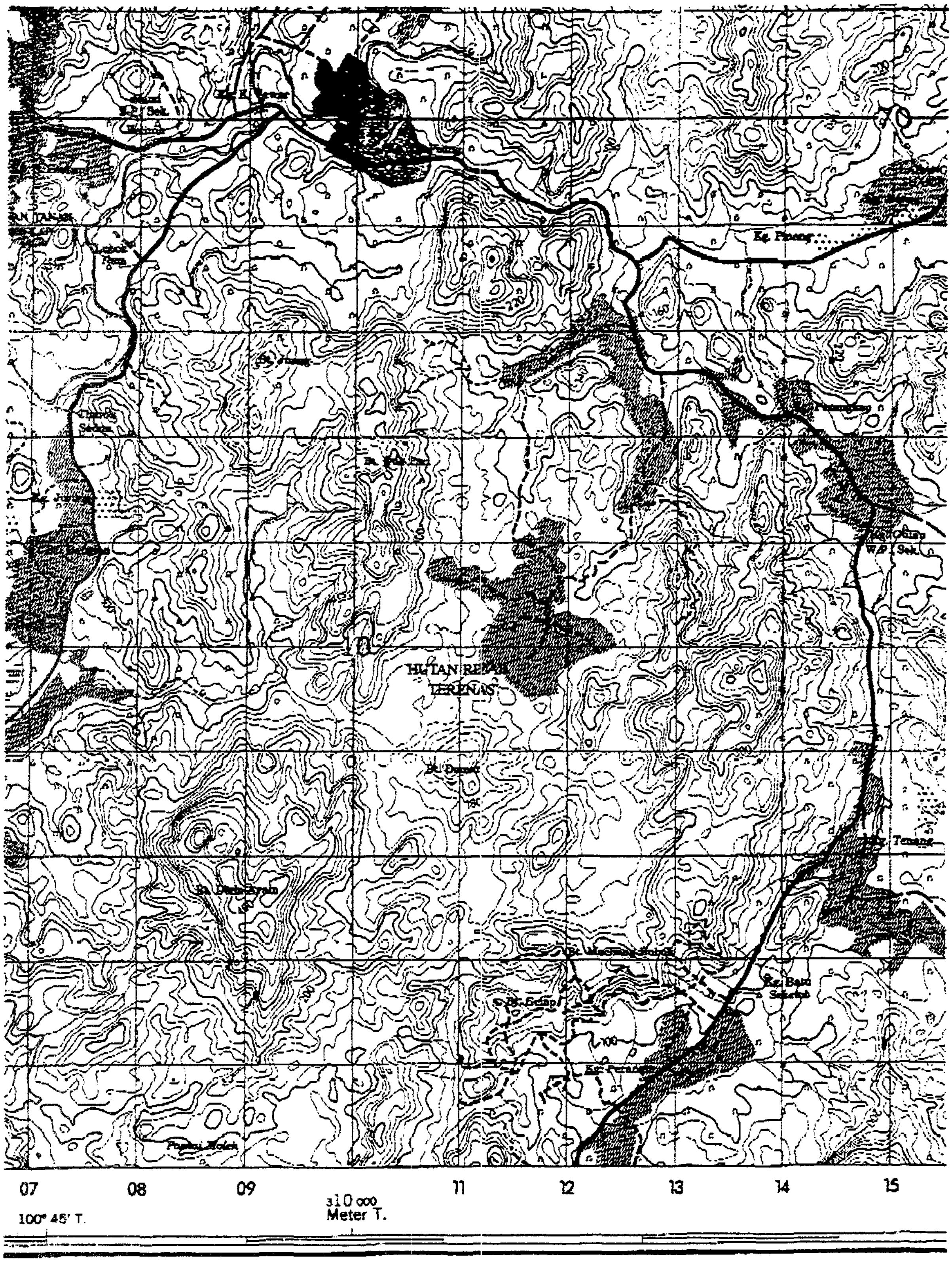


Figure 4-3. Portion of Topographic Map Produced over Malaysia
(Source: Rochon et al. 1987)

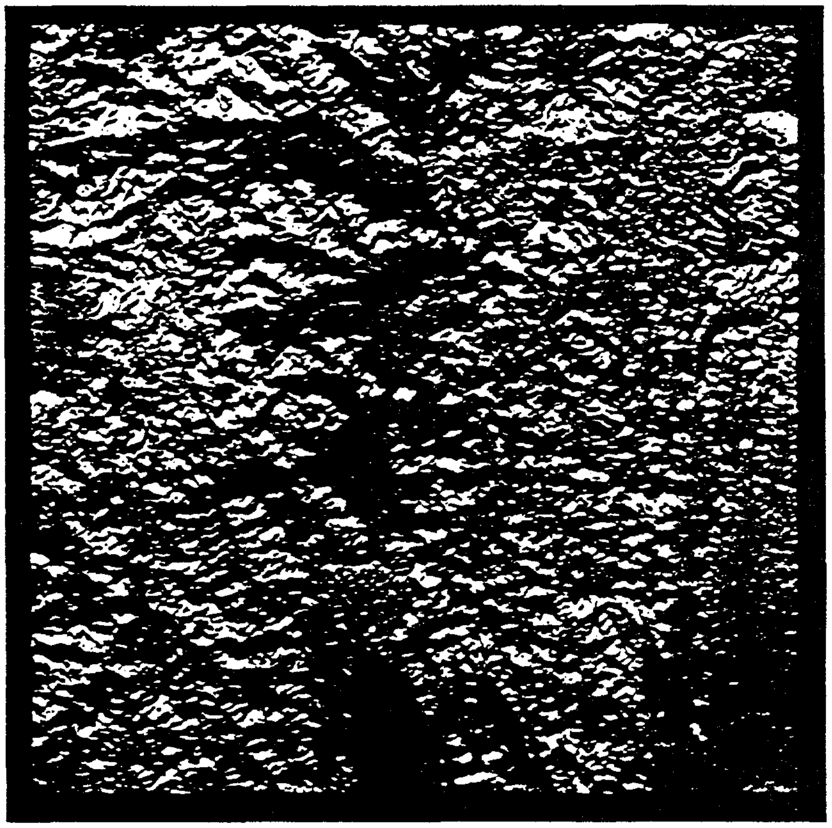


Figure 4-4. *Example of a Shaded Relied Image*
(Source: Rochon et al. 1987)

FUTURE DEVELOPMENTS

The development of very fast algorithms and new systems based on high-performance computers will soon result in systems with the capability of producing the altimetric data for a single map sheet in a few hours, with a precision near the theoretical limit of the input data. Epipolar calculation and transputers and expert systems linked to intelligent stereo display workstations are the basis of most of these new cartographic systems (Guichard et al. 1987; Muller et al. 1988).

Planimetric information extraction will still rely mostly on the experience and capability of the operator, who will be assisted in varying degrees by computers, which will feature full stereo presentation and overlays of ancillary data, including existing maps at any given scale.

PERFORMANCE AND COST

Cost figures are highly dependent on salaries, productivity, system performance, equipment financing conditions, and other conditions that vary depending on the location. Local conditions must therefore be taken into account when evaluating the merits of the present technologies in comparison with other systems.

Tables 4-4 and 4-5 compare costs in the Canadian context. These figures and other published papers (De Soyres, 1989) show that:

- cost reductions of 25-50 percent over conventional techniques are possible for small- to medium-scale line maps (1:50,000 to 1:250,000);
- greater cost reductions are possible for DEM, orthoimages, spatiomaps, and other derived products;
- in the small number of countries where thematic and topographic maps are produced simultaneously, still greater overall cost reductions are possible;
- for map revision, the use of satellite imagery is very cost-effective, if point features are a minor issue;
- where time is a critical factor, base mapping using SPOT images has a definite edge over conventional techniques.

Table 4-4. Comparison of Costs for Topographical Mapping at 1:50,000 (US$/km^2)

Steps	SPOT	Conventional mapping
Acquisition of images/photos	2,5	4,0
Ground control	10,0	14,0
Production of digital map	29,0	52,0
Field verification	10,0	10,0
Drawing and edition	17,0	17,0
TOTAL (rounded)	69	97
Percentage	71	100

Table 4-5. Comparison of Costs for Analog Map Revision at 1:50,000 (US$/km²)

Steps	SPOT	Conventional mapping
Acquisition of images/photos	0,5	4,0
Ground control	0,0	0,0
Production of analog map	2,5	15,0
Field verification	6,0	6,0
Drawing and edition	5,0	5,0
TOTAL (rounded)	**14**	**30**
Percentage	47	100

CONCLUSIONS

Topographic maps are tools. SPOT is another tool. Both tools have similar goals: the better management of land and natural resources and human activities that have an impact on the environment. SPOT provides accurate data for the production or revision of small- to medium-scale topographical maps, and such activities can be done at a lower cost and in a shorter time than with conventional techniques.

These advantages must be balanced against some limitations in precision. There is no hope of creating NATO-level 0 maps at medium scale (3-meters RMS error in altimetry for 1:50,000 maps) or of meeting the planimetric requirements for the identification of man-made features.

With the growing need for digital base maps for establishing of national data bases to fulfill the above goals, this debate may become quite academic. We may simply have no other choice than to use this new technology. In preparation, international organizations must rapidly develop new standards and references based on SPOT to avoid some of the confusion and unrealistic expectations that may arise from immature derived technologies or unreliable commercial systems.

REFERENCES

Brandenberger, A. J., S. K. Gosh, and M. Dellenseler, 1980. *The Status of World Topographic and Cadastral Mapping*, New York: United Nations.

Begni, G., and P. Henry, 1988. The SPOT 1 image quality: Two years Experience. *International Archives of Photogrammetry and Remote Sensing*, Vol 27, Part B10, ISPRS, pp.1103-12.

CFS & SMRS, 1988. Briefing on the advanced linear array imager system and its applications. Canadian Forestry Service, Dept. of Agriculture and Surveys, Mapping & Remote Sensing Sector, Dept. of Energy, Mines and Resources of Canada, unpublished document.

CISM, 1987. *Digital Mapping and Land Information*, Ottawa: CISM 250.pp.

CISM, 1988. *Topographic Applications of SPOT Data*. Ottawa: CISM, 333 pp.

De Soyres, F., 1989. Economic aspects of new cartographic products. *International Journal. of Remote Sensing*, Vol. 10(2), pp. 381-84.

Dowman, I. J., and G. Peacegood, 1988. Information content of high resolution satellite imagery. *International Archives of Photogrammetry and Remote Sensing*, Vol. 27, Part B8, ISPRS, pp. IV84-IV93.

Gauthier J. R. R., 1987. Topographic mapping from satellite data: A Canadian point of view. *Geocarto International*, Vol. 2(3), pp. 61-66.

Guichard H., G. Ruckebusch, E. Sueur, and S. Wormser, 1987. Stéréorestitution numérique SPOT: une approche originale de formation des images épipolaires et de mise en correspondance. In "*SPOT 1. Utilisation des images, bilan, résultats.*" Paris, Collection CNES n° 187, pp. 1371-92.

ISPRS, 1988. *Proceedings of the XVIth Congress of the International Society of Photogrammetry and Remote Sensing*, Kyoto, July 1-10th.

Konecny G., K. Jacobsen, P. Lohmann and W. Muller, 1988. Comparison of high resolution satellite imagery for mapping. *International Archives of Photogrammetry and Remote Sensing*. Vol. 27, Part B9, ISPRS, pp. IV226-IV237.

Leclerc A., 1988. Le système CARTOSPOT. *Actes du Symposium International sur les Applications Topographiques des Données SPOT*. Ottawa: CISM, pp. 86-100.

Moore H. D., 1988. SPOT vs Landsat TM for the maintenance of topographical databases in *Proceeding of the International Symposium on Topographic Applications of SPOT Data*. Oct. 1988. Ottawa: CISM, pp. 297-307.

Muller J. P., K. A. Collins, G. P. Otto, and J. B. G. Roberts 1988. Stereo matching using transputer arrays. *International Archives of Photogrammetry and Remote Sensing*. Vol.27, Part B3, ISPRS, pp. III559-III586.

NATO. 1978. NATO Standardization Agreement (STANAG) in *Evaluation of Land Maps*. STANAG 2215/Edition 4. NATO Enclosure I TO/MAS(AIR)111-MC/2215.

Piskulin V. A.. 1989. Economic relations of the all-union trade association Sojuzkarta and the geodetic and cartographic services of the U.S.S.R. to foreign countries. *International Journal of Remote Sensing*,Vol. 10, Number 2, February 1989, pp. 319-32.

Rochon G., et al. 1987. First results of topographical mapping using SPOT images of Malaysia. *Proceeding of the 8th Asian Conf. on Remote Sensing*. Oct. 22-27, Jakarta, Indonesia.

Simard R., G. Rochon, and A. Leclerc, 1988. Mapping with SPOT imagery and integrated data sets. *International Archives of Photogrammetry and Remote Sensing*, Vol. 27, Part B11, ISPRS, pp. IV440-IV449.

United Nations, 1985. *La cartographie mondiale*. Département de la Coopération Technique pour le Développement, Vol. XVII, ST/ESA/SER.L/17, pp. 123. New York: United Nations.

INVENTORY OF SMALL AND MEDIUM-SIZE IRRIGATION SCHEMES IN ALGERIA USING SPOT NUMERICAL DATA

P. Carton

SCOPE OF THE STUDY

The Algerian Ministry of Hydraulics, Environment, and Forestry wishes to prepare an inventory of small and medium-size irrigation schemes throughout the north of the country (250,000 square kilometers).This work is to be financed by the World Bank.

In fact, all the schemes in Algeria are included in this inventory, with the exception of about ten large irrigation areas of national importance. The size of the schemes varies from a few tenths of a hectare to several hundred hectares, and the water supply systems are of many types: small hill dams, pumping from wadis, boreholes, flood spreading, etc.

Remote sensing is a well-adapted technique for such an inventory for the following reasons:

- the available data are recent, exhaustive, and homogeneous,
- the different wavelengths of the shots allow better identification than aerial black-and-white photographs,
- numerical data processing allows automatic mapping of the analyzed subjects, and
- for the same unit area, satellite data are much cheaper than aircraft photographs.

This paper describes the performance and results of a pilot study carried out by SOGREAH in order to set up the best possible methodology for the general inventory.

AIMS OF THE PILOT STUDY

SOGREAH used two SPOT scenes to carry out the pilot study in order to reach the following main objectives:

- to identify every irrigation scheme of each scene,
- to check the smallest irrigation area it is possible to identify,

- to present color printouts on a scale of 1:50,000, geometrically corrected, diplaying the identified schemes, and
- to compute the irrigation areas per geographical unit.

Reasons for the choice of SPOT over Landsat are listed below. Both system Landsat-TM and SPOT-XS provide multispectral data that can both be used for such an inventory.

The first point is that for the same area observed Landsat's data cost is lower than SPOT's (US$ 0.2/km^2 for Landsat and US$ 0.5/km^2 for SPOT; a ratio of 1:2.5). This ratio roughly corresponds to the resolution difference between the two systems: related to the same area, SPOT provides 2.25 times more pixels than Landsat.

The second point is that a Landsat scene is about nine times larger than a SPOT scene. Consequently, if you examine the contours of the general area of study, you will notice that you need a larger land cover using Landsat than using SPOT, even if you order Landsat quarter scenes. In economic terms, that means that SPOT's cover for the entire area remains 90 percent more expensive than Landsat's.

SOGREAH chose SPOT because better accuracy was thought to be worth it because of:

- better display and estimation of size for very small schemes,
- precise location of each scheme with respect to main roads and landscape features,
- inner details better represented in the largest schemes (irrigation network, main tracks, etc.), and
- the data base it provides for northern Algeria that will be available for other land use studies.

Moreover, SPOT makes the programming of new shots to complete the catalog with some up-to-date images possible.

LOCATION OF THE TWO PILOT SCENES

The choice of the pilot scenes was made in association with the Ministry of Hydraulics in order to work within two different agroclimatic zones. The first one is the area of the confluence between wadi Mina and wadi el-Abd and the second one is much more arid and is located on and around chott el-Hodna.

Figure 5-1 shows the location of each scene.

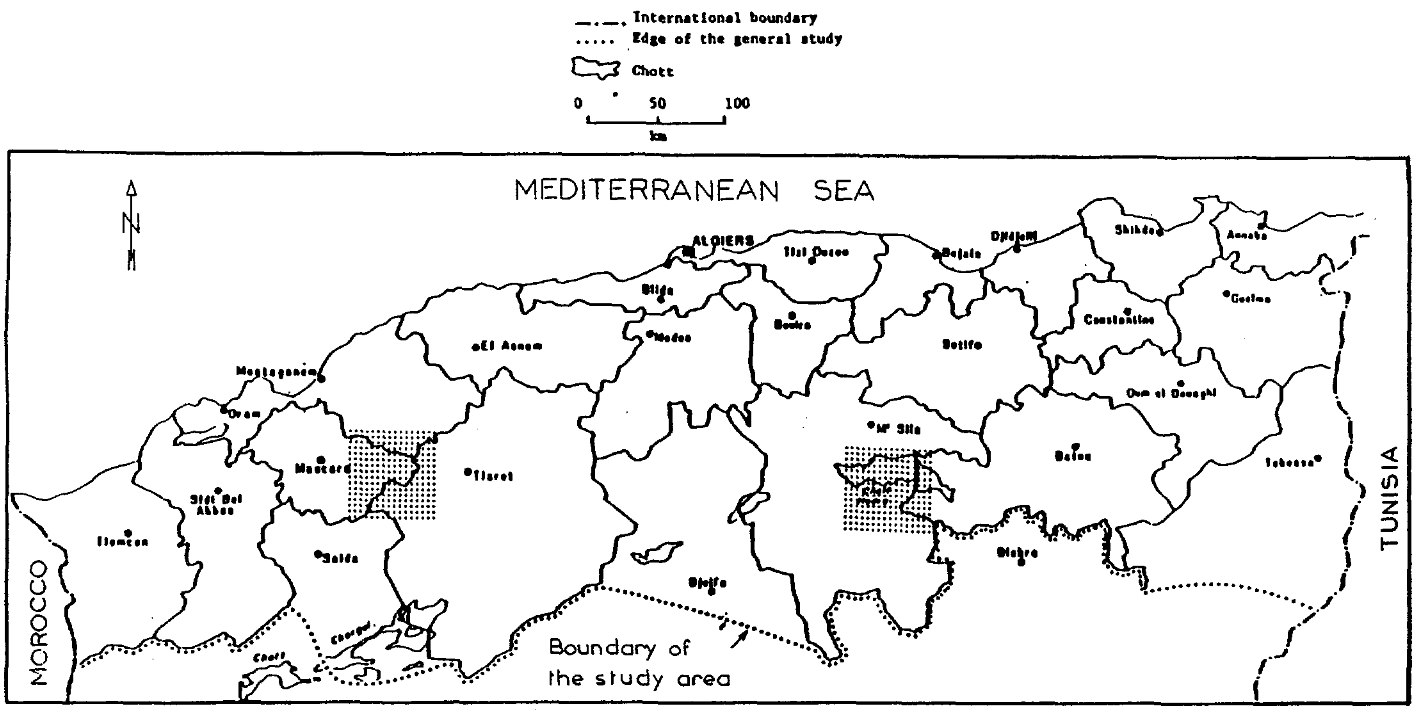


Figure 5-1. Location of the Two SPOT Scenes Used for the Inventory of Small and Medium-Size Irrigation Schemes in Algeria.

The best period for the shots was thought to be June. This period corresponds to the largest spreading of the schemes while the surroundings are supposedly already dry, thus enhancing the green color of the schemes. Consequently SOGREAH bought two scenes dated June 1986 from the SPOT catalogue.

PRODUCTION OF COLOR COMPOSITE MAPS

The first step is to process the numerical data to produce color composite maps using the three channels of SPOT. These maps were geometrically corrected to allow a precise overlay on the basic topographical drawings of the country. They were produced on a scale of 1:30,000 with Lambert coordinates and cut into convenient-size pieces for fieldwork.

FIELD OBSERVATIONS

A mission for field checks was organized in June 1989, exactly two years after the date of the study that provided the shots ordered by SOGREAH. It was made for both areas in association with local representatives of the Ministry of Hydraulics and with three research workers of the Algerian National Space Technics Center. It lasted four days for each area.

In the el-Abd wadi area (figure 5-2) the polygonal, dazzling green parcels corresponding to the fully operating irrigation schemes were quite obvious in the field as well as on the map (bright red spots). Few differences as regarding the location of the schemes were noticed two years after the shot; that means that the farmers cultivate the same parcel each year and do not move their pumps and pipes from one year to the other. A few new irrigation schemes were found, created since the date of the shot. The main irrigated crops are vegetables (onions, potatoes, tomatoes) and, to a lesser extent, orchards (apricots, figs, almonds). In the chott el-Hodna area, the irrigation schemes were found to be very small and centered around boreholes or artesian wells.

We observed that June was not the best period to take a picture of these arid areas because the largest irrigation schemes correspond to flood spreading used to grow cereals. The best period for studying these crop areas is April. In June all the cereals are already harvested and there is a strong confusion between straw from rain-fed cereals and straw from irrigated cereals.

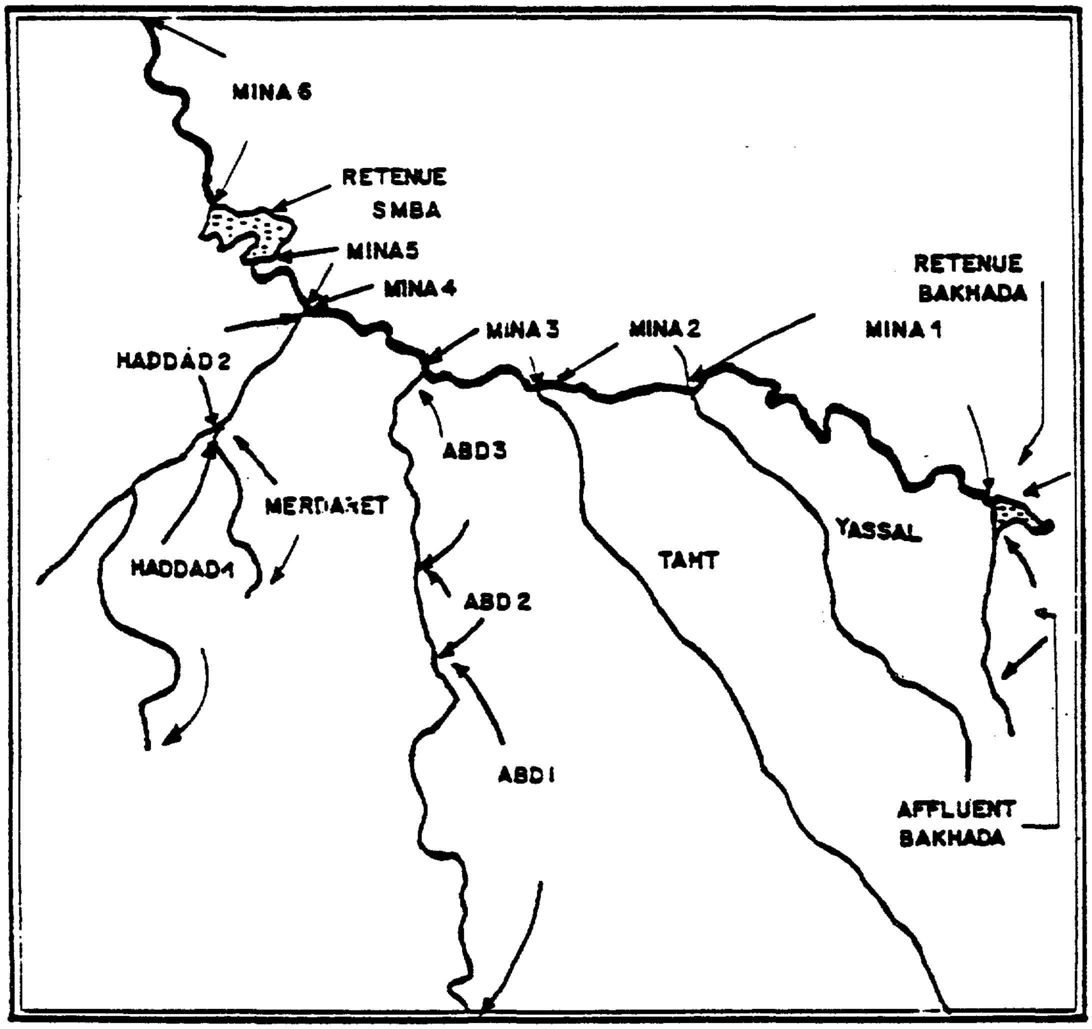


Figure 5-2. Location of the 15 Subwatersheds in the el-Abd wadi scene

NUMERICAL PROCESSING

Two different methods were compared to process the numerical data, taking into account the field observations: calculation of vegetation index and supervised classification.

Vegetation index

The vegetation index is the result of a calculation applied to each pixel.

$$Vi = 127,5 \times \left(\frac{XS3 - XS2}{XS3 + XS2} + 1\right),$$

where XS3: is the radiometric value of the pixel in the infrared wavelength and
XS2: is the radiometric value of the pixel in the red wavelength.

Sample areas corresponding to field checked irrigation schemes were extracted from the image and their vegetation index was examined. This index always reaches high values for each sample area. These values correspond to the high vegetative level of the analysed samples.

The aim of this work was to check if these values were specific to irrigated schemes. This would undoubtedly have provided a very convenient method to identify them. Unfortunately, some other areas in the image presented vegetation index values that partly overlapped those of the schemes. This was the case especially for Alep pine plantations and riverine natural vegetation of the wadis.

Supervised classification

This method is based on the statistical analysis of the sample irrigation areas using the three SPOT channels, and even a fourth channel (vegetation index channel).

This analysis leads to a good spectral identification of the irrigation schemes, different from the neighboring land covercategories. Consequently, it makes it possible to classify each pixel of the image either in the irrigation scheme class or not.

RESULTS OF THE CLASSIFICATION

The land covercategory classified is the full extent of growing irrigated crops at the date of the shot. It must be pointed out that these results do not allow quantification of the real physical extension of a scheme. For instance, already harvested plots or unirrigated parts of the scheme cannot be identified through remote sensing. These points must be clearly stressed to the user of the inventory to avoid any confusion about what is being classified.

The main results of the study are as follows:

- display of irrigation parcels as small as 1/4 hectares; that is, six grouped pixels corresponding to the minimum reliable identification size,
- production of color printouts on a scale of 1:50,000, displaying every scheme in bright red color,
- computerized calculation of the classified pixels, giving the area of irrigation schemes in the whole scene and within specific divisions (administrative divisions, watersheds, etc.).

Table 5-1 presents the number and acreage of the different schemes in 15 subwatersheds of the el-Abd wadi scene.

COMPARISON WITH A STUDY USING TRADITIONAL METHODS

SOGREAH carried out the same national iventory in Algeria in 1968 using traditional methods;that is man-years of consultants working in the whole country with large investigation teams. The result of this inventory was a series of maps of the irrigation zones on a scale of 1:200,000, each zone including a large number of individual unidentified plots.

Nowadays it would be too expensive to implement such an inventory, and we can say that remote sensing accuracy is far better. As a matter of fact, what sort of traditional inventory could identify and map on a scale of 1:50,000 thousands of schemes, some of them as small as 1/4 hectare?

The duration of a remote sensing study is by far shorter than a traditionally investigated one (12 months including mapping, were required in SOGREAH's proposal for the general inventory).

Table 5-1 Summary Table of the Irrigation Schemes over 0.25 ha

Subwatershed	Number of schemes	Total area (ha)
Mina 1	27	48.0
Mina 2	7	17.2
Mina 3	6	15.0
Mina 4	7	4.8
Mina 5	9	18.0
Mina 6	14	29.8
Haddad 1	58	105.1
Haddad 2	3	1.3
Merdaret	5	16.5
Abd 1	122	267.5
Abd 2	8	11.8
Abd 3	23	52.5
Taht	5	21.7
Yassal	4	9.3
Bakhada tributary	2	2.8
Remaining zones	25	48.5
Total	325	669.8

The remote sensing technique does not make it possible to avoid fieldwork to investigate the existing network and the socioeconomic characteristics of the schemes, but it allows a general, preliminary, exhaustive view of the schemes which makes a useful stratification of these investigations possible.

Last, but not least, the color printouts produced offer homogeneous, unequivocal, visual information.

EXTENSION OF THE PILOT STUDY TO THE ENTIRE NORTHERN REGION OF ALGERIA

The processing of 90 SPOT scenes instead of 2 generates very different problems concerning the management of the processing chain, the production of image mosaics, and the equalization of radiometric differences between the scenes. Preliminary agroclimatic zoning is necessary to group the periods of the ordered shots and the subsequent verification missions in the field. The approximate cost estimate for such a general inventory, including statistics and color printouts is US$ 3.00 per square kilometer.

THE ROLE OF REMOTE SENSING IN IRRIGATION MANAGEMENT: A CASE STUDY ON ALLOCATION OF IRRIGATION WATER

M. Menenti, T. Visser and J. L. Chambouleyron

MANAGEMENT OF IRRIGATION WATER

Large-scale irrigation systems cannot in practice be separated from their social and economic environment. This issue has been hotly debated in the recent literature on irrigation and it would be improper to elaborate on it here. The issue is, however, relevant to the identification of useful remote-sensing-supported services.

The interest for such products (their shadow price) depends on how closely such services fit into the set of priorities already established by the irrigation community, the latter being the individuals and institutions making use of a particular irrigation infrastructure.

It is particularly useful to follow, in our analysis, the conceptual categories proposed by Lenton (1988), especially the clear separation between irrigation management and irrigation water management, with the latter being a part of the former. It will be shown in the following that specific remote-sensing-based products can be identified that are relevant to both categories.

According to Lenton (1988) the concerns of irrigation management can be grouped into the following categories:

- setting objectives;
- establishing adequate conditions to achieve the objectives;
- controlling processes to achieve the objectives;
- performing activities compatible with the external context;
- improving the system to enhance its capacities.

Each category takes a concrete shape according to the following scheme:

- objectives: irrigation policies;
- conditions: system installation, institutions, governance;

- processes: management of water, land, crops, institutions, finance facilities, information;
- context: specific social and economic constraints;
- renewing: improvement of physical facilities, institutional reform.

This framework quite aptly illustrates the role of the remote-sensing-based services defined later in this report. Such services will primarily support different management components (category processes). Their appeal will depend on how clearly they relate to local irrigation policies (category objectives). Their actual impact on irrigation performance will depend on whether conditions and context have been properly taken into account. Their actual benefit will depend on the extent of renewal required to apply them.

Strictly speaking, remote sensing is simply a technique to gather information on different aspects of land use. Such information is not directly useful for irrigation management unless management procedures and tools are already available that require exactly this type of data. Experience teaches that this is not the case in general. It is, therefore, necessary to include in the design of our remote-sensing-based services proper analysis and management tools, which can be fed with remote sensing data and fit into the framework set forth in the preceding lines.

With remote sensing, information can be obtained that is relevant to the following management components:

- water: crop water requirements, water-logged areas, salinization-affected soils;
- land: actually irrigated versus irrigable land;
- crops: cultivated area by crop, uniformity of green biomass;
- institutions: actually irrigated land versus area having established rights;
- finance: due versus actually paid water charges (proportional to irrigated land or by crop).

This information is effective when combined with data describing other aspects of irrigation management. So proper software tools (Geographic Information Systems and Data Base Management System) have to be applied. When management of water and crops is the issue, then models of the relevant hydrological processes have to be applied. Such a package of methods translates basic information, like that obtained with remote sensing, into quantitative results directly useful to irrigation management.

OBJECTIVES OF IRRIGATION MANAGEMENT

As mentioned in the previous section, the acceptance of remote sensing services depends on how accurately the specific irrigation policy applying to each case is taken into account.

Objectives of irrigation management are formulated at different levels:

- definition of irrigation strategy, that is the overall expected outcome of a particular irrigation project;
- allocation of resources, such as staff and machinery for maintenance of tertiary units on a monthly basis;
- scheduling of activities required to implement the preestablished allocation scheme.

When irrigation water management is considered, the sequence is:

- establish which water management strategy is required to achieve the overall objective of the project;
- work out the water allocation scheme required to implement the preset strategy;
- work out the detailed irrigation water scheduling required to implement this water allocation scheme.

In general, all the activities mentioned above can be formulated and solved as optimization problems; the three levels considered so far translate into:

- detailed quantitative analysis of different scenarios → strategy;
- calculation of target amounts of water to be delivered to, say, tertiary units;
- calculation of detailed irrigation scheduling, for example, by minimizing losses.

Precise definition of this hierarchy of objectives is essential to assess the contribution of remote sensing to irrigation management. The preceding sequence of concepts can be translated into the following sequence of questions:

1) What should the irrigation system deliver on the basis of current objectives and regulations?
2) What should the irrigation system deliver on the basis of current objectives and improved regulations?
3) What should the irrigation system deliver on the basis of improved objectives and regulations?

Evaluation of irrigation management should address two basic issues:

4) How far is the irrigation system from target delivery?
5) How do we get the system back on target?

An essential feature of our package should be its capability to provide answers that carefully take into account constraints relating to the categories of conditions, context and renewing mentioned earlier. In this respect the concepts put forward by Rogers et al. (1988) are illuminating.

Experience teaches that optimal allocation of irrigation water may often clash with context. It is, therefore, necessary to go through an iterative procedure by comparing feasible irrigation policies with the optimum solution. Since this comparison should be done on the basis of system performance, the capability of simulating system behavior under different hypotheses is very helpful. To this purpose Decision Support Systems (Van Walsum, and Drent 1987) are effective management tools.

It should be realized that the sequence of questions on irrigation management does apply to the three levels mentioned above: strategy, allocation, and scheduling. This implies that simulation and optimization tools are definitely necessary to specify in detail objectives and to assess the deviation of actual from target system performance.

ROLE OF REMOTE-SENSING-SUPPORTED SERVICES IN IRRIGATION MANAGEMENT

Regarding information requirements, the questions mentioned earlier imply that the most basic need is measurement of system performance, independent of further use of such data. This conclusion is supported by the experimental evidence reported by Abernethy and Pearce (1987).

Different categories of individuals professionally involved in irrigation clearly agreed on the urgent need for performance data. It must, therefore, be concluded that our effort is properly focussed on mapping performance indicators (Visser et al., 1989). Satellite data are an essential category of data in this respect.

By recalling the management components mentioned earlier, we can identify the following candidate remote-sensing-supported products:

- water → map of cultivated area by crop, map of crop coefficients, map of salt-affected soils, map of water-logged areas;
- land → map of actually irrigated land;
- crops → map of cultivated area by crop, map of uniformity of green vegetation cover;
- institutions → map of actually irrigated land (in relation with water rights management (see Verdin et al. 1986);
- finance → map of actually irrigated land, map of cultivated area by crop.

It has already been mentioned that these data are necessary to formulate properly the objectives of system management. Barrow (1987) aptly underscored the variety of possibilities that have to be dealt with in practice.

It should be mentioned here that when the available water resources (groundand surface water) are scarce, information essential to establish a proper water allocation scheme is the marginal benefit associated with a unit quantity of water. Such marginal benefit depends on place and time, since system response does vary in space and time.
Examples of marginal benefit are: rate of change of evapotranspiration, of crop yield, of total cost, and of net benefit or of utility (English 1981).

IRRIGATION MANAGEMENT IN MENDOZA, ARGENTINA

In the Province of Mendoza, in western Argentina, nine irrigation districts can be distinguished (Figure 6-1).

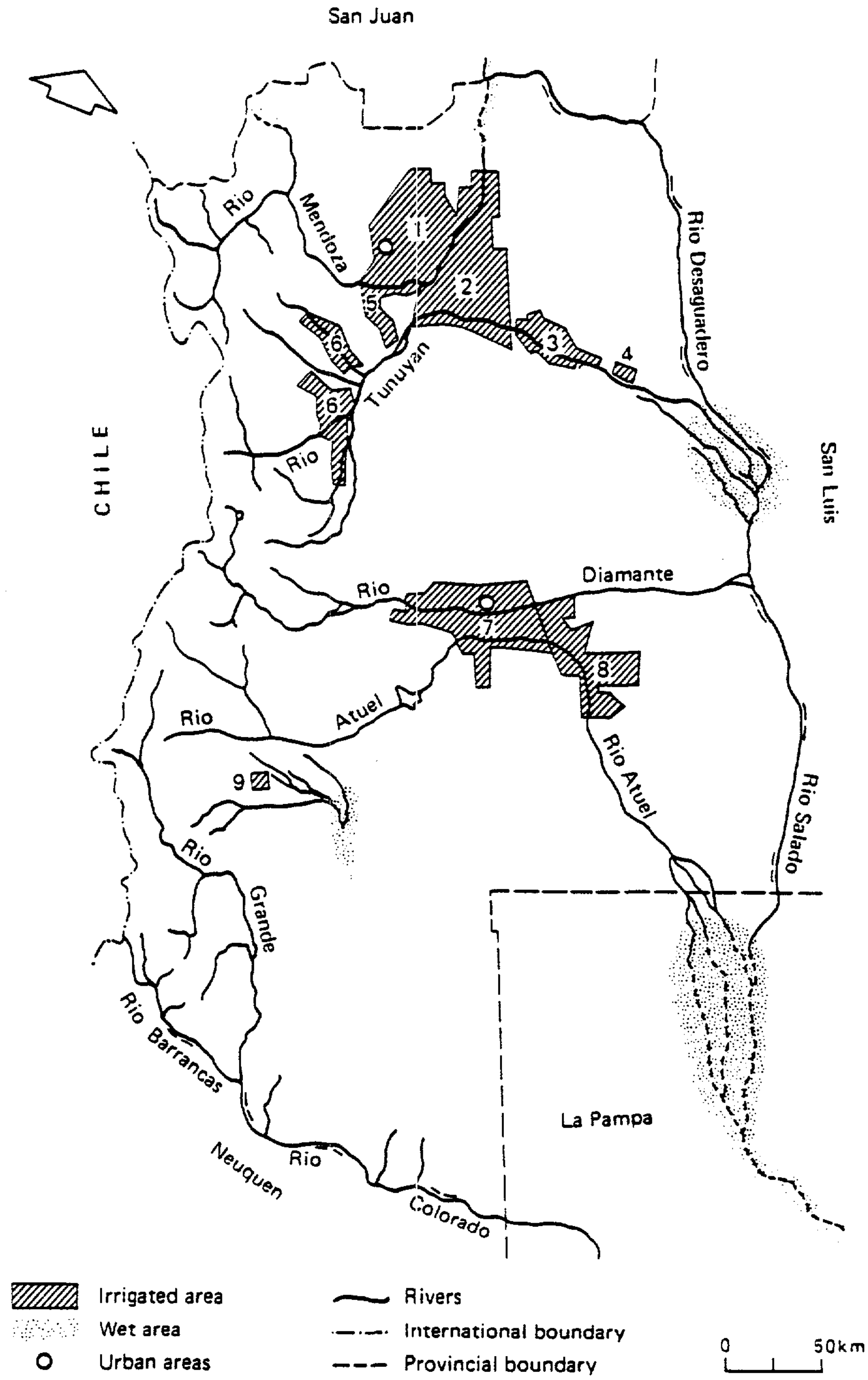


Figure 6-1. Main Irrigation Districts in the Province of Mendoza, Argentina.1 = río Mendoza, 2 = río Tunuyán Medio, 3 = Santa Rosa, 4 = La Paz, 5 = Ugarteche, 6 = Valle de Uco, 7 = San Rafael, 8 = General Alvear, 9 = Malargué

Irrigated agriculture has been the main driving factor of development until very recently. In the 1970s the shrinking market for the main produce of Mendoza (wine) and economic instability sparked a deep crisis. Rapid changes are taking place that pose challenging management problems, partly related to the complex hydrology of the region (figure 6-2).

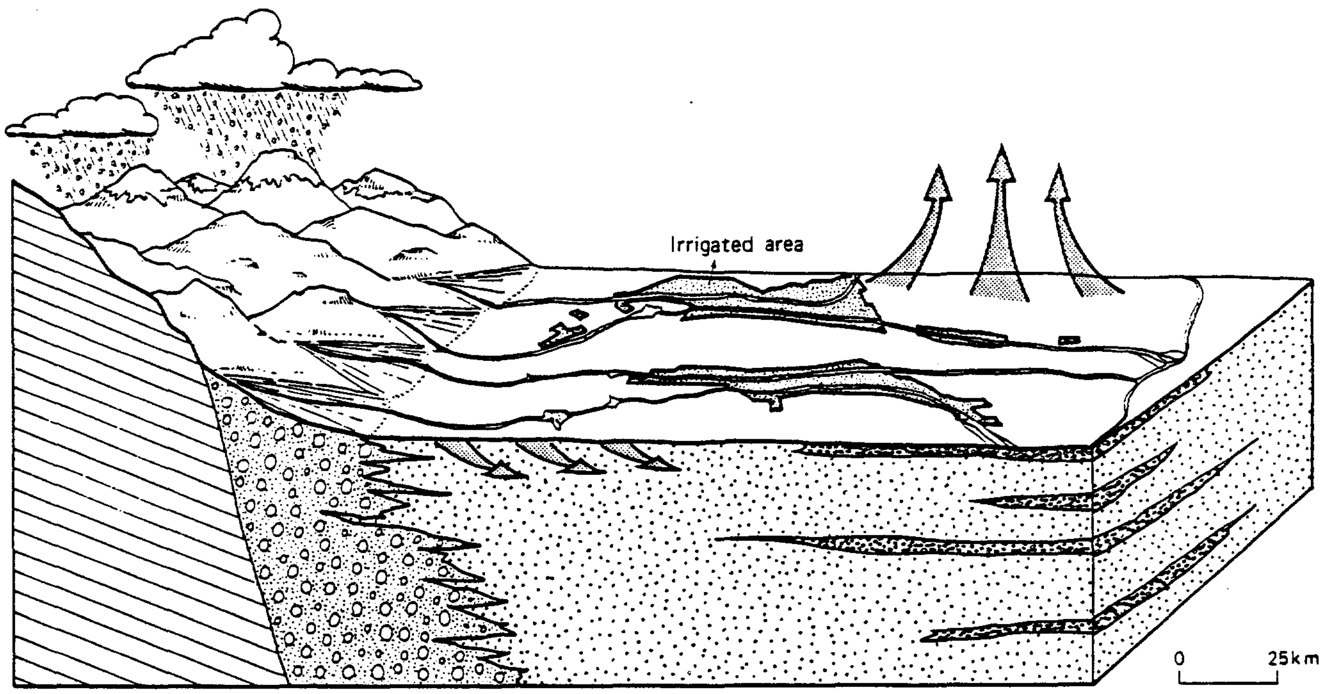


Figure 6-2. Sketch of Physiography and Relevant Hydrological Processes in the Region of Mendoza, Argentina

These conditions have induced a natural concentration of the aims of research institutions and of technical agencies present in the region on issues closely related to irrigation water management in the extensive cultivated area. Later in this paper water allocation policies are discussed in some detail. Here only a short overview is given.

