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THE LARGE AREA CROP INVENTORY EXPERIMENT (LACIE) - AN APPLICATION OF REMOTE SENSING BY MULTISPECTRAL SCANNERS

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ABSTRACT

The Large Area Crop Inventory Experiment (LACIE) is a major step in the application of the multispectral remote sensing technology which has been developed over the last decade to the inventorying of agricultural crops on a world-wide basis. Primary data sources for LACIE are (1) multispectral radiance measurements acquired by the Landsat satellite, (2) meteorological data from both ground weather stations reported through the World Meteorological Organization (WMO) network and from meteorological satellites and (3) certain historic information. These data are computer processed to estimate wheat area from the Landsat data, yield from meteorological data and production, the product of area and yield. Experimental reports are produced on wheat area, yield and production on a periodic basis for selected wheat-producing regions. LACIE is being conducted jointly by the NASA, NOAA, and USDA to prove out an economically important application of remote sensing from space. The experiment has completed its first phase of activity in estimating wheat area, yield and production for a "yardstick" area in the U.S. Great Plains. The results are generally very encouraging and the basic technology appears sound. Further tests are underway and the prospect of an operational crop inventory system using multispectral scanners aboard satellites as a major sensing device appears well within reach. This paper describes the technical approach to LACIE, the activity already completed and the tentative results of the first phase of the activity.

INTRODUCTION

For perhaps 10,000 years most of the inhabitants of this earth have depended on agriculture for food and fiber. While this has resulted in a much greater stability than was enjoyed by food-gathering societies there has often been an imbalance between the supply and the need. This problem has been aggravated in recent years and food shortages have become, sadly, common place. One key element in addressing this problem is the issue of better crop information.

The theme of this conference, Productivity through Instrumentation and Control is most apt in helping us to focus on the role of instrumentation in addressing a critical problem on the planet. The need for crop inventory information was pointed out by the U.S. Department of Agriculture*

> The U.S. Department of Agriculture has broad responsibilities for maintaining the production of commodities at optimum levels. To fulfill these responsibilities to farmers, consumers, and to customers abroad, we must be able to estimate the volume of crops we can produce, the volume we are producing, and the volume needed by both foreign and domestic markets. In doing this, accurate production estimates, both here and abroad are essential.

The process by which human nutrition is accomplished is very complex with production, transport, marketing and other decisions required. For each of these decisions sound information is essential and this is often lacking or in error. For example, a couple of years ago in Texas many wheat farmers anticipated a world price of around $2 a bushel and chose not to harvest a marginal crop. Had the probable picture on world production been better known a more realistic price would have been assumed and the crop, poor though it was, would have been harvested.

The earth-looking satellite offers a new vantage point from which to conduct resource surveys and this in turn can lead to improved information because of the sophisticated instrumentation carried aboard such satellites. This paper deals with a major experiment in applying the capabilities of such a satellite to the very practical problem of inventorying agriculture crops.

*The author wishes to acknowledge the many contributions to this experiment, its planning implementation and execution, by his colleagues not only in NASA, but more particularly in the USDA and in the NOAA of the U.S. Department of Commerce. This is truly a joint venture among the three agencies and many have played important roles in bringing the experiment to its present state.

*From a public announcement by Dr. William L. Ruble, Deputy Administrator, Management, Agricultural Stabilization and Conservation Service, U.S. Dept. of Agriculture at the ERTS-B Press Briefing, January 14, 1975.

In anticipation of such information needs the remote sensing community has for several years been developing a new technology for conducting large-scale inventories.

The major events in the development and application of this technology were as follows: In the late 1950's surveys of agricultural terrain were carried out by black and white aerial photography using camouflage detection film sensitive in the reflective infrared wavelengths; in the early 1960's the development of airborne multispectral scanners and large-scale digital-processing techniques made possible computer-aided classification of wheat and other crops which was first successfully done in 1966, also in 1969 the Apollo multiband camera experiment (S-065) simulating Landsat spectral bands was flown and the first computer-aided classification of wheat and other crops using satellite data was carried out, in 1971, a corn blight watch experiment was the first large area agricultural effort and used both image analysis and computer-aided analysis of airborne multispectral scanner data; then, beginning in 1972 with the launch of Landsat 1, numerous investigations into crop identification using satellite data were carried out and it is these investigations on which the present experiment is building.

Interest in pursuing inventory techniques was intensified by grain-production shortfalls in some areas of the world in 1972 and 1973 and by an increase in consumption during those years. This interest spurred planning activity in NASA, USDA, and NOAA, and by 1974, the time was judged appropriate for a large-scale experiment. This experiment is called the Large Area Crop Inventory Experiment (LACIE) or LACIE for convenience.

Wheat was selected for the LACIE for a number of reasons. Principal of these is that considerable experience has been acquired over the past decade in the use of multispectral remote sensing measurements to identify wheat. Additionally, wheat tends to be, relatively, a less complex crop for which yield is controlled primarily by temperature and available moisture, thus allowing simpler approaches to the estimation of yield. Also, wheat has long been one of man's most important crops and is certainly the most important in international trade. Wheat is the national food staple in 43 countries around the world (Reference 1) and provides about 20 percent of the total food calories of the people of the world and is second only to rice, which provides on the order of 21 percent of the total food calories. The land area under cultivation for wheat far exceeds that of any other grain crop. Because wheat is grown extensively throughout the world, it merits observation somewhere at virtually all times of the year. Thus, an inventory of wheat makes good use of the global and repetitive coverage capabilities of earth-orbiting satellites.

