SATELLITE AGRICULTURAL SURVEYS-CONTRIBUTIONS OF H. O. HARTLEY

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PREFACE

Professor Herman O. Hartley was a most gracious individual - a top professional whose knowledge and leadership in his field were unequaled. We are especially appreciative of the many opportunities we had to associate and work with him and to learn from him. From HOH we learned the true meaning of professionalism; everyone who had an opportunity to meet and know him had a very deep respect for this man. Yet, with all the qualities of greatness that he possessed, his approach in dealing with others was never less than one of warmness and understanding. It is indeed a privilege for us to pay tribute to HOH by presenting an area of research to which he made many significant contributions. In view of the expanse of this research, our presentation is primarily expository. We can only hope, in so short a space, to give but a small flavor of the many contributions HOH made in the area of satellite agricultural surveys.

1. INTRODUCTION

In the last decade the National Aeronautics and Space Administration has been pursuing the development of a remote sensing technology based on satellite data for local and global monitoring of the earth's resources. In July 1972, NASA launched its first earth resources technology satellite (Landsat). A second Landsat was placed into orbit in January 1975, a third in early 1978, a fourth in July of this year (1982), and a fifth is planned for 1984 or 1985. The purpose of these earth viewing satellites is to test the feasibility of using remotely sensed data acquired from space to assist in achieving better management of our environment and natural resources. The instruments aboard Landsat measure the intensity of the sunlight reflected from the surface of the earth, with the latter two satellites also containing instruments to acquire 'thermal band' data. These measurements are then converted into electronic signals, transmitted to earth, recorded on magnetic tapes, and reconstructed into photographic images. Because different materials on the earth's surface reflect light differently, the reconstructed image exhibits the different substances on earth viewed by the instruments, e.g., water, forests, and crops. When these measurements are statistically modeled and correlated with ground features, it becomes feasible to assess earth resources for the specified area by acquiring and analyzing its Landsat data.

The image analysis techniques are used to correlate spectral classes to features on the ground and label them, e.g. crop-types. An area segment of many square miles in size is generally needed to delineate discernible patterns and identify the possible crop-types. A single crop can be separated from others in a Landsat image by monitoring the temporal development of its fields from planting through harvest, a technique which is feasible because of the availability of the imagery and digital data acquired every 18 days. This process of temporal development requires registration of one Landsat image to another acquired during a crop-season. (Registration is the process of accurately aligning two or more images of the same scene.) To determine the possible crop acreage in an area, its various acquisition data sets are classified using a discriminant analysis technique. Thus, the entire method of crop acreage estimation for an areal segment involves techniques of scene registration, image, and discriminant analyses.

In 1974, satellite remote sensing technology developed over the previous decade was combined with statistical survey techniques for the development of a global crop inventory system. This experimental study was referred to as the Large Area Crop Inventory Experiment (LACIE) and was concluded with the LACIE Symposium conducted at NASA/JSC in October 1978 (ref. 44). Following LACIE, a program referred to as AgRISTARS (Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing) was initiated at the outset of fiscal year 1980 in response to an initiative issued by the U.S. Department of Agriculture (USDA). Led by the USDA, AgRISTARS is a cooperative effort with the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Department of the Interior (USDI), and the Agency for International Development (AID). With an overall goal to determine the feasibility of integrating aerospace remote sensing technology into existing or future USDA data acquisition systems, the overall approach is comprised of a program of remote sensing research, development, and testing which would address needs for a wide range of information on domestic and global resources and agricultural commodities. A key part of the planned activities is the development and testing of procedures for using aerospace remote sensing technology in conjunction with the methodology of sample surveys to provide objective, timely, and reliable forecasts of foreign crop acreage and production.