Río Mendoza

Water supply in the irrigation district of Río Mendoza comes from the río Mendoza (figure 6-1). The regime of this river depends on snow melt in the Andes, through the Cipoletti diversion dam having a maximum capacity of 80 m^3 s^{-1}. There is no reservoir upstream of the Cipolletti dike and a rotational water allocation scheme is established for primary, secondary, and tertiary canals. When streamflow in the river exceeds 80 m^3 s^{-1}, flow in primary canals is continuous. The allocation scheme for the primary canals is established by the overall water authority, the

Departamento General de Irrigacíon (DGI). An elected representative of the farmers belonging to a particular primary canal is responsible for the water allocation to the secondary canals and for supervising and planning maintenance work.

Water is allocated to tertiary canals in much the same manner by other elected representatives. Although this organizational scheme seems to have a sound social nature, it is doubtful whether it facilitates the achievement of the highest possible efficiency in water use. Decisions by the DGI are made with poor information since the slow-response decisional scheme described above carries little feedback information to the DGI about possible inconsistencies between water deliveries and water requirements at farm inlets.

In the río Mendoza district, 80,354 hectares have water rights, while the total irrigated area downstream of the Cipolletti dam amounts (according to DGI) to some 150,000 hectares. Flow rate at farm inlets is in the range of 0.05 to 0.25 $m^3 s^{-1}$. A more detailed description of the area, with additional references, can be found in Chambouleyron et al. (1983).

Río Tunuyán Medio

Water allocation in the irrigation district of río Tunuyán Medio takes place in much the same manner as outlined above for the río Mendoza district. Water supply to the district, however, can be regulated by means of a reservoir (capacity is 3.6 x 10^8 m^3) and of the Benegas diversion dam, having a maximum capacity of 60 $m^3 s^{-1}$. The area with water rights amounts to 62,914 hectares but, as in the río Mendoza, a much larger area can be irrigated. In the río Tunuyán Medio district flow rate at farm inlets is large: between 0.20 and 0.35 $m^3 s^{-1}$ (0.5 l. s^{-1} ha^{-1}). This implies that the unit duration of irrigation must be short. Flow rates at farm inlets as large as 0.5 $m^3 s^{-1}$ and unit durations as short as 5 min. ha^{-1} have been observed.

Implementation of irrigation management

Irrigation management in Mendoza is implemented under the responsibility of two bodies at different levels:

- The Departamento General de Irrigación (DGI), through river basin agencies (Sub-Delegaciones), is responsible for the management (in the comprehensive sense explained earlier in this paper) of rivers, storage and diversion dams, and of primary canals.

- Water users associations are responsible for managing secondary and tertiary canals and for actual delivery of irrigation water to users. There are 712 associations, but they are being aggregated into 40 large associations, each one supplying water to about 7000 hectares. This reorganization is a keyissue in the assessment of the practical applicability of remote sensing to improve irrigation management.

The DGI is an independent organization, directly responsible to the House of Representatives of the province. The action of the DGI is regulated by a number of laws on water management. These legislative milestones are briefly recalled here to illustrate with facts the changing irrigation management issues:

1884 : First Water Law; irrigation water has to be allocated proportionally to areas having water rights; water rights can be withdrawn when land is not actually cultivated.

1916 : New Constitution of the Province; responsibility of the Departamento de Aguas (established in 1884) is restricted to irrigation waters; water rights are issued by the House of Representatives upon approval by the DGI of requests by farmers.

1953 : Law on unauthorized cultivated areas; serious shortcomings in the enforcement of the provisions of the 1884 law brought about a new water allocation policy; water rights are inherent to each property, and only in principle still subject to actual use of land.

1962 : Law on groundwater; responsibility for groundwater management is assigned to the DGI; lack of adequate technical means and rigidity of 1884 and 1953 laws on surface water make it impossible to fully enforce this law.

Present : A new law assigning responsibility to DGI for conjunctive management of surface water and groundwater is under development.

ALLOCATION OF IRRIGATION WATER ON THE BASIS OF WATER RIGHTS VERSUS ACTUALLY CULTIVATED AREAS

The original objective of the water distribution in the rió Tunuyán irrigation scheme was to supply surface water in proportionally to the area cultivated. Since an adequate registration of the cropped areas appeared to be impossible, it was decided to develop a system in which water rights could be acquired permanently by the farmers. It was assumed that the area with water rights would be representative of the actually culivated area in a secondary or tertiary unit.

In this chapter the possibility of improving the irrigation water management using remote sensing techniques to map actually cultivated areas is considered. Two possible water allocation policies are considered:

- allocation of surface water in proportion to the area with water rights;
- allocation of surface water in proportion to actually cultivated area.

In principle there are two different ways to apply satellite data to improve implementation of the equitable water allocation policy:

- update water rights that are temporary and subject to the condition that land be actually cultivated;
- map actually cultivated area and allocate water accordingly, notwithstanding the permanent character of water rights.

Mapping irrigated land in the Province of Mendoza

To underscore the magnitude of the problems arising because of the excessive water allocation in the irrigation districts, one should consider the implications of a mis-estimation of actually cultivated land. This concept is supported by the data in Table 6-1 obtained with Landsat-MSS data.

Table 1. Irrigated land, as Obtained with Landsat MultiSpectral Scanner (MSS) Data

Region	Irrigated land MSS (ha)	Irrigated land DGI (ha)	Water rights (ha)
North	178,040	202,680	265,360
South	129,100	155,840	212,160
Total	307,140	358,520	477,520

Note: irrigated land, as estimated by the Departamento General de Irrigación (DGI) and land having water rights; in the Province of Mendoza, Argentina (Thomé 1988).

When taking an irrigation project efficiency of 40 percent into account, the 477,520 hectares having water rights reguire 8.5×10^9 m^3 a^{-1}. How real this problem is, is aptly illustrated (Menenti 1988) by a Landsat-MSS scene of the southern part of Mendoza, which clearly indicates that downstream of the irrigation district, natural vegetation cover is high with water supply essentially the return flow from the irrigation districts.

To illustrate in detail the implications of different estimates of the area having water rights, the available data on total areas and areas with water rights of the tertiary units of a test area (Viejo Retamo in district 2, figure 6-1) are presented with comments. Next how to map cultivated and uncultivated areas is described. Finally the analysis of the distribution of cultivated area in the total area of the Rio Tunuyán irrigation scheme is presented.

Irrigable areas and areas with water rights of the tertiary units of the Viejo Retamo

The areas with water rights as they are applied by the tomero (person in charge of the water distribution) to supply water to the different tertiary units of the Viejo Retamo have not been updated in more than ten years. The total irrigable area of the tertiary units was determined by means of a survey. During this survey the exact location of the tertiary canals and the boundaries of their area of influence was determined. In 16 out of 33 cases the area with water rights used in the water supply exceeds the total irrigable area of a unit. Therefore the assumption that the area with water rights is representative of the area that is actually cultivated does not seem correct.

Table 6-2 shows a comparison between the area having water rights within the Viejo Retamo according to the gate operator and the area having water rights according to the DGI. It also shows the total area of influence of the Viejo Retamo resulting from a map made at the INCYTH and the same area resulting from the survey. It is especially remarkable that the data of the gate operator and of the DGI do not coincide, as they were expected to.

Table 6-2. Areas Having Water Rights and Total Area of Influence of the Viejo Retamo

Source	Area with water rights (ha)	Total area (ha)
Tomero	4789	
DGI	4435	
INCYTH		5006
Field survey		4902

Actually irrigated areas within the tertiary units of the Viejo Retamo

An accurate registration of the actually irrigated area in the different tertiary units of the scheme during a certain growing season appeared impossible using conventional techniques. Satellite remote sensing does offer a possibility to achieve this accuracy. Four different methods (Visser et al. 1989) to classify irrigated and nonirrigated areas were applied in the area of the Viejo Retamo. In all four cases a Landsat Thematic Mapper (TM) image taken in January 1986 was used.

To assess the accuracy of this land use mapping, crops present in five tertiary units of the test area were mapped in detail. In table 6-3 the results of this assessment are presented, which indicate that an accuracy of 6,4 percent can be achieved.

Table 6-3. Accuracy of Four Different Classification methods for Five Tertiary Units of the Viejo Retamo Area:

$$\frac{\text{irrigated area (class)} - \text{irrigated area (survey)}}{\text{irrigated area (survey)}}$$

Tertiary unit	Classification accuracy (percent)			
	Ratios method	PC method	Automatic classification	Ext. automatic classification
Gonzales	8.8	17.0	11.5	3.8
Alcaraz	8.4	22.2	7.6	11.6
Orrego	13.7	14.5	8.8	7.5
Day	10.6	12.8	9.3	8.3
Segundo Razgo	8.6	7.8	5.6	0.9
Mean	10.0	14.9	8.6	6.4

Irrigated areas in all secondary units of the Río Tunuyan Irrigation Scheme

In addition to the analysis of the irrigated areas and water distribution in one secondary unit, a classification of irrigated and nonirrigated areas was done for the whole area of the Río Tunuyan Scheme (District Nr 2 in figure 6-1) (70,000 hectares). In this case a Landsat-MSS image was used. MSS images have a lower spatial resolution (80 meters x 80 meters) than TM images. They contain two bands in the visible part of the spectrum: green (MSS 4) and red (MSS 5), and two bands in the near infrared (MSS 6 and MSS 7). Using the lower resolution data, the size of the image files was reduced significantly.

Figure 6-3 shows the percentage of the area that is irrigated. In general the units at the tail-ends of the main canals tend to have a lower percentage of irrigated land than the ones closer to the head of the main canals. This could be caused by the lack of sufficient surface water reaching the tail-ends of the main canals. If such was the case it would be incorrect to base the future water distribution on the currently irrigated areas. An existing, inequitable situation would then be maintained. This once more illustrates the fact that before deciding which water allocation policy has to be applied, it is very important to consider all technical and socioeconomic factors involved.

In this case the decision whether to apply water according to the actually irrigated area or according to the total irrigable area is quite relevant. Given the fact that the difference between total irrigable area and actually irrigated area is much higher for the secondary units located at the end of the primary canals, target volumes would be very much affected by the choice of the water allocation policy. It should be emphasized that the core issue here is the proper appraisal of the main limiting factor of irrigated agriculture: water or market demand.

If market-absorption capacity is the limiting factor, rather than water supply, then the correct strategy is to control hydrological side effects of irrigation through allocation on the basis of actually irrigated land. If not, water should be allocated on the basis of either water rights or irrigable area, taking into account the option between use of surface water and groundwater.

Figure 6-3. Irrigated Area as Percentage of the Command Area of Each Secondary Unit of the Rio Tunuyan Medis Obtained with Landsat-TM data. Irrigation Scheme (District Nr2 in figure 6-1)

APPRAISAL

The relevance of remote sensing for irrigation management has been demonstrated in the preceding pages from a technical point of view. From the institutional point of view, it should be stressed that all activities described here have been initiated by the Departamento General de Irrigación of Mendoza.

The real issue is twofold: 1) assessment of the direct monetary benefit of the use of satellite data, and 2) acceptance of the intervention of the irrigation authority into water allocation at the secondary and tertiary levels. As regards the first point the findings of this case study and of another one carried out in northern Italy (Azzali 1987) will be considered. The difference (table 6-1) between actually irrigated land and the area for which water charges are paid to the DGI (200,000 hectares) implies that un-paid water fees amount to some US$ 1.106 a year. This is about one order of magnitude more than the cost of mapping irrigated land each year. The investment in hardware and in setting up the data base with the required boundaries of management units (e.g., tertiary) would be recovered very quickly.

A similar conclusion was reached (Azzali 1987) on the basis of experience in two irrigation districts in northern Italy. Water fees there are paid according to crop type: rice is the most expensive, while no fees are due for growing wheat.

By mapping crops through multitemporal analysis of TM data, it was found that some farmers stated that they were going to grow wheat, while they actually grew soyabeans, for which crop water fees amount to some US$ 100 per hectare per year. It was estimated that by identifying just 250 hectare within one TM quarter-scene of erroneously declared crops, the costs of the analysis would be covered.

It is by now quite clear why issue 2) is relevant. For the above cost-benefit analysis to apply, farmers have to be convinced to accept the regulatory action of the irrigation authority. Here we are back to the concepts presented at the beginning of this paper. The use of additional information, such as that obtained by satellites, must be accommodated in the context of irrigation management as a means to achieve a consensus on allocation of irrigation water. The aggregation of water users associations into larger units, as is being done in Mendoza, is crucial to this purpose. The larger associations will provide technical assistance to farmers on irrigation water use on the basis of a broad mandate by the members of the association. This organizational structure is expected to facilitate the introduction of new management procedures.

REFERENCES

Abernethy, C. L. and G.R. Pearce, 1987. Research needs in third world irrigation. *Proceeding Colloquium Hydraulics Research*, Wallingford, U.K., 28-29 April 1987, pp. 98.

Azzali, S., 1987. The contribution of Landsat data to water management in two Italian irrigation districts. Nota 1764. The Netherlands: Institute for Land and Water Management Research (ICW), Wageningen, 52 pp.

Barrow, C., 1987. Water Resources and Agricultural Development in the Tropics. New York: Longman Development Studies, 356 pp.

Chambouleyron, J., M. Menenti, L. Fornero, J. Morabito, and L. Stefanini, 1983. *Evaluación y optimización del uso del agua en grandes redes de riego*. Roma: Instituto Italo-Latino Americano (IILA), 176 pp.

English, M.J., 1981. The uncertainty of crop models in irrigation optimization. *ASAE transactions*, pp. 917-928.

Lenton, R., 1988. Strategy development in IIMI. ODI/IIMI Irrigation Management Network Paper 88/1e. 23 pp.

Menenti, M.(ed.), 1988. *Mecanismos de aprovechamiento hidrico en la región andina: imagenes satelitarias y modelos de simulación*. Mendoza, Argentina: INCYTH-CRA 350 pp.

Rogers, P. P., J. J. Harrington, and M. B. Fiering, 1988. New approaches to using mathematical programming for resource allocation, In G.T. O'Mora (ed.). *Efficiency in irrigation. The Conjunctive Use of Surface and Groundwater Resources*. Washington: D.C./ World Bank. pp. 122-27.

Thome, R., H. E. Yañez, and J. M. Zuluaga, 1988. Determinación del area bajo riego en la Provincia de Mendoza, in M. Menenti, ed. *Mecanismos de aprovechamiento hidrico en la rigión andina: imagenes satelitarias y modelos de simulación.* Mendoza: INCYTH-CRA. pp. 203-227.

Van Walsum, P. E. V. and J. Drent, 1987. *Decision Support Systems for Water Management in Regions with Intense Agriculture. Systems Analysis in Water Quality Management*. London: Pergamon Press. 231-240. (Techn. Bull. 62. Institute for Land and Water Management Research (ICW), Wageningen, The Netherlands, pp. 10.)

Verdin, J. P., M. P. Crane, and G. P. Lyford, 1986. Application of a digital geographic data base to irrigation water rights management in *Remote Sensing Applications for Consumptive Use* (evapotranspiration) pp. 35-47. American Water Resources Association.

Visser, T. N. M., M. Menenti, J. A. Morabito, and A. Drovandi, 1989. Digital analysis of satellite data and numerical simulation applied to irrigation water management by means of a data base system. *Proceeding International Conference on Use of Computers in Scientific and Technical Research,* Mendoza, Argentina: Universidad de Mendoza (ed-in press).

REMOTE SENSING APPLIED TO HYDROGEOLOGY THROUGH CASE STUDIES

Thierry POINTET

SCOPE OF THE STUDIES/2

In the number of scenes bought per year, BRGM is the leading user of SPOT images. In 1988, remote sensing (SPOT and Landsat) was integrated into about ten hydrogeological studies abroad. The following three projects are good examples because remote sensing is not used simply for describing a situation. It is used at an early stage of a study, is part of a multidisciplinary approach, and gives access to very detailed information. This has two merits: it ensures added efficiency for the exploration or prospection of difficult zones, and it saves money on the field reconnaissance of a freshly discovered zone.

The physical environments covered are varied, from wet tropical regions with very dense vegetation to arid ones with rocky or bare substrata beneath weathered coverings. For the fractured hard rock and karstic environments, because of the presence of linear objects such as fractures and stream bed segments, remote sensing helps in understanding the fractured substratum structure. One thing is, however, always evident: the less the human occupation of the ground, the greater the exploitation possibilities of the images.

In July 1988, the National Society for Senegalese Water Development wanted to spread its groundwater exploitation into the hinterland of Dakar with the purpose of supplying the tourist centers that are being developed south of this city. Rather than a classic approach by a substantial geophysical campaign, exploration based on remote sensing and field observation was chosen. This choice resulted in a very appreciable gain in time, a considerable saving in cost on geophysical prospecting, and a gain in information. To a description of the environment, which would have been only static, was added information on the functioning of the water-bearing media (recharge zones, flow compartmentalization). New boreholes are planned for 1989.

In 1987, two space maps with a hydrogeological theme were drawn up for the southern Moroccan provinces, for which available data were extremely scarce. The inaccessibility of these regions, the absence of geological maps, and the impossibility of programming airplane coverage led to the use of Landsat scenes that identified the outcrop zones of the sedimentary and basement formations where a few boreholes had been drilled. Due to the relatively simple structures, this information was sufficient to discover the layout of the water-bearing formations and to propose zones that were potentially favorable to groundwater development. These maps were printed and are in use at the moment.

The theme of the third study, carried out in 1988 in Burkina-Faso, was small-scale irrigation using water contained in the fractured basement rocks in a Sahelian climate. The irrigated patches that were formed as a result of this study were put into production in the first months of 1989. The yields required for these developments are three to ten times greater than those sought from the classic village water supply boreholes. These prospecting methods must, therefore, increase in efficiency for sites with high yields to be found rapidly.

The use of remote sensing to identify linear geological objects and recognize tectonic structures is of prime importance. Integration of the results of analysis of the structures, the relief shapes, the drainage pattern and the study of small-scale fracturing in the field enables an indispensable preinvestigation. Precise checking methods in the field (geophysical prospecting and radon tracing) lead to the desired efficiency.

The rapid classification of the surfaces by aptitude to infiltration and to cultivation is possible by remote sensing exclusively. These results, added to the first, make it possible to propose sites that are doubly favorable for groundwater development and cropgrowing. Such a methodology is new and, while not exactly economical, the double exploitation of the satellite images gives it a great advantage over others.

PRESENTATION

The high quality of the satellite images had promptly brought expectations of rich and rapidly available information, in geology and other fields. Very quickly it had to be acknowledged that image interpretation was more difficult than had been expected at first; therefore, work was restricted to a simple reading of the more-or-less arranged images, which gave a demarcation of homogeneous scene units.

Later it was realized that indirect information, which was not necessarily hydrogeological, could be brought to light. This, united with other data, integrated into a line of argument that took in structural geology and relief-form analysis, and provided and pertinent hydrogeological information. This approach is generally subtle and cannot be transposed without adapting one natural medium to another. It needs to be put into practice often but already supplies two positive results: increased efficiency in exploring, prospecting, and hydrogeological mapping and, for the same performance, a financial saving on these same themes. The satellites used are, almost exclusively, Landsat 4, Landsat 5, and SPOT 1. The sensors are also almost exclusively multispectral, MSS and TM for Landsat, XS for SPOT.

In practice, XS of SPOT and MSS of Landsat are equivalent in the details of the spectra analyses. The use of the images of one or the other is only a question of the scale at which the work is being done. The resolution is not an aim in itself. It is an advantage readily made use of for large-scale work. Usually, it is the price of coverage that limits the number of scenes to be bought for a project. A Landsat scene covers an area of 185 x 185 kilometers, compared with 60 x 60 kilometers for a SPOT scene, a ratio of 9.5 to 1 in area and a similar one in the number of scenes to be bought to cover a chosen zone. The extreme scales accepted are 1/150,000 for Landsat-MSS and 1/50,000 for SPOT-XS.

The three projects set out below describe this multidisciplinary approach and the resulting gains, in both performance and money.

SELECTION OF SITES FAVORABLE FOR WATER BOREHOLES (IN AN ALREADY-EXPLOITED ZONE - -SENEGAL - CAPE VERDE PENINSULA)

In July 1988, the National Society for Senegalese Water Development wished to increase its groundwater exploitation in the hinterland of Dakar to supply the tourist centers that are being developed on the coast to the south of this city.

Two water-bearing levels supply practically all these resources. They are recharged by the infiltration of rain collected in zones where each, in turn, outcrops. The passage of the groundwater is, however, practically unknown, as these formations are affected by faults, some of which reach lengths of several tens of kilometers.

In addition to this, two phenomena limit the locations where the resource can be used:

- inside large zones, this water is saline, and therefore unusable, especially near the coast;

- the extent of some present-day exploitations, located near these saline zones, is bringing about slow displacements of unclean water fronts. New developments will have to be very carefully arranged not to accelarate this evolution.

The search for new sites under these conditions is complicated, as it must :

- take into account the aquifer recharge zones and the groundwater displacement;
- avoid competition with existing exploitations;
- be located outside the zones where there is a risk of salt infiltration.

Remote sensing was chosen to:

- speed up exploration of the geological structures while providing heretofore unavailable details;
- rough out the work of prospecting the aquifer recharge zones and the sites favorable for installing water points.

Geological structures

The first interpretation of the SPOT images enabled a precise outline of the fracture network. It is known that, in this type of structure, only vertical displacement can be formed along fractures. The same geological formation is found, therefore, on both sides of the faults, but at different levels. By combining the information supplied by SPOT and the study of many borehole logs, a map could be drawn showing at what levels of the top and bottom of each water-bearing formation. The difference of level between two similar formations was measured. The size of this "thrust" enabled identification of the largest faults. It is these main fault zones that have the best chance of interrupting or diverting the groundwater flow. This work was controlled in the field with the help of geophysical prospecting, and made thus it possible to reduce the costs to a minimum.

As a comparison, classic exploration of this type of zone would have required the use of geophysical prospecting alone, by squaring off the zone in the form of large profiles and detailed prospecting. Based on a rough knowledge of the regional structures, geophysical prospecting, which is an indirect method, would have been hard to use, considering the great number of faults crossing the region. It would have been very tricky to make these faults correspond from one profile to another.

Functioning of groundwater systems and reconstitution of groundwater resource

At a second stage, large zones (which showed up as being demarcated by the main faults) were indentified on SPOT images where the presence of vegetation, to a greater or lesser extent, shows that there is a runoff or infiltration of water. The natural recharge zones of the upper aquifer were thus located. Later, the reality of this infiltration was confirmed by piezometric recordings that showed the presence of swellings of the groundwater surface perpendicular to the corresponding zones.

In the next stage, sampling of the borehole water indicated the exact position of the salt water masses, and this brought out the hydraulic-barrier role of some faults, on both sides of which fresh and salt water were found. The position of these barriers, combined with that of the recharge zones, and with the knowledge that the sea is an inevitable outlet, made it possible to draw up a plan of the groundwater circulation.

By using these data knowledge of the faults, the recharge zones, the saline zones, and the zones that risk salinization sites potentially favorable for new boreholes could be proposed.

A numerical model, derived mainly from the structural study conducted with the data supplied by SPOT, was used to check the possibility of exploiting the proposed yields on the sites in question.

Specific contributions of method

First, the method gives more information on the aquifer structures compared with geophysical prospecting alone. Second, there is more information on the hydraulic behavior of the systems, in particular on the position of the recharge zones for which black-and-white aerial photos would not have revealed the point of departure; that is, subtle differences in the vegetation covers. Finally, there is a saving of about 12 percent in the operational budget. The following table compares the fractions of the budgets given over to exploration and the expense that had to be agreed upon for using geophysical methods alone.

Table 7-10

Exploration phase: Multidisciplinary approach, including remote sensing		Exploration phase: classic methods	
Water point inventory	57 units	57 units	Water point inventory
Remote sensing	161 units	350 units (approx.)	Geophysics over the whole zone
Geophysics, limited to the uncertain zone	145 units	50 units	Search for main faults on aerial photos
Synthesis of data of various origins	66 units	30 units	Geophysical interpretation and proposal of a structural plan and zones to be explored
TOTAL	429 units	487 units	TOTAL

SPACE MAPS OF SOUTHERN MOROCCO

THEME: HYDROLOGEOLOGY SCALE: 1/250,000

The available public information on southern Morocco is very sparse and fragmentary:

- no geological map at a scale larger than 1/1 000 000;
- very approximative topographical maps limited to tracks and villages;
- an inventory of natural water points (springs);
- a few borehole logs;
- an imprecise geographical location of all these points;
- very few hydrogeological data on the aquifer systems in general.

In 1987 it was decided to collect and exploit the available data and present them in the form of hydrogeological orientation maps, in view of the development of the southern provinces. Exploration based on fieldwork (geophysical prospecting, observations, tests) would have been arduous and preference was given to work based on the exploitation of Landsat 5-MSS satellite images.

The image processing was simple:

- numerical assembling of two scenes for one map;
- geometrical agreement;
- making colored compositions with dynamic exposure to accentuate some contrasts;

- making derived images (black-and-white) to identify the image discontinuities corresponding, generally, to the main faults.

The geological structures are relatively simple and consist of transgressive, little-folded sedimentary series on an uplifted basement. The line of argument used for the description of hydrogeologic systems is based on the comparison between the geological sections of the deep boreholes and the distribution of homogeneous out-cropping areas that correspond to the various geological formations.

The few hydrodynamic characteristics that had been noted on the borehole logs gave information on the hydraulic potentialities of the water-bearing formations. The hydrogeological representations are those of the usual keys of geological maps. They bring out the interformation contacts and the types or absence of exchange between the formations and their environments. This work was hard to envisage without remote sensing, which supplied a precise backing, an objective means for following and mapping the homogeneous formations, and replaced a classic topographic background. In a program of about ten maps, the cost of one map covering 16,500 square kilometers at a scale of 1/250,000 would be US$ 25,000 to US$ 35,000, depending on the information available.

HYDROGEOLOGICAL PROSPECTING FOR SMALL-SCALE IRRIGATION (BURKINA-FASO)

Remote sensing was used for hydro-prospecting as part of an on-going project entitled "Study of the Aquifer Recharge in the Cristalline Basement in Burkina-Faso. The exploration was based on two themes: 1) the search for sites favourable to the installation of high-yield boreholes by supplying descriptive factors of the fissured medium intended to be included in a multidisciplinary approach; and 2) the search for zones suitable for irrigated crop growing.

For the first research, concerning the fractured structure, two of the three sites proved to be disappointing due to the dominant lateritic cover. For these two sites, the minimum processing consisted of identifying the image-discontinuity networks that were acquired and digitized and on which statistical processing was applied. For the third site, in the Sahel zone, located on the granite basement and presenting a considerable sandy cover, the processing was taken further and concerned the image-discontinuity network, and, especially, the drainage pattern.

The results were integrated into a multidisciplinary approach that included geophysics and natural radon tracing. The results were very convincing, and the final yields, from eleven boreholes, were distinctly higher than those which could be expected by classic village water supply methods.

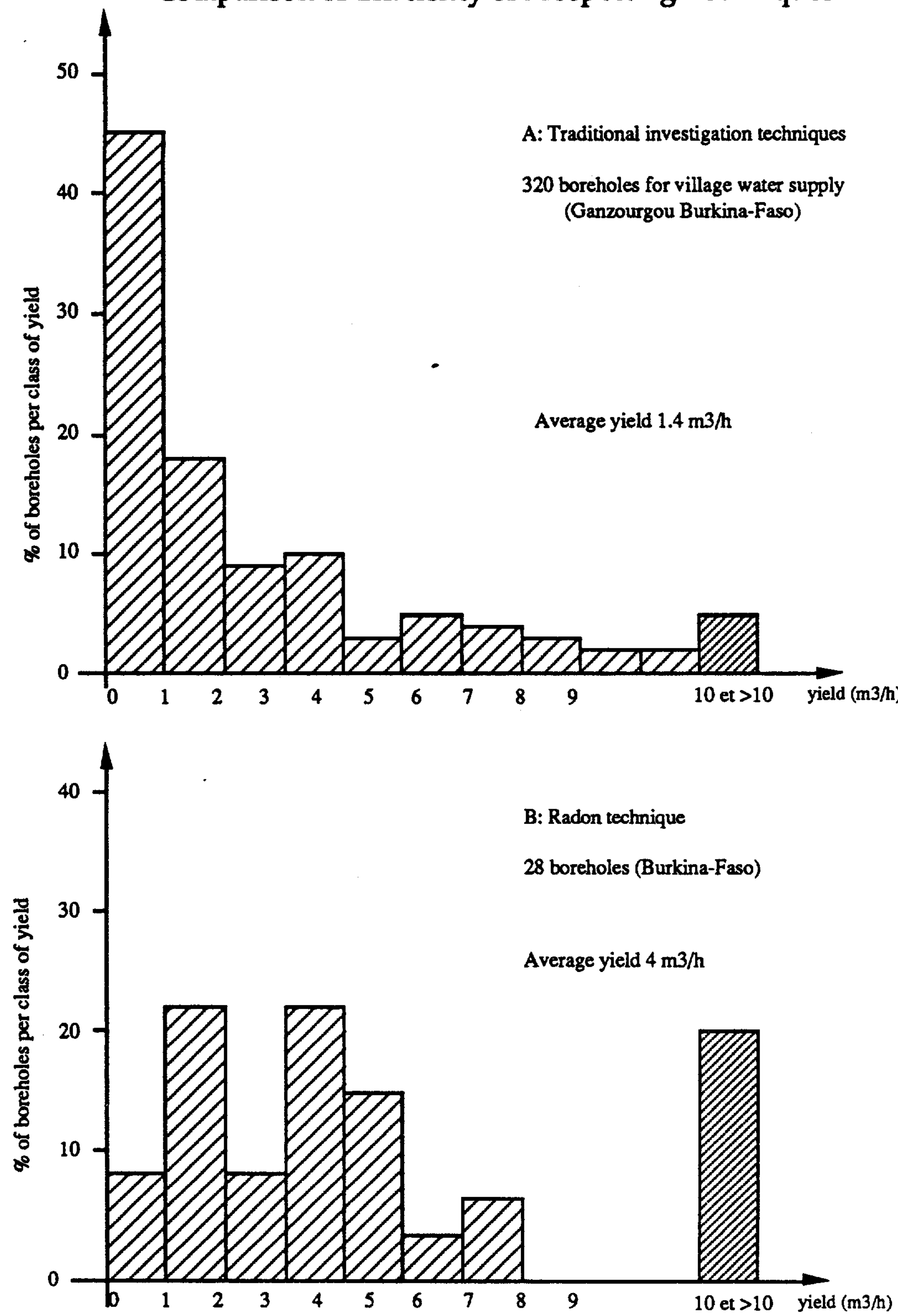
The drainage pattern was, studied regarding the density of order 1 drains (upper "wadis" sections), this supplying information that was very close to the aptitude of the ground to allow run off or, additionally, to permit infiltration. The result, along with a classification of the surfaces by type of spectral response, was oriented on the aptitude of the ground for crop-growing and on the potential for groundwater resource reconstitution.

For this site, therefore, the conclusion provided increased efficiency. Remote sensing, provided an in understanding of the structure of the aquifer medium, which allowed the selection of favorable zones, and the preparation of development schemes which demanded that hydrologically and agronomically favorable zones be identified concurrently and in close proximity.

The application of two uncommon techniques, remote sensing and prospection by quantitative analysis of the radon in the gases of the earth, makes a comparison with a traditional approach difficult. These two methods appear in the program as extra expenses, but the result; that is a certain increase in borehole productivity, could only be obtained at this price. The graph that follows gives the productivity statistics for the boreholes constructed as part of this program on three sites (27 boreholes in number) and for those that were constructed following prospecting by classic methods in village water supply program, also in Burkina-Faso.

Over and above the size effect of the two samples, the gain in productivity is seen by the displacement toward the right of the modal value of the two histograms, as is seen in the increased proportion of boreholes that gave over (10 m^3/h during tests).

Comparison of Efficiency of Prospecting Techniques



A: Productions for boreholes sited with traditional techniques for village water supply
B: Productions for boreholes sited with the Radon technique

Figure 6-2

SATELLITE HYDROGEOLOGY

Donald R. Wiesnet

INTRODUCTION

The term "satellite hydrogeology," is seldom used in the literature on remote sensing, and, indeed, the use of satellite remote sensing information for hydrogeologic studies is not common. Satellite hydrogeology may be defined as the application of satellite data, imagery, or information to the study of groundwater systems. It is a subset of the well-known term "satellite hydrology" (Deutsch, Wiesnet, and Rango 1980).

Although geologists have used aerial photos for geologic mapping for many decades, it was the impressive photographs from the manned Skylab experiments and later the Landsat Multispectral Sensor (MSS) digital images (1972) that ushered in the era of satellite hydrogeology. Large-scale or regional aquifer systems suddenly could be viewed synoptically and monitored throughout the seasons. At a lesser resolution NOAA's Very High Resolution Radiometer (VHRR) was also launched in 1972, to be superseded by the Advanced Very High Resolution Radiometer (AVHRR) in 1978. The 1986 French satellite, SPOT-1, was followed by the Japanese MOS-1 in 1987. Both are capable of furnishing information on surface manifestations of groundwater systems, as is the geostationary satellites such as GOES.

SATELLITE CAPABILITIES

Despite some early propaganda by an overzealous NASA public relations man, there is no camera or sensor that can "see" groundwater as it lies under the surface of the Earth. Radar, an active sensor, has the ability to penetrate dry sand to depths of perhaps 10 meters and has a useful role to play in detecting structural elements of the landscape and the geology, but its use in civilian satellites is currently restricted to selected missions of the space shuttle and to future satellites, Radarsat and ERS-1.

Table 7-1 compares the satellites currently used in satellite hydrogeology. Much of the emphasis in remote sensing sensors is on resolution and spectral band definition. SPOT has the best resolution (20 meters) of the multispectral sensors. However, Landsat's TM (30 meters) has--in the opinion of many--a slightly better set of spectral bands for vegetation and geology. Its thermal band (120 meters) also has unique and useful applications for groundwater studies, e.g., detecting seeps and springs. On the other hand, SPOT's panchromatic mode has an unsurpassed resolution (10 meters) in the civilian arena, which is most helpful in lineament and fracture trace analysis.

NOAA's AVHRR can monitor vegetation over large areas with its 2,600-kilometers swath width. The resolution is 1,100 meters, which limits its application in hydrogeology to general studies of large areal extent.

GOES is a geostationary satellite that acts as a weather warning satellite. Its major function in hydrogeology lies in its ability to determine precipitation extent and duration, which is necessary for recharge calculations. MOS-1, sort of a low-resolution Landsat, is appropriate for regional or mesoscale studies of groundwater or geology.

BASIC HYDROGEOLOGICAL REQUIREMENTS

A list of basic hydrogeological requirements is given in Table 7-2. In the column on the far right, a "Y" indicates a positive answer, while an "N" indicates a negative answer. The asterisk indicates a qualified yes or no.

Table 7-1. Comparisons of Selected Satellite Remote Sensing Systems

	Landsat Multispectral Scanner (MSS)	Landsat Thematic Mapper (TM)	SPOT Multispectral (XS)	SPOT Panchromatic (P)	MOS-1 (MESSR)	NOAA, 8, 9 (AVHRR)	GOES (VISSR)
Spectral Bands		0.45-0.52					
(Micrometers)	0.5-0.6	0.52-0.60	0.51-0.59		0.51-073		0.51-0.59
	0.6-0.7	0.63-0.74	0.61-0.68		0.61-0.70	0.58-0.68	0.54-0.70
	0.7-0.8	0.76-0.90	0.79-0.89		0.72-0.80		
	0.8-1.1				0.80-1.10	0.72-1.10	
		0.55-1.75					
		2.08-2.35					
						3.55-3.93	
		10.50-12.50				10.50-12.50	10.50-12.60
Area coverage per image (square kilometers)	34.225	31.450	3600	3600	10,000	2940 (NOAA-8)	
Width of swath	185	185	60	60	100	2600 (NOAA-9)	
Instantaneous field of view resolution, meters)	80	30 120 (thermal)	20	10	50	1100 (NOAA-8) 500 (NOAA-9 visible) 1000 (NOAA-9 thermal)	100/4000
Repeat cycle	16 days	16 days	5/20 days	5/20 days	17 days	12 hours	20 min./1 min
Turnaround (time between acquisition and delivery)	4 weeks	4 weeks	4 weeks	4 weeks		2 weeks	Real time
Data cost per sq. km (Digital data)	$0.020	$0.105 (full scene) $0.210 (quarter scene)	$0.444	$0.444		$0.00003	
Data cost per scene (Digital data)	$660	$3,300 (full scene) $1,650 (quarter scene)	$1,600	$1,600		$150	

Table 7-2. Basic Hydrogeologic Information Requirements

Requirement	*Met by Satellite Data*
Well inventory	Y
Define boundary of surface basin	Y
Define boundary of ground-water basin	Y
Map geologic framework	Y*
Map geologic structure	Y
Map geologic lineaments	Y
Map fracture traces	Y*
Locate springs and seeps	Y
Eestimate recharge rate	Y*
Locate recharge/discharge areas	Y
Map aquifer extent/locate boundaries	Y*
Estimate soil moisture	Y*
Determine ground-water flow patterns/movement	Y*
Locate best well sites	Y
Locate artifical recharge sites	Y*
Locate areas of possible salt-water intrusion	Y*
Locate areas of pollution/contamination	Y*
Identify probable paths of contaminant flow	Y
Determine aquifer porosity/permeability	N*
Determine specific yield/specific retention	N
Measure infiltration rate	N*
Map piezometric surfaces	N
Measure well drawdown information	N
Determine depth of wells	N
Determine quality of aquifer water	N*
Measure depth to water table	N*
Determine safe yield	N*

SATELLITE APPLICATIONS TO HYDROGEOLOGY

Exploitation for groundwater in undeveloped land involves a series of steps or phases.

1) **Research Phase**: Searching out existing maps and data on geology, physiography, geophysics, climatology, hydrology, etc.
2) **Planning Phase**: information about the target area is assembled, synthesized, and analyzed. Plans for exploration are developed.
3) **Fieldwork Phase**: On-site geologists, geophysicists, engineers, and hydrologists survey and test areas of potential development.
4) **Development Phase**: Wells are drilled and developed. Pumping tests are run. Well field design is completed and water quality tests completed. Distribution networks are completed.
5) **Environmental Monitoring Phase**: The operation and maintenance of the system is monitored to ensure efficiency and safety of the system.

How can satellite hydrogeology best assist these endeavors? In the research phase, there is no better, more up-to-date information base than a satellite multispectral high-resolution, computer-compatible tape. Using conventional digital analysis techniques and off-the-shelf software, a trained hydrogeologist can prepare a drainage map, basin boundaries, a reconnaissance geologic map, and a groundwater favorability map.

Even hand-held or fixed camera images from manned space flights can be used for some studies, although these photographs are less useful because one cannot manipulate the spectral bands for selective enhancement. Thermal images may provide information on seeps and spring location or information on shallow aquifer extent. In the research phase the emphasis is on using all the information available, and that would include the satellite data as well as published and unpublished sources.

In the planning phase, the geology, the landforms, and the geologic structure, especially the fracture patterns and lineaments (Figures 7-1 and 7-2), are combined to develop a composite picture of the areas favorable for groundwater. Megascale projects would include subdividing the region into groundwater provinces, which would then be subdivided into groundwater basins so that comprehensive basin analysis could be initiated.

The fieldwork phase includes carefully rectified, enlarged, enhanced satellite image maps on tough plastic film for field use. Satellite image maps are the maps of the future simply because ordinary maps contain much less information (with the important exception of topographic contours).

The developmental phase also uses the image maps mentioned above under the fieldwork phase. In many developing countries, detailed maps are commonly very old or nonexistent. Satellite image maps can be used as base maps on which to plot geophysical, geological, or well-site thematic information.