An underlying philosophy of LACIE is that the contribution which remote sensing technology can make most immediately is the provision of more accurate and more timely information on a global scale. Given this philosophy, it is not the intent of LACIE to provide extremely accurate domestic estimates as does the Statistical Reporting Service (SRS) of the USDA. Rather, the goals are oriented to large areas; that is, multicountries, as follows: the first goal is to develop and exhibit a capability to make estimates of wheat production at harvest time; a second goal is to establish how accurately production estimates can be made with this approach earlier in the crop year; a third goal is to develop and exhibit a capability to handle the quantity of data required to inventory wheat on a global basis in a timely manner; a fourth goal is to develop information and other support data to support the design and cost effectiveness analysis of a future prototype system.

LACIE is being conducted jointly by the NASA, NOAA, and USDA to prove out an economically important application of remote sensing from space. The agencies involved placed a high priority on accomplishing the stated objectives of LACIE as soon as feasible, and resources were made available to pursue the LACIE objectives vigorously with a goal of delivering at the culmination of LACIE, proven technology plus a definition of the key problems to be solved prior to the implementation of an operational inventory system.

GENERAL TECHNICAL APPROACH

The general technical approach to the LACIE is to estimate production of wheat on a country-by-country basis where production is the product of area and yield. Initial attention has been given to the U.S. Both of these components, area and yield, are estimated for local areas and aggregated to regional and country levels. Area is derived by classification and mensuration of Landsat multispectral scanner (MSS) data acquired on a sampling basis over regions in which wheat is a major crop. That is, wheat area is estimated from identification of wheat in the Landsat MSS data by knowing the spectral properties of wheat. Maximum use is made of computer-aided analysis to provide the most timely estimates possible.

Yield is estimated from statistical models which relate crop yield to local meteorological conditions, notably precipitation and temperature. Initially, these data are being obtained from the World Meteorological Network of ground stations. As the experiment progresses, supplemental meteorological data from NOAA environmental satellites will be used.

AREA ESTIMATION

The critical contribution from the multispectral scanner data is to allow an estimate of the area growing wheat. The time may come in the future when crop condition and yield-related variables can be interpreted from spectral data but for now LACIE depends on such data only for a determination of where wheat is growing and the areal extent. This section will treat the instrumentation onboard the satellite and the way information on wheat area is extracted from the data.

The Multispectral Scanner (MSS) (Reference 2) gathers data by imaging the surface of the earth in several spectral bands simultaneously through the same optical system. The MSS for Landsat 1 and 2 is a 4-band scanner operating in the solar-reflected spectral band region from 0.5 to 1.1 micrometer wavelength. It scans crosstrack swaths of 185 kilometers (100 nm) width, imaging six scan lines across in each of the four spectral bands simultaneously. The object plane is scanned by means of an oscillating flat mirror between the scene and the double-reflector, telescope type of optical chain. The 11.56 degree cross-track field of view is scanned as the mirror oscillates ±2.89 degrees about its nominal position. The scanning arrangement is shown in (Figure 1).

The instantaneous field of view of each detector subtends, from the nominal orbital altitude, an earth-area square of 79 meters on a side. The area viewed instantaneously is referred to as a picture element or "pixel". Field stops are formed for each line imaged during a scan, and for each spectral band, by the square input end of an optical fiber. Six of these fibers in each of four bands are arranged in a 4 x 6 matrix in the focused area of the telescope.

Light impinging on each glass fiber is conducted to an individual detector through an optical filter unique to the spectral band served. An image of a line across the swath is swept across the fiber each time the mirror scans, causing a video signal to be produced at the scanner electronics output for each of 24 channels. These signals are then sampled, digitized and formatted into a serial digital data stream by a multiplexer. The sampling interval is 9.95 sec, corresponding to a cross track motion of the instantaneous field of view of 56 meters.

The along-track scan is produced by the orbital motion of the spacecraft. The nominal orbital velocity causes an along-track motion of the subsatellite point of 6.47 km/sec neglecting spacecraft perturbation and earth rotation effects. By oscillating the mirror at a rate of 13.62 Hz, the subsatellite point will have moved 474 meters along track during the 73.42 millisecond active scan and retrace cycle. The width of the along-track field of view of six detectors is also 474 meters. Thus, complete coverage of the total 185 kilometer wide swath is obtained. The line scanned by the first detector in one cycle of the active mirror scan lies adjacent to the line scanned by the sixth detector of the previous mirror scan.

The MSS spectral bands are:

Band 1	0 5 to 0.6 micrometers
Band 2	0.6 to 0.7 micrometers
Band 3	0.7 to 0.8 micrometers
Band 4	0.8 to 1.1 micrometers

Bands 1 through 3 use photomultiplier tubes as detectors; band 4 uses silicon photodiodes. The analog video outputs of each detector are sampled by the multiplexer during the active portion of the west-to-east sweep of the mirror.