The late Professor H. O. Hartley greatly influenced the technical developments in these programs. The purpose of this paper is to summarize HOH's many technical contributions to the developments experienced in satellite agricultural surveys over the past five years. The material herein is necessarily summary in scope, for otherwise it would be impossible to discuss the expanse of Hartley's research (some 43+ papers and technical reports) which directly addressed the problems and questions that were specific to the satellite-based global crop inventory endeavor. More in-depth discussions of the technical aspects are documented in the LACIE Symposium Proceedings (ref. 44) and in the Proceedings of the Annual ASA Survey Research Methods Session held in San Diego (ref. 47). The remainder of this paper will concentrate specifically on those areas researched by Professor Hartley during the years 1974-80 in support of global crop inventory. There will be several instances in which his specific contributions - which were many - are not directly referenced, although they had direct bearing on the technology that resulted.

1.1 SPECIFIC AREAS OF RESEARCH

The magnitude of the contribution of HOH to the LACIE and AgRISTARS projects is reflected in the numerous technical reports he prepared. The majority of these may be categorized into five areas:

(1) sampling and estimation for large area crop inventorying (refs. 1 through 16); (2) yield prediction (refs. 17 through 26); (3) crop modeling and parameterization (refs. 27 through 30); (4) sample unit crop proportion estimation (refs. 31 through 37); and (5) advanced multicrop/multiyear estimation approaches (refs. 38 through 43). At the outset of LACIE in 1974, a contract was initiated with Professor Hartley at Texas A&M University to take the lead in putting forth a sampling and estimation approach for global inventorying of area and production for wheat. Some of the key questions which had to be addressed at that time included the following: (1) Can a sampling strategy for acquisition of Landsat data be designed to achieve the required accuracy with a manageable data load? (2) How can the geographic wheat distribution characteristics (e.g., within-stratum variances) best be determined so as to achieve efficient sampling and reliable estimates? (3) What is a viable configuration for the sampling unit and what should the sampling frame be? (4) Does loss of sampling units due to cloud cover cause excessive bias? The remainder of this paper summarizes the approaches taken in answer to these questions. In this attempt to convey a very summary part of the in-depth thinking that HOH devoted to this already expansive topic, we take full responsibility for errors of misinterpretation that may have resulted in our reading of his extensive documentation.

2. LARGE AREA SAMPLING AND ESTIMATION

2.1 SAMPLING UNIT SIZE

The purpose of the LACIE project was to provide an estimate of the production of wheat in a given country (initial target countries were the United States, the U.S.S.R., India, Australia, China, Canada, Brazil, and Argentina) that is 90 percent accurate, 90 percent of the time (referred to as the 90-90 criterion and defined by

$$\mathrm{Prob}\left[\,|\hat{P} - P| \leqslant .1P\right] \geqslant .9$$

where P is the actual wheat production in a country and $\hat{P}$ is an estimate of P. The purpose of the LACIE sampling plan was to provide estimates of wheat acreage with minimal sampling errors so that when these errors were combined with the errors due to classification (the so-called measurement errors) and yield estimation, the 90-90 criterion could be met.

A key first sampling design issue faced was that of the geographical configuration and size of the sampling unit. For various reasons, it was impractical to consider sampling units as small as the measurement unit size (approximately 1.1 acres). The sampling unit size and the total number of sample units were initially based on some technical considerations other than the precision of the estimate. The sampling unit size that was eventually arrived at was a rectangular area of 5 by 6 nautical miles. It may be argued that this unit (it contains approximately 25,000 acres) is too large from the standpoint of sampling efficiency; the following considerations, however, were important: (1) It was necessary to register the acquisition of data from sampling units acquired during the various passages of the satellite over the same unit. Under the guidelines, the sample segments were each to be acquired four times, cloud and snow cover permitting, so that the temporal analysis and classification of spectral data could be made, resulting in segment wheat proportion estimates with minimum classification errors. The technology of identifying the same unit in these various passages required key points within the unit that are easily recognized and, in turn, this dictated the need for the sampling unit to have a rather large geographical extent. (2) The satellite imagery and its interpretation by the analysts, as well as the computation of crop 'signatures' (i.e., class parameters) custom-made for the unit, required a unit of adequate size. (3) Based on a study of having smaller sampling units, the gains did not justify changing from the above selected unit size in view of the aforementioned and other practical limitations.

