WORLD METEOROLOGICAL ORGANIZATION

AGRICULTURAL METEOROLOGY

CAgM REPORT No. 50

PART I - Operational Remote Sensing Systems in Agriculture

by

E.T. Kanemasu and I.D. Flitcroft

Part II - Applications des satellites en agrométéorologie

Développements technologiques pour la période 1985-1989

Satellite Applications to Agrometeorology - Technological developments for the period 1985-1989

par/ by

Bernard Seguin

Part III - The Use of Satellite Information in

Agricultural Meteorology

by

A.D. Kleshchenko

(CAgM-IX Rapporteurs on Developments in Operational
Remote Sensing)

WMO/ID-No. 508

Geneva, October 1992
This report submitted to the tenth session of the Commission for Agricultural Meteorology was prepared prior to the political changes in the former USSR. The name USSR has therefore been maintained throughout this publication.

"This report has been produced without editorial revision by the WMO Secretariat. It is not an official WMO publication and its distribution in this form does not imply endorsement by the Organization of the ideas expressed."
PART I - Operational Remote Sensing Systems in Agriculture

by

E.T. Kanemasu and I.D. Flitcroft
This report has been produced without editorial revision by the WMO Secretariat. It is not an official WMO publication and its distribution in this form does not imply endorsement by the Organization of the ideas expressed. The designations employed and the presentation of material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the World Meteorological Organization concerning the legal status of any country, territory, city or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.
Operational Remote Sensing Systems in Agriculture

by I.D. Flitcroft and E.T. Kanemasu

1 Introduction

The advent of satellites has provided the means to monitor the earth's surface regularly and objectively. The large variety of sensors flown today (Asrar, 1989) provide signals with a range of spectral, spatial and temporal resolutions. Different sensors receive radiation over differing bandwidths and those which sense in a narrow band of the spectrum have either poor spatial resolution (pixel size) or return to an area on the globe infrequently. There is thus no ideal satellite system for use in agricultural production and related activities. The dynamic nature of vegetative growth in many regions of the world, particularly in water limited regions has led some groups to use low spectral and spatial resolution satellite sensors to assess agricultural conditions over large regions of the world. Satellites carrying the NOAA - AVHRR sensors, and the geostationary satellites are able to view the scene of interest relatively frequently (several times per day) and can therefore be used to monitor rapid changes in the state of the vegetation.

A survey of government, university and other groups using remote sensing data to estimate aspects of agricultural production such as yield, land area, crop condition, irrigation requirements, leaf area index, moisture stress etc., shows that very few use products from routinely captured remote sensing data to make operational decisions related to agriculture. Two groups have been identified, namely the Foreign Agricultural Service (FAS) of the US Department of Agriculture (USDA) and the ARTEMIS system for Global Information and Early Warning System (GIEWS) of the FAO in Rome, through the FAO ARTEMIS system. In addition there are several groups such as the AGRHYMET centre in the Republic of Niger and the Famine Early Warning System (FEWS) group set up by USAID, who use remote sensing data (in their agrometeorological bulletins) but do not make decisions based on such data. The information collected by these organisations is disseminated to
many decision makers in government and non-government organisations as well as other interested groups. It is not clear to what extent the information which these groups deduce from satellite data is used to make decisions related to agriculture. Furthermore, the types of satellite data obtained and the methods of processing the data differ only in detail from those of the groups whose operations are described in detail below.

No group or individual was identified who uses satellite based information (other than weather forecasts supplied by the media) to make decisions directly related to agricultural production.

A description of the satellite data used by FAS and FAO, subsequent processing and the type of products produced are described in this paper.

2 FAS System

The FAS system uses the MSS bands on LANDSAT and the AVHRR bands on the NOAA series of satellites to create image and single pixel measurements of a variety of vegetation indices. Loading and initial processing of the image data from both satellites is handled by a VAX8800 which serves four processing and analysis systems consisting (with minor differences) of four IVAS I^2S image processors, and four I^2S model 675 computers with maths co-processor and monitor for data manipulation. The IVAS image processors have a monitor resolution of 1024 × 1024 pixels and are used for viewing and registering images. A third monitor is used to display single grid cell data, meteorological and other data which are stored on the VAX8800.

2.1 Satellite Data Collected

NOAA AVHRR

Channels 1 and 2 of the AVHRR radiometers aboard NOAAs 4 to 11 have been used to aid in crop production since 1980. Full
resolution data is collected at the World Weather Building in Suitland and a tape is cut which provides coverage of India, China, the Soviet Union, Eastern Europe, Brazil, Argentina, Australia and the U.S. East of the Rockies. From each scene the central one thousand lines are extracted and used to build a composite frame of 1024 by 1024 pixels. By discarding pixels which are viewed off nadir, excessive ambiguities due to variations in sensor view angle are avoided but complete coverage of the scene (which may include cloud) is only achieved every nine days.

The tape cut at Suitland is sent to FAS where cloud screening and data quality is performed automatically on the VAX8800. Pixels with digital numbers (DN) above 255 on channel one are discarded as these are indicative of either rocky areas or cloud contamination. Two vegetation indices are calculated for each remaining pixel and each of these indices is gridded onto a cell which is approximately 40 km by 40 km. The average vegetation index over the grid cell is calculated using pixels with a positive EVI greater than 23 (see below) to yield the value which is stored in the GIS. The vegetation indices are

\[
\text{NDVI} = \frac{\text{Ch2} - \text{Ch1}}{\text{Ch2} + \text{Ch1}}
\]

\[
\text{DVI or EVI} = \text{Ch2} - \text{Ch1}.
= 0 \text{ when } (\text{Ch2} - \text{Ch1}) < 23 \text{ counts}
\]

Time series of the indices for grid cells are stored in the GIS and comparisons between years for one or many boxes can be shown graphically to allow subjective comparisons to be made between years and across regions within one year.

Little of the image data is archived and a matrix camera is used for obtaining hard copies of images displayed on the image processor.

Landsat MSS

The Goddard Space Flight Centre (GSFC) have been contracted
to provide FAS with all four bands of Landsat MSS data since 1978. Data costs are presently about $2.5M a year. Initial processing of a tape from the raw data by GSFC includes cloud screening and selecting areas of interest to FAS, which are those countries listed in the section above.

Further processing of the imagery is done by FAS using the same techniques as are used for the Metesat imagery. A number of vegetation indices are calculated from various bands of the Landsat imagery. These indices were developed specially for FAS to estimate the areas of individual crops in a scene. Similar work is sometimes conducted by cluster classification analysis.

All full frames are sub sampled to 5 by 5 pixel blocks from which the average greenness and the number of green pixels are calculated for each grid cell. Full resolution samples are also used.

2.2 Use of satellite products in decision making

The foreign Agricultural Service provides forecasts and estimates of grain and other food production in several countries. The information used to make forecasts and deduce yields must be both timely and credible which has led to a substantial dependence on the use of satellite data to provide subjective indicators of yields which are interpreted by skilled analysts. Comparisons against the vegetation indices and corresponding yields of the years 1978 to the present allow analysts to make predictions of production shortfalls or good harvests on a regional scale. When an unusual feature appears in the vegetation indices derived from either satellite both data sets are analysed more extensively to interpret the anomaly.

Meteorological data (humidity, rainfall, temperature, wind, global radiation) from the GTS network are used to drive crop production models for some of the crops. Cereal production is estimated using an adaptation of the CERES model (Ritchie and Otter, 1985) and the results from the model are used within season to predict poor yields due to adverse meteorological conditions. The Landsat data plays a role here in helping to determine, for a region, the acreage under different crops.
3 Food and Agriculture Organisation (FAO) ARTEMIS System

3.1 Introduction

Beginning in 1976, the remote sensing centre of the FAO of the United Nations has been using products derived from satellite data to improve the capabilities of the FAO's Global Information and Early Warning System (GIEWS) on food and agriculture and to aid their Desert Locust Plague Prevention Programme. The ARTEMIS system (Africa Real Time Environmental Monitoring using Imaging Satellites), which was implemented in 1988, is designed to provide near real time assessments of vegetation and precipitation in Africa, the Near East and South West Asia, using Meteosat and NOAA AVHRR data. The system was developed in conjunction with NASA Goddard Space Flight Centre, the National Aerospace Laboratory (NLR) of the Netherlands and the Universities of Reading and Bristol.

3.2 Hardware and Software

The ARTEMIS system was developed to handle two streams of satellite data and to process these data to provide decadal rainfall estimates and to monitor vegetation status.

Rainfall: To estimate decadal rainfall and the number of events, hourly images from the thermal infra-red channel of Meteosat are received and processed into decadal and monthly maps. The methods to derive rainfall have been developed by the TAMSAT group in the department of Meteorology, University of Reading (Milford and Dugdale, 1990a) and are described in section 3.3.

Vegetation: Global Area Coverage data from the AVHRR on the NOAA satellite series is obtained jointly with the Global Inventory, Modeling and Monitoring Systems (GIMMS) group at NASA Goddard Space Flight Centre (Tucker et al., 1985). Data covering Africa and Southwest Asia are processed by FAO to produce maps of the
maximum Normalised Difference Vegetation Index (NDVI) over ten days and over months. Details of the processing of these maximum value composite maps are given in section 3.4.

The ARTEMIS system is comprised of a number of hardware and software components which receive and process the two main streams of data:

- A Meteosat primary data user station (PDUS) which receives full resolution digital Meteosat data in the visible, thermal infra-red and water vapour channels via a three metre dish antenna and receiver, controlled by a dedicated VME 68000 microprocessor. A quick look display is available as well as quality control software.

- A Hewlett-Packard 1000 A900 minicomputer, with two gigabyte of disk storage and two 6250/1600 b.p.i. tape drives.

- A 19 inch high resolution colour monitor, graphics terminal, printer and other image processing hardware is linked to the HP 1000 A900.

- A colour hard copy camera and 6 pen colour plotter provide hard copies of images.

- Applications software has been developed by the NLR of the Netherlands (Van Ingen Schenau et al., 1988) to process and map Meteosat and NOAA AVHRR data into a common geographic format (Hammer Aitoff equal area projection) and to generate products in particular formats for specific users. Management of the database and the integration of various archived products with current data is also achieved with software developed by NLR.

The hardware is linked to terminal connections in GIEWS and the Emergency Centre for Locust Operations (ECLO) to provide other groups in FAO access to the database and image products, for further analyses on microcomputers. The ARTEMIS hardware connections are summarised in figure 1.
3.3 Rainfall estimation

A rainfall estimation technique developed by the TAMSAT (Tropical Agricultural Meteorology using SATellite and other data) group at the University of Reading is being used to create decadal and monthly rainfall maps for Africa. The method uses the duration of cold cloud over individual pixels, below some locally defined temperature threshold (usually between 213 and 233K), to estimate the corresponding rainfall for the period considered. The choice of threshold and the regression equation coefficients used, are determined from comparisons between rainfall measured in conventional gauges and the cold cloud durations for the pixels which contain those gauges. There is considerable error in the estimation of daily rainfall using this method but when averaged over several events the relationships improve and appear to be stable for particular areas between years (Milford and Dugdale, 1990a). The method is therefore suited to decadal or monthly estimation when the large variability in the cold cloud to rainfall relationship for a single event is reduced by averaging over many events.

