1980 CENSUS WEIGHTING AND VARIANCE ESTIMATION STUDIES, DESIGN AND METHODOLOGY

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I. BACKGROUND AND PURPOSE

A critical phase in planning for the 1980 census was developing appropriate methodologies to weight the data collected from the census sample, and to estimate and present measures of sampling variability of the published figures. This paper describes the research undertaken to explore and evaluate alternative estimators, both for weighting the sample data and for obtaining a measure of the sampling variability.

During the 1980 census, seven items were asked of the more than 226.5 million persons who were to be counted in the census. Also, a few items were asked at each of over 86 million housing units, the number depending on whether the unit was occupied or vacant. This so-called short-form information constitutes the 100% or complete count data from the census. Additional data items, called sample or long-form information, were collected from approximately twenty percent of all persons and housing units according to the following scheme: In incorporated places of estimated population less than 2,500 persons, every other housing unit and its occupants were in sample. In all other areas, every sixth unit and its occupants were sampled. The purpose of this differential sampling scheme was to provide more reliable data for small areas than would have been obtained by use of a single uniform sampling rate. In "group quarters," such as college dormitories, nursing homes and other places where persons are not attached to specific housing units, the appropriate sampling rate was applied systematically to individual persons.

The purpose of the study described in this paper was to derive sample weighting and variance estimation procedures which would be optimal in terms of reliability, accuracy, cost and operational feasibility. Both the weighting and variance estimation studies were based upon an empirical comparison of alternative techniques using a study population created from data collected in the 1970 census.

II. FORMING THE STUDY POPULATION

A. Source of Data

The study population for the 1980 census estimation study was created from the 1970 census sample, which contained demographic and socioeconomic data similar to that collected in the 1980 census.

The 1970 census sample was available on computer files for states or "pseudo" (part) states. In selecting states or pseudo-states for the study population, it was desired to choose areas with substantial Black, Spanish, and Asian and Pacific Islander populations. This would permit the evaluation of potential estimation procedures in terms of their reliability and accuracy in making estimates of the characteristics of these major population groups. The following three areas were selected as best meeting this criterion:

1. The pseudo-state of California consisting of counties alphabetically from Madera to San Diego;
2. The pseudo-state of California consisting of counties alphabetically from San Francisco to Yuba and
3. The pseudo-state of Texas consisting of counties alphabetically from Erath to Loving.

B. Partitioning the Study Population into Samples

In each of the three selected pseudo-states, the study population or universe consisted of all 1970 census sample records--one for each housing unit and its occupants, and one for each group quarters person. These records were in sort by census geography. The 1980 census sampling scheme was applied to each pseudo-state file. The 1970 geographic codes were used to determine size of place, so that the appropriate sampling rate could be applied. In places of more than 5,000 2/ people, then, all six possible 1-in-6 systematic samples of records were defined; in smaller places the two possible systematic half-samples were defined.

C. Structuring of Weighting Areas

At this point, the concept of "weighting areas" must be introduced. In terms of their application to the 1980 census, weighting areas are geographic areas in which a given weighting procedure is applied. Weighting areas are mutually exclusive and partition the total area of the United States.

As will be seen in discussing the criteria for selecting various estimation procedures to be tested, it was important that equality between certain sample and 100% data item totals be achieved. Therefore, the alternative weighting procedures would need to produce agreement at small geographic tabulation levels. These levels could not be too low, or the estimates would be too variable; they could not be too large, or the desired agreement would not result for smaller tabulation areas contained within a weighting area. It was decided, therefore, to define weighting areas to be the smallest tabulation areas meeting the following three criteria:

1. The weighting area must have a minimum of 400 persons included in one of the six or two possible systematic samples defined above;
2. Weighting areas must never cross county boundaries (even if a county contained less than 400 sample persons; and
3. Given criteria 1) and 2), the weighting area must respect all place-within-county boundaries.

