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Satellite environmental monitoring for migrant pest forecasting by FAO: the ARTEMIS system

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(*Paper introduced by G. B. Popov, FAO, Rome*)

Since 1975, the Food and Agriculture Organization of the United Nations (FAO) has been pioneering the development of the use of satellite remote sensing techniques for improving the surveillance and forecasting capabilities of the centralized Desert Locust Reporting and Forecasting Service at FAO Headquarters and, indirectly, those of Regional Organizations and National Plant Protection Services.

On the basis of findings from experimental activities on the use of Landsat and NOAA satellite AVHRR data for Desert Locust habitat detection and monitoring through vegetation assessment, and the use of Meteosat data for rainfall monitoring, FAO defined an operational system for satellite environmental monitoring in support of the FAO Desert Locust Plague Prevention Programme and the FAO Global Information and Early Warning System on Food and Agriculture.

The system, African Real Time Environmental Monitoring using Imaging Satellites (ARTEMIS) is an advanced computer hardware and software configuration, equipped for direct acquisition of hourly Meteosat digital data and for automated thematic processing of Meteosat and NOAA AVHRR data for large area precipitation and vegetation condition assessment, being the key environmental factors for supporting Desert Locust population development.

Since August 1988, the ARTEMIS system has generated a number of operational products documenting the occurrence of rainfall and vegetation development in the Desert Locust recession area on a 10-day and monthly basis at spatial resolutions varying from 7.6–1.1 km.

These products are being used by the FAO Emergency Centre for Locust Operations (ECLO), along with synoptic weather and locust data, for the preparation of the bulletins containing the Desert Locust situation summaries and forecasts.

For making ARTEMIS output products and other relevant data available in a timely manner at regional and national levels, a dedicated satellite communications system, Data and Information Available Now in Africa (DIANA), is currently being developed by the European Space Agency in cooperation with the FAO Remote Sensing Centre.

The DIANA system will, by mid-1991, provide a capability for high speed (64 kb s^{-1}) two-way transfer of facsimile images of documents and maps, character-coded text documents and digital images in raw or processed form from computers at FAO Headquarters to personal computer based terminals of recipients, initially in Africa, by using the commercial Intelsat satellites.

1. Introduction

During the 1970s several earth resources and environmental satellites were launched from the United States and Europe, which offered new prospects for mapping the preferred habitats of the Desert Locust (*Schistocerca gregaria* (Fôrskal)) and for monitoring key environmental parameters for the successful development of Desert Locust populations, that is, precipitation and vegetation development, on the scale of the Desert Locust recession area, which covers some 16 million km^2 between the West African coast and northwest India.

After a successful demonstration of the use of Landsat imagery, by using visual image analysis techniques, for detecting potentially active Desert Locust breeding habitats on the Tihama plains of Saudi Arabia by the former Centre for Overseas Pest Research (COPR) (Pedgley 1973), the Food and Agriculture Organization (FAO) of the United Nations has since 1975 been actively involved in the development and testing of various satellite remote sensing techniques for improving Desert Locust monitoring and forecasting on an operational basis (Roffey 1975; Hielkema & Howard 1976).

The experience gained in various developmental programmes in this respect, undertaken by the FAO Plant Protection Service and FAO Remote Sensing Centre, with the cooperation of the FAO Commissions for Controlling the Desert Locust in northwest Africa, the Near East and Southwest Asia as well as the Regional Locust Organizations Desert Locust Control Organization for Eastern Africa (DLCO–EA) and Organisation Commune de Lutte Antiacridienne et de Lutte Anti Aviaire (OCLALAV), resulted in the formulation, development and implementation of the Africa Real Time Environmental Monitoring by using Imaging Satellites (ARTEMIS) system. The formulation and development of this system was a cooperative effort between the FAO Remote Sensing Centre, relevant FAO user divisions, NASA Goddard Space Flight Center (GSFC), the National Aerospace Laboratory of the Netherlands (NLR) and the Universities of Reading and Bristol, U.K., financially supported by the Government of the Netherlands through an FAO Trust Fund. The environmental information requirements of the FAO Global Information and Early Warning System (GIEWS) on Food and Agriculture were also taken into account.

This paper summarizes the development of the use of satellite remote sensing techniques for operational Desert Locust monitoring and forecasting from the mid-1970s to the mid-1980s. Furthermore, it describes the technical characteristics of the ARTEMIS system, its present data-processing capabilities and output products and telecommunications aspects as developed in the Data and Information Available Now in Africa (DIANA) project of the European Space Agency (ESA) in cooperation with FAO.

2. Satellite remote sensing systems for Desert Locust monitoring

The satellite systems carrying sensors with spectral, spatial, temporal and radiometric characteristics suitable for precipitation and vegetation detection and monitoring, including habitat mapping, can be broadly divided in two major groups.