The methodology described above has been implemented in the ARTEMIS system as follows (figure 2):

- Meteosat digital TTR data are acquired hourly through the automated PDVS and transferred twice daily to the central computer (RFPRO). Temperatures are calculated from raw pixel counts (8 bit data) to a temperature using calibration coefficients inserted in the header of each image transmitted by Meteosat.

- Images with missing lines are rejected automatically and accepted images are mapped to the Hammer Aitoff equal area projection (Van Ingen Schenau et al., 1988).

- The available imagery is processed to determine the cold cloud duration (CCD) for each pixel for a day (DAYPRO).

- The number of rain days and the cumulated CCD are calculated using DAYPRO and at the end of a dekad (ten days) DECPRO is used
to convert the cold cloud duration map to a decadal rainfall map using predetermined linear regression coefficients (APARM and BPARAM).

A programme called MNTPRO is used to add the decadal quantities (CCD, rainfall and number of cold cloud events) to monthly totals. These monthly maps are compared with climate reference values to create absolute and relative rainfall anomaly maps.

The decadal and monthly rainfall products derived from the cold cloud duration method have been tested against other methods on a set of rainfall data from 50 raingauges in the Republic of Niger, for July 1986. The test showed that estimates based on the automated collection of CCD using high frequency imagery corresponded much better with gauge rainfall than those obtained through analysis of Secondary Data User System (SDUS) data (Snijders, 1988).

3.4 Vegetation Indices

The Global Inventory, Modeling and Monitoring Systems (GIMMS) group at NASA Goddard Space Flight Centre is using NOAA AVHRR data to derive a vegetation index (the NDVI) with global coverage every 2-3 days. The NDVI is calculated using the following band combination:

\[
\text{NDVI} = \frac{\text{Channel 2} - \text{Channel 1}}{\text{Channel 2} + \text{Channel 1}}
\]

and the index is derived from Global area coverage (GAC) data which is produced by on-board resampling of the full resolution data to a resolution of 3 by 5km (Justice, 1986). Tapes of the GAC data are sent from NASA Goddard Space Flight Centre to the FAO centre as they are produced.

The high temporal frequency of the mapping is ideally suited for monitoring the rapid changes in the green vegetation state during the Sahelian wet season. Clouds reduce the observed NDVI and to eliminate their effect the maximum NDVI over each pixel for
a period of ten days is taken. The NDVI also varies with sun
zenith and satellite look angles but the effect of compositing is
usually to eliminate off nadir satellite passes (Holben, 1986).
Recent work by Holben et al. (unrefereed manuscript) has shown
that there has been considerable drift in the sensitivity of the
AVHRR aboard NOAA 9 and 11, and this effect must be accounted for
if NDVI values are compared between seasons. Cloud clearing is
also undertaken using a thresholding technique with imagery from
the thermal infra-red channel of the AVHRR radiometer. The NOAA
AVHRR data processing software as developed by the GIMMS group has
been implemented on the ARTEMIS system by NLR and integrated with
the Meteosat data processing software.

The FAO remote sensing centre has developed and tested the
use of the NDVI for assessing crop conditions and rangeland
productivity. Areas which could support the explosive growth of
desert locusts populations might be pinpointed using a combination
of the vegetation index and Meteosat derived rainfall estimates,
because it is thought that locusts lay their eggs and these hatch
in numbers when the soil holds water equivalent to about 20mm of
rainfall (for sandy soils). The soil moisture is also necessary
to allow vegetative growth which the young locusts can feed on
(Hielkema, 1980, Milford and Dugdale, 1990b).

3.5 ARTEMIS database

The thematic maps of decadal and monthly vegetation index,
which are archived on computer tape, cover two areas;

Africa  18°W, 52°E : 38°N, 35°S.
Southwest Asia  50°E, 95°E : 40°N, 0°N.

Decadal, monthly and monthly anomaly rainfall maps are produced
and archived for the African continent only. Each of the maps is
stored in a single file and is made up of 1280 by 1024 pixels,
with a pixel size of 7.6 km. Similar maps containing soil and
climate information are also stored in the database, to be used
for reference and calibration.

In addition to the CCD, rainfall, rainfall anomalies and NDVI
maps a few experimental products have been produced. The crop
moisture availability map is derived from a water budget which has been developed by FAO using decadal rainfall and the number of rain days as input. A map of potential breeding activity is also being developed; it is derived from the current NDVI map and a reference map of desert locust habitats.

The thematic maps in the database, the area they cover and the duration of archiving are shown in the table below.

<table>
<thead>
<tr>
<th>THEMATIC MAP</th>
<th>FROM</th>
<th>AREA COVERAGE</th>
<th>DEKAD MONTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Cloud Duration</td>
<td>1988</td>
<td>Africa</td>
<td>*</td>
</tr>
<tr>
<td>Estimated rainfall</td>
<td>&quot;</td>
<td>&quot;</td>
<td>*</td>
</tr>
<tr>
<td>No. of rainfall days</td>
<td>&quot;</td>
<td>&quot;</td>
<td>*</td>
</tr>
<tr>
<td>Absolute and relative</td>
<td>&quot;</td>
<td>&quot;</td>
<td>*</td>
</tr>
<tr>
<td>rainfall anomalies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop moisture availability</td>
<td>exp</td>
<td>&quot;</td>
<td>*</td>
</tr>
<tr>
<td>NDVI</td>
<td>1979</td>
<td>Africa/S.W. Asia</td>
<td>*</td>
</tr>
<tr>
<td>Potential breeding activity factor</td>
<td>exp</td>
<td>Africa</td>
<td>*</td>
</tr>
</tbody>
</table>

(from Van Ingen Schenau et al., 1988)

The ARTEMIS database is the principal source of products generated by special or routine requests. Products include the map data, extracted areas or single pixel data which are all available to users at FAO headquarters and to the national and regional institutes in Africa.

4 Conclusions

A concise description has been given of the activities of two agencies which use remotely sensed data routinely to aid in decision making. The products derived from the satellite data are used by the respective agencies to provide forecasts and assessments of crop, pasture and soil moisture conditions in various regions of the world. The costs of acquiring the data are considerable in the case of the USDA’s FAS, but this reflects the
amount of data which is processed and the lack of viable alternatives.

Both agencies use satellite derived products because these are the only means of assessing the vegetative (whether crop, pasture, forest etc.) conditions over large regions, objectively and in near real time. At present there is no competing method of obtaining such information quickly and with comparable spatial coverage. However, the feature of interest can hardly ever be observed directly by satellite, but has to be deduced, usually through models of varying complexity and empiricism. Uncertainties are thereby introduced and these are compounded by the contamination of the received signal by the intervening atmospheric gases, clouds, aerosols and other particles.

The estimates of various surface properties from satellite data are often made using the signals from more than one radiometer. The information which can be acquired on a routine basis is restricted by the limit to the data stream which can be transmitted and also the limits to subsequent handling and processing of that data stream. As a result the information acquired will not be as impressive as that found in papers describing the results of case studies and specific research (Milford, 1989).

Nevertheless, the information which can be gathered from satellites is sufficiently reliable and precise to be useful in making some decisions related to agricultural activity. The regions of concern are large and it is difficult to obtain the information by other means, due to poor communications and inadequate ground observations, or for political reasons.

Future generations of satellites which will carry sensors covering many narrow bands may provide means of improving satellite based estimates of surface features. It remains to be seen to what extent they will be used in agricultural decision making.

5 References

Asrar, G. (ed.) 1989: Theory and applications of optical remote
sensing. Wiley and sons.


Ritchie, J. and Otter, S., 1985: Description and performance of CERES wheat: a user oriented wheat yield model. USDA-ARS, ARS-38, 159-175.


Figure 2. Rainfall processing overview
(from Van Ingen Schenau et al., 1988).
Part II - Applications des satellites en agrométéorologie
Developpements technologiques pour la période 1985-1989*
Satellite Applications to Agrometeorology - Technological
developments for the period 1985-1989

par/by

Bernard Seguin

* English translation of the French version also included.
Le présent rapport n'a pas été révisé par le Service d'édition du Secrétariat de l'OMM. Il ne s'agit pas d'une publication officielle de l'Organisation météorologique mondiale et sa diffusion sous cette forme n'implique de sa part aucune prise de position quant aux idées qui y sont exprimées. Les désignations utilisées dans cette publication et la présentation des données qui y figurent n'impliquent de la part du Secrétariat de l'Organisation météorologique mondiale aucune prise de position quant au statut juridique de tel ou tel pays ou territoire, ou de ses autorités, ni quant au tracé de ses frontières.
RAPPORT POUR LA COMMISSION DE METEOROLOGIE AGRICOLE DE L'OMM

Applications des satellites en agrométéorologie
Développements technologiques pour la période 1985-1989

Bernard Seguin
INRA - Station de Bioclimatologie
BP 91
84143 Montfavet Cédex (France)

Introduction

A l'occasion de la précédente session de la Commission de Météorologie Agricole, j'avais été amené à rédiger un rapport bibliographique relativement exhaustif (81 pages et 169 références), faisant le point sur l'évolution des recherches dans le domaine de l'application des satellites en agrométéorologie, à partir des travaux publiés jusqu'à fin 84.

Le partage des tâches entre les trois rapporteurs désignés par la 9ème session (Dr E. Kanemasu, Dr A.D. Kleschenko et moi-même) se traduit logiquement pour moi par l'actualisation de ce document, de manière à analyser l'apport des développements récents, qui couvrent donc la période 1985-1989.

Pour des raisons évidentes de conformité de présentation, ceux-ci seront présentés suivant le même plan que pour le document de 1986, et comportera donc les points suivants :

I. Apport aux données climatiques
   a) Le bilan radiatif
   b) La température
   c) Le bilan hydrique

II. Apport au suivi des cultures
   a) Occupation du sol et surfaces cultivées
   b) Estimation du rendement
I. APPORT AUX DONNÉES CLIMATIQUES

Il résulte de l'utilisation des satellites météorologiques, soit géostationnaires (METEOSAT, GOES, etc...) soit à défilement (série des NOAA, équipés du radiomètre AVHRR).

A. Le bilan radiatif

1. Le rayonnement solaire

L'estimation du rayonnement solaire à partir de la télédétection, essentiellement dans l'objectif de permettre une interpolation spatiale permettant une meilleure résolution que celle du réseau au sol, n'a pas fait l'objet d'avancée particulière en ce qui concerne les méthodes. Celles-ci (qui associent des approches indirectes à partir de la fraction d'isolation et des approches directes en utilisant les lois du transfert radiatif) avaient été élaborées précédemment [1][2][4][5][6][7], et c'est donc plutôt l'évaluation de ces méthodes et leur évolution vers l'opérationnalité [3] qui a fait l'objet principalement des travaux récents.