The video outputs from each detector in the scanner are sampled and commutated once in 9.95 microseconds and multiplexed into a pulse amplitude modulated stream. The commutated samples of video are either transmitted directly to an analog-to-digital converter for encoding or, for Bands 1 through 3, are directed to a logarithmic signal compression amplifier and then to the encoder. This selection is made by ground command. Encoding for either the linear or compressed mode is to 6 bits. The signal compression mode is normally used since the photomultiplier detectors have a better signal-to-noise performance.

A very detailed treatment of the instrument characteristics is given in Reference 2. The instrument platform is the Landsat spacecraft (formerly known as the Earth Resources Technology Satellite or ERTS). The Landsat, Figure 2, is an earth-pointing, stabilized spacecraft with subsystems that provide the power, environment, orbit maintenance, attitude control, and information flow required to support the sensors for a period of one year in orbit. It weighs approximately 2100 pounds (953 kg) and has an approximate overall height of 10 feet (3.04 m) and a diameter of 5 feet (1.52 m), with solar paddles extending out to a total of 13 feet (3.96 m).

Data is relayed to the ground either directly or by playback from a wideband video tape recorder. Three domestic ground stations are in operation in the U S. and several other countries have or are installing their own stations to avail themselves of Landsat data.

The NASA Data Processing Facility at our Goddard Space Flight Center in Greenbelt, Maryland, processes and stores the MSS data and disseminates it to users in the form of film imagery or computer compatible tapes.

Analysis of Landsat Data is key to the estimation of wheat area. The basic premise in the analysis of MSS data is, of course, that different features on the earth (such as wheat) display different spectral signatures (or combinations of reflectance levels in the various spectral bands). If these signatures were very stable for a given crop then the stored signature data bank approach could be taken and wheat, say, could always be identified just like a chemical compound can be from its characteristics observed on a mass spectrometer. Unfortunately, the situation is not so simple. Wheat, to take a single crop, displays vastly different reflectance characteristics depending on the plant maturity, the extent of ground cover (never 100%) and hence the soil color, the variety, the state of health, the clarity of the atmosphere, etc. All these causes of variation make it necessary to extract a "local" signature and use this to train the classifier. In some cases limited application or extension of such local signatures can be made to adjacent or analogous sites.

The classification subsystem design is based upon the judgement that wheat can be separated adequately from other crops by analysis of up to four acquisitions of Landsat data during the biological development of wheat. The biostages chosen are (Figure 3):

a. Crop establishment: planting to jointing (with a gap during dormancy for winter wheat.)

b. Green: jointing to heading

c. Heading: heading to soft dough

d. Mature: soft dough to harvest

Signatures obtained on one calendar date within a biostage are not necessarily valid for other acquisition dates within the same phase.

The analysis of the MSS data is being intentionally carried out without the current ground data. Ground observations will, of course, be used for evaluation purposes but the only data used operationally will be those typically available in real time over large areas from existing sources. This self-imposed constraint makes it necessary to train the classifier using Landsat data themselves together with crop calendar information, that is, information which defines the stage of growth of the crop at various times during the growing season. To enhance the utility of such information, seasonal adjustments are made to the crop calendar using current year weather data.

The initial crop calendar adjustment model implemented for LACIE (operated at Washington, D.C. by NOAA) is based on the Robertson model (Reference 3). This model requires measurements of maximum and minimum daily temperature and an estimate of the planting date. It is used in LACIE to provide biweekly updated estimates of the actual times at which various growth stages are reached. In addition to use in training field identifications, the outputs of this model will be used to specify time for Landsat data acquisition to GSFC.

Following receipt in Houston, Landsat digital data over 5 x 6 mile sample segments is converted to film image form and analyst interpreters select 40 to 50 training fields for wheat and for other agricultural categories and provide a definition of the boundary of such fields to a data processing analyst for the computer-aided classification. This represents manual analysis of about 10 percent of all Landsat data acquired.

In these segments, the analyst interpreter (AI) relies mainly on interpretation keys which distinguish wheat from nonwheat based on tonal appearance, change over the growing season and spatial information such as field shape. In addition, the AI is provided with historical cropping practice data. In regions where wheat has a crop calendar distinctly different from other crops, the AI should be able to accurately distinguish wheat from other, provided he has an accurate knowledge of the current year's cropping calendars for the various crops.

The AI is provided with weather summary data (from NOAA) each week summarizing meteorological events known to affect crop appearance. Snowfall, heavy precipitation or drought, and temperature extremes will be the key variables of interest in the meteorological data.

While the AI procedures described above are the backbone of the initial LACIE effort, the concept of extending signatures between regions known to be "analogous" to each other is being investigated.

Procedures for the classification involve, basically, a clustering of the training data to aid in selecting suitable training classes. A feature selection process can be employed to reduce the number of spectral channels considered by the classifier. Finally, the segment is classified pixel-by-pixel with a maximum likelihood classifier into wheat and nonwheat classes. The fraction of each segment's area classified as wheat is determined by ratioing wheat pixel count to total pixel count. The details of this procedure are provided in Reference 4. A high degree of analyst interaction is currently allowed but the intent of the experiment is, eventually, to automate the classification as completely as possible.