(a) *Environmental satellites*

This group consists of both geostationary and polar orbiting satellites which are characterized by relatively low spatial (1–5 km) and high temporal (30 min–12 hrs) resolutions. The European Meteosat, U.S. Geostationary Operational Environmental Satellite (GOES) and National Atmospheric and Oceanic Administration (NOAA) Satellites and the Japanese Geostationary Meterological Satellite (GMS) belong to this group. The sensors of these satellites were designed for observing atmospheric processes to support weather forecasting, including snowcover and precipitation assessment. Moreover, the Advanced Very High Resolution Radiometer (AVHRR) sensor on the NOAA satellites has spectral and radiometric characteristics suitable for vegetation detection and monitoring. Environmental satellite data allows monitoring of dynamic atmospheric and terrestrial phenomena. Facilities for receiving and processing this type of data are relatively low cost and the spatial characteristics of the data, combined with the orbital characteristics of the satellites, permit simultaneous observations on regional and continental scales.

(*b*) *Earth resources satellites*

This group of satellites is characterized by relatively high spatial (10–80 m) and relatively low temporal (16–18 days) resolutions. The U.S. Landsat, French Satellite Probatoire d'Observation de la Terre (SPOT) and Japanese Marine Observational Satellite (MOS) polar orbiting satellites belong to this group. Their sensor characteristics make them suitable for Desert Locust habitat mapping and for detailed vegetation monitoring at a local scale.

At present, some of the above satellite systems, for example, Meteosat, NOAA, Landsat, SPOT, provide data on a fully operational basis generally within the time constraints of applications requiring realtime or near-realtime data to satisfy user information needs.

3. Remote sensing techniques and methodologies for Desert Locust monitoring

The strategy of Desert Locust plague prevention, which is coordinated and supported by FAO, is based on detection of areas in the vast recession area where enough rain has fallen to create suitable soil moisture conditions and vegetation development for egg laying, hatching and subsequent population development, using the vegetation as a source of food and shelter as well as an agent in the insect's phase transformation into gregarious behaviour. Early detection of these areas, which are highly variable in time and space, allows for effective aerial and/or ground surveys to be undertaken and preventive control of potentially dangerous populations, thus minimizing the use of environmentally dangerous insecticides and preventing the spread of locust populations to agricultural production areas.

Remote sensing of soil moisture in desert regions is possible with microwave sensors (Schmugge 1981) and by thermal techniques (Wetzel & Atlas 1981; England *et al.* 1983). However, no satellite-based soil moisture remote sensing system, using microwave techniques, is currently available on an operational or semi-operational basis for an area the size of the Desert Locust recession area; thermal remote sensing techniques that use Meteosat data are still in the research phase.

Remote sensing of meteorological events that cause soil moisture changes relevant for locust population development, can be undertaken from geostationary environmental satellites, e.g. Meteosat for Africa and the Near East. The high temporal frequency of this type of data in the visible and thermal infrared wavelengths permits detailed monitoring of weather systems likely to produce the rainfall necessary to initiate locust breeding.

Various schools have developed and tested remote sensing techniques for estimating rainfall quantitatively from Meteosat data. FAO has been closely involved in these developments as undertaken by the Universities of Bristol (Barrett 1977, 1980; Hielkema 1980; Barrett & Harrison 1986) and Reading (Milford & Dugdale 1987). The technique developed by the University of Reading, based exclusively on the use of Meteosat thermal infrared data, which was selected by FAO for implementation on the ARTEMIS system, is discussed in detail by Milford & Dugdale (this symposium).

Table 1. Characteristics of four satellite sensor systems with capabilities for vegetation monitoring

characteristic	Landsat MSS	Landsat TM	NOAA/AVHRR	SPOT
spatial resolution	80 m	30 m	1100 m	20/10 m
spectral resolution	4 bands	7 bands	5 bands	3 bands
useful bands for vegetation monitoring	2	4	2	2
radiometric resolution (quantitative levels)	64	256	1024	256
temporal resolution	16 days	16 days	2–3 days every 9 days	9 days
swath width	185 km	185 km	2700 km	92 km
single frame cover	34000 km^2	34000 km^2	2.10^6 km^2	8500 km^2
scenes/orbits required for Desert Locust recession area coverage	700 scenes	700 scenes	7 orbits	2800 scenes

Remote sensing of green vegetation biomass is a well developed technique for which several satellites frequently collect data on a worldwide scale. The technique involves measuring reflected spectral radiance that results from the interaction between the green-leaf vegetation cover and incident solar spectral irradiance. These measurements can be made from any altitude above the surface (1 m, 10000 m, 1000 km) depending on the remote sensing system in question (ground-based, aircraft or satellite, respectively). Spectral estimation of green-leaf biomass generally involves the use of two wavelength regions, the red (0.6–0.7 μm) and near infrared (0.75–1.1 μm), although the specific wavelengths used often vary slightly between instruments. The 0.6–0.7 μm region correspond to the *in vivo* red region of chlorophyll absorption and is inversely related to chlorophyll density. In the 0.75–1.1 μm region, reflectance is proportional to green-leaf density. Ratio combinations of these two wavelength regions thus contain information related to the chlorophyll-green-leaf density (Tucker 1979). Use of these two bands for making plant canopy inferences by non-destructive techniques is facilitated by the proximity of the two bands in the electromagnetic spectrum. This proximity enables simple band ratios or other combinations to be used to compensate for differences in solar flux intensities. Linear or ratio combinations of red/near infrared spectral data have been used to quantify a variety of vegetation types (Tucker 1980; Curran 1983).