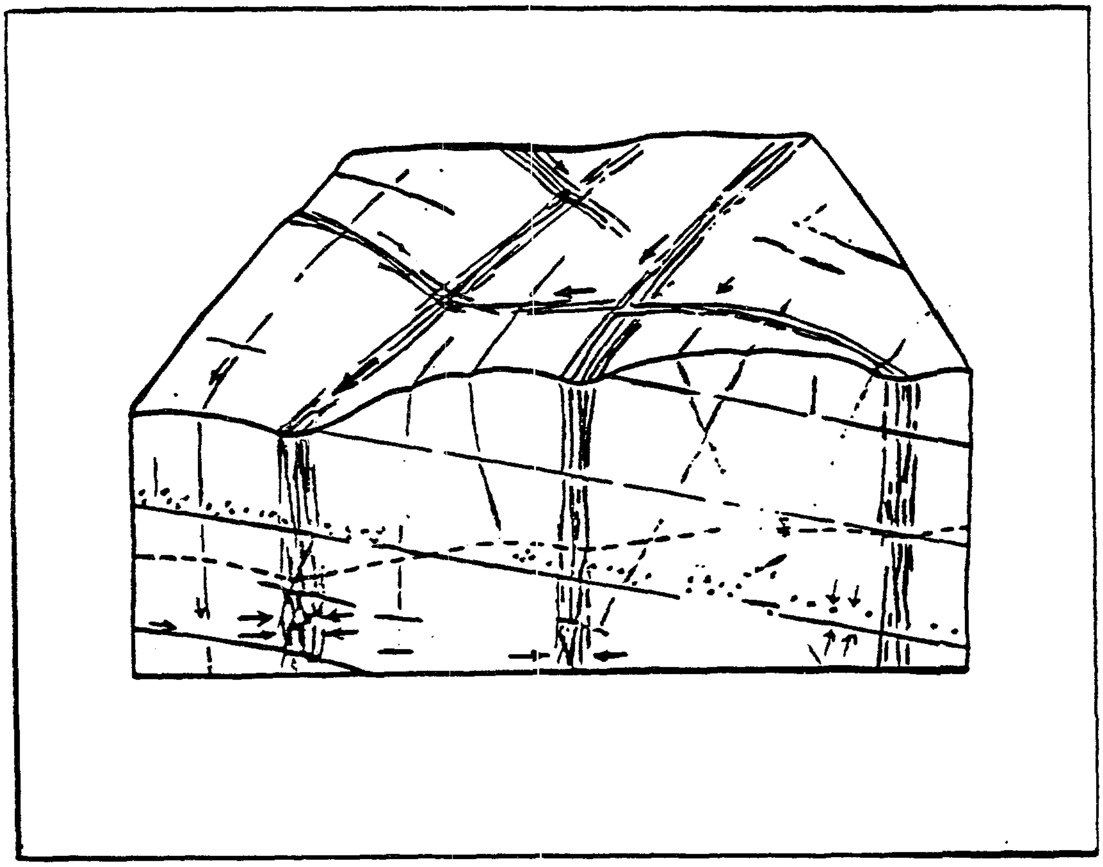


Figure 7-1. Block Diagram Showing Massive Blocks of Rock containing intergranular and Vugular Permeability and Bounded by Joints and More Permeable Zones of Fracture Concentration (Source: Parizek 1971)

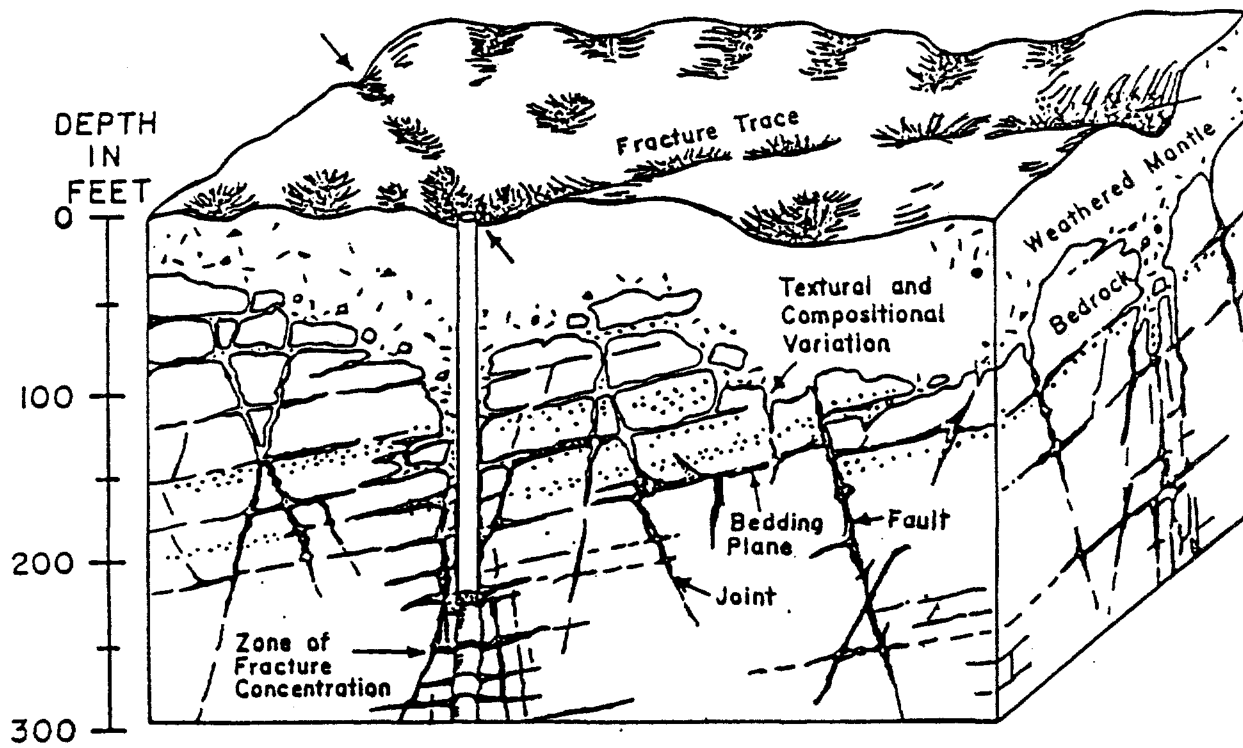


Figure 7-2. Block Diagram Showing Geologic Factors that Account for Cavern Distribution, including Fracture Traces (Source: Lattman and Parizek 1964)

The environmental monitoring phase can utilize satellite image maps to compare the "before" and the "after" images and to note any changes. Because the satellite and sensor are the same in both cases, bias is eliminated. Thus "apples" are not compared with "oranges." The development of industrial or agricultural areas can be quickly detected and monitored. Precipitation and snowmelt can be monitored by a combination of GOES and a network of ground stations. Convective storms are routinely monitored by a GOES/VISSR image technique at the NOAA/NESDIS in Camp Springs, Maryland. A system for monitoring the Nile River Basin is now under consideration for hydrological forecasting of the flow of the Nile River in Egypt.

WHAT SATELLITE HYDROGEOLOGY MEANS TO DEVELOPING COUNTRIES

Satellite hydrogeology represents a means for developing countries to explore, develop, and use their groundwater resources expeditiously, and with minimal exploration costs. As most interest centers on undeveloped semiarid and arid lands, areas of untapped groundwater can be the foundation for agricultural development and new settlements. The satellite data now available to the planners can expedite development by providing up-to-the-minute data for accurate topographic, geologic, hydrologic, and hydrogeologic maps. Groundwater and surface water basins can be delineated and areas favorable for groundwater can be outlined and quickly tested.

While the techniques of satellite hydrogeology are tried and effective, ground-truth follow-on surveys are always essential prior to test drilling. By employing a regional approach to groundwater exploration, hydrogeologists and resource planners will derive a better understanding of the nature, quantity, quality, and movement of groundwater supply, thus leading to better management of the resource. Satellite monitoring of recharge (precipitation and snowmelt) and discharge (changes in lakes, swamps, rivers, and springs), as well as vegetation growth and vigor, provide additional controls for optimum management.

REFERENCES

Deutsch, M., Wiesnet D. R., and Rango A., eds., 1980. *Satellite Hydrology, Proceed. 5th Ann. William T. Pecora Memorial Symposium on Remote Sensing*, Sioux Falls, South Dakota, June 10-15, 1979, Minneapolis: American Water Resources Association, 730 pp.

Lattman, L. H., and R. R.Parizek, 1964. Relationship between fracture traces and the occurence of ground water in carbonate rocks, *Journal of Hydrology*, vol. 2, pp. 73-91.

Parizek, R. R., 1971. Hydrogeologic framework of folded and faulted carbonates - Influence of Structure, p. 28-65, in *Hydrogeology and Geochemistry of Folded and Faulted Carbonate Rocks of the Central Appalachian Type with Land Use Problems*, ed. R. R Parizek, W. B. White, and D. Langmuir, Mineral Conservation Series Circ. 82, Coll. of Earth and Mineral Sciences, The Pensylvania State University, 192 pp.

MONITORING OF NATURAL RENEWABLE RESOURCES AND CROP FORECASTING IN SAHELIAN COUNTRIES

E. Barisano

THE PROJECT

Presentation

SODETEG T.A.I. is a French computer engineering company and a subsidiary of the THOMSON group, specializing in:

- Industrial automation
- Distributed microprocessors
- Real time computing systems
- Communication networks
- Industrial services and consultancies
- Remote sensing and geographic information systems.

Activities of the Remote Sensing Center of SODETEG T.A.I. are numerous in terms of information gathering (radar, satellite data, aerial photos, soil studies, ground surveys, statistical data, etc.) and processing (Geographic Information System, multivariable synthesis, etc.) for further follow-up and monitoring applications, including agriculture and forestry management.

This Center is in charge of the operational part of the project "Monitoring of Natural Renewable Resources of the Sahel," and more specifically of the satellite data processing and statistical processes. Project funding is assured by the European Fund for Development (EFD) of the European Economic Community. The main thematic goal of the project is to use methodological tools to improve an operational manner of handling remote sensing and ground survey data for further statistical estimations of annual agricultural resources.

These methods must result in pertinent information for government administrations as far as crop estimations and the monitoring of agricultural campaign and yield predictions are concerned.

The flowchart below illustrates the articulations of the project among the funding institutions, the coordinator (ECR), the operators (SODETEG T.A.I. and J.R.C.[1]), and the national team of each beneficiary country.

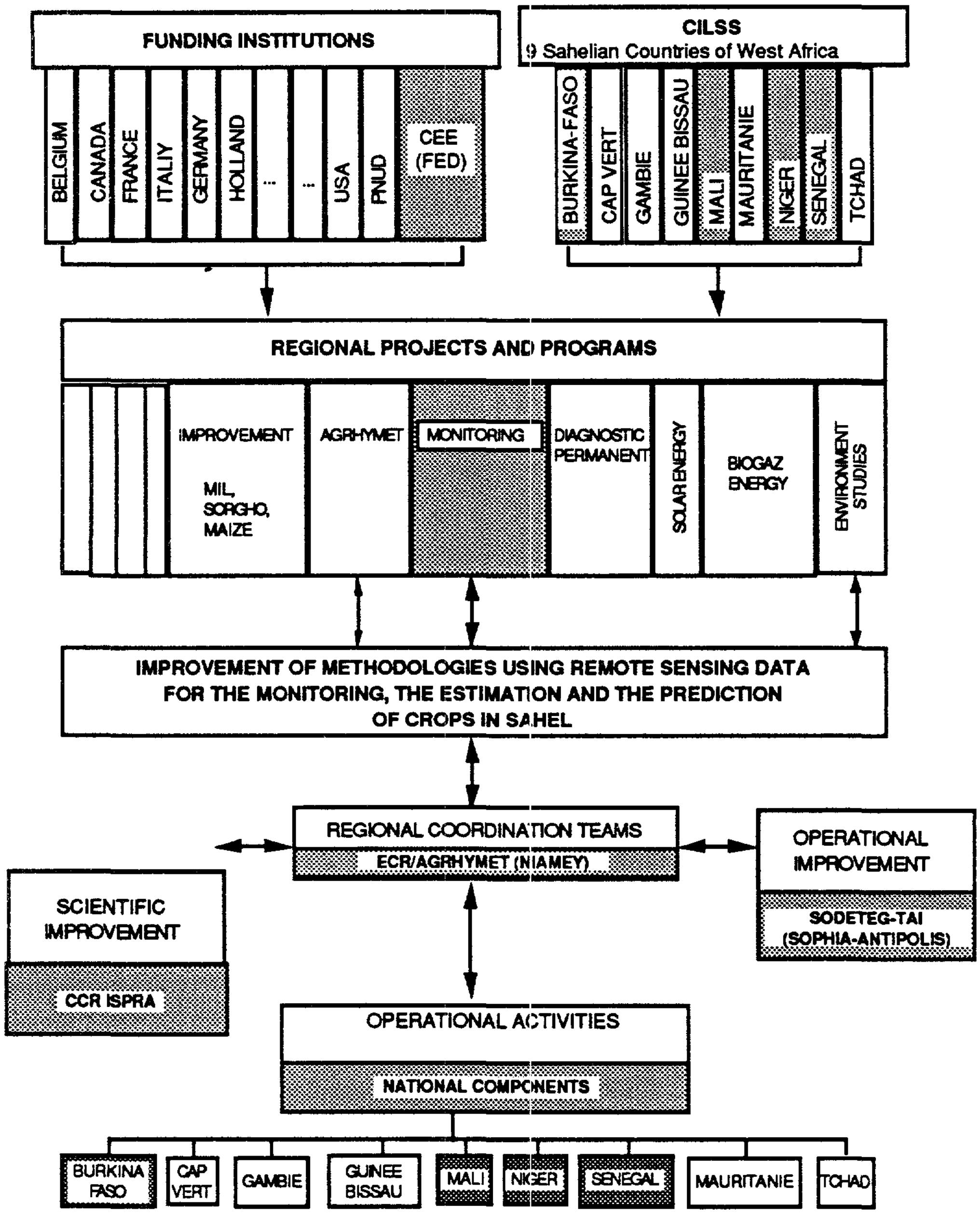


Figure 9-1. Project Articulation

The project began in Mali in 1986 and continued through 1989. In 1988, the CILSS decided to extend the studies in Niger, Burkina-Faso and Senegal.

[1] Joint Research Center (E.C.) located in ISPRA (Italy)

The general methodology

The technical aspects of the project are based on a specifically designed spatial segmentation approach. This is based on a cut-out of landscape corresponding to the best level for the use of specific ground or remotely sensed data in an exhaustive or sampling manner, with finally a statistical handling of all data, and production of agricultural statistics of administrative units. It is divided into four major steps:

- the agroecological stratification,
- the agricultural domain identification,
- the landfacet unit identification,
- the agricultural parcel survey.

The general methodology is presented in the flowchart below, with an indication of the two main goals: crop estimation on the one hand and monitoring of the agricultural campaign and crop prediction on the other. The flowchart shows the main connection between these two goals, particularly with the AGRHYMET program, which is presently receiving and handling the AVHRR-NOAA data in Niamey (Niger).

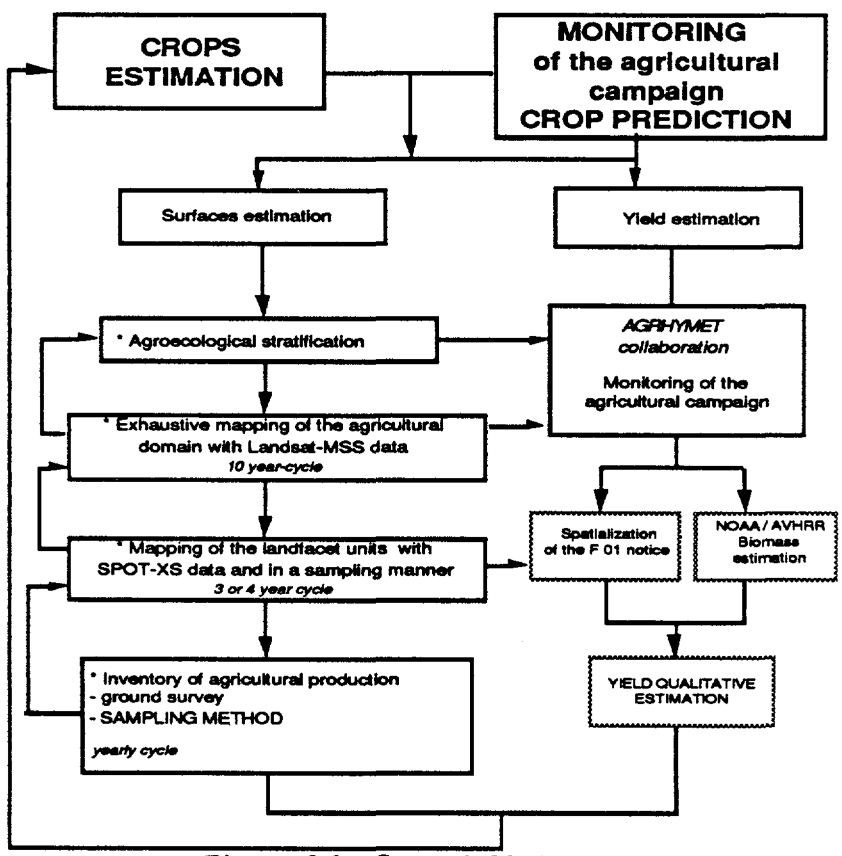


Figure 9-2. General Methodology

THE REMOTE SENSING APPROACH

Methodology

As indicated in the general methodology, one of the principles of the project is the handling of satellite data as spatial support for the statistical processes. As for a standard remote sensing project, we have used a complete range of procedures, and in particular, the integration of aerial photography, ground survey, and satellite data, either to supervise or to validate the image/processing. The following flowchart illustrates the general methodology, especially as employed in this project.

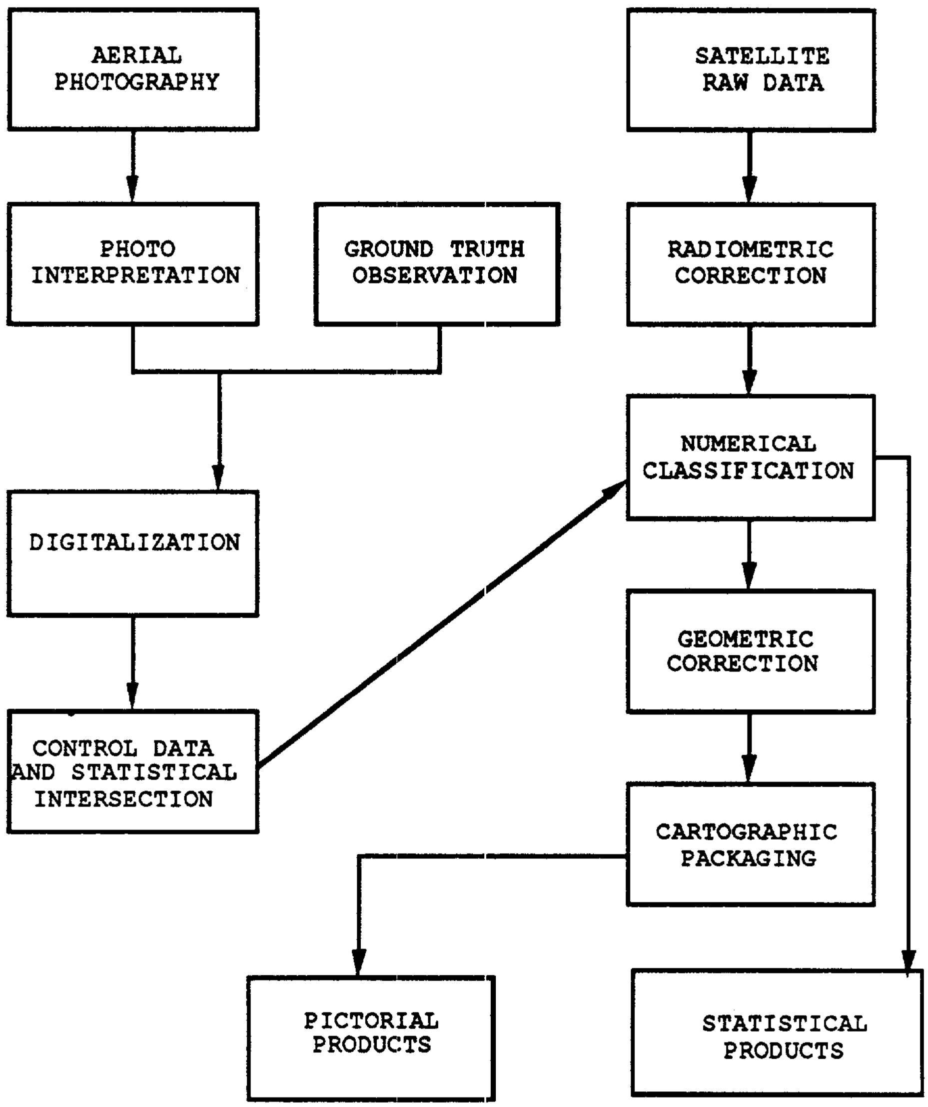


Figure 9-3. Remote Sensing Data Processing

Geographical Information System

For better processing and handling, all data were input in a Geographic Information System, the structure of which is presented below.

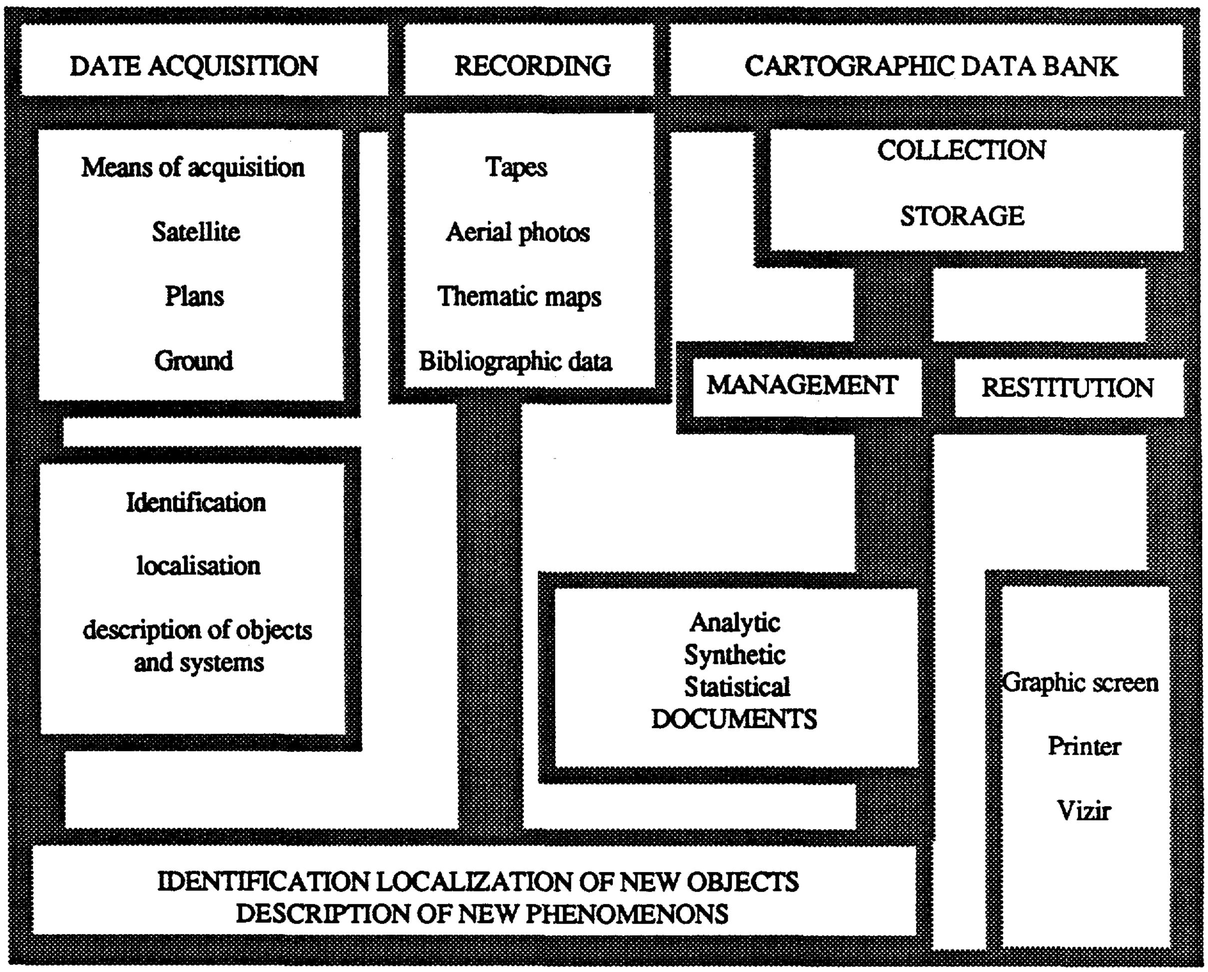


Figure 9-4. Basic Computer Tools, Integrated Geographical Information System

Review of data

A review of the differents type of data and their characteristics is provided in the table 9-1; NOAA and METEOSAT data were used for the initial phase of the project. This table gives characteristics about size and resolution of the basic units and their utilization in the statistical processes and at the thematic level.

Table 9-1.

MEANS	AREAS AFFECTED	RESOLUTION	REMARKS
INVESTIGATORS **segment** **transect**	1 KM ■1 KM several KM	1 meter SAMPLING	**SURFACES AND YIELD INVENTORIES** **problems :** **- slow** **- costly** **- subjective** ***CILSS 5 000 000 KM²***
Aircraft **aerial photography**	10 KM 10 KM	1 to 10 meter SAMPLING	**INVENTORY AND LANDFACET MAPPING** **problems :** **- costly** **- analogical interpretation : slow and dull** **- poor crop discrimination**
SATELLITE SPOT XS **images**	60 KM 60 KM	20 M ■20 M SAMPLING	**INVENTORY AND MAPPING LANDFACETS** **problems :** **- the cost** **- slow analogical interpretation** **- quick numerical processing** **- no CROP discrimination** ***approximatly 1400 images for all the countries and 700 images for the agricultural portion***
LANDSAT MSS **images**	185 KM 185 KM	80 M □ 80 M **exhaustive**	**MAPPING OF THE AGRICULTURAL DOMAIN** *with an automatic process* **- contribution for theagro-ecological stratification** ***approximatly 150 images for all the countries and 90 images for the agricultural portion***
NOAA/AVHRR **data**	2700 KM 6000 KM	1 KM 1 KM **exhaustive daily**	**VEGETATION MONITORING** **- vegetation index** **- crop monitoring** **- yield**
METEOSAT **data**		5 KM 5 KM **exhaustive**	**METEOROLOGICAL MONITORING** **- clouds** **- rainfall** **- surface temperature**

THE SPATIAL SEGMENTATION CONCEPT

Each step of the spatial segmentation is illustrated by a specific figure.

The agroecological stratification

This step is obtained with the crossover among existing data such as climatology, pedology, agronomic data and photomorphic interpretation of Landsat-MSS scenes. The results of this approach offer a better and faster homogeneous stratification for a regional inventory of agroecological stratification. This work can be carried out in an analogical way without computers, and the best results are obtained by an interdisciplinary team and good ground knowledge. The following figure shows a general approach to agroecological stratification.

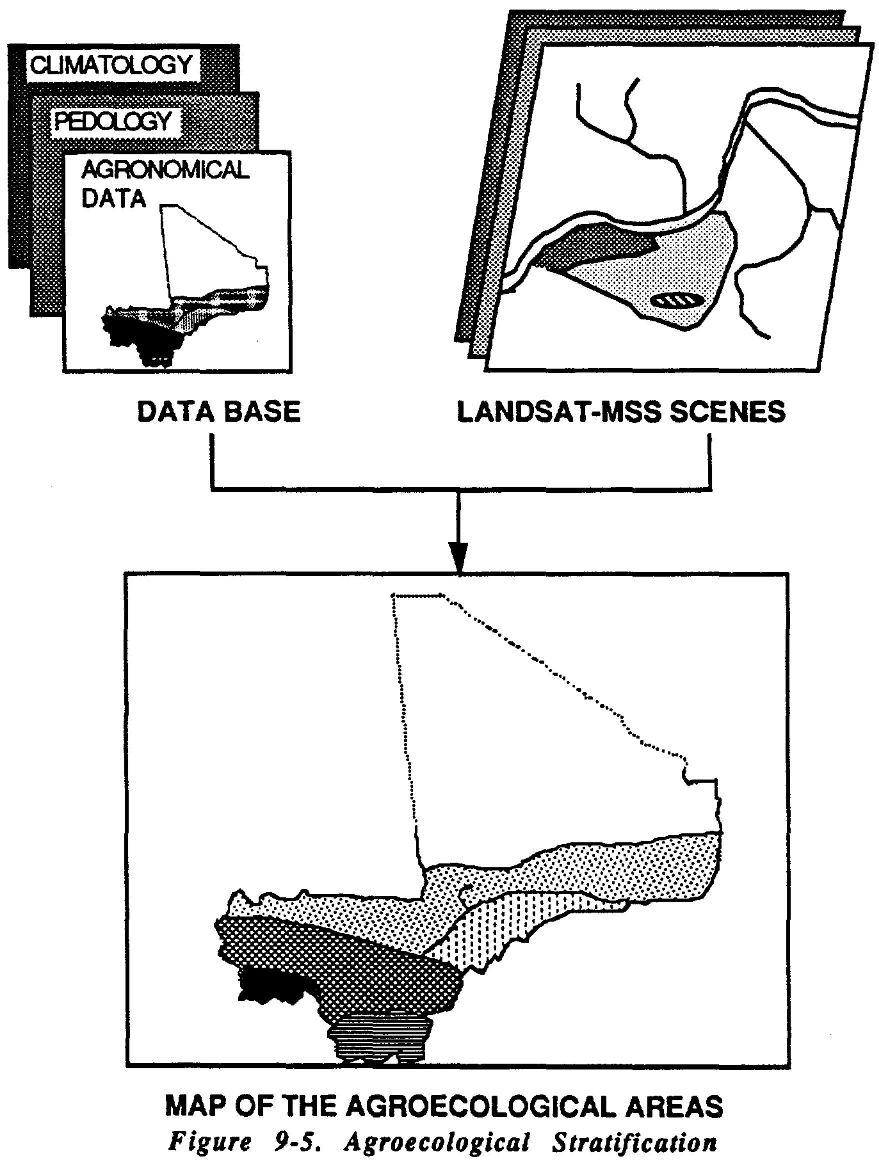


Figure 9-5. Agroecological Stratification

The agricultural domain identification

For a given agroecological strata, we must identify and build a cartographic reproduction of the agricultural domain; this is the second step of the spatial segmentation concept. This step is carried out with Landsat-MSS imagery. The choice of this type of image is determined by the adequate relation between the resolution (80 meters) and the physiographical feature of interest. The definition of the agricultural domain is the portion of the landscape used for agriculture, including cultivated fields, fallow fields, and the villagers' pastureland. These agronomical characteristics present a geographical coherence even if one can observe a local spatial discontinuity.

The core of this approach is satellite mapping of agronomical characteristics; these are considered a unique theme. This step is fully digitally processed, with an introduction of ground data and aerial photography into the processing chain. The final result is to provide the information in a specific map to a scale of 1/200,000, as in the cut-out West Africa mapping cover. The following figure illustrates this approach.

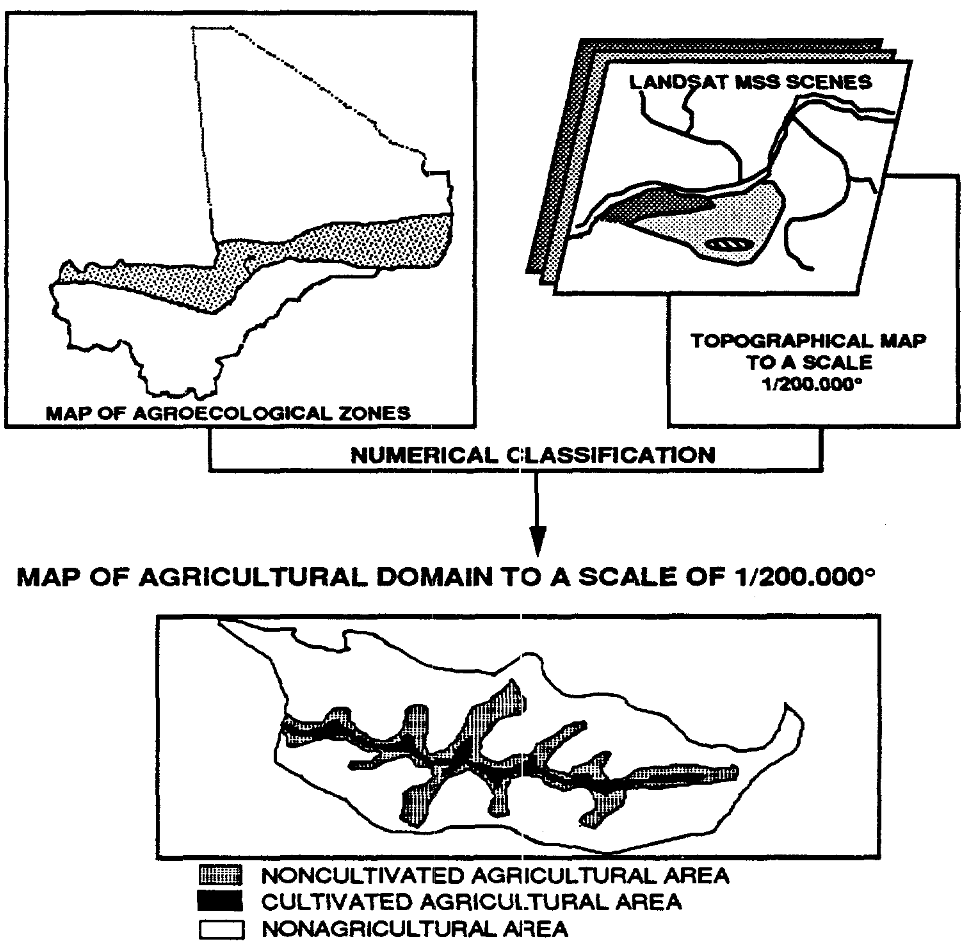


Figure 9-6. Extraction of Agricultural Domain

The landfacet unit identification

This step is organized in a "sampling frame" in reference to the agricultural domain. In each frame, the landfacet identification is made of subunits of the agricultural domain. How can we obtain this information? It is possible by using either aerial photography or high-resolution satellite data. We have to choose, for this phase of the project, the SPOT-XS (20-meter resolution) image. The reason for this choice is essentially the high accessibility of the data for a sampling-frame strategy (in practice, from any part of the area study), and also the very good correlation between the radiometry and resolution of SPOT-XS and the thematic unit of interest (landfacet unit).

It must be noted that the "sampling" way is essentially due to the important cost of a full coverage with SPOT images, i.e., for agricultural areas of CILSS countries, more or less 700 SPOT images are required.

The figure below shows the agricultural landfacet unit approach.

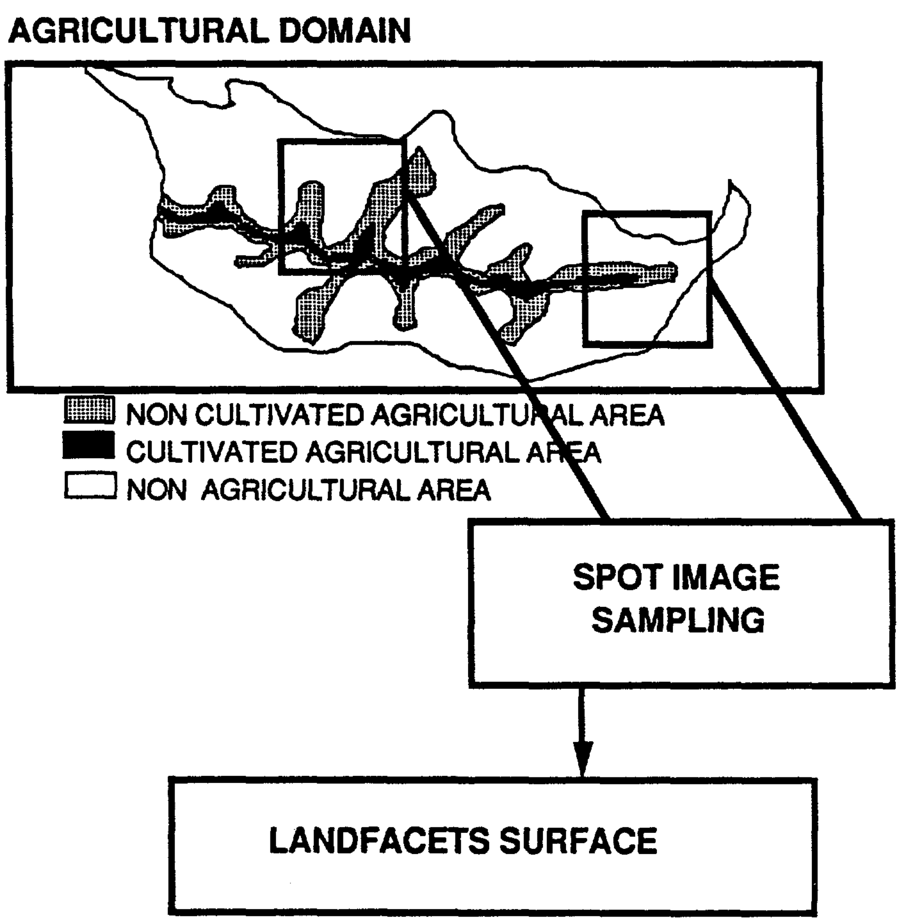


Figure 9-7. Approach to Agricultural Landfacets Surface

The agricultural parcels survey

This fourth step is conducted also in a "sampling-frame" manner at the level of the landfacet unit. Two different types of surveys of agricultural parcels are tested. The first is the "transect" method where the surveyor gathers information as to percentages of the different crops along a line crossed orthogonally by the agricultural landfacet. The second method is the "segment" method, where the survey is based on a mapping of the parcels on 1 square kilometers, using areal photography and ground survey.

The following figure shows the agricultural-parcels approach.

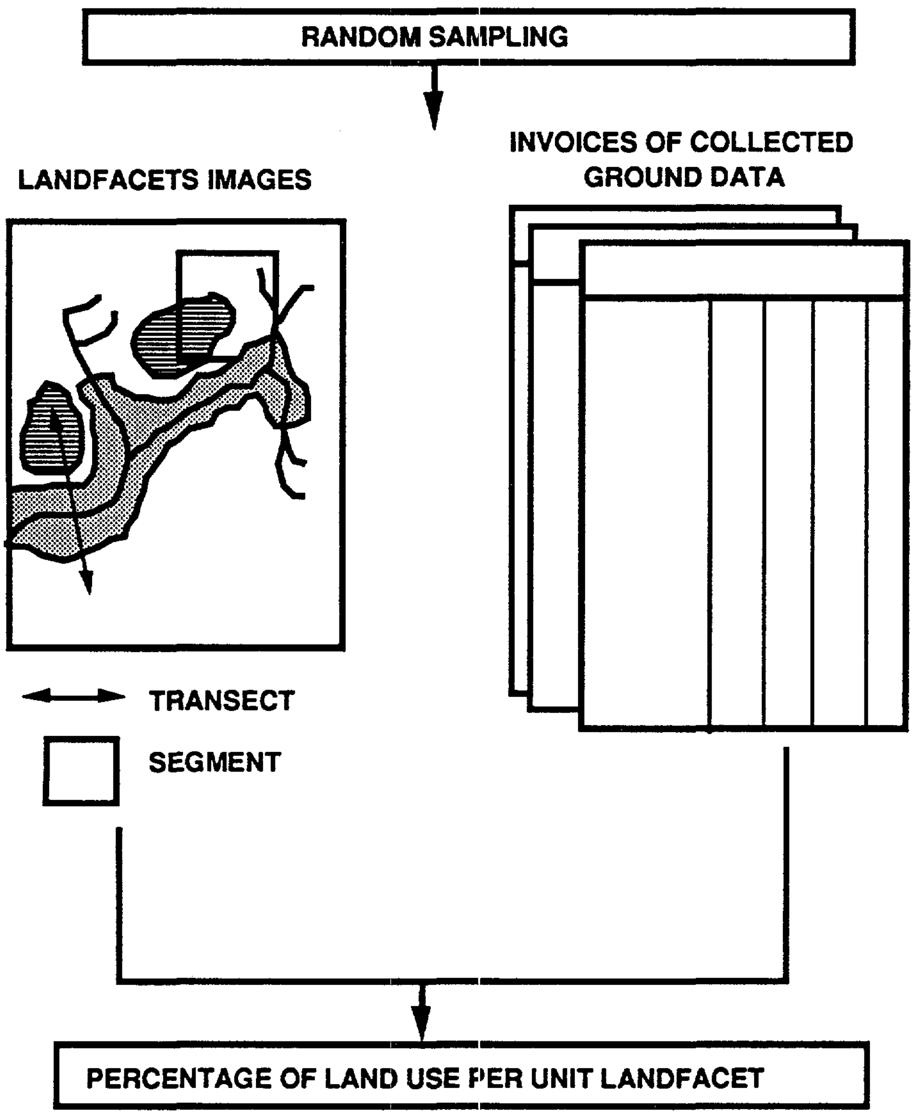


Figure 9-8. Agricultural Parcels

THE STATISTICAL PROCESS

Statistical data processing is thus based on a multistage sampling in correlation with the spatial segmentation concept.

In the flowchart below, one can follow the progress of the statistical process. In this statistical process, the basic information in the ground survey is obtained through a sampling frame at the level of the landfacet unit, is itself a "sampling frame" of the agricultural domain.

Thus we can obtain the estimation of the surfaces of agricultural production by following three main steps:

- the first step is the extrapolation of ground survey data to the entire landfacet field.
- the second step is the extrapolation of the landfacet data to the entire agricultural domain.
- the third step is the compilation of the final result as related to the administrative level taking into account the influence of the agroecological stratification.

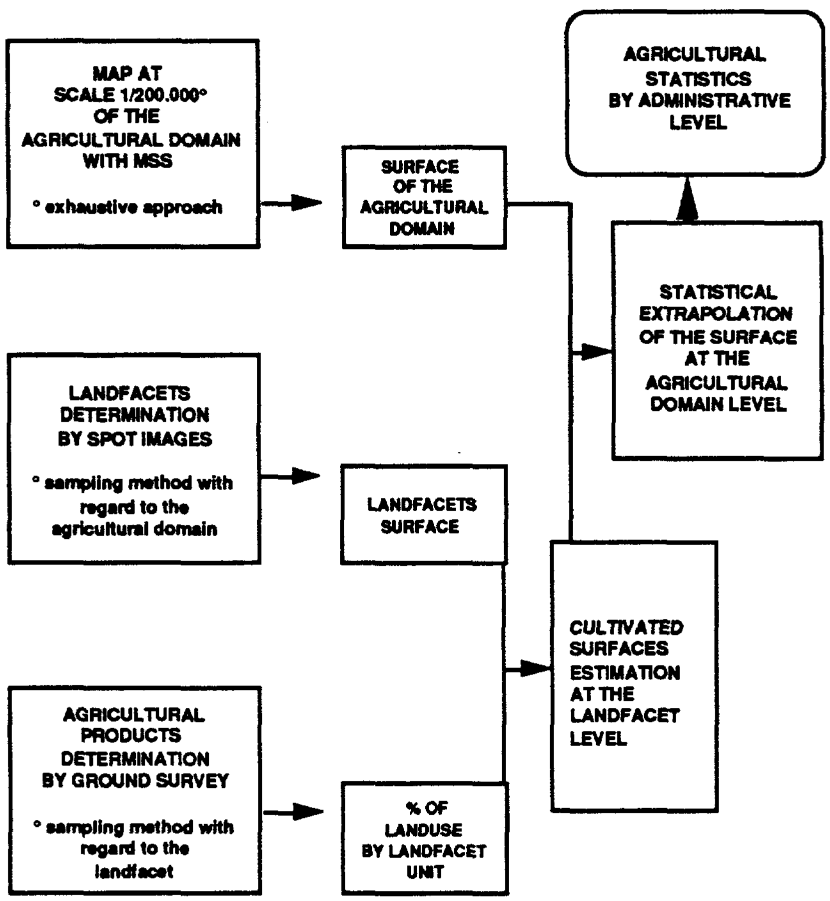


Figure 9-9. Statistical Data Processing. Multistage Sampling

CONCLUSIONS AND PERSPECTIVES

This present phase of the "monitoring" project is essentially a methodological phase with a strong request from CILSS management to provide operational procedures in view of a project extention to all CILSS countries. In 1989, this methodological phase will be completed. Present results are encouraging. They are provided in the following flowchart.