L'évolution vers des systèmes opérationnels (pouvant s'appuyer sur un système léger combinant réception et traitement par microordinateur) se confirme donc, avec des perspectives d'estimation du rayonnement solaire journalier avec une précision de l'ordre de 10%.

2. L'albédo

L'évolution est assez semblable (certaines méthodes pouvant d'ailleurs servir aux deux objectifs [7][2]) : les dernières années ont surtout vu progresser la fiabilité des estimations, en incorporant à la fois les effets de correction atmosphérique, le passage de réflectances bidirectionnelles aux albédo hémisphériques et de mesures spectrales à l'albédo sur l'ensemble du spectre. Les estimations obtenues [8][10], en particulier sur l'Afrique [2][9][11], permettent d'évaluer la précision actuelle sur l'albédo à ± 0.05.
3. Le bilan radiatif

Le passage du rayonnement solaire au rayonnement net, compte-tenu de la connaissance de l'albédo, suppose la prise en compte des rayonnements de grande longueur d'onde [7].

Le rayonnement terrestre, qui est celui mesuré par les capteurs dans l'IR thermique, ne doit pas poser de problèmes très difficiles, à partir du moment où la correction atmosphérique est prise en compte (et par ciel clair évidemment). Le problème du passage de la mesure instantanée à l'échelle journalière est en bonne voie.

Par contre, l'estimation du rayonnement atmosphérique descendant est encore assez peu abordée. Il devrait être possible de le déduire des profils de température de d'humidité du sondeur TOVS de NOAA, avec une précision de l'ordre de 5 à 10% [12]. On peut aussi utiliser plus classiquement les formules climatologiques courantes, en s'appuyant sur les satellites géostationnaires pour approcher les variables mises en jeu [13]. Au total, on peut ainsi espérer estimer et cartographier le rayonnement net avec une précision variant entre 15 et 20%.

B. La température

L'obtention de la température de surface à partir des mesures satellitaires dans l'IR thermique, déjà bien abordée pendant la phase précédente, a progressé au niveau de la précision des estimations par l'amélioration de la prise en compte des corrections atmosphériques et de l'émissivité [14] [15] [23] [24], en particulier en ce qui concerne l'ajustement des coefficients de la méthode de combinaison linéaire (split window) des canaux 4 et 5 de NOAA-AVHRR [14] [20] [21] [22] [24]. A l'heure actuelle, on peut ainsi espérer obtenir une précision de l'ordre 2 à 3° (en valeur absolue) sur la température des surfaces naturelles.

Les données ainsi recueillies ont fait l'objet de certaines études agroclimatiques, en particulier pour la cartographie des zones atteintes par le gel à partir des thermographies nocturnes [16] [19] [25] ou de la structure de certaines régions agricoles en fonction de l'occupation du sol ou des gradients climatiques [17] [18] [26]. Les études topoclimatiques sont pratiquement absentes, sans doute à cause de la résolution insuffisante de NOAA. Le canal thermique de LANDSAT-TM, avec ses 120 m environ de résolution, devrait faire l'objet de travaux plus nombreux dans un proche avenir.
Par ailleurs, l'utilisation de l'IR thermique en relation avec l'alimentation hydrique des couverts végétaux reste la principale source d'applications de l'estimation de la température de surface : elle est développée dans le prochain paragraphe.

C. Le suivi du bilan hydrique

Il fait intervenir, d'une part l'estimation de la pluviométrie, d'autre part celle de l'humidity du sol ou de l'évapotranspiration à partir de mesures satellitaires.

1. La pluviométrie

La possibilité d'estimer la pluviométrie au sol à partir de la télédétection a continué à faire l'objet de nombreux travaux... et aussi d'avis contradictoires. Nous nous contenterons donc de mentionner quelques références significatives parmi les nombreuses publications et conférences spécialisées, en indiquant les principales tendances qui en ressortent [27].

Le suivi des images à partir de satellites géostationnaires, et en particulier de ceux à sommet froid (avec un seuil de -40° ou -60° suivant les cas) identifiés dans l'IR thermique permet d'obtenir des estimations relativement satisfaisantes (± 25%) pour des périodes de temps longues (de l'ordre de la saison des pluies ou du mois), en particulier lorsqu'il est associé avec l'analyse de la température du sol en ciel clair [28]. Le suivi d'épisodes plus courts [29][30] donne des résultats encourageants, mais devrait faire l'objet d'analyses plus approfondies sur l'évolution de la forme des images précipitantes. C'est l'objet de plusieurs programmes internationaux (ISCCP, HAPEx) en cours ou prévus, en particulier sur le territoire africain.

Les travaux à partir de microondes passives (capteur MSU sur les satellites NOAA, avec une résolution de l'ordre de 100 km et en perspective le capteur amélioré AMSU à partir de 1993, avec des résolutions de 50 à 20 km) ouvrent d'autres possibilités, en cours d'analyse. La combinaison du suivi par les domaines visible, IR thermique et microondes devrait faire l'objet de développements intéressants au cours des prochaines années.
2. Humidité du sol et évapotranspiration

L'humidité du sol, essentiellement accessible à partir du domaine des microondes, a surtout fait l'objet d'évaluations à une échelle très large (supérieure à 100 km) à partir du capteur SMMR sur Nimbus 7 à 37 GHz [33] [34] [37] [41] [42], qui permet ainsi d'obtenir des informations globales sur la situation climatique et hydrologique.

A échelle plus fine, si les études au sol, tant sur les microondes passives qu'actives (radar) ont permis d'approfondir les connaissances sur les relations entre les signaux mesurés et l'humidité du sol, l'absence de capteurs satellites adéquats ne permet pas encore de juger des applications en agrométéorologie. Il faudra attendre au minimum l'arrivée d'ERS-1 en 1991 (bien qu'il soit plutôt destiné aux applications sur mer) pour obtenir une première évaluation.

C'est donc essentiellement l'infrarouge thermique qui fournit l'essentiel des informations dans ce domaine, en permettant d'accéder au calcul et à la cartographie de l'évapotranspiration à partir du bilan énergétique et à l'humidité du sol par le biais de l'inertie thermique.

Ce domaine a fait l'objet d'un grand nombre de travaux tant sur le premier plan [31] [35] [38] [39] [40] [43] [44] [47] [48] [49] que sur le deuxième [36] [50].

La méthodologie a donc notablement progressé, mais essentiellement à partir d'études spécifiques portant sur des journées particulières, avec des échelles de temps ne dépassant guère 24h. Au niveau purement agrométéorologique, il est nécessaire de prendre en considération des périodes plus longues (passage à la décade, puis au mois), ce qui suppose de mettre au point des méthodes simplifiées s'appuyant sur un minimum de données accessoires. Une telle démarche est envisageable, et permet d'obtenir des estimations de stress hydrique de nature comparable à celles obtenues par modélisation au sol, mais avec l'atout de l'interpolation spatiale permise par les durées satellitaires [44] [45] [46]. La précision obtenue sur l'évapotranspiration réelle ETR est alors de l'ordre de ±1mm/j. A noter également la possibilité de cartographier la variation spatiale de l'évapotranspiration maximale ETM, à partir de l'identification des couverts végétaux et de l'estimation du coefficient cultural en relation avec les réflectances [32].
II. APPORT AU SUIVI DES CULTURES

Ce domaine a considérablement progressé, au cours de ces dernières années, à partir des éléments suivants :

- le développement important de programmes de suivi global de la végétation et des cultures à partir de NOAA-AVHRR (à des échelles allant de 1 km pour les données LAC à partir des stations de réception, 4 km pour les données GAC enregistrées et environ 20 km pour les données GVI synthétisées par NOAA).

- L'évolution des possibilités au niveau des satellites d'observation de la terre, avec des résolutions de 30 m pour LANDSAT-TM et 20 m pour SPOT et la disponibilité de séries multitemporelles par ce dernier satellite (depuis 1986) grâce au système de dépouillement avec visées latérales permettant la programmation des scènes à acquérir.

- La mise au point de procédures analytiques pour l'estimation de la biomasse (et ultérieurement du rendement) s'appuyant sur le formalisme prenant en compte l'absorption du rayonnement photosynthétiquement actif (PAR) absorbé par le couvert végétal.

\[ MS = \sum \epsilon_b \times \text{PAR}_a \]

où le PAR absorbé (\text{PAR}_a) est converti en matière sèche MS par l'efficience de conversion \( \epsilon_b \), \( \text{PAR}_a \) pouvant être calculé par la relation :

\[ \text{PAR}_a = \epsilon_i \times \text{PAR} \]

Le PAR peut être déduit du rayonnement solaire \( R_g \) par le biais du coefficient \( \epsilon_c \)

\( \text{PAR} = \epsilon_c \times R_g \), connu à partir des caractéristiques climatiques du site.

La télédétection intervient alors par l'estimation de l'efficience d'interception \( \epsilon_i \), à partir des indices de végétation (dont le plus couramment utilisé est l'indice de végétation normalisé NDVI).

A. Occupation du sol et estimation des surfaces cultivées

L'estimation des surfaces cultivées à partir de LANDSAT-TM ou de SPOT peut être maintenant considérée comme pratiquement opérationnelle et fait l'objet d'applications courantes (incorporant éventuellement les informations dans le moyen infrarouge, disponible sur TM et qui sera introduit sur SPOT4 à partir de 1994). Tout au plus peut-on
noter les limitations liées à la résolution encore insuffisante dans certains parcellaires agricoles tels que l'Afrique.

A une autre échelle plus globale, les possibilités nouvelles offertes par NOAA [52] ont été largement appliquées à l'analyse de la phénologie de la végétation à l'échelle continentale [51] [54], permettant une classification de l'occupation du sol à grande échelle [57] [59] en s'appuyant éventuellement sur la complémentarité avec les microondes passives [58]. Ces études ont également permis d'évaluer des changements globaux, en particulier la déforestation [53] [55] [56] [60].

B. Suivi des cultures et estimation du rendement

Compte-tenu des différentes échelles d'espace accessibles indiquées plus haut, ce thème est abordé avec différents niveaux de précision, que l'on peut classer ainsi :

1) Suivi global de la végétation à l'échelle continentale
S'appuyant principalement sur les données de GVI (ou éventuellement de SMMR), il s'agit là de la mise en évidence de variations spatiales ou temporelles à très grande échelle, traitant de la végétation dans son ensemble (naturelle et cultivée) et donnant donc des indications très globales, d'intérêt général évident mais peu applicables en agrométéorologie "stricto-sensu" [61] [62] [63] [64] [65] [66] [67] [68].

2) Mise en relation avec la productivité végétale
A partir des profils temporels de NDVI ainsi obtenus, de nombreux travaux ont permis de mettre en corrélation les caractéristiques de ces profils (généralement le cumul de NDVI) avec la productivité primaire de biomasse et l'évapotranspiration (ainsi qu'avec la concentration en CO2 à grande échelle) [69] [70] [71] [72] [73].
Les résultats sont importants pour la quantification du fonctionnement de la biosphère continentale dans l'optique des problèmes liés au "Changement Global" (programme IGBP), mais, dans le contexte de l'agrométéorologie, sont surtout utiles à une appréciation globale des phénomènes de sécheresse (végétation naturelle et cultures confondues) [74] [75] [76].