The choice of suitable satellites for remote sensing observations for particular applications depends upon satellite spectral, spatial, temporal and radiometric resolutions, orbital considerations and the spatial–spectral–temporal characteristics of the objects to be observed. Successful detection and monitoring of active Desert Locust breeding habitats requires a satellite that can, at any one time, detect the presence of green-leaf vegetation biomass with a suitable spatial resolution over very large areas, while radiometrically maintaining the spectral contrasts of the surface materials, and do so at frequent intervals (Tucker *et al.* 1985) (table 1). Moreover, satellite detection of vegetation cover in desert regions, which normally develops during the rainy season with frequent cloudcover, requires elimination of the latter for obtaining information on presence and amount of vegetation biomass. A technique for compositing cloudfree NOAA AVHRR vegetation index data from multiple daily NOAA orbits was successfully developed and tested by NASA Goddard Space Flight Center (GSFC) (Holben 1986).

Landsat Multispectral Scanner (MSS) data has been evaluated for mapping and monitoring Desert Locust habitats by Pedgley (1973) and Hielkema (1977, 1979, 1980), by using both

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visual and digital image analysis techniques. These studies showed that Landsat MSS data could accurately detect the presence of green vegetation and monitor its phytodynamics. In addition, Landsat MSS data can make an important contribution to the systematic mapping of potential Desert Locust habitats on through visual interpretation of suitably enhanced imagery at a scale of 1:250000. The imagery provides synoptic and yet detailed information on the geomorphology and soil characteristics of an area. At present, FAO is undertaking, following the 1986–1988 Desert Locust plague, a systematic mapping of potential Desert Locust habitats in the recession area, by using a methodology developed by Popov.

The Landsat Multispectral Scanner/Thematic Mapper (MSS/TM) and SPOT sensors were primarily designed to look at agricultural targets, which include many small fields. These sensors have excess resolution for repetitively detecting and monitoring the relevant phenomena of the 16 million km^2 Desert Locust recession area as required.

Moreover, the large number of scenes needed to cover this extensive area makes periodic monitoring with the Landsat and SPOT satellites logistically difficult and prohibitively expensive.

The AVHRR sensor on the NOAA satellites, providing data at 1.1 and 4 km spatial resolutions, is ideally suited for routine and cost-effective monitoring of vegetation development over large areas, such as the Desert Locust recession area. The vegetation monitoring capabilities of the AVHRR sensor in general are extensively documented in Justice (1986). Discussions of the consequences of the sensor's 56 degrees field of view on directional reflectance and atmospheric effects are given in Kimes (1983) and Holben & Fraser (1984), respectively.

The use of data from the AVHRR sensor for detecting and monitoring of active Desert Locust habitats at both resolutions, evaluated against high resolution Landsat and field data, has been developed and tested by Tucker *et al.* (1985) and Hielkema *et al.* (1986*b*) for test areas in West Africa and the Indo-Pakistan region. On the basis of the positive results of these studies, a NOAA AVHRR based vegetation monitoring technique, developed by NASA GSFC in cooperation with the FAO Remote Sensing Centre, was implemented on the operational ARTEMIS system (Hielkema *et al.* 1986*a*).

NOAA AVHRR data is operationally available at 4 km resolution on a global basis from the National Oceanic and Atmospheric Administration (NOAA) in the U.S.A. The full 1.1 km resolution data can be obtained from regional direct readout receiving stations as established in Maspalomas, Canary Islands, Spain; Niamey, Niger; Nairobi, Kenya and Islamabad, Pakistan, thus providing virtual total coverage of the Desert Locust recession area.

4. Artemis system characteristics

The ARTEMIS system, which became operational at the Remote Sensing Centre at FAO Headquarters in August 1988, was conceived and developed as a highly automated, dedicated satellite data acquisition, thematic processing and production system, based on the use of high-frequency Meteosat and NOAA AVHRR data. It consists of a number of integrated hardware and software components, which are summarized as follows (van Ingen Schenau *et al.* 1986).

(*a*) *Hardware*

(i) A Meteosat Primary Data User Station (PDUS) for direct, automated reception of high frequency (hourly), full resolution digital Meteosat data in the visible, thermal infrared and water vapour channels through a three-metre dish antenna, down converter and receiver. The

PDUS is controlled by a dedicated VME 68000 microprocessor and stores data on two 150 Mb disks before transfer of data through an ethernet link to the central system computer for mapping and thematic processing.