The key technology issues being addressed in the classification of Landsat data are methods for developing training signatures, methods for extending the developed signatures over large areas, and improved methods for estimating wheat proportions within the sample segments.

The technology required for LACIE represents a departure from the existing technology base in that in situ ground observations have been traditionally used to "train" the classifier. The LACIE effort in this regard is focused on improving analyst interpreter techniques and the development of the "analog" area concept discussed earlier.

Signature extension is key to LACIE in that manpower expended per segment decreases drastically with increasing ability to apply training statistics over large areas. Signature extension is focused on: (1) definition of methods to determine signature strata; that is, geographic regions for which multispectral signatures are sufficiently homogeneous so as to not significantly degrade classification performance (such strata will most probably be uniform in soil spectral characteristics, crop development stage, and agricultural practices employed) and on (2) development of algorithms which permit signature extension between areas with different environmental conditions, for example, different atmospheric conditions or sun angle. The area estimation procedure is summarized graphically in Figure 4 for a situation in which signature extension is not employed.

YIELD ESTIMATION

Yield predictions are made from models which involve weather data, typically, precipitation and temperature. The development of the yield models was carried out by NOAA at the Center of Climatic and Environmental Assessment (CCEA) at Columbia, Missouri. The initial models are statistical in nature, i e., expressions for yield as a function of key meteorological parameters and were derived from regression analyses using historical yield and weather data over each of a number of regions for which the dependence of yield on weather is expected to be rather uniform Twelve such regions were identified in the U.S. Great Plains. Within any one region, the same set of regression coefficients in the model apply; however, varying weather conditions at various locations within the region result in different projected yields. The operation of these models takes place at NOAA facilities in Washington, D.C. Basic meteorological parameters currently available on the World Meteorological Organization (WMO) network of ground stations provide the input data to the models.

The equations are of the form:

Yield = a + b (Preseason precipitation) + c (temperature) + d (Seasonal precipitation) -

The coefficients for each region are determined from existing historic yield and meteorological data and vary from region to region because of differences in climatological and agricultural factors between regions.

The later phases of LACIE may employ yield models of a more sophisticated type in which plant growth phenomena are taken into account more explicitly. Also, observations from environmental satellites may be utilized to extend and interpolate the meteorological data from the WMO network.

PRODUCTION ESTIMATION

The area and yield determinations per stratum provide the basic inputs to a production estimate. The LACIE system will produce monthly yield estimates, area estimates, and production estimates for each major wheat-producing Crop Reporting District, State, and Region under study. The production estimation procedure is summarized graphically in Figure 5.

SCOPE AND PHASING

The development of the LACIE system and its operation is being conducted in three phases, each tied to the wheat-growing cycle and expanding in scope as capability increases. The first phase covered the 1974-75 crop year (in the United States) and addresses area estimates for nine wheat-growing states in the Great Plains. Over the same region, yield models were tested and production feasibility tests were made. Classification tests were conducted on representative segments in other wheat-growing regions, and 29 intensive test sites in North America were analyzed to provide one basis for performance assessment.

The second phase from the fall of 1975 to the spring of 1977 will include area, yield, and production estimates for several wheat-growing regions, a continuation of tests on representative sites elsewhere and on intensive test sites, and will cover a longer crop cycle to include both northern and southern hemisphere wheat crops.

The third phase, from the fall of 1976 to the spring of 1978, will again provide area, yield, and production estimates over several regions and will incorporate those refinements to the technology developed in the research efforts of the earlier phases.

The schedule for LACIE is clearly very success-oriented. This was considered necessary, however, to exploit fully the Landsat 2 capability and to demonstrate a large-scale application of space remote sensing at the earliest possible time.

RESULTS

The first phase of LACIE was a period of bringing system components into operation and testing their ability to meet experiment goals. Area estimation was performed in a quasi-operational mode, yield and production estimation in a feasibility test mode.

The progress of the project during the first phase can be best described by a summary of goals and accomplishments. Such a summary is given in Table I.

The results, in terms of accuracy of the survey estimates, are to be compared to a performance criteria which calls for an estimate of the production for a country to be 90% accurate 90% of the time at harvest.

There is considerable confidence from the early results that the area-estimation component of LACIE will with planned modifications meet the project goals. The principal questions remaining are the reliability with which wheat can be separated from other small grains, and the possible decrease in accuracy of results when surveying areas with fields smaller than those in the United States.

In the area of yield estimation, tests during the first phase indicate that the yield-estimation capability will meet experiment goals.

The first phase was a highly successful step in LACIE. Results of the second phase to date are also very promising and the improvements made on the basis of Phase I experience are working well.

Overall, substantial progress has been made in validating a crop-inventory system based on multispectral remote sensing and mathematical yield models. The activity in LACIE has provided the best demonstration to date that wheat can be identified and the area measured by satellite remote sensing.

CONCLUSIONS

The Large Area Crop Inventory Experiment (LACIE) is a major step in the application of the multispectral remote sensing technology developed over the last decade to the inventorying of agricultural crops on a worldwide basis.