Three types of weighting areas resulted from the above procedures--weighting areas composed entirely of portions of the pseudo-states with a 1-in-6 sampling rate or with a 1-in-2 sampling rate, and weighting areas containing both types of areas. Only a small number of the "mixed" sampling rate weighting areas were obtained; they were dropped from further consideration due to extreme programming problems. Additionally, only the 1-in-2 weighting areas in the Madera through San Diego counties pseudo-state were processed. The other 1-in-2 weighting areas were dropped from any further consideration in the study due to time and budgetary constraints, and the fact that about 90-percent of the 1980 census sample would be derived from areas sampled at the rate of 1-in-6.

A summary of the results of the weighting area formation operations is given in the following table.

Table 1: Study Population Pseudo-States, Weighting Areas and Sampling Rates

Pseudo-State Description	Number of Weighting Areas Formed	Sampling Rate Assigned to Weighting Areas
California Counties Madera-San Diego	124	1-in-2
California Counties Madera-San Diego	51	1-in-6
California Counties San Francisco-Yuba	46	1-in-6
Texas Counties Erath-Loving	19	1-in-6

D. Introduction of Nonsampling Bias

Studies of the 1970 census sample indicated that there was some undersampling bias in the census sample for certain age, sex, race, and household size strata, (1). A crude attempt was made to simulate the effect of this bias in the Texas pseudo-state portion of the study population. In each of the six possible systematic samples in each weighting area, person records within the demographic categories shown by 1970 census data to have this type of bias were deleted based on the undersampling rate calculated from the 1970 census data.

This attempt to introduce sampling bias was used only to determine if the alternative estimators behaved similarly in the presence or absence of this bias. There was no attempt to reflect nonsampling errors which might be present in the census because we had no adequate model for such a study. It was hoped that the methods which would minimize sampling error and bias (e.g., sampling bias that could arise if a ratio estimator were selected) would also minimize nonsampling error.

III. EMPIRICAL STUDY OF ALTERNATIVE WEIGHTING METHODS

A number of proposed weighting techniques (estimators) were independently applied to each of the mutually exclusive and exhaustive systematic samples in each weighting area formed in the study population. It was then possible to calculate the variance, bias, and mean square error of estimates from each procedure for a given set of demographic and socioeconomic characteristics.

These measures were used to evaluate the alternative estimators and select the one most appropriate for use in the census. This empirical approach was employed since, even though preliminary research had indicated that the methods being considered had similar properties asymptomatically (2), (3), (4), it was important to see how they would behave under the census sampling scheme and for a representative set of data items included in the 1980 census. 2/

This section of this paper describes the planning of the weighting study, including the constraints considered in identifying alternatives to be studied, and the estimators actually studied. Details of the study results appear in (5).

A. General Constraints Imposed on the Estimation Procedure

A series of discussions with Census Bureau staff in the subject matter, computer support, and data publication areas indicated that any estimation procedure must result in the assignment of weights to individual sample person and housing unit records. These records would be stored on data files that had undergone various computer edits for accuracy and consistency. For any census tabulation area, a characteristic total would then be estimated by simply summing the weights assigned to the appropriate sample person or housing unit records. It was also determined that any estimation procedure selected to assign weights to sample records must meet the following three criteria:

1. Only a single weight should be assigned to each individual sample person and housing unit record. This weight, which could vary from person to person or housing unit to housing unit would then be used to produce all sample estimates. The constraint was imposed because the massive amount of data published from the sample would make it infeasible to store, control and utilize different weights for each data item.

2. The assigned weights were required to be integers. This was necessary for data user convenience, since it eliminates problems of differences due to rounding between data tables with similar margins. It was also desirable because it would ease iternal Bureau review of the complex weighting and tabulation programs.

3. The sample estimates of certain characteristics collected for the entire population were to equal the 100% (complete count) figure. This agreement was required for total population and housing counts for as many tabulation areas as possible. Agreement between the sample and 100% counts for other characteristics, such as age, race, sex and origin, was to also be achieved whenever possible. This constraint was also imposed for data user convenience.

B. Basic Estimation Methods

Three basic estimation procedures were selected to be compared in the 1980 census estimation study. Comparisons of the estimation procedures were to be based on estimates of totals, since the majority of census data published is in this form. The three basic procedures were:

Method 1: The sample total inflated by the inverse of the selection probability.