2.2 THE SAMPLING FRAME

The sampling frame was constructed by first covering a map of the wheat growing regions of a country by a large grid which divided the area into segments each measuring 5 by 6 nautical miles. Next, those segments which appeared to have less than 5 percent agriculture, as determined by an examination of Landsat imagery from previous years, were excluded. The remaining segments constituted the frame from which the actual sample segments were chosen.

2.3 SAMPLING DESIGN AND ACREAGE ESTIMATION

It was particularly in these areas that Dr. Hartley made many significant contributions (refs. 1 through 16) as a result of not only his extensive knowledge in sampling, but also his foresight in anticipating many problems that were unique to this particular environment. The sampling design went through a progression of approaches that attempted to make maximal usage of available products and data as they became available.

No previous large-scale Landsat data were available at the outset of LACIE to develop an adequate Landsat sampling plan. Instead, the historical agricultural statistics were used to develop an area sampling frame and stratification for a country and to approximate stratum parameters such as size and variance. Then, of course, there was a concern about not having reliable and detailed historical records for some countries. Of the sampled countries, reliable historical crop statistics were available at a small political subdivision level for five countries: the United States at the county level, Canada at the crop district level, Australia at the shire level, and Argentina and Brazil at the partido level. For the other three countries, the historical data were available at a much larger political subdivision level, e.g., oblast in the U.S.S.R., province in China, and state in India. Given this disparity between the countries, a single within-country sampling strategy could not be adopted globally. To resolve this and other difficulties, Professor Hartley first divided the eight countries into two groups, one consisting of five countries with detailed historical records and another consisting of three countries with less detailed historical records, and then proposed two separate sampling plans for the two groups of countries. He also made the assumption of a binominal model for the crop acreage in a sample segment in order to approximate its stratum variance. Under this assumption, a sample segment contains either all wheat or no wheat at all. For the LACIE sampling unit (5 by 6 nautical miles in area), the stratum variance is perhaps much smaller than that given by the binomial model. He justified the latter for use in sample allocation, however, because of the lack of any other estimate for a stratum variance. Moreover, its use may still result in a near optimal stratum sample allocation if the total sample size is fixed and the stratum variance is underestimated or overestimated approximately by the same amount across all strata.

The sampling and estimation approach was designed primarily as follows: (1) the sampling plan was based on stratified random sampling without replacement; (2) the initial strata were political subdivision-level boundaries which were later changed to strata along natural boundaries (once the synoptic coverage from the satellite-acquired color infrared imagery became available); and (3) the sampling unit was the 5- by 6-nautical-mile segment. Initially, in the U.S. 'yardstick' region (which was comprised of the nine major wheat growing U.S. Great Plains States), counties were the level for the first stage selection with categorizations into Group I counties (those receiving 1 or more sample segments with probability 1), Group III counties (those not sampled at all), and Group II counties (the remaining counties from which a subset were sampled in a PPS manner). As mentioned earlier, the initial allocation was based on the binomial model and was a Neyman allocation (ref. 46) with $n_i \propto N_i \sqrt{p_i\ (1-p_i)}$, where n_i was the number allocated to county i, N_i was the total number of segments in county i, and p_i was the proportion of wheat in the county as derived from historical data.

After the first year, the Neyman allocation was determined with improved estimates of the within-stratum variances. Once the Landsat color infrared imagery became available, the opportunity existed for ignoring political subdivision-level boundaries and creating strata along natural boundaries. These strata were developed based on soil types, climatic conditions, and agricultural density. Different soils were ranked as to their suitability for growing the crop of interest and were rated on the basis of several characteristics such as texture, depth, water-holding capacity, drainage, salinity, and slope. The stratification approach was oriented toward achieving the same soil suitability rating and similar agricultural density within each stratum. Also, the annual temperatures at any two areas in a given stratum were not to differ by more than 1 degree Centigrade. The resulting strata were referred to as 'natural strata' or 'agrophysical units.' Professor Hartley felt particularly strong about the fact that in a country like the U.S.S.R., considerable differences in agricultural practices frequently exist, for political (referred to by HOH as the 'czar effect') or other reasons, between two contiguous oblasts. Consequently, he strongly recommended that an intersection be taken of the political subdivision with the natural strata resulting in a stratification that became known as the 'refined strata' and, consequently, amounted to incorporating the political influence into the stratification. The resulting stratification also simplified obtaining estimates at the various political subdivision levels since political subdivisions were merely unions of the resulting refined strata.