3) Mise en relation avec la production agricole globale
L'analyse des NDVI sur des régions agricoles permet, par la comparaison interannuelle, la mise en évidence des tendances climatiques d'une année donnée et la localisation des impacts d'accidents climatiques significatifs (gel, retard ou avance de végétation, le plus souvent sécheresse).
La comparaison qualitative des courbes d'évolution du NDVI avec les données de rendement confirme les tendances, ce qui permet d'utiliser ensuite le suivi de l'indice pour porter un diagnostic sur les tendances de rendement (voir [78] [79] pour les USA, [80] [87] pour l'Afrique, [82] pour l'Amérique Latine, [77] [84] pour l'Europe, etc...).

La multiplication de ce genre d'études peut permettre la mise au point de relations approchées entre le cumul des NDVI et la biomasse produite, plus particulièrement dans les climats soumis aux sécheresses et où l'eau est le facteur limitant essentiel. Le passage au rendement peut ensuite être problématique, compte-tenu des variations possibles de l'indice de récolte ("harvest index").

A priori, l'application aux pâturages (estimation de la biomasse) devrait être la plus directement envisageable ([85] pour le climat humide de la Nouvelle-Zélande). Mais, dans les conditions sèches où elle prend beaucoup d'importance (cas du Sahel, par exemple), les relations avec la biomasse mesurée au sol montrent encore une forte dispersion (influence du sol, compte tenu du faible taux de couverture végétale, échelles spatiales très différentes...).

A noter également les applications possibles à l'appréciation du fonctionnement des forêts [83], des situations à risques pour les incendies [81] et de la localisation et de l'intensité de l'activité des criquets [86].

Au total, des applications d'ores et déjà significatives en ce qui concerne le suivi global, les alarmes éventuelles et le diagnostic approché du rendement des cultures ou de l'état des pâturages. Par contre, l'estimation quantitative reste problématique : des relations approchées avec la biomasse sont possibles dans les climats secs, mais des développements méthodologiques sont nécessaires pour progresser significativement. Ils doivent concerner les deux points suivants :

- analyse des pixels (généralement) mixtes de NOAA, par combinaison avec des images TM ou SPOT, pour pouvoir extraire les NDVI de chaque culture importante;

- mise en relation de l'évolution des NDVI avec des calculs de biomasse prenant en compte le PAR intercepté et avec des modèles agrométéorologiques de simulation des cultures pour obtenir des indications de rendement (voir paragraphe suivant).
4) Estimation du rendement à l'échelle parcellaire

La disponibilité de LANDSAT TM, puis de SPOT, permet de travailler réellement au niveau des parcelles (à l'exception de modes de cultures basés sur des champs de moins de 1 ha). Il est alors possible de mettre en application les méthodologies développées en parcelles expérimentales, en particulier le suivi de l'évolution du profil spectral [90] en tenant compte des possibilités du système SPOT.

Certains travaux ont poursuivi la démarche empirique, mettant en relation rendement et indices de végétation à des dates fixes [88] [91]. Elle permet une analyse fine d'une situation agricole précise, mais est évidemment limitée dans son extension géographique. C'est pourquoi la démarche analytique, prenant en compte le PAR absorbé [89], a fait l'objet de nombreux travaux, de nature méthodologique sur parcelle expérimentale. Les premières applications sont en cours avec les données SPOT [92] [93] les résultats sont encore limités dans une perspective d'application, mais encourageants.

La combinaison de ces suivis parcellaires avec les données SPOT ou LANDSAT et de modèles de simulation de culture [94] paraît la voie à suivre pour dépasser les limitations actuelles. On peut envisager la combinaison d'un suivi global à partir de données NOAA et d'études localisées sur des zones-tests définies par échantillonnage (avec des données SPOT) pour être en mesure d'utiliser réellement la télédétection de manière quantitative dans l'estimation et la prévision du rendement.

III. CONCLUSION

Ainsi que doivent le confirmer les deux autres rapports, la télédétection est maintenant entrée dans le domaine de l'opérationnel pour ce qui concerne le domaine de l'agrométéorologie. Les dernières années ont vu se constituer les structures spécialisées nécessaires à la mise en application en routine des observations satellitaires (NOAA, FAO, CEE...). Il faut, bien sûr, résoudre d'énormes problèmes de traitement et d'assimilation de la masse de données acquises, mais l'évolution est significative et devrait pouvoir s'appuyer sur les développements technologiques qui viennent d'être analysés.
BIBLIOGRAPHIE

I.A.1.

An assessment of the ability of a geostationary satellite-based model to characterize the mesoscale variability of solar irradiance over the lower Fraser valley. Atm OC, 24, 128-144.


Radiation budget at the ground from satellite data. In "Applications of remote sensing to agrometeorology". Kluwer Academic Press, 241-256.

I.A.2/3


I.B.


On the derivation of land surface temperature from AVHRR data. 4th AVHRR data user meeting/Rotherburg (FRG) Sept 89. A paraître dans les Proceedings.


I.C.1.


I.C.2.

Use of METEOSAT for mapping thermal inertia and evapotranspiration over a limited region of Mali. J. App. Meteor., 25, 1489-1506.


[34] Choudhury B.J. (1989)


The assessment of regional crop water conditions from meteorological satellite thermal infrared data. Submitted to Rem. Sens. Env.


II.1.

Comparison of North and South American biomes from AVHRR observations. Geocarto. Intern., 2, 27-41.


Determining the rate of forest conversion in Mato Grosso, Brazil, using LANDSAT MSS and AVHRR data. Int. Journ. Rem. Sens., 8, 1767-1785.


II. B.1.


II. B.2.


Application of AVHRR vegetation index to study atmospheric biosphere exchange of CO₂. J. Geoph. Res. 92, 2999-3017.


II. B. 3.

   Sens., 24, 54-64.

   Large area crop monitoring with the NOAA-AVHRR: estimating the silking stage of
   corn development. Rem. Sens. Env., 27, 73-80

   The use of AVHRR data in operational agricultural assessment in Africa. Geocarto
   Int., 2, 41-61.

   Monitoring grassland dryness and fire potentials in Australia with NOAA-AVHRR

   Operational interpretation of AVHRR vegetation indices for world crop information.

   Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forests in different climates. Rem. Sens. Env.,
   24, 347-369.

   Suivi agroclimatique des cultures à partir des données des satellites NOAA-AVHRR

   Determination of seasonal and interannual variation in New-Zealand pasture

   The potential of remote sensing of ecological conditions for survey and forecasting

   Comparison of vegetation indices derived from NOAA-AVHRR data for sahelian crop
II. B. 4.

Relation entre le rendement de cultures de betterave à sucre et des indices de végétation calculés à partir d'images LANDSAT-MSS. In "Spectral Signatures of objects in remote sensing". Proc. 4ème Colloque Intern. Aussois (France). ESA SP 287, 167-170.


Étude d'une scène SPOT : inventaire des cultures et prévision de rendement du blé d'hiver (Beauce, France). Photointerpretation, 2, 39-46.


Estimation de la biomasse et du rendement de cultures de blé dur à partir des indices de végétation SPOT. In "Spectral Signatures of objects in remote sensing". Proc. 4ème Colloque Intern. Aussois (France). ESA SP 287, 137-141.

REPORT FOR THE WMO COMMISSION FOR AGRICULTURAL METEOROLOGY

Satellite Applications to Agrometeorology

Technical developments for the period 1985-1989

Bernard Seguin

INRA - Bioclimatological Station

BP 91

84143 Montfavit Cedex (France)

Introduction

For CAgM-IX, I was called upon to draft a fairly exhaustive bibliographical report, comprising 81 pages and 169 references, summing up the latest research relating to satellite applications to agrometeorology, and based on works published up to the end of 1984.

Given the terms of reference of the three rapporteurs appointed by the session (Dr E. Kanemasu, Dr A.D. Kleschenko and myself) it was logical for me to update this document with a view to analyzing inputs resulting from recent developments, covering the period 1985-1989.

For obvious reasons of consistency, this report will follow the format of the 1986 document and will cover the following:

I. The contribution to climatic data
   (a) Radiation balance
   (b) Temperature
   (c) Water balance

II. The contribution to crop monitoring
   (a) Land use and area under cultivation
   (b) Yield estimates

I. THE CONTRIBUTION TO CLIMATIC DATA

This results from the use of meteorological satellites of either geostationary (METEOSAT, GOES, etc...) or polar orbiting (NOAA-AVHRR) types.

Radiation balance

1. Solar radiation

Methods to estimate solar radiation using remote sensing techniques, with the main objective of allowing spatial interpolation giving higher
resolution observations than land-based systems, have not advanced significantly. These methods, combining indirect approaches using the percentage of possible sunshine with direct approaches using the radiation transfer theory have been described in detail previously [1] [2] [4] [5] [6] [7]. Therefore, an evaluation of these methods and their move towards operational use [3] has tended to be the focus of recent studies.

The trend toward operational systems, based on a lightweight system combining reception and micro-computer processing, is apparent and could lead to the possibility of estimating daily solar radiation with an accuracy of about 10%.

2. Albedo

The development trend is similar (some methods may in fact be used for both objectives [7][2]). In recent years estimates have become increasingly reliable through incorporation of both the effects of atmospheric correction and the shift from two-way reflectances to hemispheric albedoes and from spectral measurements to the albedo covering the entire spectrum. Estimates obtained [8][10], particularly over Africa [2][9][11], help to put the present accuracy of the albedo at +/- 0.05.

3. Radiation balance

The change from solar to net radiation, on the basis of the albedo, supposes that longwave radiation is taken into account [7].

There should be no major difficulties in determining terrestrial radiation, measured by thermal infrared sensors, provided that atmospheric adjustment is taken into account (for clear sky). Good progress is being made on the problem of shifting from instantaneous measurements to a daily scale.

On the other hand, the estimation of downward terrestrial radiation has still not been studied in depth. It should be possible to derive it with about 5-10% accuracy from the humidity and temperature profiles of the NOAA-TOVS sounder. Conventional climatological formulae can also be used, using geostationary satellites to provide an approximation of the variables involved [13]. It should be possible to estimate and chart net radiation with an accuracy of 15 to 20%.

Temperature

Extraction of surface temperature from satellite thermal IR data, already studied in some depth in the previous phase, has undergone development in respect of estimate accuracy through better incorporation of atmospheric corrections and emissivity [14] [15] [23] [24]. Concerning specifically coefficient adjustments for the split window method using NOAA-AVHRR channels 4 and 5 [14] [20] [21] [22] [24]. It should therefore be possible at the present time to determine natural surface temperatures with an accuracy of 2 to 3 degrees (in absolute values).

(POOLE 5652)
Agroclimatic studies have been carried out on the data collected, particularly for mapping freeze zones using night thermographs [16] [19] [25] or for mapping the structure of certain agricultural regions according to land use or climatic gradients [17] [18] [26]. Topoclimatic studies are almost non-existent, probably because NOAA resolution is insufficient. The LANDSAT-TM thermal channel with a resolution of around 120m should form a basis for more extensive studies in the near future.