Method 2: Estimators of total derived from iterative proportional fitting or "Raking Ratio" estimators. In each weighting area, the sample person or housing unit records were used to determine counts for the interior cells of a multidimensional array, referred to as a "weighting matrix." 3/ These interior cell counts were adjusted via iterative proportional fitting or "raking" to bring them into close agreement with the corresponding marginal complete count totals. The adjusted cell counts are then allocated back to the sample person or housing unit records. A number of different matrices or arrays were considered as described below.

Method 3: Post-stratified estimators of total. In each weighting area, person or housing unit sample records were post-stratified into a set of strata defined by demographic characteristics. The usual stratified estimator of total was then applied to produce weights for sample records. Various stratifications were considered.

A detailed description of the methods, which were applied separately to person and housing unit records, follows.

1. Inflated Sample Mean or "Single Cell" Estimator

This method is well known and simply assigns each sample person a weight of N_p/n_p, where N_p is the weighting area 100-percent census count of persons and n_p the corresponding sample count. The weights are "rounded" to integer values, in such a fashion that the sum of all the weights is N_p, (6), (7).

Sample occupied housing units and vacant housing units receive similar weights based on the 100-percent and sample counts of occupied and vacant housing units.

2. Iterative Proportional Fitting or Raking Ratio Estimators

a. Background

This type of estimator was used by the Census Bureau in producing the 1970 census sample estimates (8), and its properties have been discussed in numerous sources (9), (10), (11).

For any raking array considered there are four basic steps in the estimation procedure:

Step 1 -- Counts are obtained from the weighting area sample for the interior cells of a multi-dimensional weighting array. Counts are also obtained from the 100-percent census for the marginal categories of the array.

Step 2 -- The rows and columns of the array are collapsed or combined together in a prescribed fashion if the sample and 100-percent marginal counts fail to satify certain "collapsing" criteria.

Step 3 -- The interior sample cell counts are then iteratively adjusted so that they respectively sum to the 100-percent census counts for the marginal categories of the collapsed weighting array.

Step 4 -- The adjusted interior cell counts are then allocated back to the sample person or occupied housing unit records as integral weights.

b. Definition of and Rational for Weighting Arrays

Several population and occupied housing unit weighting arrays were tested based on the availability of complete count totals for various demographic characteristics.

For population characteristics, the column categories of all arrays tested were defined by Race, Origin (Spanish/Not Spanish), Sex and Age. These column controls were used since it was hypothesized that these characteristics were correlated to other sample population data items and were likely to be optimum variables in terms of minimizing variance. As a by-product, there use as a final stage of adjustment would ensure agreement with the corresponding 100-percent counts.

The row categories tested included (1) family type by size of household (2) value or rent of living quarters by tenure (owner, renter occupied) and (3) size of household by head/nonhead status.4/ In addition to the four two dimensional arrays, a three dimensional array was tested. This array was defined by the Race, Origin, Sex and Age column categories, the family type by size of household row categories and a third dimension for head/nonhead status.

These particular row category variable combinations were used to test their impact on sampling bias, socieconomic data such as income and poverty statistics and to evaluate their effect on estimates of family and household characteristics.

For occupied housing unit characteristics three arrays were tested. Each array had two dimensions defined as follows:

Array #1 - column categories defined by tenure by race or origin of the head by value/rent; row categories defined by family type by size of household;

Array #2 - column categories defined as in array #1; row categories defined by family type by number of rooms;

Array #3 - columns categories defined by race and origin of the householder by tenure by number of rooms; rows categories defined as in Array #1.