An inventory system has been developed and testing is underway. Results to date indicate that a useful crop inventory system can be based on the LACIE technology.

Future efforts will undoubtedly push in the direction of operational systems surveying many crops on a worldwide basis and provide a new source of information for wise stewardship of our planet's resources.

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TABLE I - PHASE I GOALS AND ACCOMPLISHMENTS

Goals	Accomplishments
Develop a system to test the components of the LACIE technology	System developed and exercised successfully
Conduct tests of the area-estimation capability over selected area within the U.S. Great Plains (the "yardstick" region)	Tests successfully conducted for the nine states selected (the U.S. Great Plains)
Evaluate the feasibility of wheat classification over representative foreign locations	Test conducted over segments in all LACIE countries. Experienced difficulties in some countries with small fields, and with cloud cover in some cases.
Conduct feasibility tests of the yield and production-estimation capability	Yield models for U.S. Great Plains checked historically over a ten-year period, production tested for 1975. Basic approaches adequate. Some improvements will be required.
Evaluate performance for accuracy, timeliness, and utility	Accuracy of results assessed as satisfactory; evaluation being conducted by USDA to assess timeliness and utility
Modify the technology as required for Phase II	Area-estimation technology revised and yardstick area reprocessed; areas for yield model improvement identified. Phase II initiated as planned.

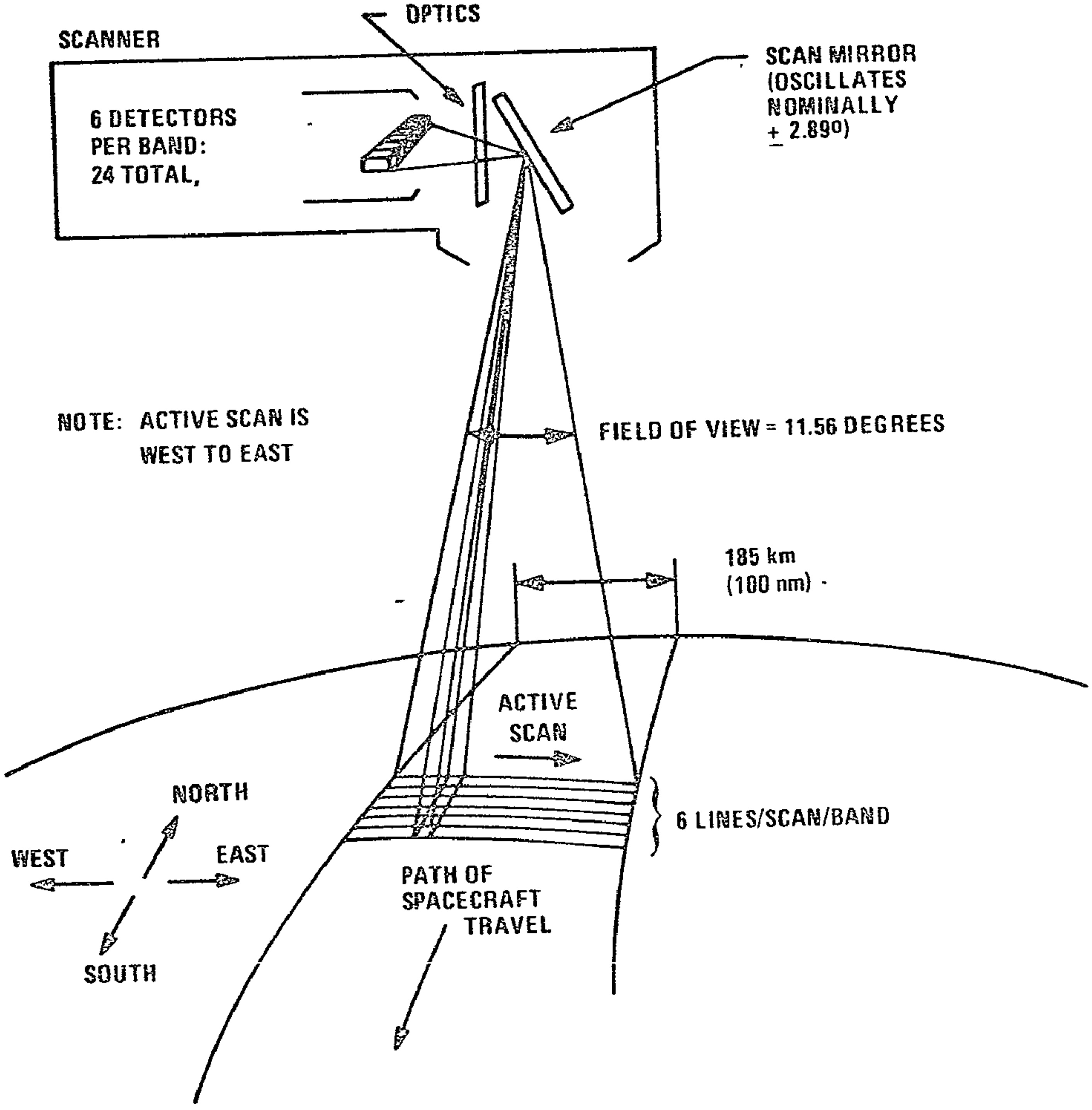

Figure 1. - Multispectral scanning arrangement.