The main data source for applications estimating surface temperature is still thermal IR in association with the water supply of vegetative cover. This is further commented in the next section.

Monitoring the water balance

This includes both precipitation estimates and soil moisture or evapotranspiration estimates using satellite data.

1. Pluviometry

The possibility of applying remote sensing to estimate precipitation on the ground has continued to figure in many studies and has given rise to contradictory opinions. Therefore, we shall simply select several significant references from among the numerous publications and specialized papers [27], and indicate the main trends which have emerged.

Monitoring images from geostationary satellites, in particular those with cold cloudtop (with a threshold of -40 or -60 degrees as appropriate) identified in the thermal IR enables relatively satisfactory estimates (+/- 25%) to be obtained for long periods of time (the rainy season or a month), particularly when ground temperature by clear sky is also analyzed [28]. Monitoring over shorter periods of time [29] [30] gives encouraging results but there should be more detailed analysis of changes in the form of precipitation images. It is the subject of several current or planned international programmes, (ISCCP and HAPEX), particularly in Africa.

Work using passive microwaves (NSU on the NOAA satellites with a resolution of approximately 100km, and the planned and improved AMSU from 1993 with resolutions of 50 to 200km) opens up other possibilities currently being examined. The combination of visible, thermal IR and microwave monitoring should result in some interesting developments in the next few years.

2. Soil moisture and evapotranspiration

Soil moisture, which can be estimated mainly by microwave techniques has been evaluated on a very large scale (over 100km) using Nimbus-7 37 GHz SMRR data [33] [34] [37] [41] [42]. Global information on the climatic and hydrological situation can then be gathered.

On a smaller scale, whilst studies of the soil using both active and passive microwaves (radar) have helped to further knowledge of the relationship between the signals measured and soil moisture, the lack of suitable satellite sensors prevents a true assessment of applications to agrometeorology from being made. A first evaluation will have to wait until at least 1991 when ERS1 will be available (even though it is intended mainly for sea applications).

(POOLE 5652)
Thermal infrared images therefore provide the bulk of information in this area, enabling evaporation to be computed and mapped on the basis of the energy balance, and moisture to be determined by means of thermal inertia.

This area has been the focus of many studies as both a major topic [31] [35] [38] [39] [40] [43] [44] [47] [48] [49] and a subsidiary topic [36] [50].

Significant progress has therefore been made in methodology, but this concerns mainly specific studies covering specific days, with time scales barely over 24h. On a purely agrometeorological level, longer periods must be taken into consideration (ten days, then one month), which means developing simplified methods relying on minimum secondary data. Such a process is possible, and gives water stress estimates comparable to those obtained by ground modelling but with the advantage of spatial interpolation made possible by the time span of satellite data [44] [45] [46]. The accuracy obtained for actual evapotranspiration is then of the order of +/- 1mm/day. Note also that it is possible to map the spatial variation of maximum evapotranspiration on the basis of identification of vegetation cover and estimation of the crop co-efficient in association with reflectances [32].

II. THE CONTRIBUTION TO CROP MONITORING

Considerable progress has been made in this area in recent years, as a result of the following:

- Extensive development of global vegetation and crop monitoring programmes using NOAA-AVHRR data (on scales ranging from 1km for LAC data from receiving stations, 4km for recorded GAC data and approx. 20km for NOAA GVI data).

- Progress in earth observation satellites, with 30m resolution for LANDSAT-TM and 20m for SPOT which offers revisit possibilities (since 1985) thanks to its off-nadir viewing capability allowing for programming of scenes to be recorded.

- Improvement of analysis procedures to estimate biomass (and subsequently yields) based on formalism, taking into account the photosynthetically active radiation (PAR) absorbed by the vegetative cover.

\[ \Delta M = \epsilon_b \times \text{PAR}_a \]

where the PAR absorbed (PAR_a) is converted into dry matter DM by the efficiency of conversion \( \epsilon_b \), PAR_a being calculated by the relation:

\[ \text{PAR}_a = \epsilon_i \times \text{PAR} \]

The PAR can be calculated from the solar radiation \( R_s \) using coefficient \( \epsilon_c \) (\( \text{PAR} = \epsilon_c \times R_s \)), determined from the climatic characteristics of the location. Remote sensing is then used to estimate the efficiency of interception \( \epsilon_i \) from the vegetation indices, the most commonly used of which is the normalized difference vegetation index, NDVI.

(POOLE 5652)
Land use and estimation of areas under cultivation

The estimation of areas under cultivation using LANDSAT-TM or SPOT is now considered as virtually operational and is being incorporated in regular applications (possibly using information in the middle infrared available on TM and to introduced on SPOT4 from 1994). Limitations due to inadequate resolution in certain agricultural land areas, such as Africa, should however be noted.

On a more global scale, the new possibilities offered by NOAA [52] have been widely applied to the analysis of the phenology of vegetation on a continental scale [51] [54], enabling land use classification to be made on a large scale [57] [59] by using, if necessary, the complementarity with passive microwaves [58]. These studies have also helped to evaluate global changes, particularly deforestation [53] [55] [56] [60].

Crop monitoring and yield estimation

This topic is covered with different degrees of precision, given the different scales of study as described above.

1. Global monitoring of vegetation on a continental scale

This involves mainly the use of GVI, or possibly SHMR data and highlights spatial or temporal variations on a very large scale, looking at vegetation as a whole (natural or under cultivation) and giving, therefore, very general information, obviously of interest but of little relevance to agrometeorology as such [61] [62] [63] [64] [65] [66] [67] [68].

2. Correlation with vegetation productivity

The NDVI temporal profiles obtained have formed the basis of many studies which have served to correlate the characteristics of these profiles (generally the cumulative NDVI) with biomass primary productivity and evapotranspiration (and with large scale atmospheric CO2 concentration) [69] [70] [71] [72] [73]. The results are important for quantifying continental biosphere functioning from the point of view of problems linked to "Global Change" (IGBP) and are of particular use in agrometeorology to give a global appreciation of drought phenomena (both natural vegetation and crops) [74] [75] [76].

3. Correlation with global agricultural production

Analysis of the NDVI in agricultural regions, through interannual comparisons, reveals the climatic trends of a given year and identifies the impact of significant freak climatic conditions, such as frost, early or late vegetation and, most frequently, drought.

Qualitative comparison of NDVI curves with yield data confirms the trends, enabling index monitoring to to be used for analysis of yield trends (see [78] [79] for the USA, [80] [87] for Africa, [82] for Latin America, [77] [84] for Europe, etc...).

(POOLE 5652)
The increase in the number of studies of this type may help develop approximate relationships between the global NDVI and the biomass produced, particularly in climates which suffer from drought and where water is the essential limiting factor. It may then be difficult to determine the yield, given the possible variations in the harvest index.

The application to pasture lands (estimation of biomass) should be the most feasible ([85] for the moist climate in New Zealand). However, under dry conditions where it is of great importance (Sahel for example) the relationship with the biomass measured on the ground shows great disparity (influence of the soil, given the lack of vegetative cover, and different spatial scales...).

Mention should also be made of possible applications in assessing forest behaviour [83], fire potentials [81] and the location and intensity of locust activity [86].

On the whole, significant applications are already being implemented in areas of global monitoring, early warning, and crop yield or pasture land condition analysis. On the other hand, quantitative estimations are still problematic. Approximate relationships with biomass may be established in dry climates, but methodological developments are needed for significant progress to be made and must include the following two points:

- Analysis of NOAA pixels (generally mixed), by combining them with TM or SPOT images to extract the NDVI of each major crop;

- Correlation of NDVI trends with biomass calculations taking the intercepted PAR into account, and with agrometeorological crop simulation models to obtain yield predictions (see the next section).

4. Small scale yield estimation

The availability of LANDSAT TM, and then SPOT, has meant that studies can effectively be carried out on plots of land (except for crops grown in fields of less than 1 ha). The methodologies developed on experimental plots of land, particularly to monitor development of the spectral signature [90] making use of the possibilities offered by the SPOT system, can therefore be applied.

Some work has been of an empirical nature, comparing yield and vegetation indices on given dates [88] [91]. This facilitates fine analysis of a particular agricultural situation but is obviously limited in the geographical dimension it can cover. For this reason, the analytic approach, taking the absorbed PAR into account [89], has been the subject of many methodological studies on experimental plots of land. The first applications are under way, using SPOT data [92] [93]. The results are still limited for application purposes, but they are encouraging.

A combination of small area crop monitoring using SPOT or LANDSAT data and crop simulation models [94] seems to be the way to overcome present limitations. A combination of global monitoring using NOAA data and localized (POOLE 5652)
studies on randomly selected test areas (using SPOT data) may be envisaged in order to make quantitative use of remote sensing to estimate and forecast yields.

III. CONCLUSION

Remote sensing, as the other two reports will confirm, is now in operational use in agrometeorology. Recent years have witnessed the development of the specialized structures needed for routine applications of satellite observations (NOAA, FAO, EEC...). Obviously enormous problems remain in processing and assimilating the vast amounts of data collected, but developments have been significant and should benefit from the technological advances which have been analyzed in this report.
Part III – The Use of Satellite Information in Agricultural Meteorology

by

A.D. Kleshchenko
THE USE OF SATELLITE INFORMATION IN AGRICULTURAL METEOROLOGY

by

A.D. Kleshchenko

1. Introduction

At the IX Session (Madrid, Spain, 1986) the Commission for Agricultural Meteorology (CAgM) appointed the rapporteurs for preparing the report The Use of Remote Sensing in Operational Agricultural Meteorology. On the basis of an agreement between the co-rapporteurs (Prof. E. Kanemasu and Dr. B. Seguin) the given presentation deals with the state-of-the-art in the use of remotely sensed data in agrometeorology operations. Taking into account the fact that despite numerous research efforts there are just few particular operational data systems which function in a particular region of the world, it may be useful to regard the following issues: main features of aerospace information, as well as agrometeorological requirements to operational remote sensing systems; operational systems proper; some efforts and projects which are close to operational usage, some issues and specific examples of the assessment of benefits of using aerospace information in agricultural meteorology.

The author acknowledges the assistance of Ms. E.F. Sotnikova and Ms. D.I. Nikitina in the preparation of the present report.