Because a critical aspect of assessing the performance of the crop area estimator requires having estimates of its variance and bias, Hartley obtained expressions for these parameters in two other reports (refs. 4 and 6). Another problem that had to be addressed was that of nonresponse; the nonresponse substrata were treated as Group III's. Recall that for Group III substrata no segments were allocated. Instead, their wheat acreage was ratio estimated based on their acreage in the past relative to the neighboring Group I and Group II substrata (ref. 3).

This was followed in March 1976 by a report (ref. 7) that was his first to emphasize foreign application (in this case, to China and the U.S.S.R.). Since Russia became the foreign area receiving most emphasis from 1976 through 1978, many discussions transpired between Hartley and NASA/JSC scientists in implementing a sampling and estimation approach in the U.S.S.R. similar to that tested in the U.S. 'yardstick' region.

2.4 BIAS CORRECTION

In October 1976, Hartley addressed yet another key question, namely that of the bias induced by engineering constraints affecting the selection of sampling units. In particular, the concern was for constraints imposed on sampling unit locations because of hardware available for selecting and stripping the segment data from a full-frame (the basic work-data unit of 100 by 100 nautical miles). This constraint did not allow for adjacent segments to appear in the sample. Hartley showed (ref. 11) that the form of the induced bias as a result of these constraints was:

$$\text{Bias}(Y) = (N^2/n)\ \text{Cov}(\pi_i, Y_i)$$

where $\hat{Y}$ is the estimate of total wheat acreage in a given stratum, N is the number of sampling units in the stratum, n is the number of units sampled, π_i is the probability that the ith unit is selected, and Y_i is the wheat acreage in sample unit i. Hartley proceeded to show that, realistically, the relative bias for a country would be in the range of 2 to 4 percent, an amount which is quite negligible.

Though many technological developments have been made since LACIE to control the classification errors and reduce the bias in a segment crop proportion estimate, no unbiased estimation method exists yet. A primary source of this difficulty is the existence of mixed pixels representing the boundaries and corner areas in a segment. When any of the existing methods of estimation requiring pixel-by-pixel classification are exercised, mixed pixels get treated like pure pixels and hence cause bias in the proportion estimate of the specific crop of interest.

Professor Hartley was highly concerned about the classification bias and wanted to see it controlled in large-scale satellite surveys. He proposed the following method to eliminate the bias in a crop survey:

1. Characterize various types of 'doubtful areas' which an analyst may find to exist in a segment from the survey area of interest.
2. Prepare a 'ground-truth data bank' corresponding to these different doubtful areas and obtain their expected crop proportions simply by aggregating for each type its actual crop acreage and then dividing this by its total acreage represented in the data bank.
3. For each sample segment, delineate all possible doubtful areas and classify only the part of the segment data that corresponds to nondoubtful areas.
4. Estimate the crop acreage of a segment by combining the above information as follows:

$$A = A_0 + \sum_i p_i a_i$$

where A_0 is the estimated crop acreage for the nondoubtful area of the segment by its data classification; a_i is the acreage of the doubtful areas of type i delineated for the segment; and

p_i is the estimate of the wheat acreage proportion for doubtful areas of type i computed from the ground-truth data bank as described in the second step above.