(ii) A computer unit consisting of a Hewlett-Packard 1000 A900 minicomputer, supported by a high-speed 6250/1600 bpi tape drive, three disks (132, 404 and 571 Mb), a clock, a system console, a printer and a modem.

(iii) An interactive image analysis workstation, consisting of a Ramtek interface to the HP 1000 A900 with a $1280 \times 1024 \times 16$ bit display memory, a 19-inch high-resolution colour monitor, a graphics terminal with touch screen capability, trackball and a printer.

(iv) An output subsystem, consisting of a hard colour copy camera for 10×15 inch polaroid and 35 mm film products, an HP Vectra microcomputer for IBM PC and ERDAS compatible output on floppy disk, the 6250/1600 bpi tape drive and a six-pen colour plotter.

The ARTEMIS system hardware was recently expanded with a multisync colour monitor and a matrox graphics card. This added capability allows the operation of the Integrated Land and Water Information System (ILWIS) geographic information system software package, which was developed by the International Institute for Aerospace Survey and Earth Sciences (ITC) (Meijerink *et al.* 1988) and implemented on the system in December 1988 for combination and manipulation of ARTEMIS digital data products with data from other sources.

ARTEMIS remote terminal connections within FAO Headquarters, through dedicated lines, linked to microcomputers of users, are currently being established in the Emergency Centre for Locust Operations (ECLO) (IBM compatible PC with IDA/ILWIS software and VGA/Matrox graphics), the FAO Global Information and Early Warning System (GIEWS) (IBM compatible PC with VGA graphics serving a network of microcomputers with IDA software and EGA graphics capability) and the Centralized Geographic Information System (GIS) Group (IBM AT with ERDAS/ArcInfo software). Two additional remote terminal ports to support other in-house users are still available on the present system configuration.

(*b*) *Software*

The ARTEMIS system software can be divided into the following groups, according to function (van Ingen Schenau *et al.* 1986; Hielkema *et al.* 1986*a*).

(i) Meteosat PDUS operating system and communications software for controlling data reception, quality control, quick-look display, data storage and transfer to HP 1000 A900.

(ii) HP 1000 A900 operating system software for operating the computer subsystem and related peripheral equipment.

(iii) Operational applications software for mapping and thematic processing of Meteosat and NOAA Global Area Coverage/Local Area Coverage/High Resolution Picture Transmission (GAC/LAC/HRPT) data and for generation of output products in specific user formats.

(iv) General applications software for image processing for operational and development purposes (NASA GIMMS software).

(v) Database management and communications software for manipulation and integration of various ARTEMIS system databases with other data and for retrieval and archival functions.

(vi) Software for definition and extraction of subarea and point data from the ARTEMIS product database and for archival of raw Meteosat data for point locations.

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5. Artemis data processing

The ARTEMIS system acquires and processes Meteosat thermal infrared data for rainfall estimation, according to the TAMSAT methodology of the University of Reading, chronologically as follows (van Ingen Schenau *et al.* 1988).

(i) Acquisition and pre-processing of Meteosat digital TIR data for Africa and the Near East on an hourly basis through pre-programmed Meteosat PDUS reception schedule and calibration data as provided by the European Space Operations Centre (ESOC), F.R.G.

(ii) At selected daily intervals, at 21h00 and 03h00, activated by the system clock, transfer of available digital Meteosat images to central system computer for processing.

(iii) Image selection for rainfall processing programme by using predefined image quality control parameters.

(iv) Computer mapping of selected images to ARTEMIS common geographic format, i.e. Hammer Aitoff equal area projection and resampling from 5 km input data resolution to 7.6 km ARTEMIS output product resolution.

(v) Execution of programme MIRPOINTS, which extracts digital Meteosat thermal infrared counts for specified point locations (some 1200 meteorological station and other locations in Africa) from available hourly images and archives extracted data in a database.

(vi) Execution of programme HRPRO, involving processing of available, in principle hourly, Meteosat images to determine cold cloud duration (CCD) for each pixel on the basis of satellite calibration data, cloudtop temperature thresholds for specific geographic regions and time intervals between successive images: product: daily cold cloud duration (CCD) images.

(vii) Execution of programme DAYPRO for determination of cumulated cold cloud duration (DCCD) and number of rainfall days (DNRFD) for 10-day periods; stores results in ARTEMIS database.

(viii) Execution of programme DECPRO, which converts 10 day CCD maps into 10-day estimated rainfall (DERF) maps, by using predetermined linear regression relations; stores result in ARTEMIS database.