2. Agrometeorological requirements to Creation of Operational Systems Using Remotely Sensed Data

Prior to the development and functioning of the resources and meteorological satellites which enable the collection of
information suitable for resolving agrometeorological problems in different countries, there functioned (and is still functioning) a certain system of collection, processing and provision of information to the user. For example, the USSR had such a system based on a rather dense observational network including the ground and aerial (aerovisual) observations /13, 17/. In such countries as the USA and Canada the greater part of information was collected on the basis of farmer questionnaires /23, 34/. In the EEC member-states this system was largely supported by statistical services /38/. Quite often such systems were able to function successfully enough, particularly in the years with the weather which was not abnormal. That is why the first attempts to use remote sensing systems as a substitute for the available ones or to contribute them to the latter without an in-depth study did not always prove to be a success. This may be primarily related to the specific features of satellite data (inadequate speed of data collection from the first satellites, cloud effects, lack of data series, qualitatively new information, etc.). Thus when experience was gained in managing remotely sensed data, requirements could be worked out to the information systems which use space data on an operational basis. The following is the main requirements to operational systems derived on the basis of generalization of the available literature in the field /1, 5, 7, 23, 24, 38/. These requirements are presented as the requirements to particular system parts: the sources of remotely sensed data, initial data processing and sorting out, data provision, data analysis, regional system configuration.
2.1. The Sources of Remotely Sensed Data

Currently some types of satellites are in operation which enable the collection of data in several spectral ranges with different spatial and time resolution. Specifically, there is an inverse relationship between the latter characteristics. The geostationary satellites (Meteosat type) have a wider image coverage (in principle, whole continents may be covered), a high sensing frequency (1–2 times an hour) for the covered area, although the resolution is low (several kilometres). For the meteorological and earth resources satellites, as a rule, a sun-synchronous orbit is selected. Moving along this orbit the satellite passes a given latitude at the same local time which thus minimizes the daily deviations resulting from the solar lighting. The choice of local time for one particular latitude means that the same local time will be selected for all other latitudes. Multispectral scanning systems at the meteorological satellites (Meteor type for the USSR, NOAA type for the USA) also have a wide coverage (ca. 1.5–2.5 thousand km), a high enough image taking frequency (1–2 times a day) and the spatial resolution from several hundred metres (Meteor) to 1.1 km (NOAA).

The multispectral scanning systems at the earth resources satellites (Landsat and Landsat-D for the USA, Spot – France, Kosmos 1939 – the USSR, and others) have a very high spectral resolution (100 to 10 nm), high spatial resolution (10 to 100 m), which enables them to be more efficiently used for resolving different problems in agriculture. However, a low scanning width (100–200 km) and a low image taking frequency of particular areas (1 time every 15–18 days) makes
the information collected less applicable. An optimal solution for the future data collection systems would be a combination of low and high resolution imagery /22, 34/. In this case the low resolution would enable a global view identifying anomalous regions, whereas the high resolution -- a detailed survey of the conditions and understanding of the reasons which resulted in the anomalous crop growth conditions.

Currently in many studies aimed at assessing the land resources the data is used which is measured in the visible and infra-red spectral bands. The applicability of this data is significantly limited by cloud cover, fog, and heavy atmospheric pollution. For the provinces of Western Canada the probability of obtaining the Landsat imagery with the cloud cover of less than 50 % is e.g. as low as 53 % /24/. For the NOAA satellites this probability is higher since the observation frequency is higher, however the problem still remains. There is a way to overcome this predicament -- the perspective use of microwave sensors.

Aircraft, as a source of remotely sensed data, may play an important role in creating operational agronomic and meteorological systems for the collection, processing and use of data for selected regions. An airborne sensor can enable the output of data with a higher resolution that a similar sensor fixed at a satellite. Besides, aircraft can carry special-purpose sensors which cannot be mounted at satellites (e.g. sensors which measure the natural gamma-radiation -- earth background radiation used to estimate soil moisture and upper soil moisture).

Aircraft may be used to collect the basic data over vast
areas if multispectral sensors with a relatively high resolution are used. However such an application may not be made frequently. On the other hand, which makes it different from the use of satellites, if emergency arises, the aircraft flight assignment may be quickly corrected on the basis of the spatial and time requirements. It stands to reason that there are definite problems in the use of aircraft too, with the flight costs playing an important role. This problem can be partially resolved if aircraft can be used for the collection of data for several users simultaneously. In such a case, although the flight tasks may vary in terms of time and space, an optimum flight schedule may be derived to satisfy all the users.

2.2. Initial Data Processing and Sorting

In the process of initial processing and sorting of data the basic "raw" satellite and aerial data is reshaped into spatially located parameters. At the satellites, the process includes the basic data correction with the help of calibration signals generated by the satellite equipment as well as the calibration data obtained during the tests prior to the launching. As soon as the radiometric calibration is over, the data is processed and transformed into a geophysical form with the use of specific algorithms and special procedures aimed at creating images. At the same time correction is made and with an account for atmospheric phenomena, earth's revolution, as well as transformation into the conventional map projection.

The process of initial processing of the aerial data also includes nearly all of the above stages.
2.3. **Data Provision**

Satellite and aerial remotely sensed data may be provided by the space telecommunications networks, ground telecommunications networks, using post facilities and messengers, or a combination of the possible ways of data provision. The structure of data provision is determined by the amount and forms of the data transmitted, the expedience of provision and the relative costs. The technical facilities for the satellite data relaying within the framework of the Landsat program described in /23/ enabled the four-spectral image acquired by the Landsat to be transmitted in 8 minutes from the Italian town of Frascati to Farnborough (UK) practically without mistakes. Whenever expediency in data acquisition is required and costs of data relaying are not taken into account, satellite communications channels may be used. Currently the most extensively used ways of data transmission are rather slow (postal services, messengers), since the costs of these services are relatively low and for most purposes this way of data transmission is justified. For example, in Canada /23/ the time from the moment the satellite data is received at the ground and until it is delivered to the user is 3 hrs for emergency (ice monitoring) and 24 hrs for vegetation monitoring.

2.4. **Data Analysis**

The analysis of a potential body of the remotely sensed data users /1, 8, 23, 24/ shows that only few users can make an independent analysis of this information. These "independent" organizations face a sufficient number of problems and can provide adequate funding. Thus these users may be assumed
to have adequate analysing systems and the personnel capable of data assessment, processing (decoding) and interpretation.

As stated in /23/, the organizations acting as "direct" users of remotely sensed agricultural information in Canada comprise only five percent of the total number of potential users.

To enable the effective use of resource data based on remotely sensed data a distribution mechanism is required with a high degree of coordination. To this end a distribution network may be used including a high capacity personal computer connected to a large number of remotely located terminals, with each of them having a limited capacity to effect the data management and analysis /8, 23/. Thus the problems involving processing of a limited amount of data may be resolved "locally", i.e. using the terminals, whereas the operations involving large bulks of data and extensive computations can be performed at the mainframe computer. Taking into account stringent requirements on the analysis tools it seems reasonable that a public access system be developed for image analysis and data integration /8/.

2.5. **Regional System Configuration**

In /7, 23/ information systems are discussed which are used for the acquisition of earth resources information at the regional level, aimed primarily for the solution of agricultural problems. Practically, these systems are a basis for an extensive use of remotely sensed data in operational practices. As for the USSR, selected parts of the system are practically used in operational activities of the USSR State Committee for Hydrometeorology. According to /7,
23/, the main elements of the system are: the satellite facilities for data collection, aerial facilities for data collection, standard data sources (for the USSR these include, for example, a relatively wide network of observational stations and, additionally, statistical services, etc.), data analysis and output equipment, and the users of the earth resources information.

The satellite and aerial facilities receive requests for specific tasks, including the type, format, quality, as well as the requests of preliminary data processing and sorting. There must be a close relationship between the process of task control and the subjects performing the data requests, to ensure the recording and processing of the data selected in accordance with the assignment of specifications, as well as the delivery of satellite and aerial data to the subject who issued the request at the specified time.

The part which is responsible for the analysis of measurements, the data received from other sources are also analysed (the data of topographical maps, soil data, data of agrometeorological and meteorological observations and measurements, etc.). Although this kind of data may be quite easily obtained from generally accessible sources, users are not always satisfied with the presentation. Thus the system's analysing part receives the data acquired at different times and at different scales. An important role in analysing and comparing all the types of data received is played by so-called geographic data systems (8, 18, 24, 44) which contain all additional information which has been structured in a definite order enabling a connection between all incoming data and the
available agrometeorological models for the development of estimates of crop state and production (dynamic and dynamic-statistical models of the CROP-WEATHER type) /2, 7, 44/.

2.6. Limitations of the Systems Created

To enable a full-scale use of the remotely sensed data in the operational applications, a sufficient progress should be achieved in the three aspects of the future data systems: data accessibility and availability, availability of procedures, and technological support to the analytical part and user training.

The accessibility and availability of the satellite and aerial data should be undoubtedly guaranteed at reasonable prices of the data acquisition prior to the time when data users get fully involved in the process of using the data. Besides, the data should be available in a corresponding form and within the time limits which would enable the useful use of the resulting information.

Depending on the nature of changes in the general data system, the subsystems and analysis procedures may vary from very simple ones (such as a fast visual analysis of the limits of a forest fire) to very complex types of the digital imagery analysis and integration of different data types stored in the data base (by means of example the digital land-use data maps may be mentioned). The costs involved will respectively differ considerably.

The personnel of a resource management agency should have adequate knowledge and skills to effect an efficient use of remotely sensed data, or the staff should have an access
to the relevant training facilities. The above skills should include an ability of analysing data, learning the potentialities and limitations of the analysis methods, as well as the potential for a most effective use of the results obtained.

In brief, the following requirements may be formulated to the functioning of operational systems which use remotely sensed data:

- reliability of work;
- continuous flow of incoming data;
- timely acquisition of data;
- stable timing of data acquisition;
- potential for a change (system flexibility);
- succession (capability for agreement with the existing systems of acquiring additional information);
- availability and accessibility of the analysis systems and procedures.

Additionally, the system development should be performed specifically for obtaining a solution of particular operational problems (for specific users).

3. Remote Sensing Operational Systems in Agricultural Meteorology and Agriculture

The description of the information system given in Section 2, including remotely sensed data as the main source of information, is currently taking shape in the form of selected parts or units specifically for resolving certain problems. It stands to reason that the system may be significantly simplified when applied to particular easy problems. However, even in such a case it should be emphasized that there are few completely operational systems in the world, which have
been especially created for particular problems and which provide, as an output, a basis for operational decision-making in agriculture or agrometeorology.

Two of such systems were described in the report prepared by Prof. E. Kanemasu and Dr. I. Flitcroft and presented to CAGM by a letter of 1 November 1990. Thus this report does not include the description of these systems. One of these is the Foreign Agricultural Service (FAS) of USDA /23, 37/, another one is ARTEMIS for the system GLEWS (Global Information and Early Warning System) under FAO, Rome, called FAO ARTEMIS System /27, 29, 30/. The above-mentioned report also notes that some centres, such as the centre AGRYMET in the Republic of Niger and the system FEWS (Famine Early Warning System) operating under USAID, make use of remotely sensed data and include this in their agrometeorological bulletins; although no decisions are made on the basis of this data. The methods of satellite data processing and interpretation differ very little from the described systems of FAS and ARTEMIS.

In addition to the above-mentioned systems the system EXTEC /9/ should be noted, used in the USSR for the determination of the winter crop acreage with the estimated crop state. This information is used to make decisions on the additional plantings in early spring in locations with the poor state of winter crops. One should also note that the USSR currently uses an aerial system of spectrometric measurement of crops; the results obtained are used to estimate the current crop state and to calculate crop yield forecasts for different areas of the USSR /7, 16/.
3.1. **Estimation of Areas with Different Assessments of Winter Crop State on the Basis of Meteorological Satellite Data (EXTEC)**

The approach used in the system is based on the capacity to distinguish green vegetation against the background of soil and other green formations. This problem may be solved for the southern regions of European Russia for autumn and spring, when winter crops are the main growing plants in these regions.