We must consider the integrated effort of the project in its basic operational function and particularly in view of participation of the national components of the CILSS countries within the project.

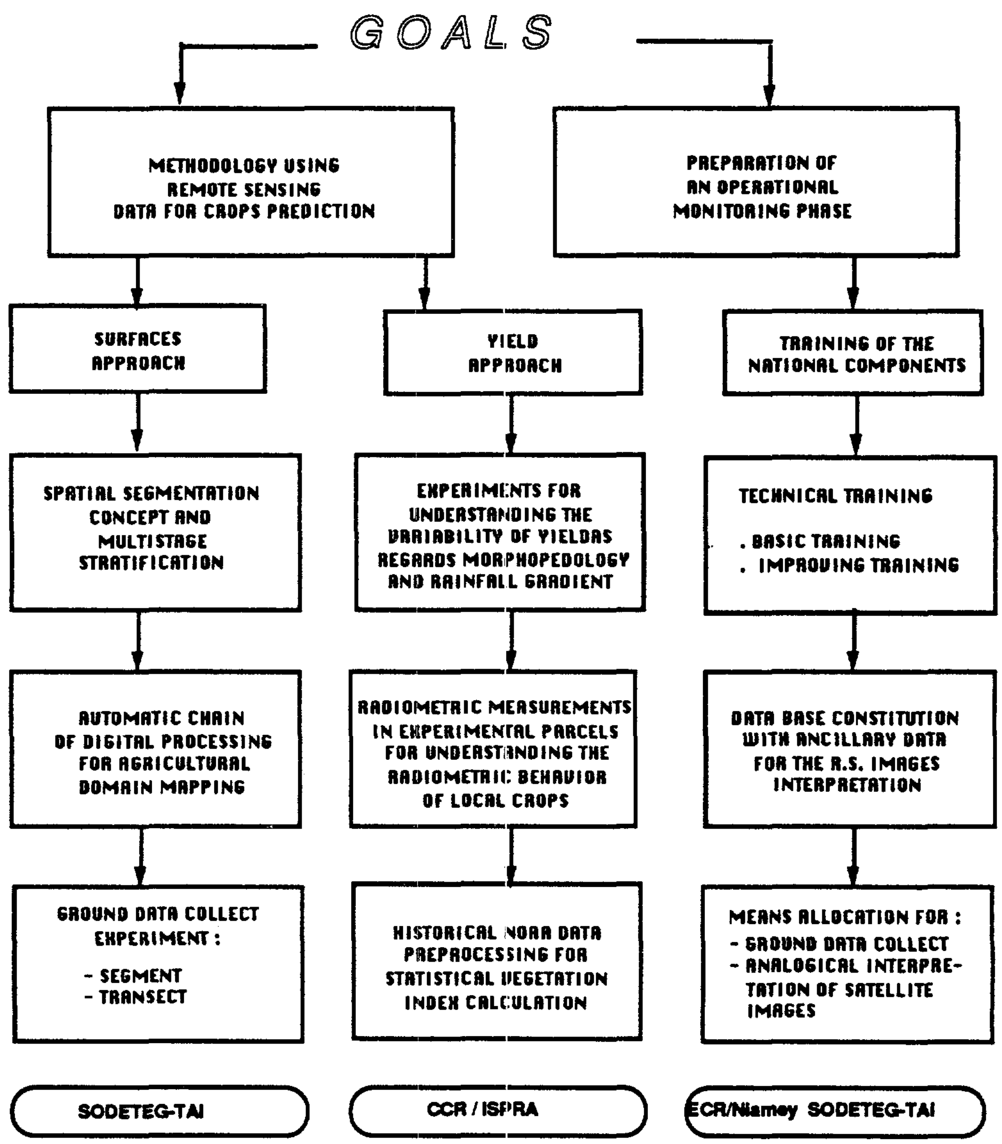


Figure 9-10. Preliminary Results

FAMINE IN AFRICA

Bobby E. Spiers

PRESENTATION

The purpose of this paper is to describe how the Foreign Agricultural Service (FAS), Foreign Crop Condition Assessment Division (FCCAD) arrived at an estimate of the 1985 sorghum and millet crop areas for the eastern Sudan using Landsat Multispectral Scanner Data (MSS). This crop estimation project was begun in early October 1985 at the request of the Africa Bureau, United States Agency for International Development (USAID)with final results reported to Sudanese and USAID-Khartoum officials in mid-December.

Sudan, and the Sahelian region of Africa in general experienced a multiyear drought during the early 1980s. The drought, along with political and economic conditions, caused much human suffering. During 1984 a major crop failure occurred that resulted in the displacement of over one million Africans and starvation of many Sudanese and Ethiopians. A massive worldwide relief effort was organized and carried out in 1985 on an emergency basis to alleviate some of the human suffering. The rainy season was near normal in 1985; however, it was spotty, causing a great deal of uncertainty in both the area of grain being grown and the potential production.

The Sudanese government and officials of the food donor nations were greatly concerned that even though it appeared that the country as a whole might have a grain production surplus, indications were that localized deficits would occur. If this was true, these areas needed to be identified and relief measures taken to ensure that the human suffering witnessed in late 1984 and early 1985 did not recur. The problem became one of distinguishing the surplus areas from the deficit areas and formulating plans to meet the food needs in the deficit areas. The Sudanese government did not have an operational procedure in place to produce the information needed to solve the problem by the end of the harvest season. With the assistance of USAID-Khartoum, the Ministry of Agriculture (MOA) had initiated a system of yield assessments, but an accurate estimate of cropped area was impossible.

USAID contacted the United States Department of Agriculture (USDA), Foreign Agricultural Service (FAS), and the Environmental Resources Institute of Michigan (ERIM) to discuss the use of remotely sensed satellite data in determining the cropped area and locations of the 1985 sorghum and millet crops. After lengthy discussions, FAS agreed to estimate a combined sorghum and millet crop acreage for the eastern Sudan from the White Nile to the Ethiopian border. This area measurement was to be made using one acquisition of Landsat Multispectral Scanner (MSS) data, coupled with information about cropping patterns gathered during extensive travel in the Sudan. The classification and digital image processing activities were to be performed at the FAS remote sensing facilities in Washington, D.C. FAS agreed to have analysts visit the country, collect pertinent ground observations, acquire the Landsat data, perform the necessary data processing, make the acreage estimations and present the information to the Sudanese government and USAID representatives in Khartoum by December 15, 1985. This agreement was reached in mid-October.

STRATEGY

The staff of the FAS remote sensing unit developed a strategy they thought would provide the most accurate crop estimate within the project constraints. The time constraint drove the approach that was adopted. FAS had less than 60 days to collect ground observations, acquire the MSS data, process the data, make the estimate, and deliver the results to Khartoum. Most of the time was allocated to collecting ground observations and familiarizing the analysts with Sudanese agricultural technology and geography of the target area. The FAS image processing system had certain characteristics that had to be factored into the final methodology that was adopted. In agreeing to this project and in developing methodology, FAS was responding to a set of USAID requirements that were typical for our operational nature. FAS normally functions in an environment that requires timely crop assessments provided at a reasonable cost. Accuracy is required, but in an operational environment an accurate answer to a problem of this type that is too late is of little value.

The project area covered approximately 51.4 million acres of eastern Sudan. Sorghum and millet cropping practices in eastern Sudan typically fall into one of four categories. In the north, near Khartoum, there are several large irrigation projects. One of these, the Gezira Scheme, was initiated by the British and currently encompasses approximately 2.2 million acres. Another in the area is the Rahad project. Both of these projects use fixed crop-rotations involving cotton, sorghum or ground nuts, wheat, and fallow. These projects are administered by bureaucratic boards and receive the largest and most modern inputs. Areas planted to specific crops are well documented.

Another type of production is on large dryland parastatal farms. Typically, these farms use modern farm practices and can be quite extensive. One farm near Damazin had 220,000 acres under cultivation. Seventy-five percent of the cropped area was in grain sorghum. All land in Sudan is publicly owned and rent on these large farms is typically $US 0.30 per acre. Acreages on irrigated and parastatal farms were called demarcated mechanized for our analysis.

In Sudan a large segment of the agricultural production capacity comes from share-crop arrangements between a farm manager who furnishes labor, and a village merchant, who furnishes capital and possibly machinery. This production typically occurs without state sanction or the payment of rent for the use of state lands. The production techniques used are mechanically rudimentary, with minimal land clearing, no fertilizer, no insecticide, and hand weeding. These farms typically produce less per unit area than parastatal farms. The Sudanese nomenclature for this type of production is undemarcated-mechanized.

Typically, subsistence farming in Sudan occurs on very small acreages with almost no inputs other than seed and hand labor. In many areas the plots may be only five acres. In our analysis the traditional and undemarcated-mechanized were lumped together as a class.

METHODOLOGY

A thorough understanding of the type, nature, and distribution of the crop or vegetation under investigation was necessary in order to accurately accomplish the digital image classification. Intensive and extensive ground observations were gathered in the project area. It took 12 Landsat scenes to cover our target area. An effort was made to transect and gather data from the area covered by each of them. FAS personnel, with AID mission support, flew from Khartoum to Damazin and then visited several parastatal farms in the area. Additionally, aerial transects were flown over these same areas and photographs of the crops were taken from both the air and ground. Aerial transects were flown from Damazin to Gedaref, Gedaref to Khartoum, and from Khartoum to Kassala. A ground trip was made to the Gezira project at Wad Medini. The data gathered about crop type, spacial distribution, cropping practice, general plant vigor, and environmental conditions were recorded, to be used by the analyst as ancillary information while the machine classifications were being made.

MSS digital data of the 12 scenes covering eastern Sudan were acquired from Earth Observation Satellite Company (EOSAT) during late October and early November. These data were received within one week of acquisition. Data products used in the analysis included computer compatible tapes (CCTs) and 1:1,000,000 false color transparencies. The full frame data array was too large to be processed on our system as a single image based on the analysis procedure that we had adopted. A method was developed to subdivide each image into 9 equal partitions and systematically sample the subimage in order that the data could be processed on the FAS analyst system. The analysis resulted in a modified census rather than an expanded aggregation.

The objective of the analysis was to spectrally separate the grain sorghum and millet class from all other classes. This was to be done by one of two methods--unsupervised or supervised classification. The cluster statistics were analyzed to ensure that the classes were uniform. The information gathered on the ground was used to identify the sorghum and millet subclasses in general and specific fields in other cases. The clusters were then interactively alarmed by the analyst, using the false color image. When the analyst was satisfied that the clustered output product for the image represented the spacial interpretation of the image, he recorded the results as a percent of the area classified. Each subimage provided a direct area measurement, but since the images did not coincide with the political boundaries, percent of total area analyzed was used to determine the final area of grain. Due to the time constraint and the configuration of our current analysis system, some tradeoffs had to be made to arrive at the final area estimation for the two subclasses of sorghum and millet.

RESULTS AND COMMENTS

Automated image classification results are largely dependent upon the data used to train the classifier and the experience of the analyst. In this instance the analyst had extensive image processing experience and was very familiar with the project area. Digital classification procedures tend to overestimate vegetative classes. Typically, an accuracy assessment is made to define the amount and nature of the misclassification and to correct image processing results. A formal assessment was not performed during this project due to a lack of systematically collected ground truth and timing constraints. The official millet and grain sorghum area for mechanized-demarcated acreage by the Sudan MOA published in late 1986 was 7.2 million acres, and our satellite-based estimate of December 1985 was 6.6 million acres, a difference of less than 8 percent.

The production estimate for the 1985 sorghum and millet crop was made by MOA and USAID personnel in Khartoum in mid-December. The FAS remote sensing analyst who conducted the analysis participated in the estimation process. The MOA yields multiplied by the USDA area determination for the eastern part of Sudan resulted in a production of 4.5 million metric tons. This estimate, combined with the estimate from the central and western Sudan contributed by ERIM, exceeded the record production by almost 2 million metric tons.

It should be noted that the application of Landsat-MSS satellite data was ideal for this project. The large fields, almost single-crop agriculture, and uniform growth stage made this a relatively easy task. The results and accuracy could have been better quantified had more time been available. It must be noted that this task could not have been done without the on-site ground observations by the image analyst. The total cost for the FAS portion of the project was less than $US1.50 per square mile of the total area surveyed.

This project was requested, designed, and carried out to provide an area estimate of millet and grain sorghum with timeliness as the primary objective. Timeliness was important because human life and suffering were at stake. The lack of knowledge on the size and distribution of this important food crop was critical to policy and planning decisions that had to be made to prevent the recurrence of a major disaster. We know that technology considered by some to be more sophisticated could have been used to perform this task. We also know that a more accurate assessment of classification errors was warranted; however, the need for timely information mandated that measures appropriate to an operational environment be taken. We know that the area determinations that resulted from this project represented a vast improvement over estimates that would have been made without this technology at a cost well within reason.

As a follow-on to this effort, Agricultural Research Service, in conjunction with the Sudanese government Ministry of Statistics, is conducting a project that will use National Oceanic and Atmospheric Administration (NOAA) Local Area Coverage (LAC) satellite data to determine yield potential. The initial portion of this research has been developed and has been reported in the proceedings of the 22nd International Remote Sensing Symposium on Remote Sensing of Environment.

REMOTE SENSING AND AGRICULTURAL INFORMATION FOR CROP FORECASTING: SUDAN EXPERIENCE

H. M. Hassan and William Wigton

INTRODUCTION

The application of remote sensing for crop estimation and forecasting implies using the technology to provide data and consequently information, that is timely and useful (directly or indirectly), in inventory and monitoring the crops. Remote sensing data are used in this exercise in a number of ways,as indicated throughout this paper.

For many years, satellite and aerial photography data have been increasingly incorporated in crop production studies, and it is now certain that their use is directly linked to improved field sampling, improved input to crop-yield models, and in planning agricultural studies associated with crop production. One of the first major attempts to apply satellite data to agricultural crop production was the Large Area Crop Inventory Experiment (LACIE) conducted by USDA between 1974 and 1980. The main objective of LACIE was to demonstrate the usefulness of remote sensing in forecasting wheat production. In the later years, the program was extended to other food crops. In 1980, a new program called "Agriculture Resource Inventory Surveys through Aerospace Remote Sensing" (AGRISTARS) was started. The main objective of AGRISTARS was to determine the feasibility of integrating aerospace remote sensing technology into existing USDA crop information systems. These projects, together with others, have demonstrated that remote sensing can be considered an important input in crop information and can be used to supplement the existing agricultural information system by integrating all these data collection systems with a rigorous statistical methodology. The area sampling frame (ASF) provides the statistical basis for the integration.

The first step in constructing an information system is to identify end-user requirements to focus the area frame construction. Next, one identifies categories of land use that will provide sampling efficiency to meet the objectives of the end-users. Satellite imageries are photo-interpreted to determine land use and, together with any existing maps provide physical features to be used as stratum boundaries.

The strata are subdivided into representative samples selected from the strata in the entire frame, and their physical creations are marked on the images and maps. Survey teams locate the segments in the field and collect data from farmers using a questionnaire about land use inside the segments. Field data are manually edited, entered into microcomputers, and computer-edited for reasonableness and keypunch errors. Then data are summarized and analyzed using special statistical software. When needed, computers are further equipped with other software in which the satellite images are digitally analyzed to give another input into the analysis. All this information can be integrated into a Geographical Information System, (GIS), together with other data, creating a powerful tool for planners and decision-makers. A plotter and a printer are connected to the computer system to supply the user with hard copies.

THE SUDAN PROJECT

Background

Following the severe drought of 1983-84, the Government of Sudan (GOS), the United States Agency for International Development (USAID), and other international donors took steps to improve the system of estimating food crops and general biomass in the Sudan. Funds were granted by USAID under what is called "Sudan Emergency and Recovery Information and Surveillance System" (SERISS) to the Ministry of Agriculture (MOA), Sudan. These funds were used to finance a contract with the Regional Center for Services in Surveying, Mapping, and Remote Sensing for establishing an area frame system with the MOA, together with all the institution-building that is required. The work was done in close collaboration with MOA and the National Remote Sensing Center.

Objective

The objective of the SERISS project was to establish a crop area and production estimates for the 1986 season in the area of central Sudan located between latitudes 10° and 16°, running across the Sudan. Full use was made of the existing Sudanese institutions, and experienced Sudanese personnel were fully utilized in this process.

The immediate objective of the project is, therefore, to strengthen and provide support to the Sudanese institution to construct an area sampling frame for the Sudan. The main purpose of the frame is to estimate food and other crop production for 1986. Other uses for the frame that will be developed later are forest inventories, rangeland condition assessment, and socioeconomic data collection and analysis.

Scope of work

To assist in ground truth surveys

- Designing sampling procedures to be used in the surveys;
- Assistance in preparation and review of the questionnaires to be used by the MOA enumerators;
- Assisting the MOA in training the enumerators and in distributing and collecting the questionnaires;
- Installation and commissioning of micro-computer systems capable of producing maps from the data collected in the surveys.

To acquire, process, analyze and interpret satellite data

- Procuring data on magnetic tapes;
- Translating this data from magnetic tapes into CCT, diskettes and hard copies;
- Interpreting the images to provide an estimate of area and types of crops and biomass production;
- Provide appropriate training for the MOA staff in the analysis and interpretation of satellite images.

To develop an aerial photo survey program based on satellite image interpretation

- Determining sample areas to be aerially photographed;
- Arrange for subcontracts for acquiring this aerial photography, integrating this with radiometric measurement;
- Assist in interpreting this aerial data.

To set the basis for developing GIS and modeling capability

- Defining a model using soil, agroclimatic, and other pertinent data;
- Using a weather satellite data to adjust the model;
- Installing the computer hardware and software to perform these objectives;
- Provide training for MOA personnel in the above procedures.

To incorporate the above data and model into a food grain production estimate program

Sudanese human resources

Human resources have been pulled together from the MOA Department of Agriculture, Planning, Economics, and Statistics (PAEA), Soil Administration and National Remote Sensing Center (NRSC).

Materials

Landsat Thematic Mapper (TM) and Multispectral Scanner (MSS) images obtained during the 1985 growing season were used as base-maps for stratification. These were enlarged to 1:250,000 scale to match the existing, out-of-date 1:250,000 scale maps. Aerial photography at scale 1:30,000 was used for more detailed work. 1986 Landsat-TM data were obtained on both CCT and hard copies.

Area sampling frame terms

- Area Sampling Frame: a series of maps and images showing all the land according to land use and land cover. Determining land use and land cover is done by interpretation of Landsat images, thus dividing them into homogeneous strata. These strata are then divided into sampling units.
- Block: a continuous area of land in one strata.
- Primary Sampling Unit (PSU): the first level of subdivision within the strata. These are numbered, measured, and listed on special forms.
- Sampling Units (SU): terminal sampling units, or smallest unit in the land within the frame. The total number of SU in the stratum is the total population.
- Secondary Sampling Units (SSU): second stage sampling. When PSU are rather large, they could be divided into SSU.
- Segments: the SUs that are selected for enumeration and interviews. Their size depends on the stratum, the purpose of the survey, the available resources, and the presence of physical boundaries.
- Strata: large, broad homogeneous land use categories.

Concept of ASF

The concepts of area sampling form are:

1) Stratify the area into homogeneous land use categories according to the agricultural usage;
2) Divide each stratum into N parcels for enumeration;
3) Select a sample of n parcels for enumeration;
4) Collect data from the selected samples;

5) Multiply the outcome from the selected samples by the correct expansion factor.

To start with, before the stratification exercise, one must make sure that there are neither overlaps nor gaps in the Landsat imageries. This is best done by establishing match lines between adjacent images.

That being done, stratification can be started. The following were the chosen strata:

- I Irrigated lands
- II Mechanized, demarcated lands
- III Mechanized, undemarcated lands
- IV Traditional agricultural lands
- V Rangelands
- VI Wastelands or nonagricultural or grazing lands
- VII Forestlands
- VIII Urban or suburban lands

The land use categories are delineated on the Landsat images using physical boundaries such as roads, rivers, trails, and field edges. The more permanent the boundaries, the better, because the boundaries located on 1985 images were again located in the field in 1986, 1987, and 1988. Strata are fairly large areas of land. Areas of land, where land use is different from surrounding land less than 25 square kilometers on the ground ($4cm^2$ on the image), were not separated out.

The importance of good physical boundaries cannot be overemphasized. This statement applies to all subdivisions where PSUs, SSUs and SUs are constructed. Many of the field enumeration problems can be eliminated by having good physical boundaries.

METHODOLOGY

Primary sampling unit construction

After stratification, the next step in the construction of the ASF is to subdivide the strata into PSUs which vary in size depending on strata. PSUs in the mechanized sectors, strata II and III, are from 200 square kilometers to 500 square kilometers Boundaries for these strata are field edges and dirt roads. In stratum IV, Traditional agriculture, the boundaries are more difficult to obtain, and therefore the PSUs will normally be large--up to 1,000 square kilometers. The entire land area included in the strata to be sampled is subdivided into PSUs. The image edge is not an acceptable boundary for the PSU. If a PSU is on the edge of an image, images are mosaicked together to make sure the PSU is closed with boundaries.

PSU measurement

The next step in the ASF construction process is numbering and measuring the PSUs. The PSUs are numbered by the strata and PSU number. For example, II-43 is a unique identification number for PSU 43 in stratum II. This numbering system is indicated on both the Landsat image frame and the PSU listing and selection form. The numbering is done in a serpentine fashion: from upper-left to right and down, until all PSUs are numbered. There may be several blocks of land in the same land-use stratum within a province. One block is numbered completely followed by the next block, until the PSUs for the entire province are numbered. The mechanized-demarcated land from several images may need to be numbered to include all stratum II land (for example) in the province. When the PSUs are constructed and numbered, the numbers are listed on the PSU listing and selection sheet.

The next step is to measure each PSU. Actually, it is not required that an accurate measurement be made of each PSU, but only rough estimates of the appropriate size. These sizes are not used in a way that requires exact areas; therefore, the size is obtained by using a grid of 4 centimeters. These sizes are rounded to nearest whole cell. The size for each PSU is recorded in the PSU listing and selection form in the appropriate space.

According to the contract, stratum I to IV are to be surveyed and stratum V to VIII will not be surveyed. Therefore, thes strata that are to be sampled, strata I to IV, are subdivided into PSUs. Each PSU is numbered, starting with upper-left and moving to the right and down. The important point is that no PSUs in the numbering process are left out, and that the PSUs on the edge of the image require going to bordering images in order to have closure.

PSU selection

The selection procedure used can be found in the book, *Sampling Techniques*, by W. G. Cochran. It is a systematic sample selection procedure using probabilities proportional to size (PPS), where size is the appropriate number of squares of 4 square centimeters in each PSU on the 1:250,000-scale imagery. The procedure requires that the sizes be accumulated for all PSUs starting with PSU numbered from 1 to the last PSU. The allocated number of PSUs is selected using the systematic procedure. The allocated number of PSUs is divided into the total number of accumulated squares to obtain an interval. A random start (RS) is selected between 1 and the interval, and the required sample is obtained by adding the interval to the RS number, the number of times needed to obtain the complete sample.

Photography

Once the PSUs have been selected by the sampling statistician, the remote sensing expert locates the PSU properly on the 1:250,000 topographic sheets. He then checks at the Survey Department for photos taken within the last few years. The remote sensing expert will determine whether the available photography is appropriate. If it is available, the remote sensing expert orders the aerial photography. If recent photography is not available, then current photography are ordered immediately for the selected SUs. Aerial photography is obtained at a scale of between 1:40,000- and to 1:20,000, depending on the area of the PSU. Most probably, it will be black and white on a nine-inch format. These areas are then subdivided into sampling units for enumeration. In the case of mechanized land, each SU contains ten holdings.

In the case of traditional agriculture, each SU should contain about 20 fields over 2 feddan each. These are the target sizes. The exact sizes vary, depending on boundaries and the sampling units and the fields. Once these PSUs are subdivided into SUs, they are numbered from 1 to the last SU in the PSU and two are selected at random using the random number tables. The same SU can not be selected more than once. Once these are selected, enlargements are ordered for each segment at a scale of 1:10,000 or larger. The probability of selection for the first stage (the PSU) and the second (the random selection within the PSU) is recorded and stored. These is used to compute the expansion factors for each segment.

Interviewers are provided training to collect data consistently using a specified procedure. Interviewers are provided with enumerator manuals that should answer questions that come up in the interviewing process. Data collection teams were utilized because there was a shortage of vehicles, and one vehicle carried a five-man team, a driver, two interviewers, a photointerpreter who could locate the segments, and a supervising interviewer. These teams visited the segments and collected the data by interviewing producers who were farming land inside the boundaries of the segment.

All land was accounted for inside the segments and, the completed segment data were placed into envelopes and returned to the data analysis section of the MOA in Khartoum. The data in the envelopes were checked for obvious errors and corrected where possible. Then the questionnaire data were entered into the computers and edited again for reasonableness. Then data were summarized by adding data in each segment to obtain segment totals and then multiplying the segment totals by the proper expansion factors. Segment data were then summarized to provide, estimates of the strata, province and regions. These data are then studied for reasonableness, and finally the data were published in official Ministry of Agriculture bulletins.

Two computers were all that were required for data entry, even for a full national survey. One computer operator with a single computer can enter between 50 and 100 questionnaires in a day. Fifty segments a week can be entered and edited in one computer.

SURVEY FINDINGS AND ANALYSIS

The following tables summarize results obtained from the data collection effort that took place from October 1986 through February 1987. In the initial stages of the survey the interest was in the area being planted in each of the food crops. Areas of each crop are important input into the crop production calculation. In order to test the methodology, the ASF was applied to the areas where management records provide some basis for checking the estimates from the survey. The table of values for crops in the irrigated sector illustrate the efficiency of the technique.

Irrigated agriculture

Table 11-1. Irrigated Sorghum (Dura) Estimates
Stratum I. Irrigated--Scheme Management Data vs ASF Estimates

Scheme	Preliminary estimates from scheme	ASF estimates 1000 fed	CV of estimate	Sample size
Blue Nile	61	94	24%	6
Gezira	443	410	7%	41
Rahad	72	84	12%	5
White Nile	22	26	32%	15
Gash	34	10	50%	5
New Halfa	73	80	21%	9
Total	705	704*	6%	81

* The estimate of the total differs from the actual target value by 0.15 percent (less than 1 percent)

Table 11-2. Irrigated Cotton Estimates
Stratum I. Irrigated Land–Scheme Management Data vs ASF Estimates

Scheme	Preliminary estimates from scheme	ASF estimates 1000 fed	CV of estimate	Sample size
Blue Nile	54	84	19%	6
Gezira	415	422	8%	41
Rahad	124	135	4%	5
White Nile	55	50	14%	15
New Halfa	72	57	28%	9
Total	720	748*	5%	76

* The estimate of the total differs from the actual target value by 3.7 percent.

Table 11-3. Irrigated Ground Nut Estimates
Stratum I. Irrigated–Scheme Management data vs ASF estimates

Scheme	Preliminary estimates from scheme	ASF estimates 1000 fed	CV of estimate	Sample size
Gezira	149	151	13%	41
Rahad	58	55	17%	5
New Halfa	25	22	43%	9
Total	232	228*	10%	55

* The estimate of the total differs from the actual target value by 2.0 percent.

The agreement between the ASF estimates and the management data is remarkably good. The measure of error expressed by the coefficient of variation (CV) shows low values and indicates that the estimates are reliable. Since this is the first time CV has been used, it is explained here in some detail. CV refers to sampling errors only. It is a measure of precision. Each statistic produced has some margin of error associated with it because of the way it was produced.

CVs indicate the range of possible values a target value can have, given the estimator and its associated CV. For example, in Table 11-1. estimates of Dura were made for the various irrigation schemes. In the Gezira, the estimate that was generated from the ASF data was 410,000 feddan, with an associated CV of 7 percent. What this suggests is that there is a good chance that the real (target) value being estimated will be somewhere between 7 percent above and 7 percent below 410,000 feddans, (438,700 and 381,300).

Table 11-1 shows what can be expected from following proper sampling procedures. It also shows the limitations of probability sampling. In the irrigation schemes, management planners can provide accurate estimates of the area planted with each crop. The irrigated fields have been surveyed so that exact areas are known. In addition, all fields can be observed by driving down the roads along the canals.

The first column of numbers was obtained from scheme management personnel in the differerent schemes. These numbers are considered accurate and true. The second column of numbers was generated from the survey data collected from the samples. In the Blue Nile, the area planted in Dura was 61,000 feddan. The CV is 24 percent. The estimate is off by 33,000 feddan, or 55 percent. With a sample of 6, the CVs and practical experience indicate that the errors are large.

In the Gezira, the estimate is off by 33,000, or 7,5 percent of 443,000 feddan. The CV computed from the sample indicates that a 7 percent error would be normal when generated with a sample size of 41. Accuracy is a function of sample size and nonsampling errors. The important point in this table is that the errors compensate between strata. For example, in the scheme totals row, the target planted area and the total of the estimates are within 1,000 feddan of each other 0.15 percent or less than one percent. The sampling errors show a 6 percent CV with a sample size of 81. This illustrates beautifully what can be obtained with good quality probability sampling. In surveys where nonsampling errors are not controlled, increasing the sample size may decrease survey accuracy.

Irrigated cotton illustrates the same phenomenon. As the schemes are combined and the sample increases, the CV decreases. Again the estimate of total area planted with cotton is 3.7 percent from the target value, and the associated CV is 5 percent with a sample size of 76 PSUs.

Table 11-3 shows the same relationships with groundnuts. In total, the estimate is quite close to the target value, but the individual estimates of the schemes show variability. The estimate of the total groundnuts is within 2 percent of the figure considered the target value. It is based on a sample size of 55 PSUs.

Mechanized farming

Originally, there were two strata identified with mechanized farming: mechanized-demarcated schemes, with clear boundaries and regular shape, and undemarcated schemes, which may or may not have clear boundaries and regular shape. The photointerpreters thought that they could differentiate between these two types of land quite easily on the satellite FCC images. It is true that in most cases the separation was correct, but in a few cases the land was not categorized correctly. Therefore the technical staff decided to combine these two strata into a mechanized stratum. The following table is a result of that decision.

Table 11-4. Comparison of estimates of Sorghum area Mechanized Farming Schemes

	Estimates of area (Feddan)			Estimate of production m.ton	
Scheme crop	MFC final	ASF plant	ASF harvest	CV ASF harvest	ASF
Gedarif	1,659	924	917	7%	524
Damazin	1,132	1,312	1,312	13%	414
Dilling	234	208	208	27%	40
Total	3,025	2,444	2,437		978

Traditional agriculture

Tables 11-5 to 11-9 present the estimates in the west. Government estimates in the west are subjective. There are no check data as in the irrigated sector. Government subjective estimates could be quite different from the survey results, especially for the minor items. In south Darfur, the ASF survey results were unfortunately based on only 12 PSUs. This is a very small sample and needs to be enlarged next year.

The survey results are reasonably close for area planted but the yield estimates from the survey are low. Subjective results from the field indicate there was extensive pest damage caused by rats, birds, and grasshoppers.

The most interesting table will be the Table 11-9, with total summarized data for the four provinces. One could expect the survey results to be within 10 percent for the entire west for the major crops, but with the sample sizes that were used, large CVs would be expected. Overall, the results for the areas of traditional agriculture show large CVs, and the small sample plus the variability strongly suggest that the stratum needs to be represented by a much larger sample. It is possible that the stratum also needs to be refined by re-interpreting the satellite images and the aerial photography. In many cases there is a need for additional aerial surveys.

Table 11-5. Comparison of South Darfur Estimates Stratum III Traditional Agriculture Estimates

	Government area	ASF plan (Feddan)	ASF harvest	CV harvest	Government production	ASF production (tonnes)	CV estimates
Millet	860	1,073	985	27%	77	70	26%
Sorghum	470	238	191	52%	42	12	49%
Sesame	80	95	87	35%	5	4	44%
Ground Nuts	500	349	342	50%	90	52	49%

Table 11-6. Comparison of North Darfur Estimates Stratum III Traditional Agriculture Estimates

	Government area	ASF plan (Feddan)	ASF harvest	CV harvest	Government production	ASF production (tonnes)	CV estimates
Millet	900	1,505	1,302	36%	68	68	38%
Sorghum	100	97	64	77%	7	3	76%
Sesame	40	5	0	--	4	0	--
Ground Nuts	85	2	0	--	8	0	--

In the areas of traditional agriculture the variability of the results is greatest. This arises because crops are sometimes replanted if rains are late, this may be reflected in Table 11-5, where the difference between figures for millet and sorghum could result from replanting or from misunderstanding the planting intentions of the farmers. The estimate of total planted area is similar if the two crops are taken together.

Table 11-7. Comparison of South Kordofan Estimates Stratum III Traditional Agriculture Estimates

	Government area	ASF plan (Feddan)	ASF harvest	CV harvest	Government production	ASF production (tonnes)	CV estimates
Millet	90	383	375	54%	11	13	56%
Sorghum	498	167	167	53%	75	15	56%
Sesame	246	45	45	49%	30	2	54%
Ground Nuts	83	124	124	80%	21	16	74%

Table 11-8. Comparison of North Kordofan Estimates Stratum III Traditional Agriculture Estimates

	Government area	ASF plan (Feddan)	ASF harvest	CV harvest	Government production	ASF production (tonnes)	CV estimates
Millet	1,635	2,701	2,344	18%	98	70	19%
Sorghum	175	136	105	53%	13	3	63%
Sesame	690	1,844	1,656	23%	35	36	27%
Ground Nuts	206	651	620	38%	41	67	41%

Table 11-9. Comparison of Estimates for the **Total** Area West of White Nile Stratum III - Traditional Agriculture Estimates

	Government area	ASF plan (Feddan)	ASF harvest	CV harvest	Government production	ASF production (tonnes)	CV estimates
Millet	3,485	5,662	5,006	14%	254	221	16%
Sorghum	1,243	638	527	29%	137	33	32%
Sesam	1,056	1,989	1,788	21%	74	42	24%
Ground Nuts	874	1,126	1,086	28%	160	135	29%

In Tables 11-5 through 11-8, the CVs are large; South Kordofan in particular has CV values of 49 percent or higher in all cases. While this is a reflection of small sample sizes, it also indicates the variability of the data. Throughout Kordofan and Darfur this pattern of high CV values is found, and the government estimates differ from the ASF estimates, especially for the area of each crop. However, the production estimates do not differ so widely in many cases, which suggests that the sample survey may be generating new data more indicative of the actual yields and areas planted.

Table 11-9 consolidates all the data for the traditional agriculure west of the White Nile. This gives a better statistical statement of the results, with smaller CVs resulting from the larger sample size over the area as a whole. The total food production estimated by the government is 626,000 tonnes and the ASF estimate is about 30 percent less, (431,000 tonnes). Of particular importance is the summary for each crop. Millet production estimates do not differ greatly between the government (254,000 tonnes), and the ASF (221,000 tonnes) but the ASF estimate of the area of millet harvested is some 1.6 million feddans greater than the government estimate. With a CV of 14 percent, it seems that the ASF might give a more accurate figure.

The figures for groundnut production do not differ greatly and the government estimate (160,000 tonnes) is within the margin of error (24 percent) of the ASF figure (135,000 tonnes). Here the interesting feature is that the ASF estimates a lower total production from a larger area. This is even more striking for sesame, where the ASF estimate (42,000 tonnes) is only 56 percent of the government figure for total production (74,000 tonnes) from an area estimate (1,788,000 feddans) almost double that of the government (1,056,000 feddans). Sorghum estimates show a large difference: the government estimates a total production (137,000 tonnes) four times greater than the ASF (33,000 tonnes), from approximately twice the area.

The conclusion from this is that the difficulties of estimating production in the areas of traditional agriculure are more complex than previously known. Clearly the yield estimates for the traditional areas require further study, and there is need for a more detailed analysis of the area under agriculture in the west.

In terms of the national food production totals the discrepancies between the government and the ASF estimates in the west are not critical--amounting to less than half of 1 percent of the total food crop. However, this area of traditional agriculture is the one most in need of further attention in future crop surveys. The size of the sample taken in these provinces must be increased and the stratification needs to be further refined. In this context the Sudan Survey Department needs to be given the priority task of gathering good aerial photographs of Kordofan and Darfur, both to assist crop estimation and for national planning, especially for development purposes.

USE OF REMOTE SENSING IN SURVEY, MANAGEMENT, AND ECONOMIC DEVELOPMENT OF TROPICAL RAINFORESTS

Frédéric ACHARD and François BLASCO

INTRODUCTION

A lot of tropical countries gain important benefits from wood trade. This market was estimated at US $ 6 billions in 1987. Tropical dense forests represent a tremendous economic potential. Their ecological importance for the biosphere is also extremely high.

Dry dense forests are progressively disappearing, due to fires, over-grazing, and intensive exploitation for firewood. Dense rainforests are logged, often without planning, or deforested for conversions to agriculture. The total area of deforestation in 1980 was 6.1 million hectares according to Food and Agriculture Organization (FAO). The common denominator of these regressive trends is a general impoverishment of the tropical world in woody vegetation.

These figures clearly indicate that there is an urgent need for surveying tropical forests. The following examples are related to three projects located in West Africa (Cameroon and Côte d'Ivoire). They concern forest reserves management plans. Remote sensing techniques have been used as a tool to assess their actual resources as well as deforested areas and to set up a methodology and principles for the proposal of new working plans.

In Cameroon the annual rate of deforestation was estimated at about 80,000 hectares in 1980, in a the total forest area 17.9 million hectares, while in Côte d'Ivoire the estimate was of about 310,000 hectares of annual deforestation among 4.46 million hectares of total, intact forest area. The following examples concern:

- an integration of forestry resources into a global land use project; i.e., agro-sylvo-pastoral development, resource estimation, and land use planning.
- conservation and protection of woody ecosystems; i.e., management of national parks and genetic resource conservation.

Considering three examples, we will produce an estimate of the cost of remote sensing data compared with the cost of conventional aerial photographs.

OKU FOREST (CAMEROON)

Project objectives

This study was carried out by Ecole Nationale du Génie Rural des Eaux et des Forêts (ENGREF), Montpellier Center (France), and Dschang University (Cameroon), with financial support from the Man and Biosphere Program (MAB-UNESCO), from February 1987 to May 1987. The title of the report is *Oku Mountain Forest, Principles for Its Classification into a Reserved Forest and Its Working Plan.*

The goal was to give a precise description of the existing series of vegetation and consequently to propose a reserve project. The study concerns an area of approximately 30,000 hectares centered on Oku Mountain (North-West province). This area is characterized by important differences in level (1,800 meters/3,000 meters). The report is the first contribution to the administrative file related to the classification of a reserved forest.

The study was split into three main parts:

- the "vegetation" topic: observations concerning structure and floristic composition of existing vegetation types allowed the discrimination and characterization of 19 different vegetation types.
- the "production systems" topic: investigations among farmers, breeders, and institutions of the region allowed an accurate description of production systems, land use, and resources, and interrelationships between forest and local society.
- the "photointerpretation" topic: aerial photographs (1963 at 1:20,000 scale) and a SPOT panchromatic image registered in 1986 were used in order to measure the forest regression between 1963 and 1986 and to establish a simplified vegetation map. Eight different vegetation types were determined by photointerpretation on the SPOT black-and-white image at 1:50,000 scale and four types were determined "a posteriori" with field investigations.

The proposed reserve project divides the forest into two main parts:

- an external area in which agricultural production systems are to be intensified,

- a central part, with well-defined ground limits. This part comes under strict public regulation.

The forest management will separate the central part into four zones:

- the protection forest,
- the pastureland: grassland of highlands and some pasturelands,
- the forest-pasture area: grazing under forest,
- the production forest: extraction of wood is permitted.

The compiled vegetation map at 1:50,000 scale was used in order to establish a map of suggested limits for the forest reserve and for the four zones in its central part.

Use of remote sensing data: methodology and achievements

We had to work and to rely on existing and accurate data; i.e: a aerial black-and-white photographic coverage at 1:20,000 scale registered in 1963/1964 (55 films) and a panchromatic SPOT image registered in March 1986. No SPOT multispectral image was availabe at the beginning of the study. For this part of the world, SPOT data are received at Toulouse, France and Landsat data can be received either in United States or at Mas Palomas (Canary Islands). We couldn't obtain a recent aerial photographic coverage (1983), which was the property of the Cameroon government. Time was insufficient to persuade CENADEFOR (foresters) of the necessity to lend their cartographic data or information.

For the vegetation mapping, it was decided to work on the existing panchromatic SPOT image because the 1963 photographic coverage was too old and was only used to map the rate of deforestation between 1963 and 1987 and data had to be taken to the field, and time was insufficient to ask for acquisition of new SPOT coverage.

Characteristics of the SPOT image

Resolution:	10 m x 10 m in the panchromatic channel (0.51 - 0.73 μm).
Date:	March 29 1986.
Acquired product:	1 quarter of the scene (30 km x 30 km) on paper backing at 1:50,000 scale. Level 1B.
Cost:	1,800 FF in 1987 (US $300) = 2 FF/km2 (0.3 $/km^2) for the full quarter; 6 FF/km^2 (1 $/km^2) for the reserve.

Result

Aerial photographs were used to map the forest regression between 1963 and 1986 at 1:50,000 scale. The SPOT image was used to map the actual vegetation types at 1:50,000 scale, latter enlarged at 1:20,000 scale.

Time

Four specialists worked during two weeks in Cameroon for the ground truth survey. Cost of fieldwork is the same whether space or conventional procedures are used. A photointerpretation specialist worked one month to produce the thematic map, including the field survey. The use of aerial photographs should have required two months of work (photointerpretation, field survey, final map).

The significant reduction of the time required for vegetation mapping using SPOT imagery is the strongest benefit of this new technology. The unavailability of recent aerial photographs was, however, a major constraint for our study at a large scale.