The family type by households size row categories were used in arrays #1 and #3 for essentially the same reasons as noted in the previous discussion of the population arrays. The race, orgin, tenure and value/rent column categories were selected primarily in view of their hypothesized high positive correlation with other occupied housing unit sample data items. The row categories of Array #2 were selected to evaluate the effect of number of rooms when used in lieu of household size and similarly the column categories of Array #3 were selected to evaluate the effect of using number of rooms in lieu of value/rent.

c. Collapsing Criteria

Three basic approaches were considered in developing the criteria for collapsing the categories in each dimension of the weighting arrays. They were --

1) Limiting the minimum number of sample cases allowable in a row or column category of the weighting array. It is well known that post-stratified estimators become unstable as the number of stratum observations becomes small. Minimum levels of 5, 10, and 20 sample observations were studied.

2) Limiting the maximum allowable ratio of the 100-percent marginal control count to the corresponding sample count. This constraint would limit the variation in sample estimates; however, it could also have an associated effect on the bias. The levels tested were 2 and 4 times the "expected" ratio.

3) Limiting the minimum 100-percent marginal control count in conjunction with the ratio was also considered. This criterion was used in the 1970 census although no substantive documentation

of the rationale behind this criterion could be found. It was studied nevertheless, since it may be better than using criteria 1) or 2) individually.

Combinations of the above collapsing approaches yielded eight criteria which were tested. Basically, advice was solicited from the demographic areas so that, when collapsing occurred, the resulting stratification would be optimal in terms of within strata homogeneity.

d. Levels of Iteration Considered

The raking procedures were all tested with 2, 3, and 5 iterations of the adjustment. Further levels of iteration were considered, but were never implemented due to timing considerations.

3. Post Stratified Estimators

a. Background

For this estimation method, a stratification is defined and each sample element is classified into a particular stratum after sample selection. The sample records in the straum receive a weight equal to the inverse of the observed stratum sampling fraction. For example, let $N_1, \ldots, N_L$ and $n_1, \ldots, n_L$ denote the 100-percent and observed sample counts for L strata. Then each sample record in the h^{th} stratum would receive a weight of $\frac{N_h}{n_h}$ (rounded to an integer).

b. Methods of Stratification

Four methods of stratification were tested for population and five for occupied housing unit estimation. In general, the post strata used corresponded to the individual column and row categories of the weighting arrays described above.

c. Collapsing Criteria

Only one collapsing scheme was tested for these estimators due to cost and storage limitations. It was also felt that enough data were available from the raking estimator processing to permit a valid comparison of collapsing techniques. The criteria of a minimum of 10 sample cases in each stratum and a ratio level of 2 was used to collapse or combine the strata.

IV. EMPIRICAL STUDY OF ALTERNATIVE VARIANCE ESTIMATION PROCEDURES

Clearly, both the census complete count and sample data are subject to error. The variance estimation study only addressed estimators of the sampling variability in the census sample data, since research to obtain upper and lower bounds on the total nonsampling error in the census data is still being conducted. The sampling variance estimates resulting from these studies may be supplemented with measures of the total nonsampling error, if the research is fruitful, (12).

The proposed census variance estimation procedures were compared in a fashion similar to that for the weighting techniques studied. The comparisons were carried out using the same study population and the results of the earlier comparisons of estimation procedures. Within the setting of this study population, the "true" sampling variance of the selected 1980 census estimator was known for a variety of characteristics. Each proposed variance estimation method was applied to each of the study population samples to obtain estimates of the variance of these characteristics. The procedures were applied to the study population samples within weighting areas or groupings of weighting areas called pseudo weighting areas (PWAs). Therefore, for each study population weighting area or PWA, it was possible to calculate the actual sampling variance, MSE, and bias of the variance estimators within the empirical study population. The variance estimators were empirically compared based on these data as well as on their respective processing costs. The detailed results of the variance estimator study are given in (13).

A. General Constraints Imposed Upon the Variance Estimation Procedures

To illustrate the problems faced in producing estimates of variance to accompany census publications, the 1970 census methodology will be briefly discussed, (14). In 1970, it was not possible to calculate variance estimates for every data item published from the 1970 census. Variances were only estimated for 834 representative population and housing items in 8 different representative states.