As a spectral characteristic of the crop the vegetation index (VI) is used -- the ratio of the difference between the recorded reflected radiation in the near infra-red (IK) and red (K) spectral ranges to their sum, the so-called normalized difference (NR):

\[ \text{NR} = \frac{\text{IK} - \text{K}}{\text{IK} + \text{K}}. \]

The system uses the data received from the meteorological satellites of the Meteor and NOAA types. The Meteor data is collected by the radiometer MSU-S in two spectral ranges, 0.58 - 0.7 and 0.7 - 1.1 mkm, with the resolution of ca. 300 m in nadir. The NOAA data (NOAA 10 and 11) is collected by the radiometer AVHRR for the five spectral ranges: 0.58 - 0.68, 0.725 - 1.1, 3.55 - 3.93, 10.3 - 11.3 and 11.5 - 12.5 mkm with the resolution of 1.1 km in nadir. The system uses the data obtained in the first two channels.

The technology involves the following stages:

- screening of images and composition of the data bulks shaped as VI;
- clasterization, i.e. splitting the entire data bulk into
at least three categories: green vegetation, soil and all the rest;

- plotting a calibration curve;
- splitting the cluster "winter wheat" into three categories based on the plant state;
- output of results.

Let us briefly review each of the steps.

After the satellite information has been recorded the image quality is assessed. The image is analysed in terms of the extent of cloud cover and the position of the study area with respect to the vertical axis line. Since the above-mentioned satellites have scanning systems with wide scanning angles (56° for NOAA and 45° for Meteor), due to the effects of the angle of sight it is only the central image area which contains useful data on vegetation. This constitutes, in case of the NOAA satellite, a band 800–900 km wide (compared to the total width of coverage of ca. 2700 km), and for the Meteor satellites, 600–700 km (with the total width of coverage being ca. 1400 km). For the selected image area VI is estimated.

To eliminate the images which are affected by clouds, an algorithm is used, making a comparison among VI's for the selected area for several days of survey, and choosing the maximum indices.

Using the VI data bulk, clusterization is made aimed at distinguishing the vegetation cluster, applying the algorithm of clusterization by the method of K-mean /9/. To this end, an initial random choice of K initial cluster centers is made as \( Z_1(1), Z_2(1), \ldots, Z_K(1) \), where \( K \) is the desired number of clusters. Then by iteration a number of steps is performed until the condition of algorithm convergence is met
\[ Z_j(K + 1) = Z_j(K) \]

at \( j = 1, 2, \ldots, K \), or the maximum allowed number of iterations is exceeded.

Out of the break-down clusters of the VI set the vegetation cluster is selected (usually this is the one which has the maximum VI in the center) with the vegetation, as was stated above, represented by winter crops, mainly winter wheat. From the assumption that the probability density distributions for the plant density and VI are normal (Gaussian), mean and variance values are calculated for the VI cluster "winter crop" and the ground measurements of plant density \( \overline{x}_v \), \( \sigma_v \) and \( \overline{x}_e, \sigma_e \) respectively for the same area selected. The plant density data is provided by the observational network or collected quasi-simultaneously at the ground test sites when space imagery is taken.

It is known that the distribution of a random value \( y \), related by means of the functional relationship \( y = ax + b \) (\( a \) and \( b \) are constants) with a random value \( x \) which is normally distributed, is also normal with the mean \( ax + b \) and variance \( a^2\sigma^2 \). Thus, given the distribution parameters \( x \) and \( y \), the constants \( a \) and \( b \) may be estimated, i.e. the linear dependence of \( y \) on \( x \) may be recovered. In this case the relationship between the plant density and VI is linear:

\[ \overline{x}_e = a\overline{x}_v + b, \quad \sigma_e = a\sigma_v . \]

Thus

\[ a = \frac{\sigma_e}{\sigma_v}, \quad b = \overline{x}_e - \frac{\sigma_e}{\sigma_v} \overline{x}_v . \]
In this way the calibration curve is calculated. By assigning a set of empirical thresholds for the plant density corresponding to the poor (additional sowing is required), satisfactory and good states of crops, the respective threshold values for VI may be calculated using the calibration line. Comparing the VI values of pixels categorized as "vegetation" to the calculated threshold values, clusterization is made with respect to the crop state. Assuming the entire green vegetation to be 100 %, the percent of areas with different crop states may be calculated.

The system has been computerized on the basis of a 32-digit PC with the INTEL 386/387 type processor. To display the data a systems VGA is used enabling the resolution of 640 by 480 pixels and up to 63 grays of the same colour.

With the help of EXTEC, NOAA and Meteor images are processed on a regular basis during the autumn and spring growing periods, with the results sent to the Hydrometeorological Centre of the USSR State Committee for Hydrometeorology(HMC). The results are used in the HMC to derive recommendations on the state of winter crops (staple grain crops in the USSR) after wintering, and to estimate the area where resowing is required.

3.2. Aerial System for Crop Monitoring

Since the 70's the USSR State Committee for Hydrometeorology has regularly conducted the aerial spectrozonal surveys of crops in different areas of the USSR /7, 16/. As a vegetation index (β) a simple ratio is used of the value of spectral brightness coefficient (SBC) for the infra-red spectral range to the SBC value for the red range. As a result of numerous
investigations a rather close relationship was derived between the values of $\beta$ and the plant cover parameters (above-ground biomass, leaf area, etc.).

As a sensor, a simple two-channel photometer is used having the following characteristics: the spectral sensitivity range is 740 to 1100 nm for the infra-red channel, and 610 to 690 nm for the red channel; the viewing angle is $35^\circ \pm 2^\circ$; the total relative error in estimating the brightness coefficient ratios of objects, at a confidence level of 0.9, is not greater than 10%.

To carry out spectrometric surveys, first the instrument has to be calibrated, viz. simultaneously measurements are made of $\beta$ of crops and soil and of the canopy parameters for the same sites (ca. 20-30 sites are used), usually $1 \times 1 \text{ m}^2$. Then the calibration curve is calculated, this being a curve (a line) of the relationship between a canopy parameter and $\beta$. Such curves are obtained for all the crops for which surveys are made.

After that the instrument is mounted aboard the aircraft and $\beta$ is measured for crops in the study area. The flight altitude is ca. 2000 m when desert pasture vegetation is surveyed, and 150-300 m for cropped areas. Conventional aircraft types are used flying at ca. 200 km/hr. When crops are studied, an operator performs a visual recognition of crops on the basis of a number of features /17/. The operator also marks the beginning and the end of measurements according to the field length and particular crops. The airborne instruments perform all the other records automatically and enable an output of data in a suitable form for operational processing on board the aircraft /7/. As soon as the working day is over, the survey results are cabled
to the respective operational departments of the USSR State Committee for Hydrometeorology.

To date, 8 aerometric teams have been established within the State Committee, to carry out on a regular basis (usually 2 times a season) the surveys of crops and pasture vegetation for the larger portion of the European Russia, West Siberia, Central Asia and Kazakhstan. Using the survey results, the desert pasture vegetation is mapped, the values of above-ground biomass are estimated for specific crops along the flight route or averaged over the area. The obtained values of plant biomass are used by operational departments as one of the predictors in issuing the forecasts of crop yields. The following crops are surveyed: winter wheat and rye, spring wheat and barley, maize, cotton.

The USSR has gained considerable experience and resolved corresponding technological and methodological problems in organizing aerial surveys. This experience can be shared with other countries, provided there are interested parties.

In recent years the former Ministry for Agriculture has established an aerial system of data acquisition on land resources (primarily crops) /1, 13/. The system uses high-altitude airplanes of the Tupolev 104 type to enable a continuous survey along the flight route, using multichannel scanners including the sensors for the visible, near infra-red and thermal ranges of spectrum. The data is processed in the same way as for the high-resolution space data (<100 m). The information is used to solve the above-mentioned problems.

In addition note that the USSR currently conducts aerial survey to estimate moisture content, using microwave sensors
/3/ and gamma-survey instruments /14/.

4. Research and Projects which are Close to Operational Usage

This category may include numerous studies aimed at the development of technologies of the use of space data in deriving crop yield forecasts. Such investigations have often been used in different projects at an experimental or quasi-operational level /1, 7, 19, 34, 35, 37, 38, 44/.

As stated above, in Section 3, among them one should note the system of USDA's Foreign Agricultural Service (FAS). To avoid the discussion of the system's details (these are given in the report by E. Kanemasu and I. Flitcroft), note that the system estimates crop yields using the Landsat's multispectral scanner and the scanner of NOAA's satellite (AVHRR). The estimates of crop development and yield production are derived with the use of VI compared for the current and past years for the same squares. The results provided by this rather straightforward system may ensure a guaranteed precision in deriving crop yield estimates for foreign countries, provided that more experience is gained and a higher competence level is achieved by the experts using the system /34/. Such a system can also be successfully used in those countries for which USDA provides crop yield estimates.

In such a case the forecasts may be successful enough, since the local experts could derive estimates in a better way for their own territory. This is proved by Canada's experience /34/.

The system used by the Canada Wheat Department is largely based on the same principles as the USDA's system. The Canadian
version is different from the American one in that use is made, along with space data, of the agrometeorological models of crop yields, which enables a better crop yield estimate.

The agricultural information system CROPCAST /34, 35/ of the company ARS Satellite Corp. is based on a structure of elements of the ground size of 24 or 48 km. This information system includes basic statistical data: description of climate, soils, drainage, cultural practices, long-term data on crop yields and plant development stages, etc. for each crop entered in the system. The system's basic dynamical models include the data of ground meteorological observations, meteorological and resources satellite data (NOAA, Landsat, etc.), information on crop growth and development stages, cropped area, data on the crop state, prices, demand. The basic dynamic models are periodically updated during the year. The meteorological data received from the ground and space sources is fed into the system every 6 hours. Different sources provide information on crop growth and plant development stages which is periodically updated; the data on crop state obtained from space as well as from ground and aerial sources is updated every two weeks; the data on prices and demand is periodically fed into the system, usually at monthly intervals.

As models using all available and incoming data the forecasting models were developed based on the Monte-Carlo process. The models are used to calculate the yield forecasts and agricultural output perspective. Besides, the models enable a spatially mapped display of the forecasted average values of any one of the modelled parameters.

In /19/ a review of a system is presented which is being
developed to provide wheat crop yield forecasts for Italy. This work is useful as an example of a sequential resolution of similar problems, from the problem statement to the provision of operational crop yield forecasts. The problem solution involved several stages.

1. Research (Project Duta 1, 1979-1981), which enabled an estimation of the possible limits of data use for the data obtained from the early family of the earth resources satellites (Landsat 1, 2, 3) to estimate crop yields (estimates of cropped acreage and yield forecasts), as well to manage water resources in agriculture (e.g. identification and estimates of irrigated area). This step also included the development of methodology of forecasting grain yields of wheat and maize suitable for the Italian territory (a large number of crops cultivated on relatively small land plots).