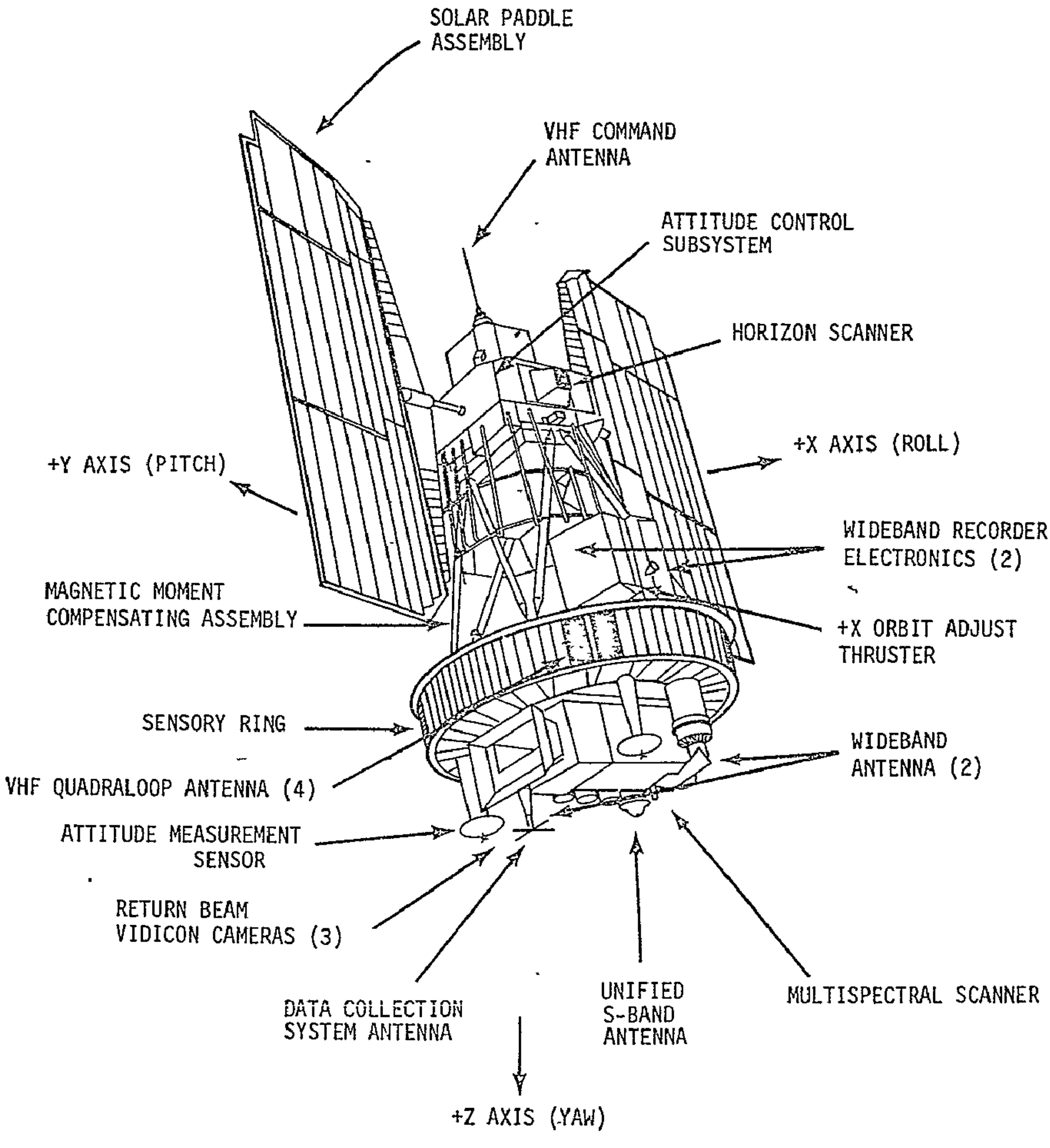

Figure 2 - Landsat spacecraft

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