HAUT-SASSANDRA RESERVE (CÔTE D'IVOIRE):

Study objectives

This study was conducted by the CTFT (Technical Center for Tropical Forest, Nogent, France) for the DCGTX (Direction and Management of National Actions of Côte d'Ivoire) between February and April of 1988. The title of the study is *Methodological Proposals for Forest Mapping*.

In 1988 one of the major landuse questions in Côte d'Ivoire was how to determine the actual area of the present forest coverage. For 30 years economic development has been based on the intensive exploitation of forest resources (wood trade, commercial plantations, agroindustrial plantations). That is why, in order to plan for economic development between 1990 and 2000, the Ivoirian institutions required recent data about undisturbed forests, degraded forests or forest areas converted into cropland.

The actual data related to forested areas in Côte d'Ivoire are given by the national inventory of 1966, updated in 1980. Estimates of the total undisturbed forest area were: 14.5 million hectares in 1947, 8.98 million hectares in 1966 and 4.46 million hectares in 1980. In 1980, 8.4 million hectares were forest fallow. These estimates stress that regression of dense humid forests is excessively high and that data related to the actual forest area are questionable.

The general goal of forest planning, decided by the Ivoirian government is to identify and to state clearly the new limits of reserved forests in order to establish a rational management plan of national land use, particulary in areas where forests are being actively depleted. Hence the main objectives of thematic mapping are:

- to inventory free fallow lands, where young farmers could be installed.
- to evaluate the actual forest areas in order to save protected forests and to set up a management plan of exploitation and valorization.

Mapping methodology

The priority was to produce a map for three forest stands at 1:50,000 scale, accompanied by detailed comments given in a separate explanatory booklet:

- Forest Reserve of Haut-Sassandra
- Forest of Scio-Debe-Cavally
- Reserve of Niegre

Aerial survey

The only aerial photographs available for the forest reserve of Haut-Sassandra were taken in 1978 and are of a fair quality. In 1986 however , SODEFOR carried out survey flights over 20 forests in southern Côte d'Ivoire. During each flight, thematic observations were collected and data were gathered on topographic maps at 1:100,000 scale.

The objective of each flight was to establish an actual state of damage of 15 important forests, including the Haut-Sassandra Reserve. The team included one chief forester from SODEFOR, one assistant from DEF/Foresty Direction for the organization of flights, and two observers from SODEFOR and DEF. The work was carried out at the rate of 150,000 hectares per manday. The main task of the team (four people) was data collection, transfer of observations to maps, and analysis of changes affecting the vegetation cover.

Remote sensing

Present earth resource satellites provide an alternative source of data for thematic mapping, particulary for the production of land use and vegetation maps. In the framework of the concerned scheme, remote sensing technology was the selected tool for forest mapping at 1:50,000 scale. The first map was devoted to Haut-Sassandra Reserve.

Two scales were selected: 1:100,000 for national planners and decisionmakers, and 1:50,000 scale. The first map was devoted to Haut-Sassandra Reserve. Two legends have been produced in agreement with the mapping scales. The legend of forest maps at 1:100,000 is a simplified version based on physiognomic criteria. That of forest maps at 1:50,000 is more detailed.
SPOT multispectral or Landsat Thematic Mapper data can be used to make thematic maps at 1:50,000 scale. The data used were mainly SPOT images since few TM data from Landsat 5 were available for Côte d'Ivoire. Almost 30 SPOT CCT images (Computer Compatible Tape) have been acquired by SAT (Autonomous Service of Remote Sensing).

The methodology included the following steps:

1. ***Preliminary step: preprocessing:***
   - collection of such documents as topographic, thematic, and land use maps, text of the forest constitution, etc.
   - drawing the hydrographic network,
   - superimposition of the topographic map on the interpretation tracing paper. The geometric accuracy of SPOT or TM images is sufficient to be superimposed on topographic maps.
   - visualization of the satellite image (FCC = False Color Composite) on color print. A standard linear stretching is adapted for the discrimination of forest areas and nonforest areas.

2. ***Photointerpretation of SPOT or TM images:***
   This method of visual interpretation (as with infra red color photographs) has been chosen because this technique is cheap, simple, and efficient. It takes into account the color dynamic as well as the texture and external elements. Provided photointerpreters are sufficiently trained; this is, for the time being, the only operational method.

Table 12-1. Comparison between Digital Analysis and Photointerpretation of Satellite Images

	Digital analysis	Photointerpretation
Advantages	- improvement of the dynamic - perception of small radiometric differences - multitemporal superimposition	- cheap - texture and external elements taken into account - easy and rapid
Limitations	- expensive (hardware and staff) - necessity to adapt the method for each image	- depends on the quality of photographic product

Comparison between digital analysis and photo-interpretation of satellite images

3. *Field control*

The aim is to evaluate the results of the image interpretation. It also allows an acquisition of information for forest planners. In this case SODEFOR requested specific data, such as the level of forest type, number of strata, or species compostition. These data could only be obtained in the field.

4. *Validation of the photointerpretation*

Field information is transferred to the sketch map, improving the reliability of the final drawing.

5. *Cartographic synthesis (statistics)*

The aim is to compute acreages of vegetation types, manually or numerically by line digitization.

6. *Mapping and printing*

The goal is to draw the final map from the sketch map and to complete the cartographic information, thanks to a descriptive booklet in which the methodology and statistics are given.

The methodology has been applied on a SPOT multispectral image of the Haut-Sassandra Reserve registered on December 26, 1986.

SPOT IMAGE Company had delivered a CCT and a photographic print at 1:100,000 scale in a standard FCC (level 1B). SAT produced an FCC adapted to forest studies (with a microcomputer) and printed it on a Tektronix 4696 printer at 1:50,000 scale.

Cost of data

Aerial survey: the total cost of the flight over the 20 forest stands is:

6 F CFA/ha = 12 FF/km^2 (US $ 2/km^2)

This cost includes the use of the aircraft during 54 hours and 30 minutes, manpower, and topographic map acquisitions (document cost = 22 percent of total cost). The mean efficiency of the flights is: 60,000 hectares/hour when considering the time of flight over the forest, and 24,000 hectares/hour when considering the time of flight over the total area. The efficiency is optimal for forest areas larger than 100,000 hectares.

SPOT image:

- CCT: 11,000 FF in 1988 (US $ 1,800)
- Photographic print at 1:100,000 scale: 1,500 FF (US $ 250) = 3.5 FF/km^2 (US $ 0.6/km^2) for the full scene or 12.5 FF/km^2 (US $ 2.1/km^2) for the forest area (≈100,000 ha).

Time requirements

Aerial survey: The publication of complete results required three months for the 15 forests concerned, including the preparation of flights, aerial surveys, transfer of observations onto maps, and the analysis of landuse changes or conversions.

Satellite image: The forest mapping itself (100,000 hectares) required two months of work for two people under the control of a forester (project leader), one specialist in remote sensing applications to vegetation inventories (photointerpreter trained on satellite imagery), and one technician (field and cartography).

Conclusions

Results are satisfactory, primarily because they allow a quite good delineation of forest limits. The flight over forests is an efficient, fast, and cheap tool to obtain actual information on the state of a forest. The utiliszation of skilled people is compulsory. However, this method does not provide reliable data either on the actual surfaces or on the most recent changes on the limits of vegetation types. The method using photointerpretation of SPOT imagery is operational and guarantees the accuracy of forest mapping.

NATIONAL PARK OF MARAHOUE (CÔTE D'IVOIRE)

Study objectives

This study was carried out by ENGREF under the control of the Ministry of Forestry of Côte d'Ivoire and the directiorate of ecological sciences of UNESCO, with financial support from the MAB program, between February 1988 and June 1988. The title of the study is *Preliminary Study for Management of the Park and Adjacent Areas*. Three topics were analyzed:

- The fauna: its richness is important with a significant number of large ungulates. The case of elephants requires additional investigations; these animals are discrete. The avifauna is also charcterized by a variety of species.
- The natural vegetation: The floristic diversity is important. Major vegetation types have been related to some environmental factors. The decrease of the specific diversity in forest species along a south-west--north-east transect is probably related to the climatic gradient.
- Production systems in adjacent areas: the guaranteed price for cocoa explains their dynamism. Consequently "black forest" is being cleared. The new field is used during two or three years for food crops and then almost exclusively for cocoa crops.

Deforestation affects southwestern and northeastern parts of the park. When it was created in 1968, its limits were not defined. A new project could save the future of the Park if the following recommendations are taken into account:

1) Proposal of new limits: the areas which have been converted to cropland, have to be excluded. The new area will be approximately 84,000 hectares (102,000 hectares in 1968). A small area (2,500 hectares) will be kept in the park with special regulations permitting agroforestry management under the control of the park administration.
2) Conversion of the park into an autonomous government institution.
3) Creation of a development project in the peripheral zone.
4) Need of new equipment for the development of recreation attributes.
5) Control of fires and fauna.
6) Development of applied research schemes concerning the park.

Remote sensing techniques were used to prepare and to complete field observations.

Comparison of methodologies

The available data were:

- a recent aerial photographic coverage registered in March 1987, in the panchromatic mode at 1:22,000 scale (200 negatives) and a photomosaic at 1:20,000 scale, produced by IGN (National Geographic Institute, France).
- a SPOT multispectral image registered on Novembre 25, 1986. The CCT and a standart print at 1:100,000 scale were purchased (Level 1B).
  No Landsat-TM data were available.

Study objectives were to delineate the forest on a map at 1:50,000 scale and to test the efficiency of SPOT image processing.

Use of aerial photographs

The main advantage of aerial photographs is their large scale (typically 1:10,000 to 1:60,000). The use of stereoscopy allows the user:

- to identify forest plantations, height, number of strata, and, in some cases, the species.
- to locate characteristic points needing ground survey.
- to map forest tracks.

Some recent aerial photographs at 1:10,000 scale could, however, replace the ground survey, but timber volume estimates in tropical dense forests require an appropriate ground survey. Correlations between timber volumes and crown parameters are usually extremely questionable.

The main limitation of the use of aerial photographs is the difficulty in estimating areas on a large number of photographs. Reliable photogrammetric mapping involves time-consuming operations such as:

- establishment of mapping control network and aerial triangulation,
- photogrammetry (compilation of orthophoto maps),
- photointerpretation.

In the study, aerial photographs and the photomosaic were used during the ground survey. It was impossible to use a reduction of the photomosaic at 1:50,000 scale because this mosaic contains local incorrigible distortions.

Remote sensing

The SPOT image was printed at 1:50,000 scale in order to draw the final map. The geometric accuracy of high-resolution satellite images is satisfactory. Major steps for mapping were:

- preprocessing: detector equalization,
- geometric rectification with eight points,
- prints at 1:50,000 scale and first draft of the map.

The deforestation was analyzed in the Southwestern part of the park. The deforested areas were identified by an automatic method of maximum likelihood classification. This part of the Park should be put under special regulations. Using the same classification method, three classes have been distinguished for the forest. One class corresponds to the Southwestern forest which is moister and has several tree layers. The two other classes in the central part should probably be interpreted as the consequence of differences in the phenology of trees. The automatic processing also allowed the mapping of the agricultural deforestation. However, information about the structure or floristic composition was not immediately available. For the time being, radiometric responses can only be interpreted in terms of the photosynthetic activity of plants.

Cost and time requirements

Existing data and their cost

IGN aerial photographs:

- Copy of films at 1:22,000 scale (≈ 200 films): 2,250 F (US$370),
- Copy of mosaic print at 1:20,000 (5 sheets): 1,900 F (US$320);

i.e., 4 FF/km^2 ($US 0.7/km^2) for the covered area (≈ 100,000 hectares).

SPOT image:

- CCT: 11,000 FF in 1988 ($US 1,800) (Level 1B),
- Photographic print at 1:100,000 scale: 1,500 FF ($US 250);

i.e., 3.5 FF/km^2 ($US0.6/km^2) for the full scene, or 12.5 FF/km2 ($US2.1/km2) for the forest area (≈ 100,000 hectares).

Data to be acquired in 1989

IGN aerial photographs:

- flight and photographs: 140,000 F ($US 23,000),

- mosaic at 1:60,000 scale: 20,000 F ($US 3,300) (mosaic at 1:20,000 scale: 100,000 F ($US 17,000);

i.e , 160 FF/km^2 ($US 27/km^2) for the covered area (≈ 100,000 hectares).

SPOT image:

- CCT: 11,000 FF in 1988 ($US 1,800) (Level 1B),
- Satellite program: 3,000 FF ($US 500);

i.e , 3.9 FF/km2 ($US 0.65/km^2) for the full scene, or 14 FF/km^2 ($US 2.3/km^2) for the forest area (≈ 100,000 hectares).

Time requirements for the forest mapping

Aerial photographs. One specialized photointerpreter needs two months work for the photo-interpretation of 200 photographs at 1:200,000 scale. One month of ground survey is necessary for the cartographer and the forester. Ultimately the photointerpretation validation and the final map drawing necessitate two months of work for the cartographer.

Satellite image. Field work is the same whether space or conventional procedures are used. One cartographer trained in satellite imagery needs two months for photointerpretation, validation, and mapping at 1:50,000 scale.

ACKNOWLEDGMENTS

The authors would like to thank Michel Deshayes (ENGREF, Montpellier, France) Hervé Jeanjean (CTFT, Nogent, France), François Lavenu (LERTS, Toulouse, France), Patrice Megin-Lecreux (SODEFOR, Abidjan, Côte d'Ivoire) and IGN (St Mandé France) for their help and contributions.

REFERENCES

C.T.F.T., 1988. *Propositions méthodologiques pour la cartographie forestière*. Technical Report - Centre Technique Forestier Tropical. Nogent, 62 pp.

E.N.G.R.E.F., 1987. Massif d'Oku: *Classement en réserve et principes pour un plan directeur d'aménagement*. Montpellier, France: Ecole Nationale du Génie Rural des Eaux et des Forêts, 128 pp.+ annexes.

E.N.G.R.E.F., 1988. Parc National de la Marahoué: *Etude préalable à un aménagement du Parc et de sa zone périphérique*. Montpellier, France: Ecole Nationale du Génie Rural des Eaux et des Forêts, 124 pp.

Kalensky, Z.D., 1985. Cost/benefit analysis of computer assisted thematic mapping at 1:250,000 scale from Landsat digital imagery -- International training course on small-scale remote sensing applications. Feldafing, FRG.

Mengin-Lecreulx, P., 1988. Aménagement des forêts tropicales : L'ENJEU. *Review Bois et Forêts des tropiques* n° 215, pp. 93-97.

SODEFOR, 1986. Survol de vingt forêts classées du sud de la Côte d'Ivoire. Document Société pour le Développement des plantations forestières, 44 pp.

USAID: REMOTE SENSING AND FORESTRY

John D. Sullivan

THE PAST

I was pleased to accept the responsibility to report on the use of remote sensing in AID for forestry purposes. Only 5 years ago, A.I.D. had 12 active projects with an average "life" of 10 years and support for remote sensing on the order of US$ 650,000 per project per year. I was certain that in 1989, with a computer-based project information system, forestry and remote sensing would show an increase, perhaps a dramatic increase.
Right? WRONG!

THE PRESENT

No matter how clever the search strategy, the AID. Project Information System revealed only three projects utilizing remote sensing for forest and related resources, supported by about $400,000 per project per year for Landsat data. Is this an apparent diminution of remote sensing activity or is this a function of some insensitivity in the information system? I suspect the latter, primarily because of the burgeoning agency portfolio in natural resource oriented strategies that practically demand resource assessment data for which remote sensing techniques are so appropriate. Other organizations may well have a better cumulative grasp of AID's remote sensing programs than any Washington office, given the agency's decentralized project selection and management system.

THE FUTURE

A number of current issues argue for the intense utilization of sophisticated remote sensing techniques as the future unfolds. The following seven issues are shown in no particular order of priority.

Biological diversity

This has become a catchword in the past several years, but in AID biological diversity is much more--biological diversity focuses at the ecosystem, species, or molecular genetic level, the essence of plant and animal life as we know it. When biological diversity (number of living organisms per unit area) is decreasing, members of the biota are dead or dying or both, and, by definition, we have an environmental problem that demands attention. Remote sensing will be particularly useful at the ecosystem level for assessment and inventory over time as well as for monitoring the "vigor" of entire ecosystems.

Global climate

Without entering into the international debate on whether the globe is heating, cooling, or remaining the same, the greenhouse effect is measurable and the contribution of various gases is not a secret! The immense forest and range resource lands of this world serve as a gigantic carbon sink. Just plain old burning converts these resources to carbon dioxide--keep in mind that 90 percent of all the wood harvested in the world is for fuelwood--and the greenhouse effect is augmented. Remote sensing to measure the rate of change of forest and range area is a necessary ingredient in defining the problem and to better concentrate strategies where the issue is most cogent.

Tropical deforestation

Slash-and-burn agriculture is the primary culprit in tropical deforestation, which is devastating to the present and future economic strength of some 60 developing countries. Spurred on by the bilateral and multilateral development community, the Food and Agriculture Organization (FAO) is coordinating the Tropical Forestry Action Plan (TFAP), designed to approach tropical forestry issues on a country-by-country basis. The nationally oriented TFAP activities include governmental and nongovernmental organizations, both of which are severely constrained by limited information on the forest resource base, area, ecosystem types, species, soils, topography, etc. Remote sensing techniques are an essential ingredient in building and maintaining real-time information bases to resolve many of these information constraints.

Desertification

Uncounted millions of hectares of once productive range and forestland have been lost in recent years to desertification. As many as one billion people derive their basic life support from such lands, and the famines of the past several years foretell a grim future unless this devastating process is reversed. If one also considers areas of the world that have been wastelands for centuries, awesome and necessary economic returns are possible if such lands are restored to their most productive state. Again, remote sensing furnishes cost-effective mechanisms to describe various components of such landscapes to assist in priority assessment and in planning of intervention strategies.

Coastal zone

One needs only to be able to distinguish blue as a color to see the importance of the ecotones between terrestrial and marine in the developing world. There is no country anywhere that does not impact on a marine environment, derive benefits from a marine environment, or both. The interactions between marine and terrestrial systems are complex, important, and subject to the influence of a large number of governmental and commercial organizations in any country. The potential is vast for remote sensing to contribute to the knowledge base on which to establish wise management of coastal resources on the land and in the sea.

Population and Environment

Population is destined to increase. Man can only influence the rate of increase and try to limit the influence of population in degradation of natural resources. Needs for food and shelter can only be satisfied from the land and water resources in such a way that the resource base remains fully capable of continuing or even increasing production of the necessities and amenities of life. Remote sensing has helped us to see and measure the profound impact of population on the environment and can help us to make the land management decisions that will spell a better future for all of us.

All of the above

My comments up to now might give the impression that all the preceding factors are somehow independent. Not true at all! They are intimately related to one another, as well as to cogent economic and political forces, representing an extremely complex matrix that cannot be resolved by the trial-and-error, case history approach. (If it works in one place, do it in another; OR, if it doesn't work in one place, do not even try in another.)

We must utilize contemporary techniques like remote sensing, G.I.S., and simulation modeling to do a better job of understanding and taking advantage of integrated effects to produce desired objectives and to minimize or eliminate unforeseen consequences.

SEASONAL VEGETATION MONITORING WITH AVHRR DATA FOR GRASSHOPPER AND LOCUST CONTROL IN WEST AFRICA

G. G. Tappan, S. M. Howard, T. R. Loveland, D. G. Moore, and D. J. Tyler

INTRODUCTION

With the return to near normal rainfall during the past several years, environmental conditions favorable for locusts and grasshoppers has resulted in large populations of these insect pests. In 1985 and 1986, the Senegalese grasshopper (*Oedaleus senegalensis*) threatened cropland in a number of Sahelian countries. A major upsurge in the population of the desert locust (*Schistocerca gregaria*) occurred in mid-1987, resulting in the present serious threat to agriculture over vast areas in northern Africa.

International donors have mounted emergency assistance programs for grasshopper and locust control in Africa. In early 1987, the U.S Agency for International Development (USAID) prepared a major campaign to control grasshoppers in West Africa. One goal of the program was to improve grasshopper prediction and survey techniques of grasshopper populations. This requires an improved capability to monitor the distribution and seasonal changes of natural and agricultural vegetation in the Sahelian and Sudanian zones where the grasshoppers and locusts hatch and develop. For this reason, the Bureau for Africa of USAID requested that the EROS Data Center of the U.S Geological Survey (USGS) conduct a pilot project to develop, test, and evaluate a near-real-time monitoring procedure using satellite data. These data, along with geographic information system technologies, were used to support the grasshopper and locust control programs. Previous studies have shown that the use of satellites for monitoring locust habitat is very promising (Hielkema 1980, Bryceson and Wright 1986).

Inherent in the pilot project was the need to format and present information for acceptance and use by decisionmakers and grasshopper control technicians. The information was presented in the form of vegetation index or "greenness" maps derived from two-week composites of LAC AVHRR satellite data.

The maps are based on the Normalized Difference Vegetation Index (NDVI), which has been shown to be directly related to the photosynthetic capacity of vegetation canopies (Sellers, 1985), herbaceous biomass production (Tucker and others 1985, Prevost 1988), and is useful for monitoring seasonal fluctuations in the extent of seasonal vegetation (Goward and others 1985, Justice and others 1985, Schneider and others 1985). The maps represent maximun NDVI value composites for 14-day periods through the Sahelian and Sudanian zone summer growing season. They were used and evaluated in the 1987 campaigns in Senegal, The Gambia, Mauritania, Niger, and Chad. The program continued in an operational mode in 1988 in support of efforts to control locusts in Mauritania, Mali, Niger, Chad, Sudan, Morocco, Algeria, and Tunisia.

BACKGROUND

Grasshoppers and locusts have caused problems for man since the beginning of recorded history. They destroy the crops and grasses upon which man and his animals feed, at times resulting in widespread starvation and disease. In 1958, locusts destroyed 167,000 tons of grain in Ethiopia, sufficient to feed one million people for a year. Following the end of the Sahelian drought in the mid-1980s, dramatic increases in grasshopper and locust populations were observed. Of particular concern to those monitoring the situation was the return of the Senegalese grasshopper and the desert locust.

The Senegalese grasshopper

The Senegalese grasshopper is one of the most economically important species of acridids in the Sahel. They can attain high densities and migrate on the wind, inflicting heavy damage on food crops. Their range of distribution is a band across Africa corresponding roughly to the Sahelian and Sudanian zones, but also reaching south into Tanzania. The grasshoppers migrate during the wet season from an area of initial breeding in the Sudanian zone, northward through a transitional breeding area, to a northern breeding area in the Sahelian zone. At the end of the rainy season, the grasshoppers migrate back into the transitional and initial breeding areas, laying egg pods as they go (Launois 1979). The eggs go into diapause dormancy throughout the dry season until a rain, generally 25 millimeters or more, triggers a hatch. Grasshopper development rates and migration patterns are determined by environmental condition including moisture, temperature, vegetation conditions, photoperiod, wind patterns, and grasshopper population levels (Launois 1979).

Damage to food crops by the Senegalese grasshopper was reported in 1986 in parts of Senegal, Mauritania, The Gambia, Mali, Burkina-Faso, Niger, and Chad (FEWS 1987). In 1986, major grasshopper control campaigns were mounted involving large-scale aerial spraying operations. As a result of the campaign and biological factors, populations of the Senegalese grasshopper were more limited in 1987 and 1988. Serious outbreaks occurred only in localized areas.

The desert locust

The desert locust is the most feared of all the locusts in the world. It has great mobility (up to 1,000 kilometers a week), a vast invasion area, a potential to reach high population densities, and the ability to consume its own weight in food every day (Pedgley 1981). Its range and biology are markedly different from that of the Senegalese grasshopper. During locust recession years, when the population is low, locusts are found in the semiarid or arid regions of 30 countries in Northern Africa, the Middle East, and Asia. During plague years, large swarms of locusts can move out of the recession areas into a large invasion area covering portions of 57 countries (Pedgley 1981).

The desert locust, like other true locusts, differs from grasshoppers by its ability to transform its physiology, form, and behavior in response to changes in population density. When populations are low, locusts are smaller, behave independently, tend to avoid each other, and are said to be in the "solitary" phase. By contrast, locusts in the "gregarious" phase are larger and swarm together. Favorable breeding conditions that lead to crowding for more than one generation are required to produce the fully gregarious characteristics associated with locust plagues.

During favorable breeding periods, a population of locusts may increase 100 times or more per generation and as many as six generations may be produced per year. Therefore, population suppression measures must strive for 98 percent mortality rates or better to be effective.

Locust breeding is seasonal, and occurs in two major east-west belts in which there is suitable rainfall: the summer breeding season extends across the Sahel, southern Sahara, Ethiopia, and the northwest Africa, the Arabian peninsula, Iran, and Pakistan. Between these two belts lies a third area of winter breeding, primarily in the Somali peninsula and the Red Sea coast.

Locusts require certain ecological conditions for breeding. The main variables are rainfall, topography, soil type, vegetation, and temperature (Pedgley 1981). Rainfall is the most important requirement for producing a favorable breeding environment because it provides the soil moisture necessary for egg development and triggers germination and growth of vegetation upon which the hoppers (nymphs) and adults feed. Topography can influence where and when breeding occurs by modifying rainfall patterns and the resulting runoff. Locusts show preference for sandy or silty soils for egg-laying. The presence of vegetation influences where swarms will settle to lay eggs, the distribution and density of egg pods, and the behavior of newly hatched hopper bands. Healthy vegetation, especially annual herbaceous vegetation that germinates in response to seasonal rains, assures the survival of the hoppers by providing both food and shelter. Temperature is the main factor in determining the rate of egg and hopper development (Pedgley 1981).

A major upsurge in the desert locust population has occurred since 1986 as a result of prolonged and widespread favorable breeding conditions in Africa. Seasonal rains in 1986 produced considerable increases of nonswarming populations in parts of the northern Sahel (FAO, 1987). In Mali and Niger, small gregarious swarms were reported, leading to gregarious breeding in October 1986. The breeding became fairly extensive, spilling into Mauritania in November. In July 1987, desert locust populations were reported in northeastern Chad following heavy rains and vegetation green-up. Breeding continued from August through November in Chad and Niger, producing several successive generations. Large-scale migrations were tracked into northern Mali and Mauritania, where further breeding occurred. Swarms also moved northwest across Algeria. Some of these moved into southern Morocco and later across north-central Algeria, Tunisia, and northwestern Libya. Spring breeding occurred in the North African belt, producing two generations of locusts, that then migrated back into the Sahelian zone prior to the onset of the seasonal summer rains. The favorable 1988 Sahelian rains have produced ample moisture and abundant vegetation growth, providing ideal conditions for widespread locust breeding and strengthening the present plague situation.

METHODS

Since the early 1980s, considerable attention and research has focused on the use of hightemporalfrequency, coarse resolution satellite data for earth resource monitoring. The primary source of these data has been the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration's (NOAA) series of meteorological satellites. These polar-orbiting satellites provide image data for the Earth's surface on a daily basis at low cost (US$ .02 per 1000 square km). NOAA-9 satellite data (launched 1984) were used for the present project.

The study area

In 1987, greenness maps were produced every two weeks from May until November for the north African countries of Senegal, The Gambia, and southern Mauritania, and from August until November for the countries of Niger and Chad. In 1988, maps were being produced every two weeks during time periods most appropriate for locust habitat monitoring for the countries of Mauritania, Mali, Niger, Chad, Sudan, Morocco, Algeria, and Tunisia.

Data flow and processing

The satellite data are recorded by NOAA-9 and transmitted to the National Climatic Data Center in Washington, D.C. Approximately three scenes per week were acquired for most of Northern Africa. The satellite data were converted from wide-band video to computer-compatible tapes (CCTs) and sent via air express to the USGS/EROS Data Center in Sioux Falls, South Dakota. At the EROS Data Center, each scene was ingested into the AVHRR Data Reception and Processing System (ADAPS) and previewed for cloud cover and to determine whether a country of interest fell into the near nadir (central) portion of the scene. Scenes that passed this initial screening were processed further by ADAPS. The visible (channel 1) and near-infrared (channel 2) data were calibrated, registered to a map base, and used to compute the Normalized Difference Vegetation Index (NDVI). The thermal (temperature) data (channel 4) were also retained for subsequent processing.

Calibration converted the raw data counts into albedo using prelaunch calibration coefficients. The images were registered using an approach that aligns image features, such as rivers or coastlines, with computer maps of the same features. Transformations were applied to register the rest of the image (Boyd 1987). The NDVI is a data transformation that combines visible (channel 1) and near-infrared (channel 2) spectral data into a single variable, which is strongly correlated to amounts of green vegetation cover and green biomass (Deering and Haas, 1980).

The NDVI was computed from the calibrated channels 1 and 2 using the formula:

$$NDVI = \left(\frac{\text{Channel 2} - \text{Channel 1}}{\text{Channel 2} + \text{Channel 1}} + 1.005 \right) \times 100$$

The NDVI and thermal data were then entered into the Land Analysis System (LAS) image-processing system for further processing. An important processing step is cloud screening. Portions of AVHRR scenes that are obscured by clouds must be replaced with data from another date when the area is free of clouds. This was accomplished by combining numerous scenes within a two-week period. The process involved determining a threshold temperature level in channel 4, which distinguishes between cool clouds and the warmer land surface. A 0-1 digital image mask was generated from the thermal channel in which zeros represented clouds. The mask was multiplied with the NDVI image, which replaced all the cloud-contaminated pixels with zeros. This process was repeated for each scene within the two-week composite period.

All cloud-masked NDVI images produced for the two-week period were merged to generate a single composite scene. The scenes were overlayed, and the maximum NDVI value at any pixel location over the two-week period was retained. Cloud-contaminated areas were replaced with cloud-free data; typically, however, a few areas obscured by clouds remained. This procedure not only "removes" clouds but during "green-up" also favors the retention of near-nadir, clear-sky NDVI values near the end of the two-week composite period. After the peak of green, however, NDVI values near the beginning of the composite period are favored.

The final product: vegetation index maps

Vegetation index or greenness maps depicting the current distribution and relative amounts of green vegetation were the primary products of this project. The maps contain locational information, including international and provincial boundaries, major roads, cities and towns, and geographic coordinates. These cartographic features were taken primarily from operational navigation charts (ONC). Map scales varied from 1:1,000,000 for the smaller countries to 1:2,500,000 for the larger ones. All of the locational map information was processed using ARC/INFO geographic analysis and plotting software. Map information and text were processed and arranged into a map "collar" including all locational data, legend, and text. The final maps were created by combining these data with the satellite-derived greenness information and output on color ink-jet or electrostatic plotters.

Since the intent of the greenness maps was to show the distribution and relative amounts of photosyntheticallyactive green vegetation, a color legend was developed to depict this information in a way that would be intuitive to the map user. The NDVI range was divided into 19 classes of unequal intervals, with the highest sensitivity (narrower class intervals) in the ranges representing low amounts of green vegetation. Areas with little or no green vegetation were displayed in shades of orange and yellow. Areas with increasing amounts of green vegetation were shown in shades of green, from light to dark. The highest levels of greenness were shown in shades of dark blue. Areas obscured by clouds were symbolized with white. The satellite-derived greenness data were thus color-coded and combined with the map collar information into a single file for plotting on the color ink-jet plotter. The maps were laminated to provide protection for field use.

Multiple copies of each map product were sent to each participating country, using an express courier. The maps were available within the individual countries for use in the grasshopper campaigns four to six days after the end of a map production cycle. In addition, greenness information was communicated to each country via telex using a geographic reference grid. This provided users with the latest greenness information immediately following a map production cycle, generally three to four days following the latest satellite pass over Africa.

RESULTS

The greenness maps were used by numerous organizations involved in grasshopper and locust control in the Sahelian countries. The primary users were the crop protection service agencies responsible for planning and carrying out control activities, and USAID and FAO personnel involved directly in supporting the campaigns in each country. The maps provided new, detailed, and more timely input for the task of monitoring a continuously changing environment. The maps assisted grasshopper and locust control teams to:

- monitor locations of favorable grasshopper and locust habitats;
- predict potential upsurges of pest populations in favorable habitats;
- survey areas likely to harbor significant populations of grasshoppers or locusts;
- plan the subsequent implementation of control operations.

The greenness maps provide a means of monitoring two key environmental factors that strongly influence the population dynamics of grasshoppers and locusts: vegetation condition (through direct monitoring of vegetation reflectance characteristics) and moisture conditions (indirectly through vegetation response to rainfall). Vegetation condition refers primarily to herbaceous stratum of the Sudanian, Sahelian, and, potentially, Saharan vegetation formations upon which grasshoppers depend for food and shelter. The herbaceous stratum responds quickly to rainfall, through germination and rapid growth, following a rainfall of at least 25 millimeters. This corresponds to the approximate threshold of rainfall needed to trigger at least partial hatching of Senegalese grasshopper eggs (FAO 1987), and for successful breeding of the desert locust.

Map use for grasshopper control, particulary the Senegalese grasshopper, was based on the principle that seasonal rainfall triggers both the growth of herbaceous vegetation and the development and hatching of grasshopper eggs present in the topsoil. For example, in comparing data from field surveys in Senegal from May to August of 1987 (Philips 1987, Cavin 1987) to the biweekly greenness maps, positive correlations were found among initial emergence of herbaceous vegetation, the presence of hoppers of various species, and NDVI values of 0.08 to 0.13. Map use in support of desert locust control differs from that of the Senegalese grasshopper, mainly due to the biological and behavioral differences of the locust. The approach, presently being tested by the participating countries, is for the maps to serve as indicators of favorable sites likely to be invaded and colonized by migrating swarms, as well as favorable breeding areas. During migration, locusts do not directly seek out and fly toward green vegetation. Instead, they are carried downwind to areas of low-level wind convergence, which is often where rainfall has occurred and green vegetation is therefore present. For successful breeding and survival of the species, the desert locust must find favorable moisture conditions. Rainfall must have occurred in an area prior to egg-laying to provide the necessary soil moisture for egg development. The equivalent of 15-20 millimeters of rain 24 to 48 hours before laying provides the most suitable conditions for laying (Pedgley 1981). Again, the same rains promote the growth of seasonal herbaceous vegetation that provides food and shelter for the hatching nymphs.

Field observations in Senegal in 1987 indicated that herbaceous vegetation begins to emerge four to six days after a useful rainfall of at least 20 millimeters (this can vary depending on soil type, slope, and other factors). Preliminary indications are that the emerging cover can be first detected using NDVI about ten days following useful rainfall, and that NDVI values of 0.07 to 0.08 correspond to initial detectable emergence. Under ideal conditions of moisture and temperature, locust hatching occurs ten days after laying (Pedgley 1981) or ten to twelve days after sufficient rainfall. Thus, the nymphs appear at about the time emerging vegetation can be detected from satellite data. The period of hopper development under ideal conditions is about 36 days, at which time fledging occurs and the locusts gain flight capability. Allowing for the four to six days it takes to produce and deliver a greenness map, and depending upon the timing between vegetation emergence and a given map-compositing period, map users have 17 to 30 days to field check areas of emerging vegetation to determine whether they contain developing hoppers. If control measures are warranted, they should be taken before the hoppers reach the mobile adult stage.

Operational use of the maps in 1987 varied from country to country. In Senegal, prior to the regular use of the greenness maps, the grasshopper control team relied upon AGRHYMET rainfall data and Crop Protection Service (CPS) field reports to estimate the general position of the advancing green-up line. The maps provided additional information on the intricate patterns of vegetation green-up. The CPS used the map information to send field teams to green areas and avoided wasting time in dry areas. The survey teams noted a positive correlation between the maps and ground observations. In Niger and Chad, USAID staff used the greenness maps as major sources of information for planning and conducting aerial surveys. In Niger, some green areas identified on the maps were visited and found to contain large populations of gregarious locusts. The CPS staff frequently used the maps for making decisions on whether to conduct field surveys. In Mauritania, the greenness data were used by both USAID and the CPS to monitor the green-up patterns as a supplement to rainfall data and to confirm field reports on vegetation conditions.

A number of users suggested providing thematic resource information in conjunction with the greenness maps (for example, land use). Using a geographic information system approach, resource information can be integrated into the greenness maps or provided on overlays. This would provide analysts with improved information on greenness and its relationship to such phenomena as vegetation types, crop condition, and drought. For demonstration purposes, existing soil data for Senegal were entered into a geographic data base. In order to show that this resource information can be used within the context of a grasshopper control program, certain attributes of the soils data, including soil texture, were identified and plotted to produce a thematic map indicating soils favorable for egg-laying by the Senegalese grasshopper. When used with greenness information, this map can serve as a tool to further narrow areas being considered for grasshopper surveys.

CONCLUSIONS

The prediction and survey of grasshopper and locust populations depend on analyses and syntheses of several major data sources. Traditionally, these analyses have included historic records on pest occurrence, weather patterns, historic and current rainfall, egg pod distributions, field reports, and various biological models. While every effort must be made to continue to integrate these sources, the data are often inadequate or unavailable for large areas in the vast Sahelian and Saharan environments. The recent use of satellite-derived greenness data for monitoring seasonal vegetation development has added another dimension to improving grasshopper and locust surveys.

Over the past two years, the greenness maps have been very useful to each country involved in pest control efforts. The maps have been used to locate actual locust infestations in a timely and efficient manner, saving survey time and expense. However, further work is needed to evaluate the use of the greenness maps, specifically for control of the desert locust during plague years, a situation that has only recently arisen. Additional research into the incorporation of GIS technologies related to the overlay of soils, egg pod survey results, and historical information is also required.

ACKNOWLEDGEMENTS

This publication was authorized by the director, U.S. Geological Survey. The work was performed under the Sponsorship of USAID, PASA AFR-0510-P-IC-7022, and U.S. Geological Survey Contract 14-08-001-22521. Any use of tradenames or trademarks in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

REFERENCES

Boyd, J. E., 1987, Implementation of an AVHRR data acquisition and processing system at the EROS Data Center, U.S. Geological Survey, EROS Data Center, Sioux Falls, South Dakota.

Bryceson, K.,P., and D. E. Wright, 1986. An analysis of the 1984 locust plague in Australia using multitemporal Landsat multispectral data and a simulation model of locust development. *Agriculture, Ecosystems, and Environment,* no. 16, pp. 87-102.

Cavin, G., 1987. Senegal 1987 grasshopper/locust control program: field notes, (unpublished), 19 pp.

Deering, D. W. and R. H. Haas , 1980. Using Landsat digital data for estimating green biomass, NASA Technical Memorandum 80727, 21 pp.

FAO, 1987. The desert locust problem and potential for action in 1988-1992, W/S5042, 14 pp.

FEWS, 1987. 1986 grasshopper and locust infestations: FEWS special report, Report No. 1, Africa Bureau, USAID, 26 pp.

Goward, S. N., C. J. Tucker, and D. G. Dye, 1985. North American vegetation patterns observed with the NOAA-7 advanced very high resolution radiometer: *Vegetation*, no. 64, pp. 3-14.

Hielkema J. U., 1980. Development project on remote sensing applications for desert locust survey and control, FAO/USAID Technical Report, CGP/INT/349/USA, 63 pp.

Justice C. O., J. R. G. Townshend, B. N. Holben and C. J. Tucker, 1985. Analysis of the phenology of global vegetation using meteorological satellite data. *International Journal of Remote Sensing*, no. 6, pp. 1271-1318.

Launois M., 1979. An ecological model for the study of the grasshopper *Oedaleus Senegalensis* in West Africa. *Trans. R. Soc. London*, B 287, pp. 345-55.

Pedgley D. E., ed., 1981. *Desert Locust Forecasting Manual*, O.D.N.R.I., London.

Philips, F. N., 1987. Senegal 1987 grasshopper/locust control program: field notes June 6 to August 14, 1987, 28 pp Processed.

Prevost, Y., 1988. *Rapport Annuel d'Activités*, Centre de Suivi Ecologique, Dakar, Senegal, 44 pp.

Sellers, P. J., 1985. Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing*, no. 6, pp. 1335.

Schneider, S.,R., D. F. Mc Ginnis Jr, and G. Stephens, 1985. Monitoring Africa's Lake Chad basin with Landsat and NOAA satellite data. *International Journal of Remote Sensing*, no. 6, pp. 59-73.

Tucker, C. J., C. L. Vanpraet, M. J. Sharman, and G. Van Ittersum, 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980-1984. *Remote Sensing of Environment*, no. 17, p. 233.

REMOTE SENSING IN INDONESIA

J.P. Gastellu-Etchegorry

PRESENTATION

Indonesia, like many other countries, is trying to improve the monitoring and management of its development activities and numerous natural resources. However, its large area --where 13,677 islands stretch 5,152 kilometers from east to west and 1,770 kilometers from north to south with a total land area of 1,905,443 square kilometerss-- combined with the fact that many areas cannot be easily accessed, makes traditional resource inventories difficult, costly, and time consuming. These can no longer meet the present requirements for good resource management in agriculture, forestry, urbanization, etc. Moreover, today most information must be available in quasi real time. Accordingly, remote sensing technology, which provides an opportunity to fulfill these requirements, is becoming an essential tool for development activities.

Indonesia has already made large investments in aerial photographs, airborne radar and satellite data. There are facilities for receiving data from NOAA, GMS and Landsat satellites; SPOT receiving facilities will be installed soon. Having been started much earlier, the airborne system of remote sensing is already widely used, whereas the spaceborne system is now being developed toward operational use. Present conditions of this development are reviewed below with a discussion of organizations able to manage remote sensing activities, in technical limitations (equipment, local environment, etc.) the possibilities (cartography, land cover, etc.) of remote sensing technology in the Indonesian context, and the economic prospects of remote sensing in Indonesia.

INDONESIAN REMOTE SENSING INSTITUTIONS

Today there are three groups of Indonesian organizations that in one way or another call upon remote sensing data sources (Malingreau and Sutanto 1986): the remote sensing agencies at a national level, the research institutions and universities, and the government departments and operational agencies. The following is a tentative list of those organizations.

National remote sensing agencies

- *LAPAN*, the National Institute for Aeronautics and Space, Ministry of Research and Technology. It is involved mainly in aeronautical research and management of the Landsat and NOAA/GMS receiving stations (Pekayon, Jakarta). Remote sensing unit with 15 staff.
- *Bakosurtanal*, the Coordinating Agency for Surveys and Mapping, Ministry of Research and Technology (Cibinong-Bogor). It has a remote sensing staff of 20 and a digital analysis center equiped with a DIPIX system; digital cartography is developed.