The technique followed in 1970 to produce variance estimates for the selected items of interest was based on a half-sample replication technique. The 1970 census weighting areas were combined into pairs of weighting areas referred to as pseudo weighting areas (PWAs). The census sample in a PWA was divided into two systematic mutually exclusive and exhaustive half-samples. Each half-sample was then independently weighted via the 1970 weighting technique. The PWA variance estimate for any item was then obtained as a function of the squared difference of the weighted half-sample estimates for the item, (15). A design effect was calculated for the PWA by dividing the estimated variance of the item by the corresponding simple random sampling variance estimate. These PWA design effects were averaged over an entire state to provide a state level estimated design effect for each of the 834 data items. The 834 data items were subsequently grouped and the individual design effects averaged into an overall design effect for each group. The square root of this group design effect was published. Tables of simple random sampling standard errors were also published for different sizes of tabulation areas and for various proportions and totals. The user could then obtain an estimate of the standard error for a particular item by obtaining the appropriate simple random sampling standard error, and multiplying this by the published design effect (square root) for the item of interest.

Clearly, assuming the same general approach for publishing sampling errors as was used in 1970, the problem of producing variance estimates to accompany the 1980 census sample publications consisted of two parts. First it was necessary to select an appropriate estimator of the variance of totals produced from the census sample data. Secondly, it was then necessary to arrive at a scheme of "generalizing" these variance estimates for publication (e.g., possibly by calculating estimated design effects). All of the variance estimation and generalization procedures considered for the 1980 variance estimation studies were subject to the following basic constraints:

1. As in 1970, the volume of sample data to be published by the Census Bureau is immense. Any variance estimation procedure was required to be flexible enough to provide reasonably accurate and reliable variance estimates for a large number of data items at various geographic levels.

2. It is not possible to publish an individual variance estimate for each sample figure as this would effectively double the size of the sample data publications. Variance estimation procedures were, therefore, required to be readily adaptable to generalization methods.

3. The census budget dictated that any procedure used to produce or generalize the 1980 census variance estimates be extremely cost effective.

4. The applications of the generalized standard errors must be comprehensible to a variety to data users, and must be appropriate to accompany data disseminated in various forms--published reports, microfiche files, and computer tapes.

B. Other Study Design Considerations

The issues involved in planning for the comparison of the variance estimation methods were much more complex than those encountered in the comparison of estimators. Other considerations in studying the proposed variance estimation procedures were:

1. Costs

For the estimator study, cost was not considered as a factor in the comparisons since all methods were about equally as expensive. However, for the variance estimation study, the procedures were seen to differ dramatically by cost.

2. Geographic Level for Application of Variance Estimation Methods

Another consideration was the geographic level at which to implement the variance estimation procedures. It was decided to perform the variance estimation procedures for three sizes of PWAs consisting of 1,2, or 3 weighting areas. It was felt that by performing the variance estimation procedures for individual weighting areas, the resulting estimates would be more accurate for the smaller areas for which the Census Bureau publishes data. It is for these smaller areas that errors in the variance estimates would be most likely to effect comparisons made by data users. It was also not possible to form PWAs of a larger number of weighting areas, in the study population, since this would not have yielded enough observations to make accurate comparisons. Finally, weighting areas were used as the "base" level for variance estimation, since it was at this level at which the full impact of the raking ratio estimator could be measured.

C. Variance Estimation Procedures Tested

The variance estimation procedures evaluated in this study were applied to the estimates derived from the raking ratio estimation procedure selected for use in the 1980 census based on the analysis of the empirical study data (5). Variations of four basic (and well known) variance estimation procedures were considered: Random Groups (RG); Jackknife (JK); Balanced Repeated Replications (BRR); and Taylor Series (TS) methods. A more detailed discussion of each variance estimation procedure and its application to the study population is also given in (13).

D. Comparison of Generalization Procedures

In planning for the 1980 census, two basic methodologies were considered for generalizing variance estimates--design effect and regression approaches. These methodologies were empirically compared using the data from the 1980 census ratio estimation study for the northern California portion of the study population. For each weighting area, the variances that resulted from the selected 1980 census estimator were generalized to the state level. The generalized variance "estimate" was then compared in each weighting area with the actual variance. The generalization methods were then analyzed based on how well they approximated the actual empirical variances. A description of the methods considered follows.