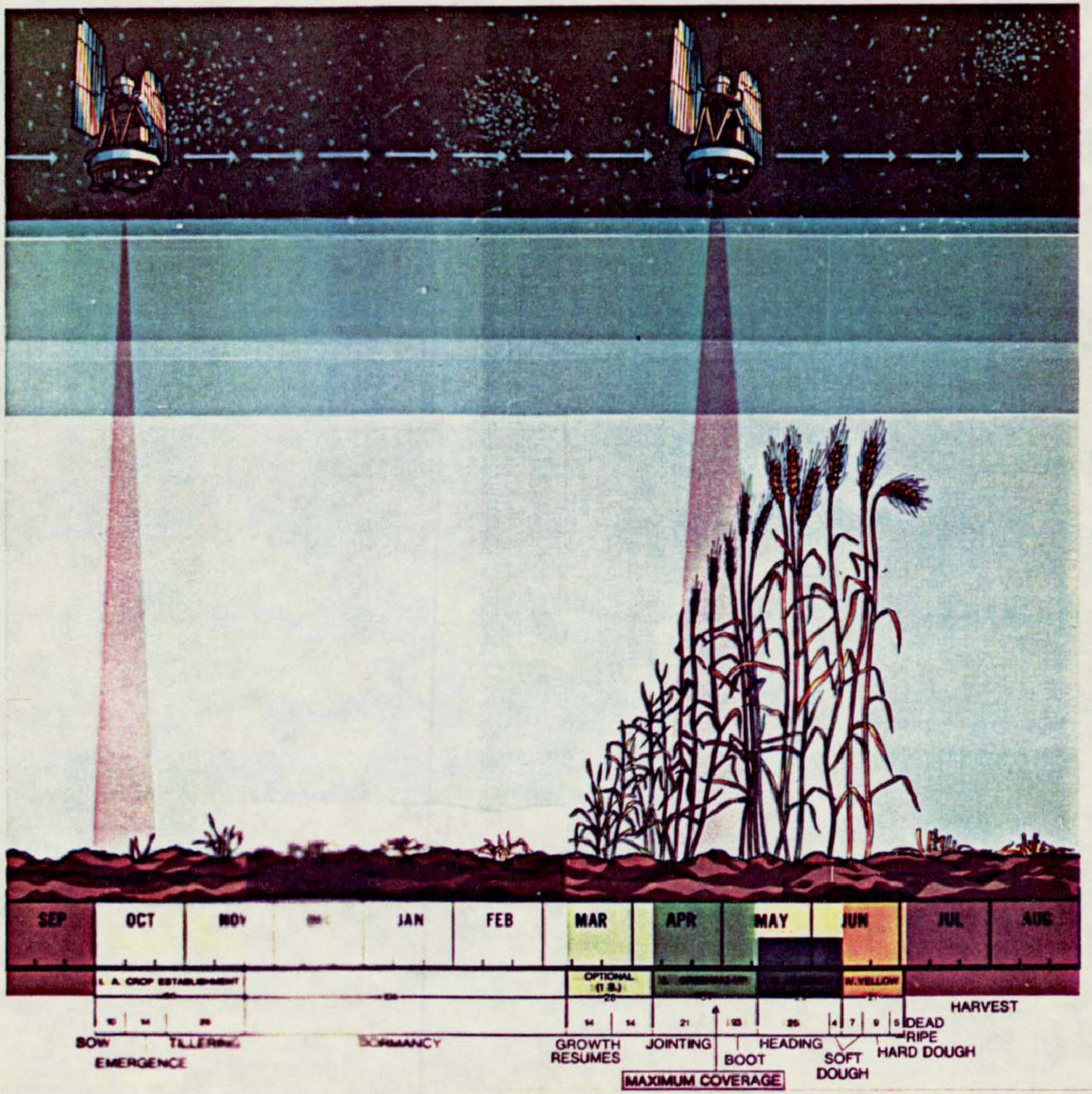
DEVELOPMENT OF WINTER WHEAT



Development of winter wheat.