Research institutions and universities

- *PUSPICS*, Remote Sensing Laboratory of Bakosurtanal and Gadjah Mada University, Yogyakarta. Important IBM digital analysis facilities. This is the main training and research center on remote sensing applications. Qualified staff of 19.
- *Gadjah Mada University*, Faculty of Geography, Yogyakarta. Its Department of geographic Techniques offers a program in remote sensing. It is responsible for remote sensing education at graduate and post-graduate levels. Qualified staff of 14.
- *Gadjah Mada University*, Research Center for Environmental Study (PPLH), and Faculties of Engineering and Forestry, Yogyakarta. Research on vegetation changes, hydrology, photogrammetry, soil mapping, etc. Qualified staff of 15.
- *IPB*, Agricultural University, Soil Science Department and Computer Center, Bogor. Applications to soil surveys; maintains an IBM digital analysis facilities with a qualified staff of 5.
- *University of Indonesia*, Department of Electronic Engineering. Remote sensing hardware development; qualified staff of 5.
- *LGPN*, Institute for Geophysics and Mineral Exploration, LIPI, Bandung. Carries out research on digital analysis for geological investigations, with a qualified staff of 5.
- *Padjajaran University*, Institute of Ecology, Bandung. Emphasis on Ecological studies (erosion, etc.) with a qualified staff of 5.
- *BIOTROP-SEAMEO*, International Center for Biological Studies, Bogor. Vegetation studies with remote sensing; qualified staff of 5; IBM digital processing facilities.
- *Geological directorate*, Bandung. Remote sensing applications in environmental geology, mineral exploration and volcanology; with a qualified staff of 5.

- *Soil Research Center*, Center for Agricultural Research, Bogor. Many photo-interpreters and up to 4 staff members trained in remote sensing analysis for resource surveys.

Department and government agencies

- *Ministry of Public Works*, Center for Digital Remote Sensing Analysis, Computer Center, Jakarta. Large remote sensing digital analysis system with a qualified staff of 15. Many photo interpreters. Concentrates on regional planning and is associated with many private consultants.
- *Ministry of Forestry*, Management Programme. In charge of nationwide forest inventories and monitoring. Many photo interpreters. Qualified staff of 5.
- *Central Bureau of Statistics*, Jakarta. Application of remote sensing for assisting in agricultural data collection. Qualified staff of 3.

Recently, the Indonesian government realized that past investments made in remote sensing training cannot keep up with the growing needs of the country. There are plans to improve this situation by establishing a strong and appropriate education and training programs. Some already exist in the Faculty of Geography of Gadjah Mada University in Yogyakarta. It is the only such faculty in Indonesia with high level education in remote sensing techniques. There are three programs on education and training:

- a short course on remote sensing, established in 1976, in a cooperative framework between Gadjah Mada University and Bakosurtanal. It is meant to train personnel from various government agencies (Transmigration, Public Works, Forestry, etc.); foreign trainees also are accepted. Since July 1983 the duration of the course has been 24 weeks and two courses are offered in one year; thirty places are offered at each course.
- a degree program (S1), it was established in 1977 by the Faculty of Geography and it is run by the Department of Remote Sensing. Its duration is four to five years.
- a master's program (S2), which runs from two to three years, it was established in the academic year 1983-84 with the help of the Faculties of Geography, Engineering, Mathematics and Forestry, and expatriate experts from United States, France and the Netherlands. Subjects include remote sensing technology and applications and research work.

Foreign aid contributed to the development of remote sensing in Indonesia: Deutch bilateral programs (NUFFIC, ITC), Ford Foundation, World Bank, French bilateral programs (DCSTD, ORSTOM), FAO, Japan pid program (JICA), US AID, Canadian aid program (CIDA/IDRC), Agricultural Development Council, etc.

CONSTRAINTS

Many constraints disturb the development of remote sensing activities in Indonesia. Most important are related to logistic (quick access to data, easy user access, etc.), equipment and the specificity of the Indonesian environment. For example, the Jakarta-Pekayon Landsat receiving station, opened in 1984 by LAPAN, still does not provide any catalog to users.

Equipment

Two complementary approaches are usually considered for satellite data exploitation: visual image interpretation and computer-based digital analysis. Now, photo interpretation of satellite images is the most common method used in Indonesia. Visual Landsat imagery has already proved useful for global surveys (Malingreau and Sutanto 1986). Generally speaking, major constraints are the poor quality of color photographic products and the unavailability of reliable mainframe computer equipment, except in some governmental agencies. This latter limitation prevents any widespread processing of digital data stored on computer-compatible magnetic tape (CCTs). Even in LAPAN, the manipulation of a few CCTs may sometimes be a laborious task, and in many institutions and agencies it is not rare to have mainframe computers down for long periods. Malfunctioning of DIPIX systems in PUSPICS and Bakosurtanal are notorious. Maintenance is a major constraint for centers equiped with mainframe computers.

Because micro-computers are common, easily maintained, and not very expensive, digital processing facilities based on micro-systems provide an interesting opportunity for decentralizing remote sensing activities. This is especially true for organizations that cannot afford to finance expensive equipment and its maintenance. Moreover, even in large bodies, the use of micro-computer-based systems should be recommended for tasks that do not require too large and/or sophisticated production. This is the strategy of IPB and BIOTROP in Bogor and Gadjah Mada University and Bakosurtanal for PUSPICS in Yogyakarta; i.e., the use of interactive micro-computer-based systems that combine Geographic Information System Capability and digital image analysis. This technology is simple but both locally operational and cost effective. It should have a great future in Indonesia. Basic but complete digital processing systems (i.e., IBM-compatible micro-computer, mathematical processor, matrix graphic board, 60 Mb hard disk, 1.2 Mb disk drive, 640 x 480 pixel high-precision monitor, color printer, 26 x 38 centimeters digitizing tablet) can be locally purchased with only $US 6,500.

Cloud cover

An objective assessment of the opportunities for use of remotelysensed data (visible and near-infrared range) requires the consideration of cloud cover. It is well known that cloud cover is the major constraint in Indonesia, but there was no quantitative information about its effect on data acquisition. Accordingly, a study was initiated (Gastellu-Etchegorry 1988) with the aid of theGeostationary Meteorological Satellite (GMS) and Landsat data. For all land areas, iterative interactive factoral analyses grouped GMS-derived pixels with similar cloud cover profiles into 18 classes (Figure 15-1). Statistics of Landsat and SPOT images, grouped by class, were used to quantify temporal profiles of probability for acquiring remotely sensed data with less than 10 percent, 20 percent and 30 percent of cloud cover for any Indonesian land area (Figure 15-2). Analysis of the spatio-temporal characteristics of local climatic conditions permitted one to explain these profiles and to verify the validity of their seasonal variations for long periods. These profiles were fitted with a seventh-order polynomial for use in computer simulation of predictive models of remotelysensed data acquisition.

Finally, Indonesian land areas have very distinct yearly probability profiles for data acquisition with relatively small interannual variabilities; e.g., Java, South Sumatra and Nusa Tenggara have a well-defined peak in December-January, whereas such a peak occurs in February-March in North Sumatra. These profiles constitute an easily and quickly readable product and are particularly useful in estimating the time necessary for surveying areas within a defined period of acquisition, in forecasting the feasibility of multidate-studies and in optimizing data acquisition. Moreover, they (Figure 15-2) indicate which surveys can be conducted with satellite data. For example, crop monitoring in Java and Nusa Tenggara can be operational with SPOT (acquisition rate up to 8 images of any Indonesian area per month), whereas it is usually impossible in Kalimantan and Irian Jaya. However, there, contrary to what is often supposed, surveys that do not require frequent data acquisition (geology, forestry, etc.) can be conducted with SPOT if it is financially and technically feasible to acquire a sufficiently large amount of images.

Atmosphere

Radiometric values of remotely sensed data depend on radiances of targets but also on additional effects that tend to confuse them. These are mainly due to absorption and scattering mechanisms of electromagnetic radiations by atmospheric components, i.e., gases and aerosol. They decrease the spectral transparency of the atmosphere and give rise to an atmospheric radiance. Consequently, a study (Gastellu-Etchegorry 1988) was initiated for quantifying atmospheric influence within satellite images of Indonesia. Results were derived from SPOT-XS data but can be easily generalized to other satellite systems that operate in the visible and near infrared part of the electromagnetic spectrum. Two major points were emphasized:

- compared to total measured radiances, atmospheric upwelling radiances were very important: 30 percent-80 percent in band XS1, 20 percent-70 percent in band XS2, and 15 percent-45 percent in band XS3. They are much larger for band XS1 (visible radiations) than for band XS3 (near infrared radiations), and to a lesser extent band XS2.
- atmospheric radiances were characterized by an important heterogeneity that was both spatial (up to 40 percent within a single image) and temporal.

Values of upwelling atmospheric radiances were used for obtaining atmospherically corrected spectral characteristics of landscape units. Because corrections that must be applied are spatiallydependant and because areas with constant atmospheric conditions cannot be delineated, it was impossible to define spectral characteristics that are constant over a single SPOT image.The implication is that identical features may have various radiometric responses, even within the same satellite image. This is an especially limiting factor for automatic classification of remotely sensed data in tropical countries.

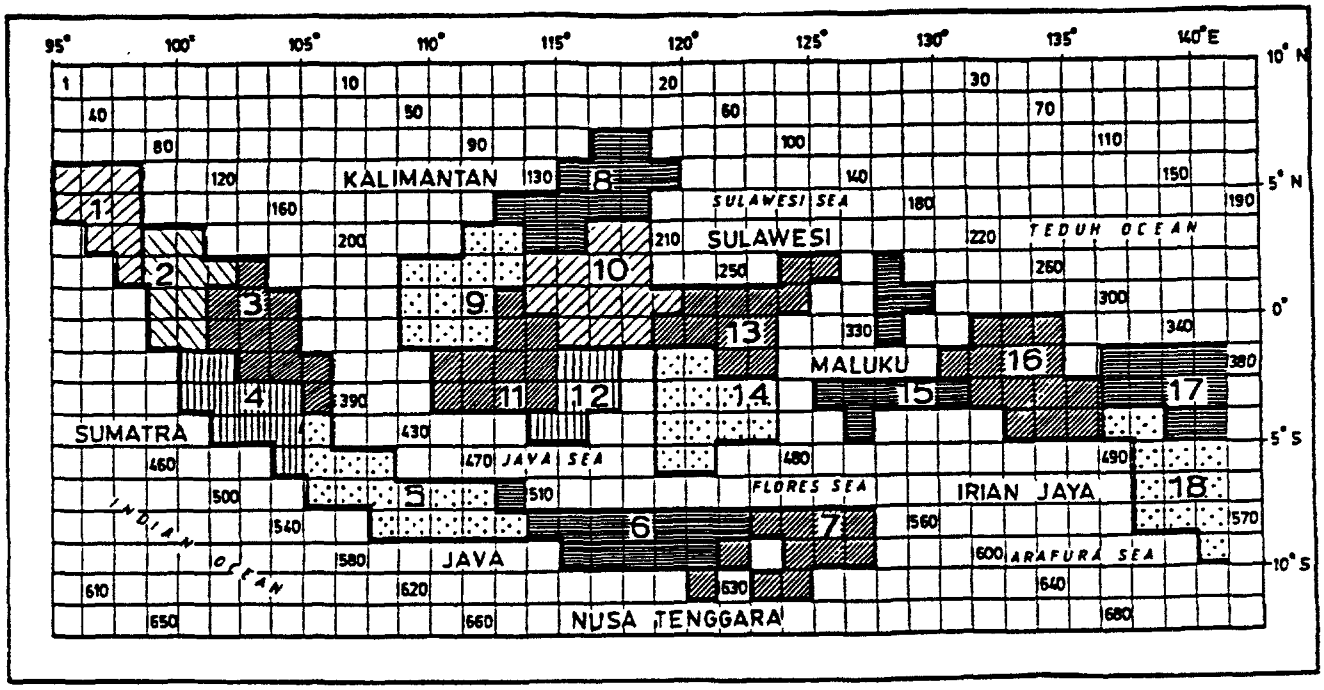


Figure 15-1. The 18 cloud-cover zones of the Indonesian archipelago

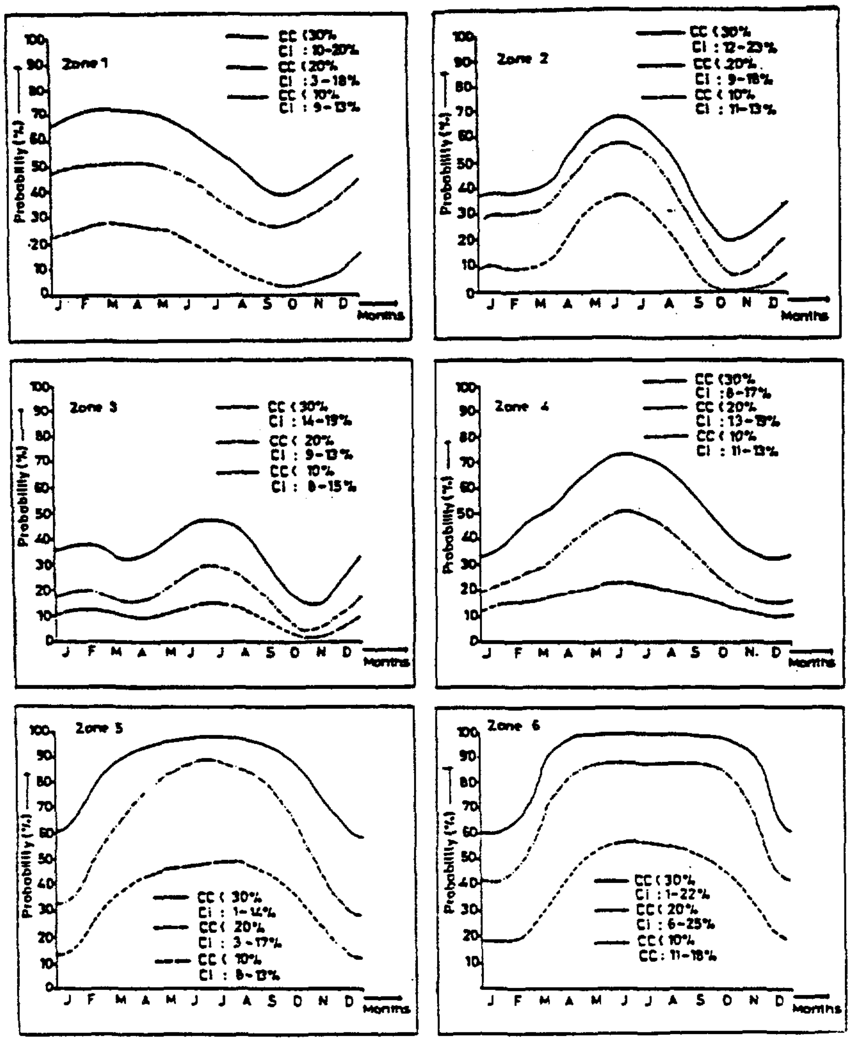


Figure 15-2. Probabilities for Acquiring Remotely Sensed Data of Zones 1 to 6 with cloud cover (CC) less than 10 percent 20 percent and 30 percent, if it is Possible to have 8 Acquisitions per Month (case of SPOT satellite. Ci represents the mean values of the confidence intervals).

Agro-forest systems

The small size, complexity, and dynamic nature of Indonesian agroforest systems create problems for inventorying and monitoring. Consequently, the author (1988) analyzed the SPOT and Landsat capability for spatial discrimination of land cover units by means of the percentage of pure pixels (*P* percent) per homogeneous land-cover unit and the proportion (*R* percent) of the dominant land cover unit per pixel. Parameter *R* percent should be about 100 percent if *P* percent is large. The larger *P* percent and *R* percent, the easier the discrimination and analysis of land-cover units, provided there is a certain contrast between targets of interest. Since pixels are very often "mixed," i.e., comprising several land-cover units, parameter *R* percent is of special importance. For example, narrow features such as roads and rivers, which are usually remotely sensed as mixed pixels, can be easily detected if the value of *R* percent is not too low; i.e., if there is a sufficiently large contrast with neighboring land-cover units. Table 15-1 stresses that for features with a "length/width" ratio equal to 4 ($R\% > 70\%$):

- Landsat-MSS (TM) data allow analysis of features larger than 5 hectares (0.56 hectare).
- SPOT-XS (P) data allow analysis of features larger than 0.16 hectare (0.04 hectare).

Because of the small size of most Indonesian land cover units (70 percent of rice fields have areas between 0.01 and 0.5 hectare with a 0.08 hectare average area; average area of dry fields is 0.2 hectare, usually between 0.01 and 1 hectare; etc.), only SPOT-P data, and SPOT-XS data to a lesser extent, appear to have a certain potential for spatial analysis such as resolving local units; i.e., whenever scales equal or larger than 1:50,000 are considered.

Three major points must be noted when fine spatial resolutions are used:

- Numerous land-cover units/subunits, such as bare soil and tree-cover patches within degraded forests, that are defined as subclass elements with coarse spatial resolutions, must be considered as spectral classes with spatial resolutions.
- Moreover, these spectral classes may correspond to subunits that are part of different landscape units; e.g., spectral class "bare soil" may be attributed to units "bare soil," "settlement," "degraded forest," etc.
- At last, land-cover units that correspond to spectral classes with coarse resolution sensors may not correspond to any spectral class with fine spatial resolution sensors. High local variance in an image is indicative of this situation.

Decreases in accuracy of classifications due to the introduction of fine spatial resolution sensors have already been observed for different environments (Latty and Hoffer 1980, Sadowski et al. 1979, Toll 1983).

Table 15-1. Mean *P* percent and *R* percent for Various Pixel and Field Sizes

Length (m)	Width (m)	Area (ha)	Landsat-MSS 80 m		Landsat-TM 30 m		SPOT-XS 20 m		SPOT-P 10 m	
			P%	R%	P%	R%	P%	R%	P%	R%
	450	20	62	91	84	97	89	98	95	99
450	225	10	45	87	76	95	84	97	92	98
	112	5	11	76	62	92	75	94	87	97
	56	2.5	0	61	32	85	54	90	76	95
	300	9	45	87	77	95	84	97	92	98
300	150	4.5	25	81	66	92	76	95	88	98
	75	2.3	0	69	45	88	62	92	84	96
	32	1.1	0	43	7	78	32	85	65	93
	150	2.3	13	74	57	90	70	93	84	97
150	75	1.1	0	63	40	86	56	90	76	95
	37	0.6	0	41	7	76	30	84	62	92
	19	0.3	0	20	0	57	0	70	32	85
	100	1	1	66	40	85	57	90	77	95
100	50	0.5	0	44	15	77	40	86	66	92
	25	0.3	0	24	0	65	7	76	45	88
	12	0.1	0	10	0	47	0	57	7	78
	80	0.6	0	56	31	81	50	88	72	94
80	40	0.3	0	37	10	73	28	82	60	91
	20	0.2	0	16	0	57	0	70	35	85
	10	0.1	0	9	0	30	0	47	0	72
	60	0.36	0	43	15	75	35	84	63	91
60	30	0.18	0	25	0	65	11	76	47	88
	15	0.09	0	12	0	44	0	61	15	80
	7.5	0.05	0	6	0	21	0	35	0	64
	40	0.16	0	25	2	67	15	75	50	88
40	20	0.08	0	12	0	52	0	65	28	82
	10	0.04	0	6	0	28	0	44	0	70
	5	0.02	0	3	0	13	0	21	0	47
	30	0.09	0	16	0	56	5	70	35	84
30	15	0.05	0	8	0	37	0	55	11	76
	7.5	0.02	0	4	0	16	0	32	0	61
	3.8	0.01	0	2	0	9	0	15	0	35
	20	0.04	0	5	0	40	0	56	15	75
20	10	0.02	0	1	0	21	0	37	0	65
	5	0.01	0	0	0	10	0	16	0	44
	2.5	0.05	0	0	0	5	0	9	0	21
	15	0.02	0	2	0	25	0	43	5	69
15	7.5	0.01	0	0	0	12	0	28	0	55
	3.8	0.006	0	0	0	6	0	12	0	32
	1.9	0.003	0	0	0	3	0	6	0	15

Consequently, accuracy of computer-aided mapping combined with conventional spectral classifiers depends on the combination of two opposing factors that-vary as a function of the local environment (Markham and Townshend, 1981; Toll and Kennard 1984):

- The finer the spatial resolution, the larger the number of pure and predominantly pure pixels, and the better the accuracy of classifications,
- The finer the spatial resolution, the larger the number of detectable subclass elements. This implies wider within-class spectral variance of classes associated with land-cover units, which decreases spectral separability and results in less accurate classifications.

Accordingly, the implicit assumption of low local variance of conventional spectral classifiers, which is verified for Landsat-MSS in most environments, becomes less valid with the fine spatial resolution of SPOT and Landsat-TM. Classifications are improved only for environments where the decrease of the number of mixed pixels outweighs the increase of within-class variances. New algorithms of classification must be developed. It must be noted that spectral classifiers well adapted to environments such as the wide agricultural systems of the Great Plains may not be valid for small Indonesian systems.

In short, the difficulties for having constant spectral characteristics over a single SPOT image and also for determining pure pixels of local landscape units are especially limiting factors for computer-assisted mapping in Indonesia. Two types of methodologies partly solve this problem (Gastellu-Etchegorry and Ducros-Gambart):

- automatic, computer-aided mapping by considering textural and contextual information. At this time such methodologies are being developed but are not yet readily operational,
- semiautomatic mapping with inputs from the operator (pattern recognition, etc.) and computer (geometric correction, image enhancement, etc.). Its implantation on locally available micro-computer-based systems is a major advantage of this technique.

LOCAL OPERATIONAL ACHIEVEMENTS

All studies that are briefly presented were achieved at PUSPICS (Gastellu-Etchegorry 1988), Yogyakarta, with readily available micro-computer-based systems and supplies. They were intended for testing the operational use of satellite data in a center without large computer facilities. The SPOT system was particularly considered because it now appears to be the best adapted satellite system for many applications in Indonesia.

Cartographic aspects

One requirement of satellite data for use in monitoring small agroforest ecosystem management operations such as those in Central Java is that remotely sensed data can be precisely registered with sources of local data. With this requirement in mind, a study was conducted to provide a basic assessment of SPOT cartographic accuracy, compared to local cartographic documents; i.e., 1:50,000 Transverse Mercator (TM) topographic maps.

Simple bilinear transformation of level-1B SPOT data led to imagery with standard deviation accuracy better than two pixels: 1.77 and 1.34 pixels for longitudinal and latitudinal directions, respectively. Moreover, in a first approximation, SPOT imagery could be considered as the result of a rotation, enlargement, and linear shift of local TM maps. Thus, if only photographic products are used, as is often the case in Indonesia, adequate rotation and enlargement of readily available SPOT films permit a direct overlay on local TM maps, with a standard deviation accuracy about three pixels for (60 x 60 kilometers) areas. Better cartographic accuracies are obtained when smaller areas are considered.

Altitude differences within the SPOT scene tested were less than 1,000 m, and it may be that the geometric accuracy of SPOT data will be worse for areas with larger altitude differences. On the other hand, this accuracy should be improved with SPOT data that are acquired with nadir viewing conditions, instead of a 17° angle of incidence, as in the present study.

SPOT was tested as an operational data source for up-dating the 1:50,000-TM map of a 20 x 20 kilometers area in Central Java. This map was 50 years old, without any revision in 20 years. During this period a major change occurred, with the creation of a reservoir eight years ago. Analysis of a SPOT image, conveniently enlarged, allowed rapid transfer onto tracing paper of lake boundaries, irrigation channels, roads, and villages. Small plots within mixed gardens could not be distinguished, whereas units comprising juxtaposed plots with similar ground-cover conditions could be delineated. Basic knowledge of the area provided the distinction between roads and irrigation channels. Simple superimposing of newly delineated features on TM maps provided an immediate up-dating with a geometric accuracy of about two pixels. Slightly better accuracy (better than 1.5 pixels) was obtained by digitally correcting SPOT data; apart from a better accuracy, a major advantage of this method is the provision of digitized maps. Map updating was achieved within seven days.with photo interpretation and geometric corrections.

Undoubtedly more accurate map updating can be obtained with more sophisticated methods; cartographic agencies (Denis 1987) have already found that for areas with moderate relief, SPOT average planimetric accuracy is 6 meters (0.6 pixel), whereas topographic accuracy is 3.5 and 7 meters with base height ratios of 1 and 0.5, respectively. However, that type of mapping is much more complex, expensive, and time consuming, and consequently less locally operational than that achieved at PUSPICS. This is of special importance in Indonesia where most base maps are very old and outdated.

Land cover mapping

The capability of SPOT was investigated for land cover and land use mapping in Indonesia. Apart from the previously mentioned atmospheric constraint a major point was noted, especially for computer-aided approaches: when fine spatial resolutions are used it may be impossible to consider broad land-cover units as classes. Consequently, hierarchical land cover legend systems must be developed independently of land use in order to exploit the full power of fine-resolution satellite data. This problem does not really arise with Landsat-MSS data because these have relatively low local variances for most environments (Woodcock and Strahler 1987).

SPOT data were tested on several study areas in Java for deriving 1:50,000 land-cover mapping. Both previously mentioned semiautomatic and layered, textural/contextual automatic approaches were considered. It was found that the level of categorization (Anderson et al. 1976) of land-cover and land use features with SPOT depends largely on the characteristics of these and of surrounding features. Second and third levels were obtained in this study. With the aid of field checking, an average 90 percent accuracy was found for SPOT-derived land-cover maps. This mapping was undoubtedly cheaper than with aerial photographs; this is clearly confirmed by Bakosurtanal, which considers that in Indonesia surveys with aerial photographs are at least 40 times more expensive than surveys with SPOT. This suggests that in Indonesia SPOT has the potential of a major data source for deriving land-cover mapping down to 1:50,000/100,000 scales.

Agricultural-suburban interface

The growth of urban areas is generally poorly monitored in Indonesia. Indeed, this rate is very fast, and numerous constraints prevent the use of aerial surveys with sufficient repeat frequency for up-to-date urban planning. For many areas, even in Java, the most recent aerial photographs may be ten years old. Moreover, once they are available, some tedious and detailed tasks must be performed to for derive cartographic documents. Accordingly, a study was initiated for testing the potential of SPOT and Landsat-MSS for surveying agricultural-suburban interfaces around Yogyakarta, central Java.

Because no detailed vegetation discrimination was required, 1:50,000 black-and-white prints of level 1B-SPOT-P data proved to be particularly useful for providing accurate mapping of settlement-agricultural interfaces. They are undoubtedly more valuable than SPOT-XS data even if digitally processed, due to the small size of local land-cover units. Mapping with SPOT was faster (ratio 1 to 5), cheaper (ratio 1 to 40 if aerial survey must be conducted), more convenient, and led to better cartographic documents than visual interpretation without stereo-plotting of 1:30,000-NIR aerial photographs (1987). Results derived from aerial photographs and SPOT appeared to be consistent. Only consistent overall acreages could be derived from Landsat-MSS data. Land-cover maps derived from photointerpretation of aerial photographs of 1965, 1981, and 1987, and Landsat data of 1983 and SPOT data of 1986 clearly showed that between 1965 and 1987 land use around Yogyakarta was very much modified (Table 15-2). The acreage of urban/suburban areas nearly doubled, whereas the acreage of agricultural lands decreased significantly.

Table 15-2 : Percentage of Settlement (Villages and Mixed Gardens), Urban Areas, Cultivated Areas and Others (Roads, Range Land) within a Study Area (400 square kilometers) around Yogyakarta. (percent)

Year	Settlements	City	Cultivated areas	Other
Photo, 1965	26	6	62	6
Photo, 1981	40	9	46	5
Landsat, 1983	43	9	42	6
SPOT-XS, 1986	43	12	38	7
Photo, 1987	45	11	37	7

Forestry

Forests are Indonesia's most valuable potentially renewable resource and the most important non-oil export commodity. Slightly less than two-thirds of the land area is forested totaling between 800,000 and 1,200,000 square kilometers depending on definition and estimates.Today, concern is increasing that this resource is being depleted rapidly rather than being managed for sustainable long-term benefit. Present deforestation is mainly due to forest logging and shifting cultivation. Moreover, access improved by logging roads encourages shifting cultivation. Consequences of forest degradation and/or destruction are often catastrophic for the environment: i.e., soil erosion, floods, and the like.

Consequently, forest management is of special importance for Indonesia. This activity requires repetitive surveys that cannot be routinely achieved with the conventional means of field checking and/or aerial surveys. In this context, remote sensing has the potential of a major data source for forest monitoring. Accordingly, a study (Laumonier et al. 1987) was initiated for assessing SPOT's capability to handle specific problems related to vegetation identification and monitoring.

Basic photointerpretation and digital processing techniques emphasized the usefulness of SPOT data for the appraisal of tropical vegetation at medium scale. This was particularly striking for the swampy vegetation types including mangroves, and for the secondary vegetation. It appeared that 20 meters ground resolution of SPOT-XS is still not sufficient to provide information on primary forest patterns, or to identify properly slightly logged areas. Nevertheless, several degrees of depletion of the forest and serial growth stages were identified. This undoubtely shows considerable progress when compared with previous remote sensing systems. In short, results of this study suggest that for tropical vegetation mapping at medium scale, SPOT is undoubtely a very good alternative to aerial photographs at 1:100,000 and 1:50,000 scale. Moreover, SPOT data partly solve past difficulties for extrapolation between the general data provided by Landsat-MSS and the detailed information of large-scale aerial photographs.

Soils and geology

The geology and soils of central Java were mapped (1:50,000/100,000) with SPOT (Gastellu-Etchegorry et al. 1988). The main power of SPOT proved to lie in high spatial resolution, combined with stereocapability. Spectral analysis is of lesser importance, since geological units are seldom sufficiently exposed, especially in a country like Indonesia. Nevertheless, it should not be completely neglected because there frequently exists a significant correlation between rock type and the spectral signature of the overlying cover type, since land use and soil development is often controlled by geological factors.

SPOT data compared well to black-and-white infrared aerial photographs (1969; 1:50,000) They proved to be more convenient, reliable, and efficient than aerial photographs for deriving small- and medium-scale geologic and soil map. Moreover, SPOT-derived map were achieved much faster. However, when SPOT stereospairs were not available, small structural features could not be observed. The opportunity to derive and correct medium-scale geologic and soil maps is very valuable in a country like Indonesia where the geology and soils of many areas are still poorly mapped or not mapped at all.

Finally, it was shown that SPOT-XS and SPOT-P data can come close to taking the place of 1:100,000 and 1:50,000 aerial NIR photography, respectively. This is especially interesting when one considers the added advantages of being able to analyze digitally data for special problems and applications, including quantifying components of land use, determining the area occupied by each such components and developing numerical discriminations to support and strengthen visual interpretations. It must be noted that whenever smaller-scale information is required, other satellite systems should be considered.

ECONOMIC ANALYSIS AND PERSPECTIVES

The following is extracted from an economic investigation that was conducted by SCOT CONSEIL (1988) at BPPT's request (Ministry of Research and Technology). Its main purpose was to appraise and possibly to quantify the potential impact of SPOT in Indonesia. It was not an easy task to quantify the economic interest of remote sensing technology because it is used in operations embracing two distinct economic approaches :

- the market economy, that aims at realizing short-terms benefits,
- the public sector, whose criteria are not exclusively economic, and can also cover protection, prospecting, management, and development areas, etc.

Moreover, the importance of remote sensing technology can be assessed in terms of :

- Direct increase in value: assessing direct increase in value comes down to putting a figure on the cost differences (man/month, logistics, machine time) between projects using remote sensing technology and projects that have been carried out using traditional methods.

- Indirect increase in value: the indirect increase in value corresponds to the saving derived from the realization of a project and its indirect effects. Such is the case of decisionmaking whose accuracy is due to the synoptic vision one can get from using remote sensing (road mapping, etc). In addition, one can rapidly have the results of a study available (for example, agricultural statistics) and/or improve the results of a program. In this connection, a study made by the Economic Bureau of the Asian Development Bank has shown that the use of remote sensing has allowed a reduction ranging from 20 to 42 percent in the total number of unproductive drilling operations (water investigation); this consequently led to a 32 percent reduction in the cost of a productive drilling operation.

It is also worth comparing the cost of remote sensing data acquisition to the costs of feasability studies and of project performance: financing development and planning projects happens to be much higher than the cost of remotelysensed data. The following table, from the American company Booz-Allen & Hamilton (1987), is presented

Table 15-3. Remote Sensing Data Acquisition Compared with Project Costs (percentage)

	Total cost of project	Cost of study using R.S.	Cost of R.S. as % of the study	Cost of R.S. as % of project
AGRICULTURE	100	10-30	2-3	0.2-0.6
FORESTRY	100	20-30	2-3	0.4-0.9
LAND USE	100	10-15	3-5	0.3-0.75
WATER RESOURCES	100	5-40	5-7	0.25-2.80
ENGINEERING	100	3-5	3-7	0.09-035
CARTOGRAPHY	100	100	3-10	3-10
ENVIRONMENT	100	30-80	3-10	0.9-8
EXPLORATION	100	5-15	1-2	0.15-1.40

The assessment of the potential market for remote sensing in Indonesia was achieved through the analysis of major development projects -- in progress or planned,-- likely to use remote sensing. Information was retrieved from international bodies (World Bank, Asian Development Bank, FAO, EC, etc.) and the list of development projects whose census was made by the Ministry of Development (BAPPENAS). These projects were analyzed during meetings with a number of Indonesian ministries and bodies. General tendancies, such as a strong demand for cartographic products were emphasized. Moreover, as a result of food self-sufficiency, the drop in oil prices, and environmental problems (erosion, etc.), the government has begun to favor transmigration projects and developed cash crops. In the near future, there might be a further evolution in the market because the Ministry of Finance intends to levy a tax on cultivated areas (inventory problems), and because the Ministry of Agriculture aims at intensifying agricultural resources. The Ministry of Environment plans to put into practice new rules about space utilization. In addition, there are important projects of road mapping and mineral exploration.

Consequently, projects that will have to be carried out in the near future and for which remote sensing technology can be useful or even necessary, were analyzed in terms of the number of SPOT images required per year. This number was determined either directly by considering the size of the respective study areas of the projects, and/or indirectly, by combining the type and cost of the projects with usual percentages for acquiring remotely sensed data. The following table presents the potential demand in the Indonesian public sector, expressed in number of images per year and field of application.

Table 15-4. Potential Demand in the Public Sector for Remote Sensing Data

	Total number of images per year	Number of images per year for projects already financed
Mapping	765	350
Geology	135	20
Planning	160	10
Urban study	30	5
Regional development	230	60
Forest	630	455
Irrigation	175	90
Agriculture	125	105
Total per year	2,250	1,095

As seen in this table, there is evidence to suggest that the potential market for SPOT imagery in Indonesia is between 2,000 and 2,500 images a year, with no distinction made among various types of images (multispectral, panchromatic, stereoscopic, digital or film). It should be stated that this demand is likely to increase in the years to come.

As a matter of fact, some of the projects considered will not necessarily be carried out, and others will not necessarily lead to remote sensing operations. On the contrary, other projects --which have not been taken into account in this study-- might imply the acquisition of satellite images. Moreover, some projects could be carried out with Landsat-MSS or TM data instead of SPOT data, especially those for small- and medium-scale geologic investigations. However, due to the small size of local land-cover units and their better cartographic accuracy, these latter should be preferred for most applications.

In the assessment of the potential market, only the public market was taken into account. In fact, the private sector has begun to have an important role in operational remote sensing activities. For example, some private companies won international invitations to tender proposals for projects financed by the World Bank and ADB.

A major concern was expressed by the private sector: it considers that it is a prerequisite to be authorized by the authorities to use remote sensing products. The private companies will not generally take the risk of introducing remote sensing technology into operations whose reference terms do not explicitly refer to this method. There is, consequently, a need to raise consciousness about the economic potential of SPOT imagery among banks and administrations that will benefit from invitations to tender, and even INKINDO, a body embracing the consultants that intervene in Indonesia. In this connection, the Indonesian Ministry of Research and Technology, through BPPT, recently appeared as an influential leader for developing remote sensing activities in Indonesia.

DISCUSSIONS

After a brief description of major Indonesian organizations dealing with remote sensing applications and training, the most important constraints concerning local exploitation of satellite data have been reviewed:

- Data diffusion: i.e., the necessity of user services in the receiving stations,
- Equipment: essentially equipment availability and maintenance. In this respect micro-computer-based systems are particularly efficient for centers that cannot afford the implantation and maintenance of large computer facilities.
- Cloud cover: in some regions applications that require frequent data acquisition cannot be conducted with visible and near infrared satellite systems; in these cases other systems, such as radar, should be considered.
- Atmospheric influence: it is particularly limiting for fully automatic, computer-based mapping.
- Small size and complexity of local land cover units: Consequently, satellite systems that are used should have a comparatively small spatial resolution. In this respect, SPOT is presently the best satellite system, especially when it is intended to resolve local land use units.

Locally processed satellite data clearly showed the technical potential of remote sensing as a major and operational data source for many applications in Indonesia. The economic potential was also clearly demonstrated.

Finally, it must be noted that being aware of the potential of this technique for its development activities, the Indonesian government recently decided to go ahead by establishing sound remote sensing education, as well as by establishing convenient satellite receiving and processing facilities.

REFERENCES

Anderson, J.,R., E. E. Hardy, J. T. Roach and R. E. Witmer, 1976. A land use and land cover classification system for use with remote sensor data, U.S.Geological Survey Professional, pp. 28.

Booz Allen & Hamilton Inc., 1987. *Report*, Paris Nov. 1987.

Denis, P., 1987. *Metric applications of SPOT's lateral stereoscopy, in SPOT Symposium*, Paris, pp. 1267.

Denis, J., A. Grotte, J. Populus, E. Dutrieux, 1987. Application of SPOT imagery for oil spill contigency planning, *Proceeding of Symposium SPOT 1, Image Utilization, Assessment, Results*, Paris, Nov. 1987, pp. 1069-78.

Gastellu-Etchegorry, J. P., 1988. Cloud cover distribution in Indonesia, *International Journal of Remote Sensing*, No 7, pp. 1267-76

Gastellu-Etchegorry, J. P., 1988. Predictive models for remotely-sensed data acquisition in Indonesia, *International Journal of Remote Sensing*, Vol. 9, No 7, pp. 1277-94.

Gastellu-Etchegorry, J. P., 1988. *Remote Sensing with SPOT - An Assessment of SPOT Capability in Indonesia.* Yogyakarta: Gama Press.

Gastellu-Etchegorry, J. P., A. Husson, J. P. Antikidis, 1988. *A SPOT/LANDSAT Receiving Station in Indonesia, an Economical Investigation of SPOT's Use and Receiving Station Configuration*, SCOT CONSEIL report.

Gastellu-Etchegorry, J. P., D. Ducros-Gambart. Computer Assisted Land Cover Mapping with SPOT in Indonesia, *International Journal of Remote Sensing*, ed. accepted.

Latty, R. S. and R. M Hoffer, 1980. Computer-based classifications accuracy due to the spatial resolution using per-point versus per field classification techniques, in *Machine Processing of Remotely Sensed Data Symposium*, West Lafayette, IN.

Laumonier, Y., U. R. Djailany , J. P. Gastellu-Etchegorry and R. Barkey, 1987. Assessment of SPOT satellite based system in humid tropical vegetation identification, classification and monitoring, in *Proceeding of Symposium SPOT Image Utilization, Assessment, Results*; Paris, Nov. 1987, pp. 613-22.

Malingreau, J.,P. and Sutanto, 1986. Remote sensing in Indonesia. *ITC Journal*, No 3, pp. 206-16.

Markham, B.,L. and J. R. G. Townshend, 1981. Land cover classification accuracy as a function of sensor spatial resolution, *Proceeding of the 15th International Symposium on Remote Sensing of Environment*, Ann Arbor, pp. 1075-90.

Sadowski, F. G., J. E. Malila, J. E. Sarno.and R. F. Nalepka, 1979. The influence of multispectral scanner spatial resolution on forest feature classification, in Proceeding of the 11th International Symposium Remote Sensing of Environment, Ann Arbor, MI, pp. 1279-88.

Toll, D. L., 1983. Preliminary study of information extraction of Landsat TM data for a suburban/region test site, in *Proc. of the Landsat-4 Science Characterization Early Results Symposium*, Goddard Space Flight Center, Greenbelt, MD, pp. 387-402.

Toll, D. L. and R. E. Kennard, 1984. Investigation of SPOT spectral and spatial characteristics for discriminating land use and land cover in Prince George's County, Maryland, in *Proceeding of SPOT Symposium*, pp. 165-170.

Woodcock, C. E., A. H. Strahler and T. L. Logan, 1987. Stratification of forest vegetation for timber inventory using Landsat and collateral data, *Proceeding of 14th International Symposium on Remote Sensing of Environment,* San Jose, Costa Rica, pp. 1769-87.

EARLY WARNING ON AGRICULTURAL PRODUCTION WITH SATELLITE DATA AND SIMULATION MODELS IN ZAMBIA

M. Menenti, J. Huygen, S. Azzali and J. A. A. Berkhout

INTRODUCTION

The concept of food security in the broadest sense, can be defined as an integrated plan to provide for sufficient food the whole population in both the short and the long run, and to ensure that equal attention is paid to sustainable domestic production, consumption, processing, distribution and food reserves. The food security concept thus provides a concise and consistent framework of the food and agricultural sector, with sufficient concern for environmental degradation, the consumption pattern and the nutritional status of the public at large. For the government to be able to make well-founded decisions with respect to food security issues, it must be provided with relevant information on which to base decisions.

In the short run, food security can only be achieved if an adequately functioning, so-called early warning system is in place, especially in drought-prone areas. Because actual crop production can only be estimated at the end of the harvest, governments should know well in advance the expected supply of food grains and other crops in order to take remedial and timely measures.

Under the denomination early warning rather different activities are grouped together that share a conceptually similar approach toward operational, real-time, crop yield forecasting. For example, data on land use, crop yield, and marketable products are collected, along with meteorological observations. With these data, forecasts on crop yield are obtained for well-defined administrative regions. Although the development of such a system is rather complex, the basic factors for constructing it --namely the acquisition, processing, storing, and analysis data-- are of primary importance.