1. Design Effect Methods

The problem of producing a design effect may be viewed as developing a factor to apply to known values of the simple random sampling standard error in the i^{th} weighting area (S_{SRSi}) to approximate the unknown standard error that arise from the census sample design and estimation procedure (S_{ci}). The problem was simply, then, to minimize some measures of the difference between S_{ci} and $F\,S_{SRSi}$ for the factor F. The five factors evaluated are, where $F_i = \frac{S_{ci}}{S_{SRSi}}$ and n is the number of weighting areas.

Loss Function	Factor
$\sum_i^n (F_i - F)^2$	$F_1 = \frac{1}{n}\sum_i^n F_i$
$\sum_i^n \lvert F_i - F \rvert$	F_2 = median value of F_i $(i = 1,2,\ldots, n)$
$\sum_i^n N_i (F_i - F)^2$	$F_3 = \sum_i^n N_i F_i / \sum_{i=1}^n N_i$, N_i is the size of the i^{th} weighting area
$\sum_{i=1}^n S_{SRSi} (F_i - F)^2$	$F_4 = \sum_i^n S_{ci} / \sum_i^n S_{SRSi}$
$\sum_i^n S^2_{SRSi} (F_i - F)^2$	$F_5 = \sum_i^n S^2_{SRSi} F_i / \sum_i^n S^2_{SRSi}$

To produce a design effect or factor for a grouping of data items, the individual design effects calculated by any of the methods described above, were averaged. There were three methods considered to accomplish this operation:

a) The simple arithmetic average;

b) A weighted average using weights inversely proportional to the variation of the individual factors; and

c) A weighted average using weights proportional to the characteristic totals.

2. Regression Methods

These methods were developed by fitting two linear models to the values S_{ci} and S_{SRSi} for the data items of interest:

1) $S_{ci} = \alpha + \beta\, S_{SRSi}$ (via least squares)

2) $V_i^2 = a + b/X_i$ (iterative method)

where V_i^2 = relative variance of the i^{th} weighting area total, X_i.

The values $(\hat{\alpha}, \hat{\beta})$ or $(\hat{a}, \hat{b})$ would then be published.

A disadvantage of the regression approach is the precedent set in earlier censuses of using design effects. If a regression approach were adopted, it was feared that data users already familiar with using design effects would be unduly confused by a change to a new publication procedure based on a regression approach. Therefore the comparison of the regression methods with the design effect methods was performed with the understanding that the regression approach would have to demonstrate considerable superiority in order to be selected for use in the 1980 census publications.

V. BASIC RESULTS AND SUMMARY

As has been noted, two papers presented in this session discuss the results of the weighting and variance estimation studies in greater detail (5), (13). In summary, for weighting purposes, these studies resulted in selecting the raking ratio estimator based purely on its superiority in terms of variance and mean square error since the cost for all methods studied were approximately equal. For population characteristics, the three dimensional array using column categories defined by race, origin, sex and age, row categories defined by family type and size of household and a dimension for householder/nonhouseholder status was selected. For occupied housing unit characteristics, the array using column categories defined by tenure, race/origin of the householder, value/rent, and row categories defined by family type and size of household was selected.

For variance estimation, the Taylor series method was found to be slightly more reliable than the random groups estimator using twenty or more subsamples, and both of these were far superior to the other methods studied. However, the Taylor series method was prohibitively expensive to implement, costing approximately ten times more than the random groups estimator. Thus, it was decided to use the random groups estimator as it was considerably more cost effective.

* *

FOOTNOTES

1/ As mentioned previously, by the time the census was taken, this cutoff had been reduced to 2,5000 persons.

2/ These were preliminary studies which used these references, among others, to technically study the estimators. The authors readily note that many more excellent papers exist on this topic.

3/ Clearly, this is a misuse of the term "matrix" if the array has more than two dimensions.

4/ In the 1980 census, the head of household concent was replaced by the householder concept. However, this new definition could not be implemented in the study population.

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