HOH thought that although no claim of an unbiased estimate of crop acreage in a segment can be made, his method should lead to essentially unbiased estimates of crop acreages for larger areas such as a state or region. The reliability of this estimate would, of course, depend upon the reliability of $\hat{p}_i$ and the accuracy with which the 'doubtful area types' could be characterized and delineated for a segment. The procedure would also require additional (costly, as well) enumerative ground information for its ground-truth data bank. However, Dr. Hartley suggested some ways (ref. 14) to avoid a proliferation of doubtful area types by using the alternative information of weather, plant bio-stage, index of greenness, etc., in place of ground truth. Other related work of HOH (refs. 27 through 37) reflect his intensive concern for the sampling unit mensuration errors and for errors due to the photointerpretation necessary in making a crop proportion estimate for a given sampling unit.

After LACIE, Hartley's research emphasis shifted to development of multiyear approaches (refs. 8, 12, 13, 16, and 38 through 43). This emphasis was appropriate as a result of the eventual availability of multiple years of Landsat data.

2.5 A MULTIYEAR CROP ESTIMATOR

HOH's feelings about the potential for improving crop acreage estimates by using the short time series of estimates made in the sequence of consecutive years led to a shift of emphasis toward the development of a multiyear estimator. Professor Hartley's initial sampling plan for the multiyear approach was essentially not indifferent to that exercised by the Current Population Survey (CPS) of the Bureau of the Census whereby households were arranged in 'rotation groups.' The units in the same rotation groups are surveyed in four consecutive months of the first year, omitted from the survey in the next eight months, and then again surveyed in four consecutive months of the next year. The estimator of a characteristic y, the so-called composite estimator, is a weighted average of the following two estimator components: (a) the first component consists simply of the best estimator for the current month employing all the data collected in the sample units for that month; (b) the second component consists of an estimate of the change of y from month t-1 to month t based only on the matched units (i.e., the units that are in the sample in months t-1 and t). This change is then added to the composite estimator for month t-1. Finally, the two components under (a) and (b) are combined as a weighted average with weights summing to 1.

The essential condition for the effectiveness of the composite estimators in rotation designs appeared to be well satisfied in the context of crop area estimation. There is usually a strong positive correlation between the wheat acreages of segments observed in consecutive years. In this context, one must also remember that since the segment is rather large (i.e., 5 by 6 nautical miles) any year-to-year 'rotation' of wheat with other crops in accordance with agricultural practices will probably occur within segments (apart from boundary effects). Such rotations will therefore generate negative year-to-year correlations of crop acreages for smaller areas within a segment and will not destroy the positive year-to-year correlation for segments. However, the following are substantial differences between the crop area environment and that of the CPS: (1) the time series for crops is yearly and extremely short as opposed to the long monthly series in the CPS; (2) whatever the rotation might be for crop area estimation, it must be anticipated that a considerable number of matched segments (i.e., segments sampled in two consecutive years) will be lost through cloud cover (and possibly for other reasons). Consequently, HOH's feelings were that it would be necessary to replace the composite estimator with one that has more flexibility capable of dealing with unbalanced segment patterns over a moderate number of years. His choice then was that of resorting to a mixed analysis of variance model. Such an estimator would deal with the unbalanced matching patterns that are likely to arise through cloud cover losses of segments, patterns which will differ considerably from any balanced rotation designs.

The model utilized by HOH had the following ANOVA structure:

$$y(p_{ts\ell}) = \alpha_t + b_s\,\delta\ell + e_{ts\ell} \tag{1}$$

where

$p_{ts\ell}$ = the estimated proportion of the wheat of segment s at phenological stage ℓ of year t

$y(p_{ts\ell})$ = a mathematical variate transform of $p_{ts\ell}$ (say its logarithm or the logit transformation)

α_t = the stratum's transformed crop acreage proportion for year t

b_s = the departure of the sth sampled segment from the stratum's transformed crop acreage proportion; the b_s's are variables with expectations zero and variances σ_b^2

δ_ℓ = the systematic difference between the early and mid-season estimates of the crop's transformed at-harvest acreage proportion and the corresponding estimate made at harvest time ($\delta_3 = 0$)