(ix) Execution of the programme MNTPRO, once a month, which adds the three 10-day DERF and DNRFD maps and stores the created monthly map in the ARTEMIS database; furthermore, this programme compares the estimated monthly rainfall map (MERF) with long-term normal rainfall reference maps and generates absolute and relative rainfall anomaly maps (MRFANABS/REL); stores results in the ARTEMIS database.

The above nine processing steps are executed in a fully automated sequence, primarily during the evening and night hours, thus leaving the system free for other operational and developmental processing tasks during the day.

NOAA AVHRR data for vegetation assessment is acquired by FAO on magnetic tape from two sources:

(i) NOAA AVHRR Global Area Coverage (GAC) (4 km resolution) data, covering Africa, the Near East and southwest Asia, as received by the satellite during daily mid-afternoon overpasses and transmitted to the receiving and archiving facilities of NOAA in Washington D.C. After quality control by NASA GSFC, data are transmitted to FAO by courier and received for thematic processing generally within 7–10 days after data acquisition by the satellite.

(ii) NOAA AVHRR High Resolution Picture Transmission (HRPT) (1.1 km resolution) data, covering West Africa, as received by the ESA receiving station at Maspalomas, Canary Islands. Data are transmitted to FAO by express mail and generally received within 10–14 days after acquisition.

Processing of NOAA AVHRR GAC and HRPT data is done automatically by the ARTEMIS system as follows:

(i) Mapping of channel 1 (red), 2 (near infrared) and 5 (thermal infrared) data of daily available orbits to the ARTEMIS common geographic format projection and resampling of 4 km resolution input data to 7.6 km ARTEMIS product output resolution.

(ii) Calculation of normalized difference vegetation index: ch 2+ch 1/ch 2−ch 1 and identification of cloudcovered areas, by using thermal infrared channel 5 data.

(iii) Generation of 10-day vegetation index composites (DNDVI) by using a maximizing technique on all available daily data.

(iv) Storing of the resulting DNDVI images in the ARTEMIS database.

(v) Once a month, generation of a monthly vegetation index composite (MNDVI) through maximizing three DNDVI images.

(vi) Storing of the resulting MNDVI image in the database.

For processing of the NOAA AVHRR HRPT data at 1.1 km resolution, essentially the same sequence of processing steps is followed. At present, this is not an automated programme and requires operator intervention.

6. Artemis output products for supporting Desert Locust monitoring and forecasting

Since August 1988, the ARTEMIS system produces the following products on a routine basis:

(i) 10-day and monthly cold cloud duration (D/MCCD) maps for the continent of Africa and the Near East, based on hourly Meteosat data.

(ii) 10-day and monthly estimated rainfall (D/MERF) maps for the Southern Sahara, Sahel, Sudanian and tropical countries of West Africa, obtained through regression relationships between CCD and ground observed rainfall.

(iii) 10-day and monthly estimated number of rainfall day (D/MNRFD) maps for Africa and the Near East.

(iv) 10-day and monthly NOAA AVHRR GAC based composite vegetation index (D/MNDVI) maps for Africa, southern Europe, the Near East and southwest Asia.

The above products all have a spatial resolution of 7.6 km and are available in both photographic and digital IBM PC compatible formats.

(v) 10-day NOAA AVHRR HRPT based composite vegetation index maps for the Desert Locust recession area of West Africa.

The above product has a spatial resolution of approximately 1.1 km and has been operationally available from mid-August 1989.

The ARTEMIS vegetation index products at 7.6 km resolution generally reveal only the major development of vegetation, following abundant rainfall, as clearly shown during the 1986–1988 plague in Sudan, Chad, Western Sahara, Morocco, Mali and Niger. This resolution is, however, too coarse for obtaining information on the basis of which detailed itineraries of field survey teams during recession periods can be planned.

The first experiences with the vegetation index product at 1.1 km resolution by the Centralized Desert Locust Reporting and Forecasting Service at FAO Headquarters has been very positive in that at this level of spatial resolution virtually all significant vegetation development in desert areas, relevant for supporting locust population development, is consistently registered, including that present in relatively narrow wadi systems. On the basis of this information, guidance can be provided for the planning of field operations.

7. Developmental research

The 1986–1988 Desert Locust plague, which affected large parts of Africa and the Near East, led to a number of initiatives by FAO, assisted by donor countries, concerning improvement of survey and control methods as well as technical and organizational infrastructures for preventing Desert Locust upsurges. One of these was the formulation and execution of a programme, financially supported by the Government of Belgium, to complete the systematic mapping of potential Desert Locust habitats in the recession area using available historical locust breeding records with Landsat imagery and to undertake a systematic evaluation of the vegetation monitoring capabilities of the NOAA satellites. For the latter programme component, the FAO Remote Sensing Centre jointly with the Plant Protection Service implemented a data collection programme between August and November 1989 in the Tamesna of Niger, consisting of the following activities.

Selection and regular ground monitoring of ecological characteristics and changes of 14 representative field sites using visual and hand-held spectral radiometer observations.