In the early warning practices, the acquisition of data appears to be one of the major bottlenecks. To meet the information requirements of these crop monitoring systems, the application of information systems using remote sensing is regarded as an effective solution. However, the regular use of remotely sensed information, especially in regard to a tropical country such as Zambia, requires an assessment of both the information source itself and the users.

The MARS project is an application-development project linking newly available tools (e.g., Geographical Information System, Data Base Management System) and methodology (i.e., crop growth simulation models) with the routine functioning of a national early warning system.

The primary objective of the MARS project is to establish a link between the data provided by meteorological satellites and the operational requirements of crop yield forecasting and monitoring at the national level. The linkages to be provided by MARS involve the use of remote sensing technology through METEOSAT; Landsat-TM or SPOT; crop growth simulation models; and weather, soil, and crop information.

In the following sections earling warning activities in Africa are briefly described to illustrate the role of the MARS project within the entire system. Afterwards the organization of the early warning system in Zambia is reviewed in detail to describe the specific contributions of satellite data and of the MARS project to early warning on agriculture in Zambia. (The meaning of all acronyms is explained in a 'List of Acronyms' at the end of this paper.)

AN OVERVIEW OF FAO REMOTE SENSING AND EARLY WARNING ACTIVITIES IN AFRICA

The early warning activities of FAO can be classified at different levels (see also Berkhout et al. 1988):

- **Global** Global Information and early warning system (GIEWS) on food and agriculture;
  Support agricultural production (SAPRO), which is based on real-time data produced by the Africa Real Time Environment
  Monitoring using imaging satellites (ARTEMIS) system;

- **Regional** Regional early warning system for food in the SADCC countries;
  Remote sensing component of the early warning systems in eastern and southern Africa; SADCC and IGADD countries;

- **National** Crop forecasting and early warning unit (CFEWU) in Zambia;
  Early Warning Unit in Tanzania;
  National Early Warning Units in the other seven SADCC countries (under development).

This network may appear as a rather well structured system. A closer look at the details, however, reveals that the interlinking between these functional units is far from satisfactory. In Figure 16-1 the organization of this early warning network is presented.

Figure 16-1. Early Warning Network in Africa (present situation). Each functional unit is specified for: input data (1), area covered (2), geographical reference unit (3) and output data (4). N.A. = not available. (For acronyms see List of acronyms.)

From this information, two conclusions may be drawn.

- The well-defined input data requirements of the regional and national early warning systems, especially as regards crop-specific information, cannot be met by the output data of the remote sensing systems.
- No effort has been made to warrant the compatibility of the geographical reference units with the different functional units.

Given these conclusions, the operationalization of these systems and their application to the regional and national level is bound to fall short of the stated objectives, as the link between these levels is not provided.

THE PLACE OF MARS IN THE AFRICAN EARLY WARNING NETWORK

The African early warning network, as it stands now, lacks two functional links:

- an interface between the geographical reference units at the global and regional level and the units of the national level;
- an interface between the crop-specific input data required at the national level and the undifferentiated output data provided at the global and regional levels.

The MARS project is intended to provide such links. In Figure 16-2 the organizational scheme of the African early warning network is again presented, but now includes the MARS functional unit. The additional support to be given to the CFEWU in Zambia lies in the integration of the present derived data sets provided by the participating departments of the CFEWU and the forthcoming remote sensing information sources (e.g., ARTEMIS). The qualitative improvement provided for the regional and global levels lies in the production of MARS output data in a form compatible with the scale of these early warning activities and with the configuration of the systems generating the early warning information at the regional and global levels.

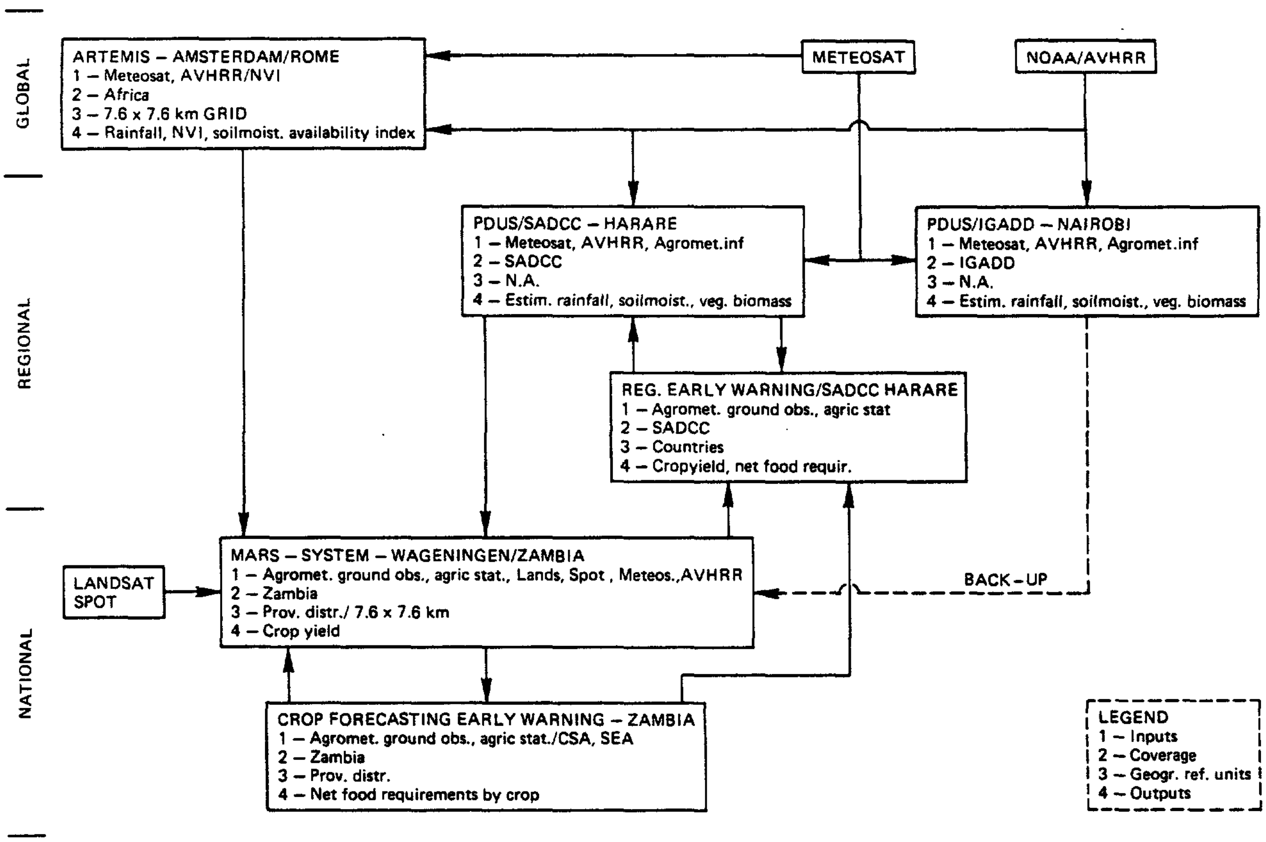


Figure 16-2. ***Proposed Early Warning Network in Africa. Each functional unit is specified for: input data (1), area covered (2), geographical reference unit (3) and output data (4). N.A. = not available. (For acronyms see List of acronyms.)***

THE CROP FORECASTING AND EARLY WARNING UNIT IN ZAMBIA

Zambia's agricultural production, and in particular its food grain production, mainly maize, has fluctuated considerably over the past period, to a large extent due to adverse weather conditions during the growing season. A rapidly growing population and a stagnating development of agriculture have caused Zambia to become a net importer of food grains. In order to strengthen the country's food security, a project has been developed to build a comprehensive crop forecasting and early warning unit (CFEWU). Within this system various ministries and departments would work closely together to monitor the food situation in the country.

Objective and organization

The objective of the CFEWU project is to strengthen national food security through the institutionalization and development of a data and information base related to agricultural development in general, and food production, supply, and distribution in particular.

The national preparedness plan (NPP) provides for continuous monitoring of the food availability throughout the country by strengthening the CFEWU through the publication of a *Monthly Crop and Food Situation Report*. The most important aspect of the NPP is that the responsibilities and lines of communication are clearly established for all individual functions in the departments involved in the government's food security policy for indentifying and coping with food/input emergencies/shortages at the national, provincial and district level.

The NPP does not replace existing procedures for meeting the normal food needs of the population, but rather complements them by providing advance warning of impending shortages.The NPP thus forms an integral part of the government's food security policy.

The CFEWU is a unit composed of staff of the following departments:

- Planning Division (MAWD),
- Central Statistical Office (CSO),
- Department of Meteorology (DOM).

To date, the CFEWU has emphasized training of local staff and the development of data gathering, processing, and analysis techniques. Each one of the three departments has developed its own method and technique of obtaining crop production forecasts. The final official estimates are set as a result of meetings held by the National Committee on Early Warning (NCEW), when the three independent estimates are compared and discussed (Figure 16-3).

Activities

The early warning activities of the three departments are summarized.(see Figure 16-3).

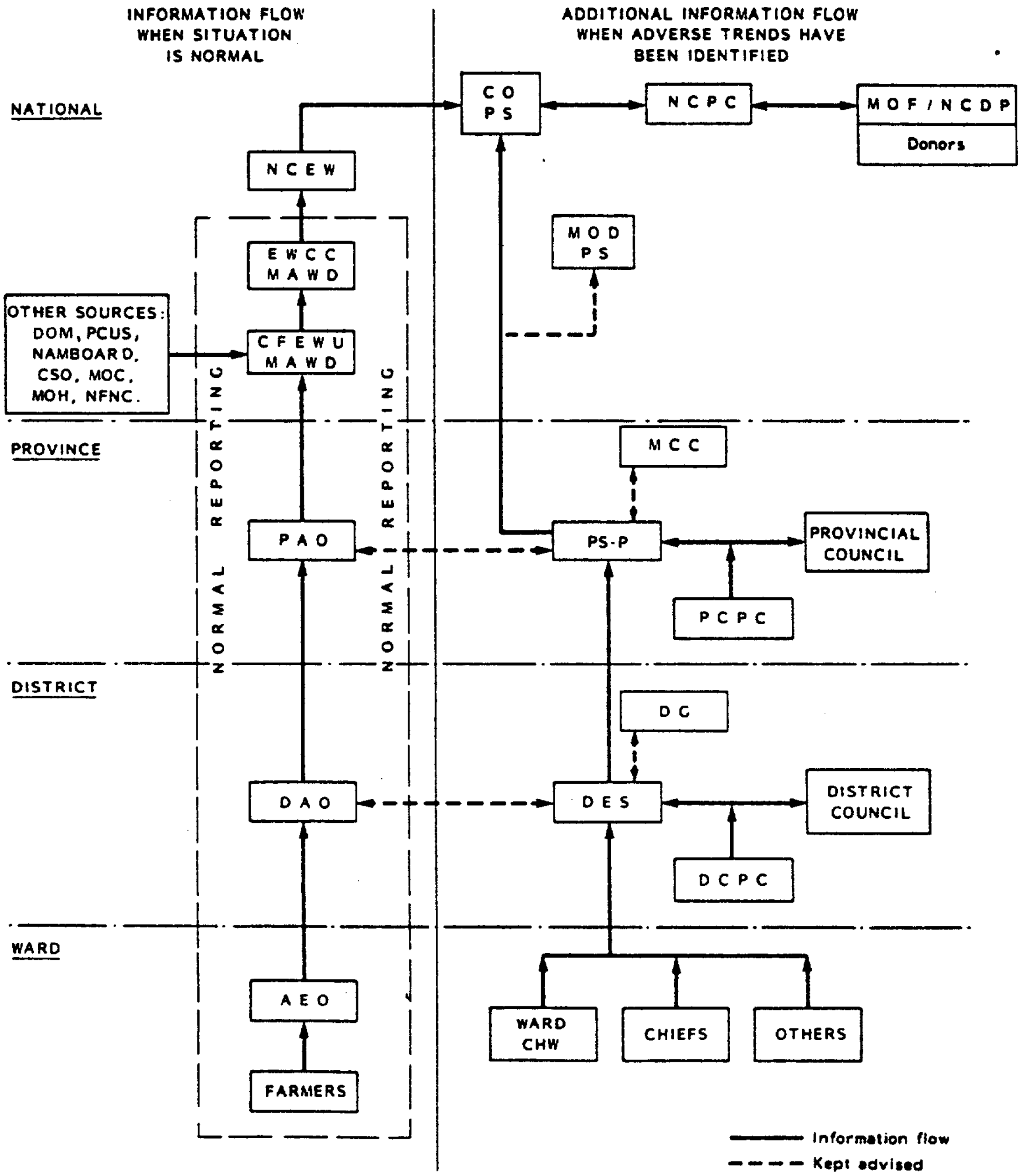


Figure 16-3. Organizational Chart Illustrating the Information Flows as Prescribed by the National Preparedness Plan (NPP) of the Government of Zambia. (For acronyms see List of acronyms.)

Planning Division (MAWD)

Cropped area, crop conditions, and yields are estimated by agricultural extension officers (AEO); there is one such officer for each camp (comprising one or more villages). A cluster of camps, about two to six, are aggregated into a block. Activities within a block are supported by a block supervisor. The agricultural extension officer (AEO) transmits data to the district agricultural officer (DAO), who in turn sends the aggregated figures to the provincial agricultural officer (PAO). The provincial figures are reviewed during provincial meetings with the participation of a statistical officer of MAWD, Lusaka. The basic data are collected by extension officers. These estimates apply to poorly defined geographical units, as the boundaries of villages are variable and difficult to identify and, therefore, difficult to replicate.

Central Statistical Office (CSO)

Data on cropped areas, yield, and marketable surplus are collected by direct interviews with farmers at three different periods: two in the growing season and one in the postharvest period. Data are collected on a sample basis by complete enumeration within the selected standard enumeration area (SEA). A number of SEAs are aggregated into a census supervisory area (CSA). Typically 20 percent of CSAs are selected, with one SEA for each CSA. The boundaries of CSAs and SEAs correspond to physical features and have been mapped at 1: 250,000 (CSA) and 1: 50,000 (SEA) for the entire country. Data are extrapolated to district and CSA level by applying so-called boosting factors, obtained as the ratio of the number of households in a district or CSA, respectively, to the number in a SEA. Yield figures per unit area are obtained by the ratio of estimated production to area (bags/hectare).

Department of Meteorology (DOM)

Meteorological data (rainfall, temperature, sunshine) are collected in a quasi-real-time mode from some 30 stations in Zambia. Some 160 rainfall stations transmit 10-day total rainfall figures and, in principle, also phenological observations by mail. Upon examination of the data of the 1984-85 and the 1985-86 growing seasons, it appeared that only a small fraction of stations transmit satisfactory phenological reports. Indicative crop yield reductions are estimated by calculating the Frère-Popov water requirements satisfaction index (WRSI). Although the density of stations is considered to be insufficient, the data collection is thought to be sufficiently reliable.

The right-hand side of the organization chart in Figure 16-3 gives an overview of the procedure to be followed in case of emergencies.

The merging procedure

Nationwide forecasts of crop production and marketable surplus are obtained twice a year (February and April) by selecting the most reasonable figures out of the three sets submitted to the NCEW (MAWD, CSO, meteorology). Such a method can lead to serious misjudgment, as exemplified by the outcome of the 1985-86 agricultural season. The final 1985-86 forecast for maize was 8.5 million bags (=765,000 tons) of marketable produce against a requirement of 10 million bags (= 900,000 tons). The expected shortfall of 135,000 tons had to be imported. The actual postharvest figure for the marketable produce was later determined to be 1,080,000 tons. The resulting surplus of 315,000 tons proved to be a serious challenge to the maize storage capacity in Zambia.

THE ROLE OF MARS IN THE CROP FORECASTING AND EARLY WARNING UNIT IN ZAMBIA

The currently applied procedure of the CFEWU, as described earlier, requires merging of the information generated by the Planning Division (MAWD), Central Statistical Office (CSO), and the Department of Meteorology (DOM). Because of the different statistical methods and survey approaches applied, problems may occur with respect to:

- the estimation of the hectarage of crops grown in Zambia, and
- the estimation of the actual crop yield per hectare, especially with reference to the crop yield reduction due to unfavorable weather conditions.

The procedures proposed by the MARS project are expected to improve the currently applied procedure with respect to:

- the estimation of the actual hectarage of the total cultivable area and the total planted areas under specific crops, making use of high resolution remote sensing images, and
- the assessment of yields of the important crops in the distinguished agroecological zones in Zambia.

Difficulties due to the low density of agrometeorological stations will partly be solved with the introduction of the low resolution Remote Sensing procedures and the implementation of a crop-specific simulation model. The low resolution satellite data will improve rainfall estimation and the determination of the start of the growing season. The simulation model will take into account the actual weather conditions, the physiological aspects, etc.

THE MARS DATA STRUCTURE AND GEOGRAPHICAL REFERENCE SYSTEM

MARS aims at the establishment of a linkage between the data provided by meteorological satellites, Meteosat and NOAA, and the operational requirements of crop yield forecasting and monitoring at the national level. The operational ARTEMIS system at FAO HQ is an integrated system that is capable of real-time acquisition of Meteosat data and processing the imagery from Meteosat and NOAA satellites. The ARTEMIS system gives the following main data products:

- the composite normalized difference vegetation Index (NDVI) map (per decade and month);
- the estimated rainfall map (per decade and month);
- the number of estimated rainfall days map (per decade and month).

An outline of the MARS system is given in Figure 16-4. The system will improve the real-time information on the crop-specific production per major agroecological zone in Zambia. This will be achieved by the implementation of the MARS-Agro-Ecological Geographical Information System (MARS-AEGIS) within the framework of the Zambian Crop Forecasting and Early Warning Unit (CFEWU).

The MARS hardware and software configuration has to accommodate the Zambian CFEWU procedures, such as the current data acquisition on the crop yields and cropping areas and the reporting (items 6 and 7). However, the MARS methodology makes use of additional information, comprising:

- *Already existing information, like that available at the agricultural research institutions, such as:*thematical information, e.g. a soil map, physiographical map, land-use and vegetation map and topographical maps (item 1); and location/site-specific information on weather, soils, and crops (item 2).

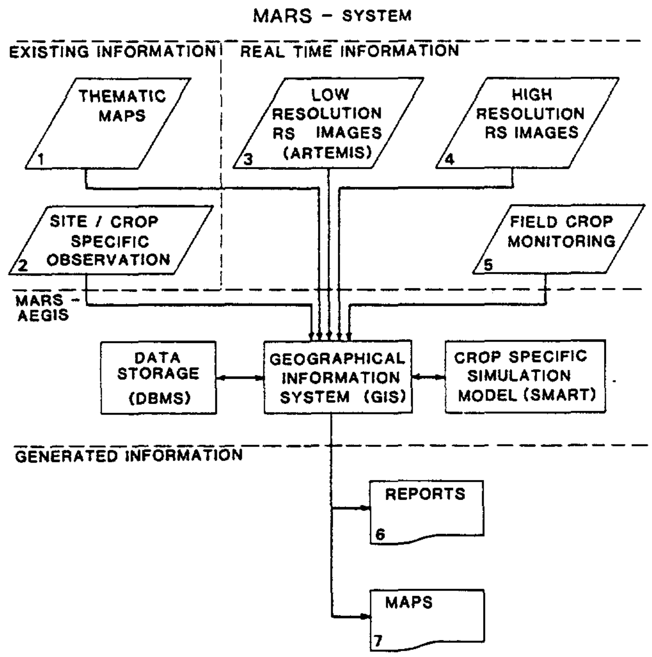


Figure 16-4. Information Flow as foreseen by the MARS-Agro-Ecological Geographical Information System (MARS-AEGIS)

- *Real-time acquired data using remote sensing, subdivided in:* low resolution remote sensing images obtained from the meteorological satellites and available via the forthcoming ARTEMIS system at FAO HQ (item 3); high resolution remote sensing images (Landsat TM, SPOT) (item 4); and field observations on crop conditions (item 5).

SPECIFIC CONTRIBUTIONS OF SATELLITE DATA TO THE ACTIVITIES OF THE CFEWU

To illustrate in detail the contribution of satellite data to the tasks assigned to the CFEWU, two references will be considered:

- the procedure (as described in the preceding pages) to work out the provisional and definitive forecasts;
- the guidelines on the information to be supplied by the Government of Zambia, when requiring emergency assistance, to the international donor community.

Procedure

Satellite data can contribute directly to three specific steps of the operational procedures applied by the CFEWU:

- Meetings at the provincial level to formulate provisional and definitive forecasts (MAWD);
- Mapping of 10-day and monthly rainfall to calculate the crop water requirements satisfaction index (DOM);
- Calculation of the boosting factors, as required to extrapolate the data collected by CSO in the sample areas (CSA, SEA).

Forecasts of food availability

The objective of these provincial meetings is that all parties represented have to agree on a forecast of food availability for each province. Each agency works out preliminary forecasts on the basis of its own approach to assess crop yield and crop conditions. In practice, results are compared in terms of relative variations against actual production in the previous year. An early, objective indicator of crop conditions within a province would be very useful to work out the preliminary and final forecast. Such an indicator can be calculated with a time series of NDVI 10-day composite as shown in Figure 16-5.

It appears that no clear-cut difference is noticed in the simple time series of mean NDVI values (Figure 16-5a). By calculating the sum of NDVI decrements (Figure 16-5b), and subsequently plotting the sum of decrements versus time (y-axis in Figure 16-5b), a clearer relationship is established between observed NDVI values and crop yield or productivity.

Estimations of the slope of the lines in Figure 16-5b can be applied as early indicators of final crop yield and, as such, improve the forecasts of CFEWU.

Crop water requirements satisfaction index

To calculate the crop water requirements satisfaction index, the DOM applies rainfall data collected daily at 24 stations. Such a network is rather sparse, so the detail of rainfall mapping can be improved, in principle, by means of satellite data. Rainfall estimations can be obtained by relating the so-called Cold Cloud Duration (Milford and Dugdal 1984) to observed rainfall. The relationships established by means of linear regression analysis are subsequently applied to map rainfall.

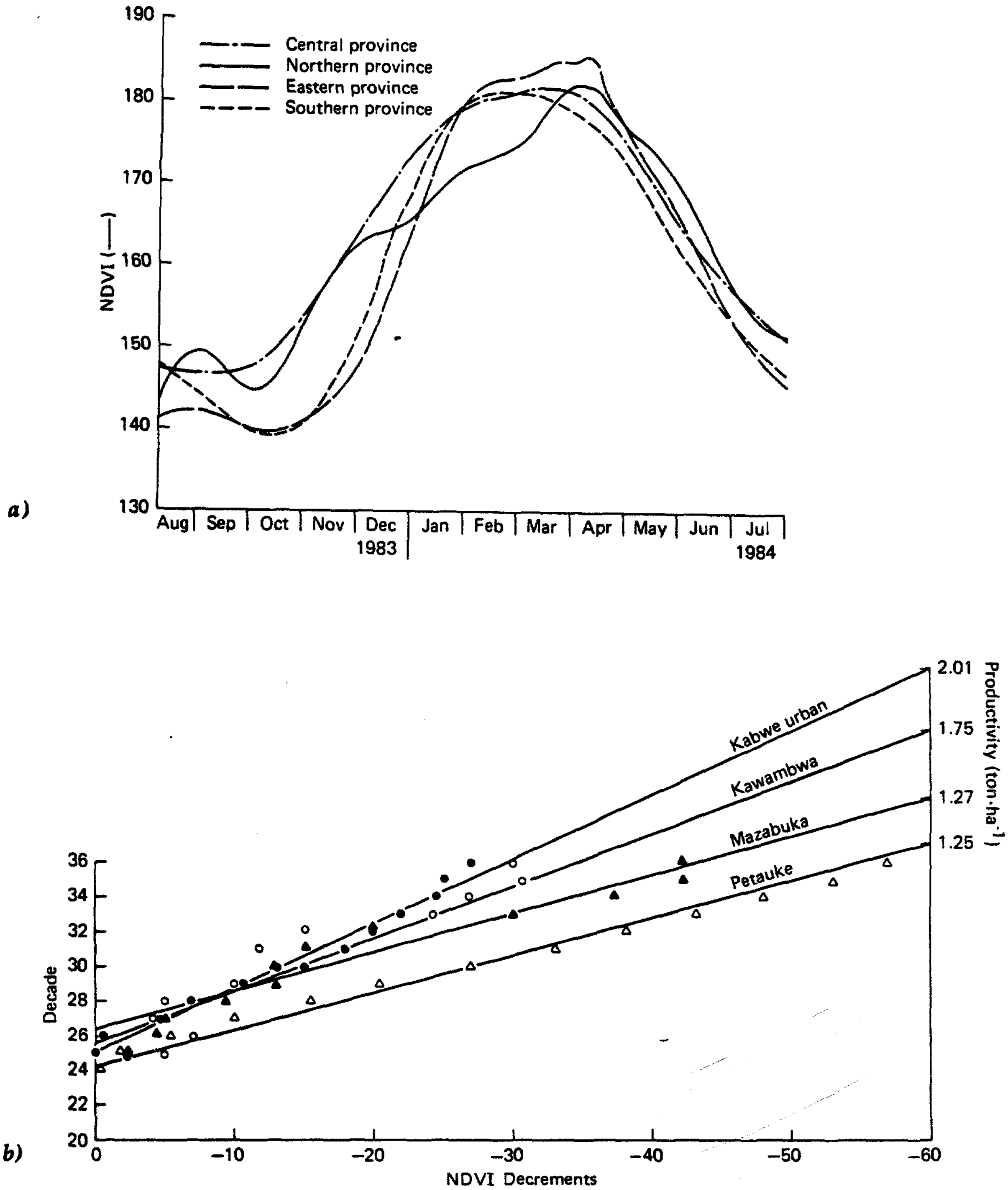


Figure 16-5. a) Time Series of Mean NDVI Values of Northern, Southern, Eastern, and Central Provinces (Zambia) ; Cropping Season 1983-84

b) Cumulative Decrements of AVHRR-NDVI Values of Selected Subareas located Respectively in Kawambwa, Kabwe urban, Petauke and Mazabuka Districts (Zambia) ; Cropping Season 1983-84

The method is basically empirical and the coefficients of the regression equation are variable in space and time.

Besides the linear regression method just described, rainfall can be mapped by:

- kriging the ground-based rainfall observations;
- co-kriging the METEOSAT-TIR data, applied to calculate the CCD-values, and rainfall observations.

To assess the performance of the three rainfall estimation methods, the relationship between the measured rainfall and the estimated rainfall for the 24 meteostations has been established. Preferably this relation should have a slope of 1 and an intercept of 0. In Table 16-1 the calculated relations are shown. As one can see, they are all deviating a bit from the ideal shape: all three methods overestimate the lower rainfall quantities somewhat, while the higher quantities are underestimated.

Table 16-1. Relation between Measured and Estimated Rainfall Quantities for Three Alternative Methods: Linear Regression, Kriging and Co-kriging.

Method	RAINest	Standard deviation (% of mean RAINmeas)	Correlation coefficient
Linear regression	4.18 + 0.91 * RAINmeas	27.5	0.95
Kriging	7.76 + 0.80 * RAINmeas	36.1	0.90
Co-kriging	6.27 + 0.81 * RAINmeas	35.2	0.91

Note: RAINest = estimated rainfall (mm), RAINmeas = measured rainfall (mm)

There is not much difference between the methods. The best results are obtained with a simple linear regression. Kriging and co-kriging give practically the same results and are lagging somewhat behind. It is amazing that kriging, which uses only raingauge measurements, performs so well. It is reassuring to have such a powerful method for situations when METEOSAT images are not available. From a scientific point of view, co-kriging is a more elegant method than simple regression and it possibly can do better than it has shown here. The 24 meteostations must be considered an absolute minimum to construct a usable semi-variogram and cross-variogram.

For situations where the raingauge network is not dense, as in Zambia, the linear regression method is preferred. Contrariwise, when a denser meteostation network exists, a fair chance should be given to co-kriging. If, for some reason, METEOSAT images are not available, not all is lost; kriging is a worthy alternative under such circumstances.

Boosting factors

The CSO collects yearly agricultural statistics by means of an area sampling frame. The data collected in the segments (SEA) by means of interviews are extrapolated to the levels of districts and provinces by applying so-called boosting factors, obtained as the ratio of the number of households, e.g., in a district, to the number of households in an SEA.

These boosting factors can also be obtained as the ratio of agricultural area in for example, a district, to agricultural area in a SEA. The results obtained by Berkhout et al. (1988) indicate that the same accuracy can be achieved by applying TM data to map agricultural land and, subsequently, to calculate the boosting factors. The advantage of using satellite data is that much less land has to be surveyed to collect ground truth data, (less than 1 percent of total land area) than to collect agricultural statistics by means of field observations only (about 20 percent).

Guidelines

A detailed list of the items (19) to be covered by the information supplied by the Government of Zambia to support a request for emergency assistance is given in the NPP. Two of these items, namely nr.2 "Area affected by emergency" and nr.7 "Estimated deficit" could be based, at least partly, on the results obtained with satellite measurements, like the early indicators of final crop production described under "Forecasts food availability".

APPRAISAL

An accurate cost-benefit analysis of the contribution of satellite data to early warning activities is a difficult proposition, since it would require data on the expenditures on food with and without a remote sensing component of a national early warning system.

It is, however, possible to compare the accuracy of current forecasts of final agricultural production with the approximate cost of a remote sensing component. In Table 16-2 the amount and value of maize imported by Zambia in recent years are given. It has been mentioned that in 1985 the CFEWU of Zambia did forecast a shortage of 135,000 tons, while the actual marketable produce was 180,000 tons more than required. We can therefore take the deviation of actual from forecast, i.e., 315,000 tons, as a measure of the accuracy of the forecasts. This amount of produce had in 1985 an estimated value of US$ 44.1 10^6.

Table 16-2. Amount and Estimated Monetary Value of Maize Imported by Zambia for Three Years

Maize import	1984	1985	1986
Amount (tons)	143,70	130,00	65,00
Estimated value (US$ 10^6)	22.4	18.4	9.2

Source : FAO 1986.

The total cost of data acquisition and analysis is, as regards the meteorological satellites, a negligible fraction of this figure. It should, therefore, be concluded that even marginal improvements in the accuracy of forecasts, as a result of the use of the early indicators obtained with NDVI data or of rainfall estimations with METEOSAT data, will always be cost-effective.

As regards the use of high resolution earth observation satellite data, a more qualified assessment is mandatory. First of all, the total cost of data acquisition and analysis depends on how dispersed is agricultural land. This quality depends on climate variability within a country, as shown by means of Figures 16-6 and 16-7. It clearly appears that the cost-effectiveness of earth observation satellite data decreases rapidly as regards both Zambia and Somalia. Due to the more dispersed agricultural land use in Zambia, a much larger number of satellite images is necessary to cover the same percentage of agricultural land. It should also be noted that even by taking the most expensive alternative indicated in Figure 16-6, i.e., the use of SPOT-XS data, and by estimating the cost of data analysis as being comparable to the cost of data, the total expenditure would be US$ 1.8 10^6 for land use mapping (mono-temporal analysis). This implies that the break-even point would be achieved with a 5 percent improvement in the accuracy mentioned above.

It might, therefore, be concluded that the issue is not the cost-effectiveness of satellite data to improve early warning on agriculture, but to establish a direct, monetary linkage between improvements in accuracy and expenditures on food imports and food emergency aid.

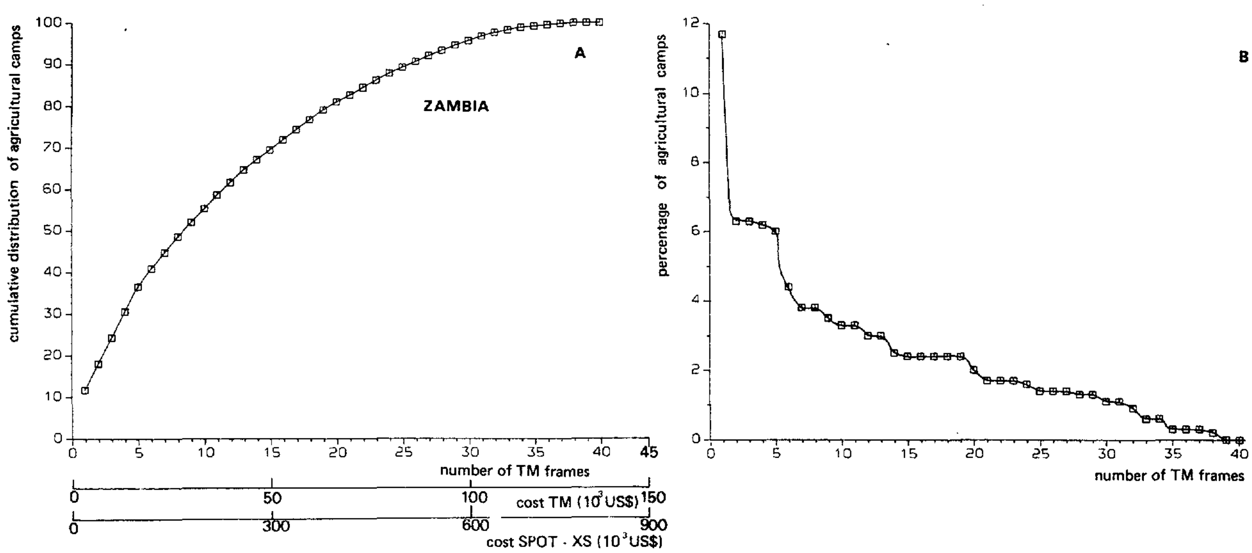


Figure 16-6. a) Cumulative Distribution of Agricultural Camps, taken as a Measure of Agricultural Area, versus the Number of TM frames Required to Map Land use and Total Expenditure for TM , and SPOT-XS Data for Zambia.
b) As a), But Percentage of Agricultural Camp.

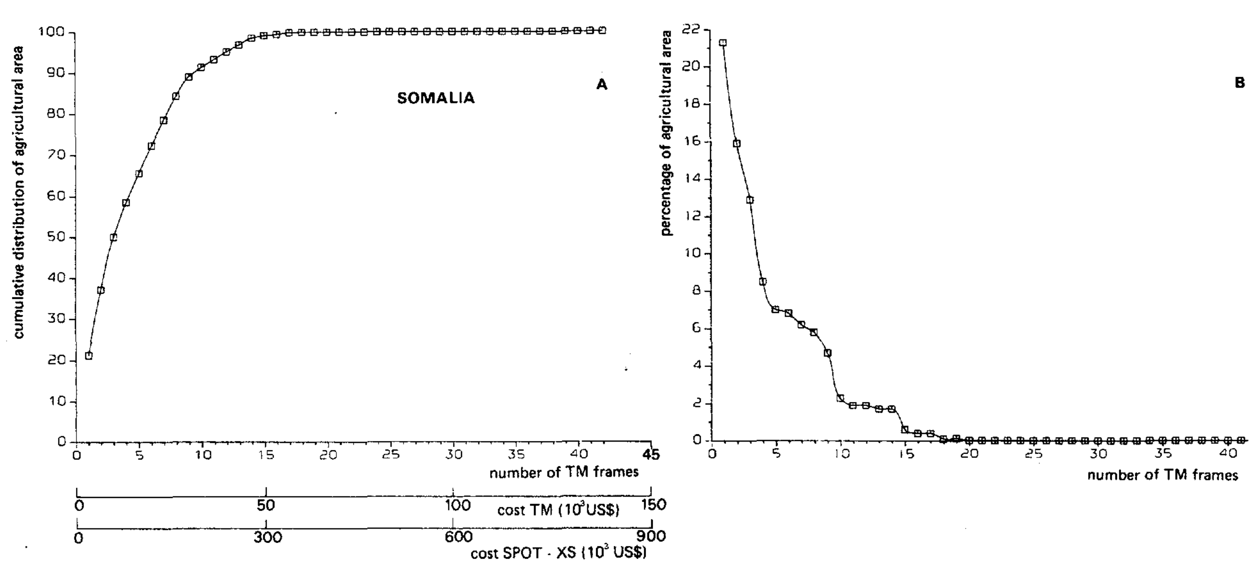


Figure 16-7. Cumulative Distribution of Agricultural Camps, taken as a Measure of Agricultural Area, versus the Number of TM frames Required to Map Land use and Total Expenditure for TM, and SPOT-XS Data for Somalia.

REFERENCES

Berkhout, J. A. A., J. Huygen, S. Azzali and M. Menenti, 1988. MARS. *Definition Study. Results of the Preparatory Phase*. Report 17 (special issue). Wageningen, The Netherlands: Institute for Land and Water Management Research (ICW), 111 pp.+ 6 color plates.

FAO, 1986. *Trade Yearbook*. Vol. 40. Rome: FAO, 151 pp.

Milford, J. R. and G. Dugdale, 1984. Short-period forecasts in West-Africa using METEOSAT-data, in: Nowcasting II: *Mesoscale observations and very short-range weather forecasting. Proceeding 2nd International Symposium on Now-casting,* Norrkoping (Sweden), 3-7 September 1984. ESA Sp-208, Noordwijk, The Netherlands: pp. 255-59.

LIST OF ACRONYMS

AEO	Agricultural Extension Officer
ARTEMIS	African Real-Time Environmental Monitoring using Imaging Satellites
AVHRR	NOAA Advanced Very-High Resolution Radiometer
CCD	Cold Cloud Duration Method, University of Reading, United Kingdom,.
CFEWU	Crop Forecasting and Early Warning Unit, Lusaka, Zambia
CHW	Community Health Worker
CO	Cabinet Office
CSA	Census Supervisory Area, Zambia
CSO	Central Statistics Office
DAO	District Agricultural Officer
DBMS	Data Base Management System
DCPC	District Contingency Planning Committee
DES	District Executive Secretary
DG	District Council
DOM	Department of Meteorology
EWCC	Early Warning Coordination Committee
FAO	Food and Agricultural Organization of the United Nations, Rome, Italy
FAO-HQ	FAO Headquarters, Rome, Italy
FEWS	Food and Early Warning System
GIEWS	Global Information and Early Warning System on Food and Agriculture
GIS	Geographical Information System
GRID	Global Resource Information Data Base
IGADD	Intergovernmental Authority on Drought and Development (Rwanda, Burundi, Uganda, Kenya, Ethiopia, Somalia, Djibouti, Sudan)
LANDSAT-TM	Landsat Thematic Mapper
MARS	Monitoring Agroecological Resources using Remote Sensing and Simulation
MARS-AEGIS	MARS Agro-Ecological Geographical Information System
MAWD	Ministry of Agriculture and Water Development
MCC	Member of the Central Committee
METEOSAT	Meteorological Satellite
M-MOD	Minister - Ministry of Decentralization
MOC	Ministry of Cooperatives
MOD	Ministry of Decentralization

MOF	Ministry of Finance
MOH	Ministry of Health
NAMBOARD	National Agricultural Marketing Board
NCDP	National Commission for Development Planning
NCEW	National Committee on Early Warning
NCPC	National Contingency Planning Committee
NDVI	Normalized Difference Vegetation Index
NFNC	National Food and Nutrition Commission
NOAA	National Oceanic and Atmospheric Administration, United States
NPP	National Preparedness Plan
NVI	Normalized Vegetation Index
PAO	Provincial Agricultural Officer
PCPC	Provincial Contingency Planning Committee
PCUS	Secretary of Provincial Cooperative Union
PDUS	METEOSAT Primary Data User Station
PS-CO	Permanent Secretary - Cabinet Office
PS-P	Permanent Secretary- Province
SADCC	Southern African Development Coordination Conference (Angola, Botswana, Lesotho, Malawi, Mozambique, Swaziland, Tanzania, Zambia, Zimbabwe)
SAPRO	Establishment of an Operational Satellite Remote Sensing System to Support Agricultural Production and Desert Locust Monitoring and Forecasting
SEA	Standard Enumeration Area, CSO, Zambia
SMART	Simulation Model using ARTEMIS Real Time Information and Environmental Specifications (MARS crop growth model)
SPOT	Trademark of SPOT Image, France
SPOT-XS	SPOT Multi-Spectral Scanner
TIR	METEOSAT Thermal Infrared Band
WRSI	Water Requirements Satisfaction Index

INSTITUTIONAL ASPECTS OF REMOTE SENSING AND ENVIRONMENTAL DATA MANAGEMENT ISSUES AND RECOMMENDATIONS

F. Falloux

INTRODUCTION

The key questions

This volume on satellite remote sensing in agricultural projects is a good opportunity for Bank staff to keep abreast with the development of a very promising technology. I am particulary impressed by the wide range of actual and potential uses of such technology in agriculture, as well as in other sectors of economic activities.

Having said that, when I consider our member countries, particulary in Africa, I see the huge gap between the extremely poor situation of existing agricultural and environmental data systems in those countries and the potential offered by modern technologies like remote sensing. To make an analogy, many of our clients are like supertankers without a panel, i.e., without the indicators to know where they are going: data are unreliable, outdated, or just nonexistent. We, the project officers of this institution, in many instances are condemned to perilous acrobatics to reconcile inconsistent statistics. In some cases, important decisions are made on a very fragile data base.

How can we improve this situation? How can we help countries develop data system(s) that meet the priority demand while remaining affordable? What sort of institutional framework is required for the management of these data systems? Do we have institutional recipe(s), or at least a few orientations? How can we make sure that the proposed institutional framework would develop data systems that would meet the priority needs of the resource users and planners? How can we ensure training? Do they need technical assistance? How can we convince them about the necessity of reliable data systems? Who is going to finance institutions involved, not only initial investment but also recurrent costs?

At the risk of disappointing this audience, I do not think that technologies are at the heart of the problem. Without denying their importance, particulary the importance for Bank task managers not to make mistakes in advising our clients in technologies, I do believe that the above-described situation is due first to a people's problem (setting priorities, institutions, organization and management, funding). I must say, however, that the recent development and the increasing cost-effectiveness of modern technologies in remote sensing and environmental data systems today makes these systems more affordable to most of our clients, whereas yesterday they were not.

Objectives

This paper thus focuses on people, their needs in terms of basic data and the institutions to meet these needs. The paper is divided in two sections: in the first one, I present the case of Madagascar, the past and current situation with regard to remote sensing and environmental data systems and the expected future in the context of an Environment Project that is being prepared. Why have I selected Madagascar? Mainly for four reasons:

- This is a country with high international visibility and priority because of its uniqueness in terms of biodiversity.
- Environmental degradation is extremely high, placing this patrimony of biodiversity, as well as the whole economy, at risk.
- Government, with donor support, intends to reverse the degradation trend. For this purpose, an Environment Action Plan has been prepared and, within this framework, a program to improve natural resource data systems, including remote sensing, has been conceived.
- Madagascar, although usually included in the Africa region, is a sort of transitional country with Asian conditions. Hence the Malagasy case may have some relevance for non-African countries as well.