$e_{ts\ell}$ = the aggregate of the sampling and classification errors in the transformed data

Writing the above model in the standard form

$$Y = X\alpha + Ub + Ie \tag{2}$$

and with $b \sim N(0,\sigma_b^2 I)$ and $e \sim N(0,\sigma_e^2 I)$, we have the Aitken least squares estimator (BLUE in this case)

$$\hat{\alpha} = (X'H^{-1}X)^{-1}\,X'H^{-1}Y \tag{3}$$

where

$$H = I + \gamma UU' \tag{4}$$

and

$$\gamma = \sigma_b^2/\sigma_e^2 \tag{5}$$

Hartley then recommended (a) that γ be estimated from the ground-observed data and (b) that his estimate be used in (4) and (5) above. The variance of $\hat{\alpha}$ is then given by

$$\text{Var}(\hat{\alpha}) = \sigma_e^2(X'H^{-1}X)^{-1} \quad (6)$$

and, hence, the variance of $\hat{\alpha}$, (the last element of the vector) can then be retrieved from equation (6). Hartley and Lycthuan-Lee, one of Hartley's students, demonstrated that reduction in variances from the use of two years of Landsat data could be expected to be as much as 25 percent.

In the 1980 contract year, HOH proposed yet a further improvement to the sampling plan in support of the multiyear estimator. He referred to the approach as the 'conditional optimization' of the multiyear, multiple crop estimator (refs. 41 through 43). In this approach, Hartley proposed the joint utilization of a modification of the multipurpose allocation approach, presented at the 1965 Annual ASA Meeting (ref. 45), in conjunction with the multiyear estimator so as to minimize Var($\hat{\alpha}$), [equation (6)]. The selection of segments for the current year was conditional on those actually acquired in previous years (e.g., taking into account the nonavailability of segments lost to cloud cover); allowances were also permitted for changes in preselected precisions and additional crops. The approach was one of abandoning a specific 'rotation group' in favor of deriving the per-stratum allocation that yielded a minimum variance [equation (6)] estimator. The resulting approach provided a minimum step search for exhaustively considering all candidate matrices U (the one determined by the b_s's, or rather, the location of the segments across strata) in equation (4) that yield a minimum to Var($\hat{\alpha}$) [equation (6)].

3. MEAN YIELD PREDICTION ERROR

Emphasis of our discussion to this point has been on area estimation, one of the two major components; the second is that of yield prediction. Yield was predicted by sampling meteorological data from weather stations within a region and inputting the information into previously fitted regression equations developed at a yield stratum level. Consequently, wheat production was not estimated directly; instead, it was computed by multiplying yield and acreage estimates (ref. 44). Hartley proposed improvements to yield prediction (refs. 17 through 26) as well as to yield prediction error variances. Summarily, the yield estimation activities consisted of two major parts: (1) the computation of prediction equations from historical data of yield and 'predictor variables' (predominantly meteorological variables such as rainfall and temperatures during various stages of the crop phenology); and (2) the use of such prediction equations for a current season by substitution of 'current levels of predictor variables' into the equations. Such predictions of the mean yield for a region were subject to two types of errors: (1) errors arising from the fact that the computed prediction equation represents only a statistical estimate of an equation in which all parameters are correct; and (2) errors arising from the fact that the available 'current levels of the predictor variables' (say, spring rainfall) represent only a sample of localities (i.e., weather stations) from the total population of localities (i.e., wheat fields) of a region. This was the so-called sampling error. Much of Hartley's emphasis (refs. 19, 20, and 21) was devoted to estimating the sampling variance component of this yield estimator.

4. SUMMARY

In preparing this manuscript, it became quite clear that it is not possible, in so short a space, to do justice to the numerous HOH contributions in the area of satellite agricultural surveys. However, this does represent the first assemblage and a brief narrative of the numerous technical reports prepared by Hartley over the 1974 through 1980 time span when he was under contract to NASA/JSC.

5. ACKNOWLEDGMENTS

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