Systematic acquisition of the following satellite data:

NOAA AVHRR GAC data at 4 km resolution (2–3 times, every 9 days)
NOAA AVHRR HRPT data at 1.1 km resolution (2–3 times, every 9 days)
MOS data at 50 m resolution (August and October 1989)
multispectral video remote sensing observations from light aircraft (October 1989).

The acquired data sets are currently being processed to establish a quantitative calibration for NOAA GAC and HRPT data and to define the lower limits of the vegetation detection and monitoring capability of this satellite. The results of this research will be available in April 1990.

8. Satellite telecommunications development: the DIANA project

The ARTEMIS system, being located in Rome, serves primarily the environmental information needs of the Global Information and Early Warning System (GIEWS) and Emergency Centre for Locust Operations (ECLO) of FAO, which communicate analysed information, combined from a number of sources, to recipient and donor countries in the form of telexed summaries and GIEWS and ECLO bulletins and publications.

Rapid communication of the high volume ARTEMIS system information products to users at regional and national levels, requires special communications facilities.

Jointly with the European Space Agency (ESA), the FAO Remote Sensing Centre has formulated a project for the development, implementation and demonstration of a dedicated satellite communications system, DIANA, based on low-cost microcomputer technology and by using the commercial Intelsat satellites through the facilities of Telespazio in Fucino, Italy (Hielkema 1988).

The DIANA system will provide a capability for high speed, two-way transfer of facsimile images of documents and maps, character-coded text documents and digital images in raw or processed form from FAO Headquarters to microcomputer based receiver terminals of users at regional or national level.

This capability will enable regional organizations and national plant protection services to receive processed satellite information and other relevant communications from FAO Headquarters in near-realtime.

The DIANA system, which is funded by ESA member countries Italy, Belgium, Spain, Ireland, Norway, U.K. and Finland, is being developed industrially under ESA management.

This phase will be completed by October 1990, followed by a testing and training period. Subsequently four DIANA terminal stations, linked to the central hub station at FAO Headquarters, will be installed at selected locations in Africa and demonstrated for various applications for the period of one year. Presently confirmed DIANA terminal locations are: Nairobi, Kenya and Harare, Zimbabwe. Candidate locations are Accra, Ghana; Addis Ababa, Ethiopia, and Djibouti, Djibouti.

References

Barrett, E. C. 1977 Mapping rainfall from conventional data and weather satellite imagery across Algeria, Libya, Morocco and Tunisia. AGP/DL/RS/1/77. Rome: FAO.

Barrett, E. C. 1980 An operational method for rainfall monitoring in Northwest Africa. Consultant Report GCP/INT/349/U.S.A. Rome: FAO.

Barrett, E. C. & Harrison, A. R. 1986 Rainfall monitoring by Meteosat in Africa. Consultants Report GCP/INT/432/NET. Rome: FAO.

Curran, P. J. 1983 Multispectral remote sensing for the estimation of greenleaf area. *Phil. Trans. R. Soc.* B **309**, 257.

England, C. E., Gombeer, R., Hechinger, E., Herschy, R. W., Rosema, A. & Stroosnijder, L. 1983 Application of Meteosat data for rainfall, evaporation, soil moisture and plant-growth monitoring in Africa. *ESA J.* **3**.

Hielkema, J. U. 1977 Application of Landsat data in desert locust survey and control. AGP/LCC/77/11. Rome: FAO.

Hielkema, J. U. 1979 Advanced training and research on satellite remote sensing techniques and applications in the United Kingdom and the United States. AGLT/RSU series 2/79. Rome: FAO.

Hielkema, J. U. 1980 Remote sensing techniques and methodologies for monitoring ecological conditions for desert locust population development. FAO/USAID Final Report. GCP/INT/349/USA. Rome: FAO.

Hielkema, J. U. 1988 Operational Environmental Monitoring and Information Dissemination by Satellite at FAO: The ARTEMIS and DIANA Systems: *USAID/NOAA International Workshop on Satellite Techniques for Estimating Precipitation, Washington, D.C., December 1988.*

Hielkema, J. U. & Howard, J. A. 1976 Application of remote sensing techniques for desert locust survey and control. AGP: LCC/76/4. Rome: FAO.

Hielkema, J. U., Howard, J. A., Tucker, C. J. & van Ingen Schenau, H. A. 1986*a* The FAO/NASA/NLR/ARTEMIS system: An integrated concept for environmental monitoring by satellite in support of food/feed security and Desert Locust surveillance. *Proceedings 20th ERIM Symposium on Remote Sensing of Environment, Nairobi, Kenya, December 1986.*

Hielkema, J. U., Roffey, J. & Tucker, C. J. 1986*b* Assessment of ecological conditions associated with the 1980/81 Desert Locust plague upsurge in West Africa using environmental satellite data. *Int. J. Remote Sensing* **6**, 1609.