2. Upgrading of methodology and experimental studies (Project Duta-PONTE and Duta 2, 1982-1984), to enable the identification of cultivated area and estimation of crop yields, mostly wheat and maize, using a thematic mapper (Landsat 5), and to analyse economic benefits of forecasting crop yields in Italy.

3. Preparatory efforts (Projects AGRIT 1 and AGRIT 2, 1985-1986) to make the test runs and finalize the equipment and techniques used for resolving technological and organizational increasingly problems associated with forecasting wheat yields for larger areas up to the coverage of the entire national territory of Italy. For example, within the framework of AGRIT 1 a forecast of wheat yields was derived for the province of Ancona for the area of ca. 0.2 million ha. When implementing AGRIT 2 it was planned to provide a forecasts of wheat yields for the entire
province of Anulia for the area of ca. 1.9 million ha.

It should also be noted that in recent years many countries are involved in studies which are more or less related to the issues of using space data and aerial data to obtain crop yield forecasts. However, as stated above, there are few data systems which use remotely sensed data in operational agrometeorology, to say nothing of decision making.

In addition to the above, a number of projects may be mentioned which could be used in operational agrometeorology provided organizational and technical matters are settled. One of the objectives may be pasture monitoring. Satellite imagery, presented as normalized difference (ND), may be a sensitive tool to identify different pasture types, which may vary in plant species and soil degradation aspects, and a tool to monitor grassland phenology /31/. The space data cited in /31/ is the NOAA's AVHRR data corrected for atmospheric effects. Here a close relationship was found between the ND values and dry above-ground plant biomass, which enables the use of ND as an indicator to monitor inter- and intra-annual variations of biomass and production levels, which in turn would enable forecasting permissible greazing levels for different pasture areas.

There are quite a number of methods of estimating different parameters of plant cover, as well as radiation, thermal, and other characteristics on the basis of remote measurements /21, 25, 26, 33, 36, 38, 39, 40, 41, 42/. Among them one can emphasize the above-ground plant biomass, leaf area, plant density, plant development stages, the share of incident PAR accepted by the canopy, evapotranspiration, etc. These parameters are not an end in itself, since they are important as
input parameters for many models which estimate and forecast crop state, production and yields for different crops, as well as estimate the effects of different stress conditions on the ultimate crop yields.

Thus they are mainly used or intended to be used in operational data systems along with other types of data as was shown in Sections 3 and 4 of the report.

5. **Economic Benefits of Using Aerospace Information in Agriculture and Agricultural Meteorology**

Since, as was stated above, there is still a little use of remotely sensed data directly for making management decisions, there are few indications of actual figures of the benefits obtained due to such a use which may be found in literature. For the most part figures of potential gain are given. Although the estimates may vary widely, the figure assessing the potential level of usefulness of space data on a world-wide scale as 60 to $150 billion is met most often. This includes satellite communications ($20-40 billion), meteorology ($20-60 billion), and earth resources research ($20-50 billion) /10/.

Economic benefits of using space data in agriculture may be ensured provided the following requirements are met:

- recovery of optimum plant density after sparse plantations have been detected;
- plant pest and disease control, rational use of allocated resources;
- rational use of water in amelioration systems;
- development of measures to control erosion and soil salinity;
- optimum use of grasslands;
- enhanced accuracy and validity of predictions and recommendations (on crop yields, hazards, etc.);
- drastic reduction of data provision costs with maintaining the data quality.

The general approach to the calculation of economic benefits (EB) of using space data (SD) in agriculture is as follows.

1. Analysis is made of the SD use strategies for particular management decisions. Here the relationship is assumed to be established between the SD users and the economic performance of the user's business. Economic indicators may include higher crop yields, net income, gains, losses, etc.

2. On the basis of the analysis, optimal versions of the SD use are found.

3. The difference between the results obtained with the use of SD and its costs is the economic benefits for a particular technological (production) management decision.

4. The total EB due to the use of SD amounts to the total of all the benefits obtained in resolving individual functional problems.

5. An indicator of the economic benefits of SD is the ratio of the total EB to the costs.

The following simple relationship is most extensively used for estimating economic benefits /4, 11/:

\[ E = (C_1 - C_2) A_2, \]  

(5.1)

where \( C_1 \) and \( C_2 \) are the reduced costs per unit production obtained with the help of space data and conventional data; \( A_2 \) is the annual production obtained with the use of SD. As \( A_2 \), usually \( S_x \) is used — the area surveyed by SD facilities.
However, this approach involves the comparison of production options with the products being of the same quality. Using (5.1), the specific costs $C_1$ involved in the conventional ways of data collection (aerial, ground techniques), are extended to the amount of work based on SD ($S_k$). The areas which provide information in conventional ways $S_{con}$ are dramatically different in both amount and quality characteristics. Thus, a system covering 125 million km$^2$, using one satellite, can provide annually 94.5 thousand images, each of which covers 35,000 km$^2$. Aerial photography can cover 40 to 360 thousand km$^2$ annually. Thus, to provide the same amount of information as satellites can, one should employ 20 to 80 thousand aircraft, which is not realistic /10/. This example clearly demonstrates a basically wrong approach of (5.1) to estimate EB of using SD.

The following formula is most applicable /11/:

$$E = (I - En K) A_2, \quad (5.2)$$

where $I$ is the income obtained when the new produce is sold; $K$ is the specific capital inputs; $En$ is the efficiency normative; $A_2$ is the amount of new produce. In /12/ is cited a modified version of (5.2) which takes into account not only capital expenses, but also current expenses in the form of the total costs:

$$E(t) = K_y \left\{ \frac{t}{t-1} \sum_{t=t}^{t} \Delta I(t) - \left[ C(t) + E_n K(t) \right] \right\}, \quad (5.3)$$

where $\Delta I(t)$ is the additional income due to the use of management practices based on SD to resolve the $i$-th economic problem in the $t$-th year; $C(t) + E_n K(t)$ are the reduced annual inputs required to support the functioning of
the system of SD collection and use in the given sector.

One of the most significant difficulties in the development of methods of estimating EB is the choice of a comparison base. Estimation of how much more income has been obtained due to the use of SD may be recommended to be made by comparisons with those areas (regions) which use only conventional data. However, such a comparison implies that all other relevant parameters characterising economic activities (soils, weather, crop yields, cultural practices) are similar, which may not be true.

The method of EB determination and assessment of SD use efficiency should be an integral part of a general system of automated management. As an example of such a system, an automated data and management system AIUS-Agroresources which performs a continuous cycle "information-decision-benefits" /15/.

There is a limited number of specific examples which may be found in literature concerning the efficient use of SD in agriculture. Ref. /6/ describes the use of SD for the purposes of land resource mapping. For the Tajik Republic (USSR) on the basis of SD a set of thematic maps was made at the scale of 1:1500000, which enabled delineation of more than 150,000 ha of low production pastures suitable for irrigation, and ca. 20,000 ha of eroded grasslands affected by overgrazing. For Kalmykia 10 thematic maps were plotted, used to specify the area of land resources, ameliorated lands, and for planning a rational use of fodder. Estimated 300 million roubles (on average) may be saved due to the SD-based mapping on an annual basis.

A method was developed to obtain estimates of the state
of winter wheat crops in autumn and spring growing seasons for southern European Russia, based on the use of SD /9/. It enables an operational and early determination of the areas to be resown and the scale of efforts required to provide the necessary amounts of seeds, oil, etc. Economic benefits due to the use of SD for these purposes were 40-50 thousand roubles for a region (ca. 40-60 thousand km²) annually.

An analysis of the expenses involved in obtaining estimates of cropped acreage at the state level with the help of the Landset data /43/ showed the following expense categories:

- computer-based processing (33 %). This includes: magnetic tape recording, data acquisition, digitizing, registry, complete classification of costs, etc. using computers like DEC 10, IBM 3320, CRAY - IS;
- SD costs (15 %);
- personnel wages (43 %);
- equipment (4 %);
- additional/all other costs (maps, images, etc.) (6 %).

There are a number of reasons which hamper further improvements in the calculation of EB of the use of SD, such as:

1. Inadequate investigation into the economic results of using SD.

2. Lack of clear ideas concerning the type of relationship that may exist between expenses and the results, which makes it difficult to choose mathematical models for an adequate description of economic situations and making optimization calculations.

3. Insufficiently well worked-out system of price formation for SD.

As for the costs of SD, it should be noted that its prices
Figure 5.1. Average costs of crop acreage estimation on the basis of remote sensing.

1 - personnel wages (43 %); 2 - equipment (4 %);
3 - other costs (6 %); 4 - computerized processing (33 %);
5 - data (15 %); 6 - total cost is $142,000.
are high enough /20, 32/, especially for high-resolution images. Besides, the satellite imagery prices are growing continuously /20/. This results in the situation when developing countries face growing financial problems in the acquisition of SD required for the earth resources studies and development of national economies.

6. Conclusions

On the basis of analysing the literature on the issues of using remotely sensed data in operational agrometeorology and agriculture the following conclusions may be derived:

- there are few operational systems which use remotely sensed data as a basis for making decisions directly related to agriculture;

- there are systems which work at an experimental or a quasi-operational level, where remotely sensed data is used as one of the components;

- numerous investigations have been conducted, aimed at the development of methods of the use of remotely sensed data in agrometeorology;

- international collaboration may be developed in the area of using remote sensing for operational agrometeorology (from the compilation of international dictionaries/glossaries of remote sensing to the establishment of an international data bank and making international experiments);

- the most useful form of further international collaboration in the area of using remotely sensed data in agrometeorology seems to be the establishment of a CAgM Working Group for the issue, with its terms of reference including preparation of guidance materials to be used in different countries.
7. References

   On the system of integrated processing of aerospace data
   5, p. 5-11 (in Russian).

2. Virchenko O.V., Kleshchenko A.D. Processing of data obtained by
   high-resolution scanning systems for estimating the state and
   production of winter wheat // Proc. AURIAIN. 1984. Issue 14,

3. Dobrynin N.P., Sazonov N.V. Basic design of a data measuring
   system for estimating physical parameters of underlying surface
   with the use of microwave radiometers // In: Issues of Creation
   of Automated System for Space Monitoring/ Proc. VNITs AIUS-Agro-

4. Iskakov B.I., Vishnyakov V.V., Abroskin A.S., Babenko I.V.
   Distinctions and principles of calculation of a statistical
   index of social and economic benefits of using remote sensing
   for space study of the Earth // In: Problems of Statistica and

5. Karpov V.N., Zarubaiilo V.T. The use of optical remote sensing
   to resolve practical problems in agriculture: Problems and per-
   spectives // In: Methods and Means of Intensifying Stable and
   Stationary Processes in Crop Production / Leningrad Inst. Agric.

6. Kienko Yu.P., Moiseenko A.E. On some practical results and bene-
   fits of using space data in national economy // In: Use of
   space Photographs for Purposes of integrated Study and Mapping
   of the USSR’s Natural Resources. Proc. of Nat. Conf., Dushanbe,