Scope

In this paper, remote sensing is taken in its broadest definition; i.e., it includes all aerial and satellite information. Furthermore, institutional aspects are not limited to information collection, but includes processing and integration into a data base up to the finished products for the users; they also refer to its multiple use in terms of mapping and geographic information in general. Despite my previous work in Latin America and Asia, and despite the fact that Madagascar may be regarded as a transition between Africa and Asia, I may have an African bias in this paper in the sense that I pay more attention to the situation and needs of the poorest of our clients.

This paper draws heavily from a regional study undertaken by my division and published as *Land Information and Remote Sensing for Renewable Resource Management in Sub-Saharan Africa* (World Bank Technical Paper 108).

THE MADAGASCAR CASE

Historical perspective

In the 1960s, Madagascar was regarded as one of the best-equipped countries in terms of remote sensing, mapping, and natural resource data in the African context. Briefly, Madagascar was covered by a good geodetic nework. The total country (close to 600,000 square kilometers) was covered by recent base maps at 1/100,000 scale; about 20 percent of the territory (the areas of dense population and economic activities) as covered with base maps at scale 1/50,000; furthermore, urban areas and large irrigation schemes were covered by large-scale maps as well. The coverage of geology, hydrology, hydrogeology, and soil maps was fairly advanced. It is worth noting that about 2 million hectares of prime agricultural land and urban areas were covered with cadastral maps at 1:2,000 and 1:1,000 scale.

All the mapping and information processing was done in Madagascar with the support of two French institutions, the Institut Geographique National (ING) and the Office de Recherche Scientifique et Technique d'Outre Mer (ORSTOM).

The current situation and issues

Since the 1960s, the remote sensing and environmental data situation of Madagascar has dramatically deteriorated. One could almost say that no progress has been made; even worse, some data collected in the 1960s have been lost. To make understanding easier, the institutional framework of Madagascar regarding remote sensing, mapping, and natural resource data is briefly described below.

- FTM is the geodetic, mapping, and remote sensing agency (theoretical monopoly on these activities). It is a public agency under the Ministry of Public Works. Its total staff numbers 140, of whom 15 are professionals. Its total annual operationg budget (excluding maintenance) is US$0.7 million, of which less than 10 percent comes from the national budget, the other 90 percent coming from the direct revenue of its printshop activities, the main bulk of which (official journal, books, public bulletins) is marginally related to mapping. FTM's investment budget is only US$30,000, grossly insufficient to maintain its own equipment. FTM, in its aerial surveys, suffers from the absence of a well-equipped aerophotogrammetric aircraft in Madagascar, which lowers the photo quality.

- La Direction du Patrimoine (DP) is the cadastral agency as well as the custodian of the private domain of the state. It is a Department of the Ministry of Economy and Finance. Its total staff includes 1,150 permanent employees, of which 325 are professionals. DP has a topographic and mapping division for large-scale mapping that includes 19 professionals. As in the FTM's case, the DP's budget does not enable it to progress significantly on cadastral surveys. In fact, the deterioration of the current cadastral records outstrips the creation of new ones (about 10,000 hectare a year).
- The Ministry of Applied Research (MRSTD) is theoretically in charge of natural resource data (geology, soils, hydrology, land use, biodiversity). Under World Bank financing, a National Inventory of Natural Resources is being conducted. For this purpose, MRSTD has acquired SPOT information (1/100,000 rectified enlargements but not the digital information) for the entire national territory. MRSTD's initial plan was to develop a remote sensing and mapping capacity, but it lacks the proper staff and equipment to do so.
- The Ministry of Agriculture (MPARA) is particularly responsible for rural infrastructure and irrigation development. For the latter, MPARA, with support from the donors, acquires aerial photos and finances remote sensing activities without always consulting FTM. Furthermore, MPARA does not have a good storage facility for photo negatives and other map records, which results in progressive deterioration.
- The Ministry of Livestock and Forestry (MPAEF) finds itself in a similar situation regarding aerial surveys and mapping for forestry. Furthermore, MPAEF is in charge of national parks, reserves, and gazetted forests and, because of this responsibility, considers that it is the custodian of biodiversity, including data systems, although not that much has been developed in this field.
- The Ministry of Mines and Energy (MIEM) again deals with mapping and remote sensing without coordinating with FTM.
- There is, finally, one private contractor in surveying and mapping. His work is wellappreciated but, as FTM, he suffers from the absence of a well-equipped aerophotogrammetric aircraft.

From this brief description, one can derive the main issues that unfortunately are rather common in the African context, as well as in the developing world in general.

- ***Lack of clear-cut responsibilities:*** between institutions involved in mapping, remote sensing, and environmental data management in general; this results in waste of scarce resources, in both human and financial.
- ***Lack of institutional coordination:*** areas may be surveyed several times for different purposes; the same satellite information may be acquired several times. FTM, according to its legal status, is theoretically responsible for coordinating remote sensing and mapping but has not been able to play this role. Again there is a waste of resources.
- ***Lack of sufficient funding:*** this is due to different reasons: (i) the low priority given to remote sensing, mapping, and environmental data in general; (ii) lack of support and/or lack of continuity in the support from the donors (e.g., the tremendous impact of the discontinuity of French support); and (iii) insufficient income generation by the institutions, often related to their legal status.
- ***Piecemeal and uncoordinated approach by the donors:*** until now, donors have financed project-related remote sensing and mapping without paying enough attention to the national issues, particularly to establishment and maintenance of a solid environmental data base.
- ***Lack of access to existing data:*** each institution is very protective of the information it keeps. This sort of institutional behavior induces each agency to be as autonomous as possible in terms of data collection and processing; this is the situation regarding remote sensing and mapping, although being fully equipped is more intended than actual.
- ***Lack of data integration:*** because of the above, data integration is very difficult. Furthermore, it may very well be possible to have more than one set of data on the same topic that are incompatible between themselves.
- ***Insufficient training (quantity and quality):*** professionals who have been trained abroad have very limited opportunity to keep abreast with the evolution of remote sensing and mapping technologies and to be able to make sound decisions in the selection of the most adaptable technologies and methodologies to meet the national demand. Furthermore, most professionals are trained in geodesy and remote sensing and mapping technologies, but very few in management, administration, and finance.
- ***Cumbersome legal systems:*** they result in dramatically increased costs. Regarding cadastral laws for example, there is only one standard in terms of topographic accuracy. This standard is fine for the intensive agricultural land, particularly paddy fields, but it is far too high for extensive areas in the hills and the western plateaus where a few meters of standard deviation would be acceptable. This results in higher costs than necessary.

- *Supply-driven rather than demand-driven approach:* a case in point is the recent acquisition of SPOT images for the whole country, under IDA financing, without having a clear view of what could be done, and according to what priorities.
- *Loss of data:* Because of inadequate storage facilities and unclear responsibilities, valuable negatives of aerial photos have already been lost.

The Environmental Action Plan

Fully aware of the alarming degradation of its environment, the Government of Madagascar has launched the preparation of its Environmental Action Plan (EAP), with support from a group of donors, international agêncies, and NGOs, under the Bank's leadership. The lack of a solid environmental data base and mapping and remote sensing tools has been selected as one of the key issues. The government has appointed a working group including high-level representatives of the different institutions described above. This group has worked for about six months; it has highlighted the above issues and complementary studies are being carried out to prepare future decisions. It has also surveyed the priority needs of Madagascar. There is now a collective recognition of the need of a solid data base and willingness to deal with the above issues.

New institutional proposal

Under the EAP, a 15-year program has been elaborated for revamping the mapping, remote sensing, and environmental data of Madagascar. A first tranche of this program is being prepared, with a multidonor appraisal scheduled for next June. It is a bit early to describe this program, and particularly the corrective measures to deal with the above issues, since no major decisions have been made yet. One can, however, sketch the expected features of this program:

- FTM would consolidate geodetic, aerophotogrammetric, and mapping activities by receiving the mapping department of DP. FTM would be a service agency, with financial autonomy. Its income would eventually be made up of fees for its services to public, semipublic and private operators. FTM would particulary provide DP with the necessary orthophotos and maps required by DP's cadastral program. FTM would be the custodian of all the original maps and negatives, which would be kept in its strorage facility. FTM would effectively coordinate all the surveys carried out in Madagascar. The private sector, however, would continue to play an important role in surveying and mapping in competition with FTM.

- FTM would also host a National Lab for Satellite Remote Sensing, which would be fully open to all agencies. This lab would provide the hardware, software, and technical assistance to these agencies.
- DP would keep its responsibility for carrying out cadastral surveys, keeping and updating cadastral records, and keeping the records of the private domain of the state. DP's activities would be prudently and progressively computerized.
- All the specialized ministries and agencies would contract the mapping either to FTM or to the private sector. They would, however, be responsible for keeping and updating the data they generate, but according to a system compatible with the other agencies. Assuming that the cost of computerized equipment for processing satellite information continues to decrease, these agencies could eventually equip themselves.
- Regarding the overall natural resource and environmental data base, there would be a progressive establishment of a network of agencies, each being responsible for its specific data and sharing them with the others.
- Donors and international agencies are prepared to support this program on a long-term basis, on the basis of a clear phasing and priorities. Their support would be, however, conditional to key reforms to deal with the main current issues.
- It is also expected that FTM would negotiate long-term twinning arrangements with a mapping and remote sensing agency from a developped country in order to ensure long-term continuity for technical assistance and training.

GENERAL LESSONS

From the Malagasy case, a series of general lessons can be drawn:

- There is a need for clear-cut responsabilites among the institutions involved in remote sensing, mapping and environmental data management.

- There is a need for a focal point for institutional coordination. Centralizing the responsibility for all the data might prove to be difficult; a network may be more adaptive, but it requires compatibility in the systems used and a strong coordination.

- There is a need for institutional simplification, particularly in conventional mapping, which requires extremely expensive equipment. In this case, a consolidation into only one agency may be justified.

- There is a need for open access to environmental data in general in order to make integration possible, particularly in geographic information systems.
- There is a need for a demand-driven approach. Hence the need for carefully assessing the priority needs of a country in all the sectors concerned.
- There is an urgent need to save the data that are at risk of being lost. Investment in storage facilities may save extremely valuable documents.
- There is a need to revise the legal status of the various institutions involved in mapping and remote sensing with the objective of turning them into real service agencies. The role of the private sector is to be maintained, even enhanced, when the public sector cannot deliver.
- There is often a need to simplify laws, particularly regarding survey accuracy and administrative procedures in order to avoid high costs.
- There is a need for training, mainly in remote sensing and mapping technologies, but without forgetting organization, management, and finance.
- There is a need to turn the main institutions involved in remote sensing, mapping, and data management into sustainable entrepreneurial agencies. It means that these institutions have to be well compensated in past by the public, for the services they render.

DONOR ROLE AND PROPOSED ACTION PLAN FOR AFRICA

The Malagasy case shows the need for strong donor coordination, a consensus with the government on what needs to be done for revamping the environmental data base, and a long-term commitment to support this effort.

At least in Africa, the lack of data on natural resources and environment is recognized by everybody, but the problem has not been fully addressed. Africa is facing a dilemma: it is probably the region of the world in greatest need of the establishment of a solid, frequently updated data base because of the extremely fast changes in land use and the rapid degradation of its natural resources. At the same time, Africa is the poorest region and may not be able to manage alone the constant improvement of its data base. Hence the need for a special action plan for Africa:

- The first phase would be to help the countries assess their current situation, reviewing all the different facets of the key issues: institutions, including their legal status, financial systems and budgetary procedures, staffing, training, organization and management; assessment of the existing data base, including geodetic network, base maps, satellite information and natural resources; surveys of the priority needs for the various economic sectors, probably with a special pitch for agriculture; review of the laws regarding surveying, security, land tenure, and cadastral operation; review of the fiscal system and the possibility of generating funds for surveying; and review of the existing education and training facilities.

- The second phase would consist of preparing a long-term program (maybe 15 years) to address the key issues raised in phase one.

- The third phase would be to prepare a detailed first tranche of investment.

- The fourth phase would be the financing of this tranche without forgetting the necessity for long-term commitment.

Phases 1, 2, and 3 could be financed, country by country, out of an international fund on a grant basis, similar to ESMAP for energy assessments. Phase 4 would probably require a blend of grants and loans on soft conditions.

EFFICIENT INVESTMENT FOR DEVELOPING REMOTE SENSING ACTIVITIES

Jean-Claude CAZAUX

INTRODUCTION

There are a number of key requirements in enhancing the use and application of remote sensing, especially in developing countries. The first requirement is that decisionmakers who are to use the data are fully involved in both project design and product development. If such consultations during the initial stages of the project are omitted, the full benefits of the new technology may not be achieved. Such consultation would include consideration of data to be used, computer requirements, and the time requirements associated with remote sensing projects. In this instance, donors may fail to recognize an important aspect such as analog or digital processing, maintenance, training of personnel, or institutional barriers to the adaptation of the technology. Such problems can delay the delivery of results and endanger the adoption of the technology by decisionmakers.

The following steps should be taken before any important technical intervention (i.e. realization of large-scale projects) or hardware investment (station, processing system).

- Assessment of the level of awareness of decisionmakers regarding remote sensing technology: resistance or excessive zeal should be tempered by explaining the prospects and constraints (technically and economically) of remote sensing.

- Analysis of projects should be undertaken in the country to identify the overall role and potential of remote sensing if it were to be used, paying particular attention to the need to recover the money invested.

- Examination of the capability of local facilities should consider infrastructure, communications, and technical environment.

- Examination should be made of human capability and further training locally or abroad within the framework of the project.

- Ability to accomodate technology transfers should be considered.

- An economic report should be drawn up.

In the more specific case of developing countries, the regional dimension must be integrated in such a way that it can rely on regional remote sensing centers if required:

- for training,
- for expertise,
- for the management and partial carrying out of the project.

Some of these aspects can be specified, and the cooperation capabilities and contacts to be made thus identified.

PROJECT DESIGN

The assistance required specifically by developing countries should be carefully tailored to fit their current levels of capability in data collection (satellite data receiving capability, aerial surveys), analysis (photointerpretation, digital processing) and dissemination and to respond as efficiently as possible to users' requirements.

As a first step, a careful analysis has to be made of the existing infrastructure and working arrangements of the different government and semigovernment institutions. A detailed assessment is required of the currently existing data collection systems, coverage, frequency, and mode of operation. An estimate of the additional assistance that may be needed for bringing the participation of cooperating agencies to the minimum level required for the purpose is necessary.

The institutional arrangements may vary in form in the different countries and may pose unexpected problems. For example, the staff responsible for data collection may not belong to the agency that provides technical guidance, or to the one that is responsible for data analysis and reporting. Responsibilities in this respect may be ill-defined and rational solutions difficult to achieve because of overlapping missions or voids in the respective areas of competence. Moreover, there may not be any arrangements for educating the policymakers who will use the information generated. Although this aspect falls outside the strict area of remote sensing applications, it is an important factor in determining end-user requirements.

It is important to look at how, in concrete terms, remote sensing can be used in the various phases of a project, from the moment it has been identified to its assessment. This will be done by discussion of actual projects carried out in developing countries for various funding agencies.

Any successful agricultural development program requires:

- a thorough project identification/feasibility study;
- a comprehensive inventory of human, economic, and physical resources;
- an appraisal of the present situation;
- an analysis of the cultural and physical problems in resource development;
- an estimate of resource potentials in spatial terms;
- an efficient implementation of the agricultural development scheme; and
- an effective environmental monitoring/evaluation system to guide the effectiveness of the project.

In all these phases, remote sensing can not only provide considerable cost savings, but also valuable information for decisionmakers to ensure environmentally sound and sustainable management of agricultural projects.

In the identification/feasibility phases of agricultural development projects, the use of existing remote sensing data from available archives has proven to be a very cost-effective way of carrying out tasks such as:

- definition/determination of the project area;
- a rapid appraisal of the existing situation;
- preliminary assessment of the agricultural potential of the area;
- deciding which areas need to be visited during the identification mission;
- a first indication of the environmental consequences that could result if a project were to be carried out in the selected area.

Such a use of remote sensing not only reduces the time necessary for identification missions, but also results in considerable cost savings, in addition to improved quality of information on which to approve or reject potential projects.

For all these aspects, experienced consultants closely involved in the project should be used from the start, especially for defining the project, but also to ensure follow-up. These consultants can be provided:

- directly by the financial backer;
- by specialized international agencies (FAO, DTCD, UNDP, etc);
- by regional remote sensing centers (AIT Bangkok, CRTO Ouagagoudou, CRTK Nairobi, CIAF Bogota, etc);
- by specialized companies in Sweden, France, and Canada, and in North American universities.

INSTALLATION OF RECEIVING STATIONS

This aspect cannot be viewed within the framework of a single application project. Such choices are either regionally (East Africa, West Africa) or nationally based (Ecuador, Argentina, Brazil, Thailand, Pakistan, Saudi Arabia). Owing to the sums invested and the operating costs incurred, thorough preliminary studies must be made. The main terms to be taken into consideration are:

- An analysis of national and regional requirements, with an estimate over a period of five to ten years, taking into consideration future large-scale development projects and the role of remote sensing. This should make it possible to identify the theoretical market in terms of the number and type of images per year of operation.

- An inventory in terms of technological, maintenance, local communication and personnel training capability.

- Marketing capability for distribution of data.

- Technical study of station dimensions and of multisatellite and future extension capabilities. Technological choices and estimates must be made: antenna (diameter and frequency), reception system (Landsat and/or SPOT and/or MOS and/or ERS 1), compact station or station with sophisticated processing and correction capability.

- An assessment of investment, maintenance, and license costs.

- Budget planning including required technical assistance.

These studies absolutely must be carried out before any decision to invest is made. They will be carried out jointly by the country concerned and by consultants, industrially independent. Our company carries out such studies for governments or for financial backers. Such assistance is being given in Sweden, Canada, and the United States, all of which are countries that are actively involved in exploitation of the ground segment of Earth observation systems.

REMOTE SENSING DATA PROCESSING SYSTEMS

Once the data has been chosen for the projects to be carried out (via a local or regional receiving station or by purchasing data from a satellite operator), the problem of deciding what methods and facilities are to be used to process the data has to be dealt with.

Starting with analog analytical aids like the densitometer, color additive viewer, density slicer, diazo printer, and zoom transfer-scope, we are now witnessing the era of digital analyzers. The analog equipment has been in use with great success since the very beginning of remote sensing technology. The equipment is simple to operate and cheap to buy and maintain. A reasonable capability combination of such equipment may cost somewhere between US$10,000-25,000. It is recommended that analog analytical instruments should not be dispensed with in favor of newly emerging digital equipment, especially for promoting the applications of remote sensing data in developing countries. Another advantage of these analytical instruments is that they require a minimum of time for manpower to be trained.

With the advent of micro-electronics, micro-processors have appeared on the scene. The increasing component density of integrated circuits has led to the development of micro-processors that are not only very fast in terms of processing, speeds but also have more capability processing functions and storage capacity. At the same time, the prices of these devices are coming down -- in fact this is the only example of an industry where, while the capability of the equipment is increasing, the prices are decreasing with the passage of time. The micro-processor has today become the centerpiece of not only desktop computers but also of all mini- and mainframe computers.

It would thus be natural to infer that more and more computer-based systems would be used for image analysis relying upon digital image processing techniques which lead to a high degree of flexibility in the manipulation of remotely sensed data for the identification of surface features. This, combined with the possibility of enhancing image utility through various techniques like ratioing, merging of data obtained from different supports, and depiction of shades of grey in distinct colors, enables the extraction of more detailed information from remotely sensed data in an unambiguous manner in a relatively short time.

In fact, once the remotely sensed data are available in digital form which satellites transmit to the ground, the next step is to process the data on high-speed digital computers, applying corrections for positional accuracy, registration, long-term variations in the performance of sensors, and, ultimately, reducing data into format and product in the form of computer compatible tapes (CCTs) or floppy disks that can be conveniently used for analytical work. There is tremendous flexibility in data analysis with digital data and computer equipment, and it is generally believed that the only limit to what one can do with a good digital system is human imagination and hardware and software capability.

The micro-computer-based systems, together with their peripheral equipment --like tape drive, monitors, printers, color copiers, trackball and function pads-- currently cost anywhere between $US20,000-50,000, depending on the capability and quality of the individual system. The mini- or mainframe computer-based systems would of course have much higher speeds and capability, but then they would cost anywhere between $US100,000-300,000. These systems would only really be justified for laboratories or research centers which are engaged in real-time data processing and developing new techniques for digital image processing for use by a broad-based user community.

For more operational exploitation entities working on huge projects, or for entities such as the regional or national remote sensing centers, the ranges of systems used are based on a conventional computer with special operators and peripherals. Investment and running costs are more considerable and decisionmaking strategies are more similar to those favored for investment choices in the field of receiving stations. Our company conducts this type of study in the Philippines, Tunisia, and Morocco (analysis of national requirement, analysis of the existing situation, financial assessment, technical specification, and associated measurements).

For advice on choices of these processing systems, procedures and addresses, we recommend the recent report from the Department of Technical Co-operation for Development of the United Nations: "Assessment on Constraints and Capabilities of Hardware and Software Systems for Remote Sensing," written by a group of experts with a SCOT CONSEIL engineer, 13-17 February 1989.

In addition to this excellent report providing recommendations and addresses of supplier industries, the support of experts from agencies, FAO, DTCD, regional remote sensing centers, or specialized companies is advisable when carrying out preliminary studies and making recommendations to users and financial backers.

EDUCATION, TRAINING, AND TRANSFER OF TECHNOLOGY

Two broad areas of training in remote sensing are concurrently necessary in developing countries: training of trainees within their institutions for formal education and practical training of technical staff and resource managers through short courses and on-the-job activities. In the former case, educational facilities are eventually assisted to establish remote sensing courses in their final curricula in resource areas, which in due course will have a multiplicative effect. In the latter, technical staff and resource managers are assisted and encouraged to incorporate remote sensing in their day-to-day problem-solving procedures by means of activities that demonstrate its practical applications.

Many developing countries have recently made substantial efforts to create national and/or regional remote sensing centers and regional programs to meet some of their needs. These centers have initially focused mostly on practical instruction through demonstration, with minimal emphasis on long-term training. Unfortunately, only a few countries have taken the initial steps to incorporate remote sensing courses in their regular university curricula. However, a number of these national or regional centers are now reaching a threshold at which international assistance to provide instruction at such higher levels would be most opportune and could yield substantial benefits. In future, provision for such longer-term training at all levels will need much greater consideration.

In the Food and Agriculture Organization, Asian Institute of Technology, ITC (International Institute for Aerospace Survey and Earth Sciences), GDTA (Groupement pour le Développement de la Télédétection Aérospatiale), and some other institutions, education and training have always

been considered as one of the main functions of technical assistance, and form an essential link in the process by which appropriate advanced technology is transferred to developing countries. Training has historically been mainly achieved through the granting of short-term and long-term courses and fellowships. These, inter alia, provide post-graduate university studies, study tours, expert counterpart relationships, and intensive short courses.
At the present moment several levels of strategy and possibilities for training in remote sensing are starting to appear.

- university training in the developed countries (U.S., Canada, France, etc.) open to foreign students and giving access to research activities
- long-term professional training in developed countries, which could be described as training of instructors (reference could be made to GDTA, France - ITC, Holland - Dundee, Scotland, GB)
- short-term training in specific fields of applications to be found in the above-mentioned institutions and also in international organizations like FAO.
- an important role has been played by the regional remote sensing centers, which have assembled facilities and personnel for a group of countries: CRTO, Ouagadougou; CRTK, Nairobi; IGAC, Columbia;. AIT, Bangkok; etc.

The training provided is of professional level and is often specific to a particular application topic. The necessity and existence of awareness seminars lasting 1-3 days and aimed at decision-makers and financial backers must not be forgotten. Last, it seems to be more and more profitable during in-project training --i.e., either the completion of small pilot projects within training cycles as described above, or within important remote sensing projects-- to provide local training or technology transfer on a local basis within a specific and integral part of the operation.

CONCLUSIONS

Remote sensing is a fresh new technology with numerous technical and economic implications in many development programs and in various topics. The way in which this technique is incorporated requires delicate choices because of human and financial investments. Costs are often negligible in comparison with overall project costs, but errors can be universally damaging. That is why a preliminary analysis of the best conditions for incorporation of this technique is indispensable: this is the role of consultancy and advisors.

- 19 -
TECHNICAL CONCLUSION

Ray Harris

CONTEXT

The World Bank seminar on satellite remote sensing for agricultural projects has shown a wide variety of successful applications of the technology. Many of the papers also show entirely new applications not possible with conventional approaches. This approach can be represented as an intersection of types of data and types of applications, as shown in the accompanying figure.

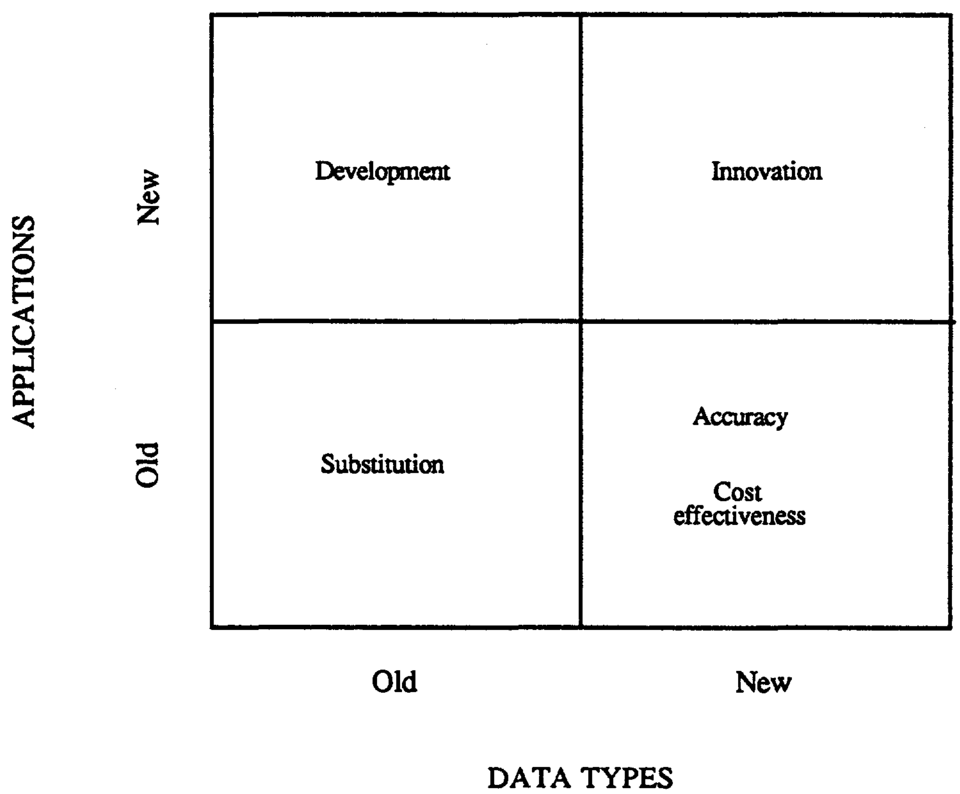


Figure 19-1. Data Types and Applications in Remote Sensing Technology.

When old data types; that is, not satellite remote sensing in the present context, are used for existing applications, then there is a substitution of technologies. When new applications use old data there is a development of the use of a technology. Satellite remote sensing is a new data type, and when used in old applications users are looking for improvements in accuracy or increased cost-effectiveness. When new data types are used for new applications innovation is the key requirement.

The World Bank satellite remote sensing seminar included many examples of these last two categories. Illustrations of improvements in accuracy and cost-effectiveness were given for land use mapping in many parts of the world (Rochon, Luscombe), for satellite hydrogelogy (Wiesnet), and for improved estimates of crop production statistics in the Sudan (Hassan). In Burkina Faso (Pointet) satellite remote sensing data improved water borehole prospecting and gave an increase in average borehole yield from 1.4 m^3/h to $4m^3/h$. Innovative applications of satellite remote sensing included natural resources in the Sahel (Barisano), famine monitoring and locust infestation assessment in Africa (Spiers, Moore), and the implications of the results of satellite remote sensing for policymaking in Argentina (Menenti).

MARKET

Satellite remote sensing is a scientific technology grown from scientific curiosity. Its use must be fitted to the needs of users and to the needs of the marketplace, albeit with an innovative approach. The next stages of the application of satellite remote sensing for developing countries will have to concentrate on needs, as discussed below.

- There is a need to identify the customers. The customers are those end-users, not primarily the influencers, who are seeking improvements in their work.
- There is a need to adopt the new technology to developing country circumstances.
- Long-term financing plans need to be put in place so that the new applications are sustainable and produce real economic benefits.
- There is a need to integrate environmental issues and natural resource management into the economic and social program of developing countries.

All these point to the need to know the market for satellite remote sensing and seek to match the technology to the market.

CONCLUSIONS

The World Bank seminar has shown the great potential for satellite remote sensing. This potential must be viewed cautiously, with a clear knowledge of the constraints of the technology itself and the constraints of the market.

Distributors of World Bank Publications

ARGENTINA
Carlos Hirsch, SRL
Galeria Guemes
Florida 165, 4th Floor-Ofc. 453/465
1333 Buenos Aires

AUSTRALIA, PAPUA NEW GUINEA, FIJI, SOLOMON ISLANDS, VANUATU, AND WESTERN SAMOA
D.A. Books & Journals
648 Whitehorse Road
Mitcham 3132
Victoria

AUSTRIA
Gerold and Co.
Graben 31
A-1011 Wien

BAHRAIN
Bahrain Research and Consultancy Associates Ltd.
P.O. Box 22103
Manama Town 317

BANGLADESH
Micro Industries Development Assistance Society (MIDAS)
House 5, Road 16
Dhanmondi R/Area
Dhaka 1209

Branch offices:
156, Nur Ahmed Sarak
Chittagong 4000

76, K.D.A. Avenue
Kulna

BELGIUM
Publications des Nations Unies
Av. du Roi 202
1060 Brussels

BRAZIL
Publicacoes Tecnicas Internacionais Ltda.
Rua Peixoto Gomide, 209
01409 Sao Paulo, SP

CANADA
Le Diffuseur
C.P. 85, 1501B rue Ampère
Boucherville, Quebec
J4B 5E6

CHINA
China Financial & Economic Publishing House
8, Da Fo Si Dong Jie
Beijing

COLOMBIA
Enlace Ltda.
Apartado Aereo 34270
Bogota D.E.

COTE D'IVOIRE
Centre d'Edition et de Diffusion Africaines (CEDA)
04 B.P. 541
Abidjan 04 Plateau

CYPRUS
MEMRB Information Services
P.O. Box 2098
Nicosia

DENMARK
SamfundsLitteratur
Rosenoerns Allé 11
DK-1970 Frederiksberg C

DOMINICAN REPUBLIC
Editora Taller, C. por A.
Restauracion e Isabel la Catolica 309
Apartado Postal 2190
Santo Domingo

EL SALVADOR
Fusades
Avenida Manuel Enrique Araujo #3530
Edificio SISA, ler. Piso
San Salvador

EGYPT, ARAB REPUBLIC OF
Al Ahram
Al Galaa Street
Cairo

The Middle East Observer
8 Chawarbi Street
Cairo

FINLAND
Akateeminen Kirjakauppa
P.O. Box 128
SF-00101
Helsinki 10

FRANCE
World Bank Publications
66, avenue d'Iéna
75116 Paris

GERMANY, FEDERAL REPUBLIC OF
UNO-Verlag
Poppelsdorfer Allee 55
D-5300 Bonn 1

GREECE
KEME
24, Ippodamou Street Platia Plastiras
Athens-11635

GUATEMALA
Librerias Piedra Santa
Centro Cultural Piedra Santa
11 calle 6-50 zona 1
Guatemala City

HONG KONG, MACAO
Asia 2000 Ltd.
Mongkok Post Office
Bute Street No. 37
Mongkok, Kowloon
Hong Kong

HUNGARY
Kultura
P.O. Box 149
1389 Budapest 62

INDIA
Allied Publishers Private Ltd.
751 Mount Road
Madras - 600 002

Branch offices:
15 J.N. Heredia Marg
Ballard Estate
Bombay - 400 038

13/14 Asaf Ali Road
New Delhi - 110 002

17 Chittaranjan Avenue
Calcutta - 700 072

Jayadeva Hostel Building
5th Main Road Gandhinagar
Bangalore - 560 009

3-5-1129 Kachiguda Cross Road
Hyderabad - 500 027

Prarthana Flats, 2nd Floor
Near Thakore Baug, Navrangpura
Ahmedabad - 380 009

Patiala House
16-A Ashok Marg
Lucknow - 226 001

INDONESIA
Pt. Indira Limited
Jl. Sam Ratulangi 37
P.O. Box 181
Jakarta Pusat

IRELAND
TDC Publishers
12 North Frederick Street
Dublin 1

ITALY
Licosa Commissionaria Sansoni SPA
Via Benedetto Fortini, 120/10
Casella Postale 552
50125 Florence

JAPAN
Eastern Book Service
37-3, Hongo 3-Chome, Bunkyo-ku 113
Tokyo

KENYA
Africa Book Service (E.A.) Ltd.
P.O. Box 45245
Nairobi

KOREA, REPUBLIC OF
Pan Korea Book Corporation
P.O. Box 101, Kwangwhamun
Seoul

KUWAIT
MEMRB Information Services
P.O. Box 5465

MALAYSIA
University of Malaya Cooperative Bookshop, Limited
P.O. Box 1127, Jalan Pantai Baru
Kuala Lumpur

MEXICO
INFOTEC
Apartado Postal 22-860
14060 Tlalpan, Mexico D.F.

MOROCCO
Societe d'Etudes Marketing Marocaine
12 rue Mozart, Bd. d'Anfa
Casablanca

NETHERLANDS
InOr-Publikaties b.v.
P.O. Box 14
7240 BA Lochem

NEW ZEALAND
Hills Library and Information Service
Private Bag
New Market
Auckland

NIGERIA
University Press Limited
Three Crowns Building Jericho
Private Mail Bag 5095
Ibadan

NORWAY
Narvesen Information Center
Bertrand Narvesens vei 2
P.O. Box 6125 Etterstad
N-0602 Oslo 6

OMAN
MEMRB Information Services
P.O. Box 1613, Seeb Airport
Muscat

PAKISTAN
Mirza Book Agency
65, Shahrah-e-Quaid-e-Azam
P.O. Box No. 729
Lahore 3

PERU
Editorial Desarrollo SA
Apartado 3824
Lima

PHILIPPINES
National Book Store
701 Rizal Avenue
P.O. Box 1934
Metro Manila

POLAND
ORPAN
Palac Kultury i Nauki
00-901 Warszawa

PORTUGAL
Livraria Portugal
Rua Do Carmo 70-74
1200 Lisbon

SAUDI ARABIA, QATAR
Jarir Book Store
P.O. Box 3196
Riyadh 11471

MEMRB Information Services
Branch offices:
Al Alsa Street
Al Dahna Center
First Floor
P.O. Box 7188
Riyadh

Haji Abdullah Alireza Building
King Khaled Street
P.O. Box 3969
Damman

33, Mohammed Hassan Awad Street
P.O. Box 5978
Jeddah

SINGAPORE, TAIWAN, MYANMAR, BRUNEI
Information Publications Private, Ltd.
02-06 1st Fl., Pei-Fu Industrial Bldg.
24 New Industrial Road
Singapore 1953

SOUTH AFRICA, BOTSWANA
For single titles:
Oxford University Press Southern Africa
P.O. Box 1141
Cape Town 8000

For subscription orders:
International Subscription Service
P.O. Box 41095
Craighall
Johannesburg 2024

SPAIN
Mundi-Prensa Libros, S.A.
Castello 37
28001 Madrid

Librería Internacional AEDOS
Consell de Cent, 391
08009 Barcelona

SRI LANKA AND THE MALDIVES
Lake House Bookshop
P.O. Box 244
100, Sir Chittampalam A. Gardiner Mawatha
Colombo 2

SWEDEN
For single titles:
Fritzes Fackboksforetaget
Regeringsgatan 12, Box 16356
S-103 27 Stockholm

For subscription orders:
Wennergren-Williams AB
Box 30004
S-104 25 Stockholm

SWITZERLAND
For single titles:
Librairie Payot
6, rue Grenus
Case postal 381
CH 1211 Geneva 11

For subscription orders:
Librairie Payot
Service des Abonnements
Case postal 3312
CH 1002 Lausanne

TANZANIA
Oxford University Press
P.O. Box 5299
Dar es Salaam

THAILAND
Central Department Store
306 Silom Road
Bangkok

TRINIDAD & TOBAGO, ANTIGUA BARBUDA, BARBADOS, DOMINICA, GRENADA, GUYANA, JAMAICA, MONTSERRAT, ST. KITTS & NEVIS, ST. LUCIA, ST. VINCENT & GRENADINES
Systematics Studies Unit
#9 Watts Street
Curepe
Trinidad, West Indies

TURKEY
Haset Kitapevi, A.S.
Istiklal Caddesi No. 469
Beyoglu
Istanbul

UGANDA
Uganda Bookshop
P.O. Box 7145
Kampala

UNITED ARAB EMIRATES
MEMRB Gulf Co.
P.O. Box 6097
Sharjah

UNITED KINGDOM
Microinfo Ltd.
P.O. Box 3
Alton, Hampshire GU34 2PG
England

URUGUAY
Instituto Nacional del Libro
San Jose 1116
Montevideo

VENEZUELA
Libreria del Este
Aptdo. 60.337
Caracas 1060-A

YUGOSLAVIA
Jugoslovenska Knjiga
P.O. Box 36
Trg Republike
YU-11000 Belgrade

RECENT WORLD BANK TECHNICAL PAPERS *(continued)*

No. 97 Asia Technical Department and Europe, Middle East, and North Africa Technical Department, *Improving the Supply of Fertilizers to Developing Countries: A Summary of the World Bank's Experience*

No. 98 Moreno and Fallen Bailey, *Alternative Transport Fuels from Natural Gas*

No. 99 International Commission on Irrigation and Drainage, *Planning the Management, Operation, and Maintenance of Irrigation and Drainage Systems: A Guide for the Preparation of Strategies and Manuals* (also in French, 99F)

No. 100 Veldkamp, *Recommended Practices for Testing Water-Pumping Windmills*

No. 101 van Meel and Smulders, *Wind Pumping: A Handbook*

No. 102 Berg and Brems, *A Case for Promoting Breastfeeding in Projects to Limit Fertility*

No. 103 Banerjee, *Shrubs in Tropical Forest Ecosystems: Examples from India*

No. 104 Schware, *The World Software Industry and Software Engineering: Opportunities and Constraints for Newly Industrialized Economies*

No. 105 Pasha and McGarry, *Rural Water Supply and Sanitation in Pakistan: Lessons from Experience*

No. 106 Pinto and Besant-Jones, *Demand and Netback Values for Gas in Electricity*

No. 107 Electric Power Research Institute and EMENA, *The Current State of Atmospheric Fluidized-Bed Combustion Technology*

No. 108 Falloux, *Land Information and Remote Sensing for Renewable Resource Management in Sub-Saharan Africa: A Demand-Driven Approach* (also in French, 108F)

No. 109 Carr, *Technology for Small-Scale Farmers in Sub-Saharan Africa: Experience with Food Crop Production in Five Major Ecological Zones*

No. 110 Dixon, Talbot, and Le Moigne, *Dams and the Environment: Considerations in World Bank Projects*

No. 111 Jeffcoate and Pond, *Large Water Meters: Guidelines for Selection, Testing, and Maintenance*

No. 112 Cook and Grut, *Agroforestry in Sub-Saharan Africa: A Farmer's Perspective*

No. 113 Vergara and Babelon, *The Petrochemical Industry in Developing Asia: A Review of the Current Situation and Prospects for Development in the 1990s*

No. 114 McGuire and Popkins, *Helping Women Improve Nutrition in the Developing World: Beating the Zero Sum Game*

No. 115 Le Moigne, Plusquellec, and Barghouti, *Dam Safety and the Environment*

No. 116 Nelson, *Dryland Management: The "Desertification" Problem*

No. 117 Barghouti, Timmer, and Siegel, *Rural Diversification: Lessons from East Asia*

No. 118 Pritchard, *Lending by the World Bank for Agricultural Research: A Review of the Years 1981 through 1987*

No. 119 Asia Region Technical Department, *Flood Control in Bangladesh: A Plan for Action*

No. 120 Plusquellec, *The Gezira Irrigation Scheme in Sudan: Objectives, Design, and Performance*

No. 121 Listorti, *Environmental Health Components for Water Supply, Sanitation, and Urban Projects*

No. 122 Dessing, *Support for Microenterprises: Lessons for Sub-Saharan Africa*

No. 123 Barghouti and Le Moigne, *Irrigation in Sub-Saharan Africa: The Development of Public and Private Systems*

No. 124 Zymelman, *Science, Education, and Development in Sub-Saharan Africa*

No. 125 van de Walle and Foster, *Fertility Decline in Africa: Assessment and Prospects*

No. 126 Davis, MacKnight, IMO Staff, and Others, *Environmental Considerations for Port and Harbor Developments*

No. 127 Doolette and Magrath, editors, *Watershed Development in Asia: Strategies and Technologies*

The World Bank

Headquarters
1818 H Street, N.W.
Washington, D.C. 20433, U.S.A.

Telephone: (202) 477-1234
Facsimile: (202) 477-6391
Telex: WUI 64145 WORLDBANK
RCA 248423 WORLDBK
Cable Address: INTBAFRAD
WASHINGTONDC

European Office
66, avenue d'Iéna
75116 Paris, France

Telephone: (1) 40.69.30.00
Facsimile: (1) 47.20.19.66
Telex: 842-620628

Tokyo Office
Kokusai Building
1-1 Marunouchi 3-chome
Chiyoda-ku, Tokyo 100, Japan

Telephone: (3) 214-5001
Facsimile: (3) 214-3657
Telex: 781-26838

Cover design by Walton Rosenquist

ISBN 0-8213-1625-7