Holben, B. N. 1986 Characteristics of maximum-value composite images from temporal AVHRR data: *Int. J. Remote Sensing* **7**, 1417–1434.

Holben, B. N. & Fraser, R. S. 1984 Red and near-infrared sensor response to off-nadir viewing. *Int. J. Remote Sensing* **5**, 145.

Justice, C. O. (ed) 1986 Monitoring the grasslands of semi-arid Africa using NOAA AVHRR data: *Int. J. Remote Sensing* **7**.

Kimes, D. S. 1983 Dynamics of directional reflectance factor distributions for vegetation canopies. *Appl. Opt.* **22**, 1364.

Meijerink, A. M. J., Valenzuela, C. & Stewart, A. 1988 ILWIS: The Integrated Land and Watershed Management Information System: *ITC Publication no. 7*. Enschede, Netherlands: ITC.

Milford, J. R. & Dugdale, G. 1987 Rainfall mapping over West Africa in 1986, 1987. Consultants Report GCP/INT/432/NET. Rome: FAO.

Pedgley, D. E. 1973 Testing feasibility of detecting locust breeding sites by satellite. Final report to NASA. London: COPR.

Roffey, J. 1975 Programme plan for improving desert locust survey and control by satellite remote sensing. Consultants report. Rome: FAO.

Schmugge, T. 1981 Remote sensing of soil moisture with microwave radiometers. Paper 81-4503, *Am. Soc. agr. Engng* 1981 Winter Meeting, Chicago.

Tucker, C. J. 1979 Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing Environ.* **8**, 127.

Tucker, C. J. 1980 A critical view of remote sensing and other methods for non-destructive estimation of standing crop biomass. *Grass Forage Sci.* **35**, 177.

Tucker, C. J., Hielkema, J. U. & Roffey, J. 1985 The potential of satellite remote sensing of ecological conditions for survey and forecasting desert locust activity. *Int. J. Remote Sensing* **6**, 127–138.

van Ingen Schenau, H. A., Nicolai, R. J., Venema, J. C., van der Laan, F. B. & Versteeg, M. 1986 System definition of 'Africa real time environmental monitoring using imaging satellites' (ARTEMIS): *National Aerospace Laboratory of the Netherlands* (*NLR*).

van Ingen Schenau, H. A., Venema, J. C., Spaa, J. & Hielkema, J. U. 1988 ARTEMIS System Overview and Presentation of ARTEMIS Products. *Paper ITC/FAO Seminar, 14–25 November 1988, Enschede, Netherlands.*

Wetzel, P. J. & Atlas, D. 1981 Inference of precipitation through thermal measurement of soil moisture. Precipitation measurements from space. Workshop Report, April 28–May 1, 1981, NASA/Goddard Space Flight Center, pp. 170–172.

Discussion

G. B. Popov (*Food and Agriculture Organization of the United Nations*, *Rome*, *Italy*). Appropriate remote sensing techniques have great potential for making surface and aerial scouting for locusts much more efficient. This is important as national and regional control organizations are often hard pressed to scout vast, remote, and potentially infested areas with severely constrained resources. Any objective guidance on the areas most likely to be infested is most valuable for the best allocation of the scarce resources available.

J. B. Williams (*Overseas Development Natural Resources Institute*, *Chatham*, *U.K.*). Migrant pests often inhabit large, remote and inaccessible regions where few people live. Appropriate remote sensing techniques for detecting feeding and breeding and migration areas would clearly be of great advantage for planning efficient aerial and ground surveys for control. To be useful, such techniques need to be accurate, inexpensive, accessible and comprehensible to scientists and decision makers in the field.

Mr Hielkema recognized several years ago that orbiting NOAA satellite 'vegetation indices' and geostationary Meteosat satellite cold cloud/rainfall estimation techniques had much to offer to both crop production and insect pest early warning systems (especially in Africa where the ground observation network is particularly weak). Much to Mr Hielkema's credit he did something about it, and created the centralized ARTEMIS system in Rome from which it is intended that data should be disseminated to a variety of users by satellite in the DIANA project. This comment seeks to evaluate how useful, accurate, accessible, comprehensible and (in)expensive the information so produced really is, and asks to what extent the present system is sustainable.

Useful. Without doubt, prompt and reliable (to a defined degree) regional and local estimates of area rainfall and vegetation change are of the greatest value to Desert (and other) Locust, armyworm and weaver-bird control programmes. In some instances the degree of spatial and quantitative precision required is quite small, and negative (i.e. no rain) information alone can be most useful in itself.

Accuracy. (*a*) Rainfall estimation: there are reservations among the French and British research community, because the methods used by FAO (developed by ODA at Reading) do have limitations and they have not yet been validated in more than half a dozen countries in Africa. (*b*) Vegetation indices are useful for a general view, especially in the more dense biomes, but NOAA (1.1 km maximum resolution) has not yet been shown to be of much value in extremely vegetation-sparse areas where Desert Locusts may thrive. Full resolution images are not available for most of the continent yet.