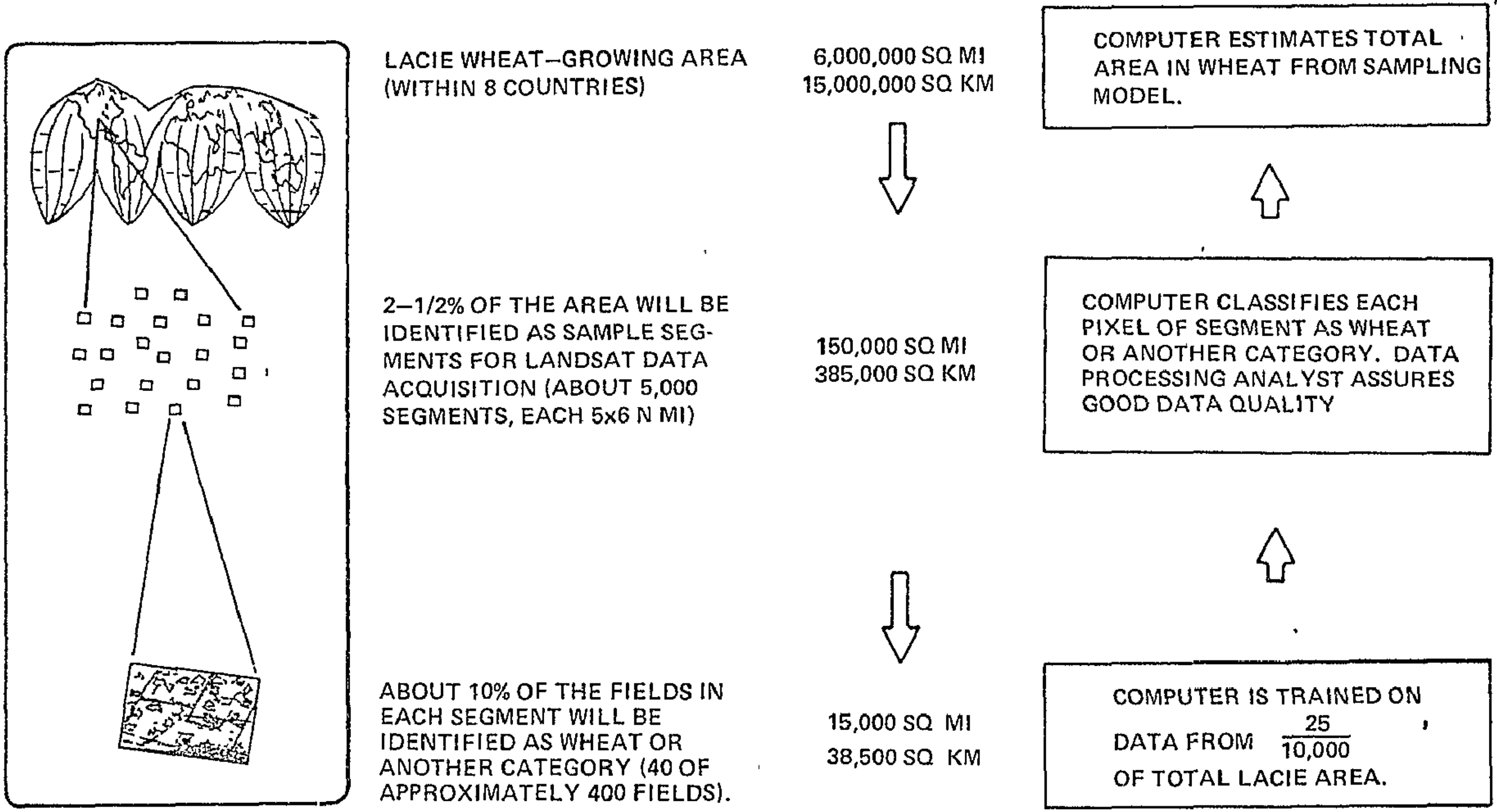
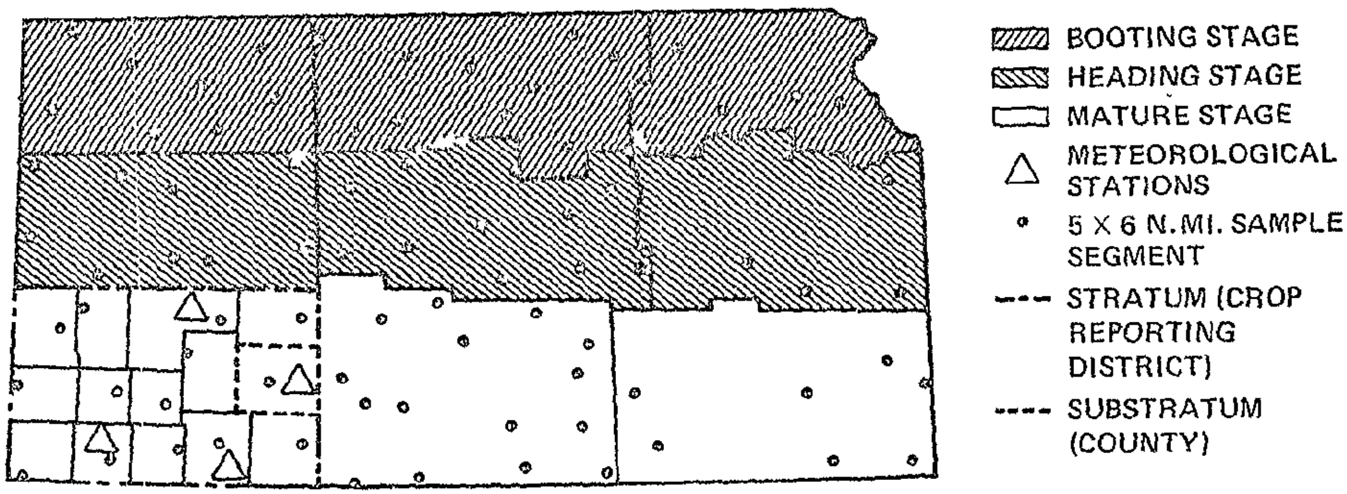


Figure 4 · LACIE classification and mensuration.



$$\text{STRATUM YIELD} = Y_S = \text{TREND} + b(\text{MOISTURE}) + C(\text{TEMPERATURE})$$

$$\text{LARGE AREA YIELD} = \sum_{\text{STRATA}} W_S Y_S = \text{WEIGHTED SUM OF STRATA YIELDS}$$

$$\text{STRATUM ACREAGE} = A_S = \sum_{\text{SEGMENTS}} U_S P_S = \text{WEIGHTED SUM OF SEGMENT WHEAT PERCENTAGES}$$

$$\text{LARGE AREA ACREAGE} = \sum_{\text{STRATA}} A_S = \text{SUM OF STRATA ACREAGES}$$

$$\text{STRATUM PRODUCTION} = P_S = A_S \times Y_S$$

$$\text{LARGE AREA PRODUCTION} = \sum_{\text{STRATA}} P_S = \text{SUM OF STRATA PRODUCTION}$$

Figure 5. - LACIE approach to area, yield, and production estimation.