Accessible. FAO dissemination plans are proceeding: DIANA intends data to reach a much wider user community but duplicates existing WMO dissemination channels. Once regional centres in Niamey, Nairobi and Harare are operational, full resolution images will be more easily available. A major question concerns the best routing of this data into national systems where operational decisions are taken.

Comprehensible. At present, few users understand the value and limitations of the images (especially the vegetation maps). When they do use them they tend to believe them as 'gospel'. Then they find that there are errors, and reject the baby with the bathwater. FAO is organizing short training courses but through Remote Sensing Centres, which tend to concentrate on mapping rather than meteorology. The images do need interpretation and workers in agricultural departments do not always have the training or experience to be able to cope with regional/synoptic scales. Meteorological departments provide an obvious route, but applied meteorology is an area where FAO and WMO have joint responsibility and where cooperation frequently leaves much to be desired.

Cost. The costs of producing satellite receiving systems are now very low (and are becoming available to departments in developing countries: portable systems will be available shortly) and running costs can be negligibly small. If the information is accurate, accessible and comprehensible it is an extremely cost effective way of estimating areal rainfall and vegetation development, and can easily be undertaken *in situ*, with the added benefits of national participation in product development. Collaboration between national, regional and continental operations is essential.

Sustainable. Continental and Regional centres (apart perhaps from DLCO-EA) do not have a happy record in Africa. Many national meteorological observing networks have never been weaker. Satellite observations are not yet sufficiently good to replace ground stations: the two methods are most powerful in their complementarity, and must be seen to be so. If the ARTEMIS/DIANA system is to be sustainable and effective it will have to focus more on improving product acceptance and use at national level in conjunction with indigenous meteorological services. Some of the difficulties experienced in establishment of the regional centres in Africa reflect the weakness of a glossy, external, top-down approach to what are sensitive national issues. More cooperation between FAO and WMO is urged.

J. Hielkema. In reply to Dr Williams, I can assure him that there has been contact between FAO and WMO about the developments envisaged in DIANA and there will be even greater collaboration in the future. The ARTEMIS project is preparing an active training programme for national participation through their regional centres in Nairobi and Harare.

R. W. Saunders (*Meteorological Research Flight, Y46 Building, Royal Aerospace Establishment, Farnborough, Hants, U.K.*). First, I must underline the importance of the ARTEMIS system described by Mr Hielkema as being operational. It is a major step forward to have a system that can be used for monitoring meteorological and surface parameters from satellite data on a daily basis throughout the year, and this takes a great deal of effort to implement. This is reflected in the U.S. $2 million cost of the system.

However, when interpreting the parameters derived from ARTEMIS, one should bear in mind the limitations of the retrieval algorithms used to derive those parameters. For instance, for the normalized vegetation index derived from AVHRR data to be valid, a cloud free and aerosol free atmosphere between the satellite and the surface must be assumed. Other workers have shown spurious vegetation indices derived from AVHRR data due to inadequate cloud clearing of the data, viewing angle effects or high atmospheric turbidities. In addition water vapour absorption is significant in AVHRR channel 2 ($\sim 90\%$ transmittance) and this varies with total column water amount. Are you confident that your cloud clearing scheme is adequate and do you correct for viewing angle effects and water vapour absorption? Do you find the occurrence of Saharan dust limits the availability of the Normalized Difference Vegetation Index (NDVI) product over northern Africa?

Finally, I believe that the inclusion of passive microwave data from the new generation of atmospheric sounders due in 3–4 years time should be considered for the ARTEMIS system. These data have the potential at least to improve the rainfall estimates presently derived only from the Meteosat infrared data.

J. Hielkema. In reply to Dr Saunders' point, I accept that the limitations that you have raised are real, but they are not usually important at the operational scale generally used by ARTEMIS. We are looking at ways, such as the use of passive microwaves, to improve the system.

J. R. Milford (*Department of Meteorology, University of Reading, U.K.*). I congratulate Mr Hielkema on his achievement in getting the ARTEMIS system to its operational status in the face of considerable difficulties over a long period since its conception.

Mr Hielkema quoted one figure showing the success of the rainfall estimates produced by the system, and this sounded impressive. However, much more detail is needed to show whether the estimates were actually able to provide the information needed by a specific user with adequate reliability. The evaluation of such estimates (as of weather forecasts) is difficult to carry out objectively, and I feel that much more needs to be done to establish the viability of these deductions from satellite data. Each of us tends to be satisfied as soon as we have the result which we wanted to show, and truly objective assessments are rare.

Another feature of the ARTEMIS programme as reported here is that the products are still some way from the end-user. The DIANA system will provide a major step forward, but there is still a reluctance to integrate the outputs with other meteorological information, and, indeed, to work sufficiently closely with meteorological organizations generally.

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