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Geographical Information Systems in the Census Process-Technology Options, Costs and Benefits

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Geographical information systems in the census process – Technology options, costs and benefits

Paper prepared for the

Workshop on Strategies for the 2000 Round of Population and Housing Censuses in the ESCWA Region

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1 Introduction

Many of the changes to the *Principles and Recommendations for Population and Housing Censuses* (United Nations 1997a) reflect the emergence of new technologies for census operations. Significant technical developments will undoubtedly benefit census data capture, processing and distribution. In the cartographic domain advances in computer hardware and mapping software have already encouraged many statistical offices to move from traditional cartographic methods toward digital mapping and geographical information systems (GIS). This shift is well reflected in the revised *Principles and Recommendations* and has significant implications for the handling of geographically referenced information in census operations.

This paper is intended to provide a discussion and commentary of the relevant sections in the revised *Principles and Recommendations,* which have been written in more general terms. The paper has two main objectives. The first is to review the most significant technical advancements that can benefit census cartographic activities. These are the use of global positioning systems (GPS) for obtaining coordinate information in field work; digital geographic data collection using aerial photography and remote sensing; and the emergence of GIS as an integrating technology to support census activities from preliminary field work all the way to data dissemination.

Like any major technical shift, the transition to digital cartographic techniques implies major costs as well as significant benefits. The second objective is therefore to provide a framework for assessing these costs and benefits. Since the shift toward digital cartographic methods implies a major investment by the national statistical organization, the issues raised in this section are intended to assist in this decision making process.

2 New technologies for census cartography

2.1 Global positioning systems (GPS)

GPS receivers collect the signals transmitted from a system of 24 satellites, several of which are within the "field of view" of the receiver at any given time (for an overview, see Dana 1997).

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Based on the time required for the signal to travel to the receiver and on the angle from which they are received, the receiver can calculate its position on the earth's surface with a fairly high degree of accuracy. According to most vendors of low-cost GPSs, the recorded position is accurate within 15 to 100 meters for civilian applications. However, according to the more precise U.S. Department of Defense specifications, there is a 95% chance that the recorded position is accurate within 100 meters and a 50% chance that it is within 40 meters. Repeated readings of GPS coordinates may give a misleading impression of accuracy since most systems use some form of averaging of repeated measurements which reduces the variance of measured positions. Turning the GPS off and on after each measurement will provide a better indication of available accuracy (see Lange 1997).

GPS receivers could achieve much higher accuracy (1 meter or better). However, the system was designed for military use, and the signal's accuracy is downgraded for "unauthorized users". It is anticipated that this "selected availability" for civilian users will be removed in the future, but a date has not been announced yet. As a workaround, and for applications requiring accuracy in the low centimeters, differential GPSs (DGPS) use information transmitted from a base station with precisely known coordinates to correct the satellite signals. This can be done in real-time or in post-processing mode using the recorded coordinate information and base station correction data files. DGPSs depend on the availability of a network of ground stations that broadcast correction information to compensate for the signal scrambling, and equipment costs are significantly higher. Currently, standard GPS receivers sell for as little as $200 US, while differential GPS receivers cost several thousand US dollars. The gain in accuracy does not always justify this larger investment. Alternatively, captured coordinates can be corrected in post-processing mode using information that is available from various sources. In this case, the receiver must be able to store the necessary information about the exact time and satellite location.

Most vendors offer integrated products which combine a GPS receiver with a palmtop or notebook computer so that the captured coordinates can be plotted on the screen immediately, either in isolation or on a digital base map. However, for census applications, the equipment required for a large number of field workers would likely be beyond the resources of a census project. Manual recording on data sheets and subsequent data entry in the office provide a lower-cost alternative, but may introduce coding errors.

GPS technology has obvious application in any kind of mapping activity, including the preparation of enumerator maps for census activities (see, for instance, Tripati 1995). The accurate geographical positions of enumeration area (EA) boundaries can be determined with GPS, and the location of point or line features such as service facilities or roads can be obtained in a cost-effective way. Coordinates can be downloaded or entered manually into a digital mapping system or GIS, and can be combined with existing, properly georeferenced information. "Georeferenced" means that the coordinates used to describe geographical information in the database are in a real world coordinate system such as latitudes and longitudes or in a known projection such as UTM (Universal Transverse Mercator).

In the application of GPS problems can arise. In dense urban settings, accuracy of 100 meters may not be sufficient to accurately define adjacent EAs. In those cases, GPS readings should always be cross-checked with additional data sources such as published maps, aerial photography or even sketch maps produced during fieldwork. Some cities, for example, Doha in Qatar, have developed a system of GPS base stations that support very high accuracy mapping using DGPS. But in many developing countries such networks do not yet exist. High rise buildings or streets lined with dense trees can also make capture of GPS coordinates difficult. A

GPS must receive signals from at least three satellites to compute an accurate position (four satellites to obtain an elevation estimate as well), and in areas where high objects obstruct the signals it is often not possible to obtain an accurate position.

Li (1996), for example, reports on a pilot study that tested the use of GPS and differential correction techniques for the development of a dwelling frame for the 2001 Census of Canada. The goal is to equip approximately 5000 census representatives with GPS and thus to obtain a coordinate pair for each building in the country. The accuracy requirements for this purpose were determined to be 3-5 meters. The study found that in general, GPS performed very well and field staff were able to use the equipment with only a few hours of training. The largest problems were encountered in areas of high building densities where operators often had to walk away from the building to obtain a position.

GPS is probably most beneficial in rural areas, where accuracy requirements are lower, available map data sources are scarce, and where there is a smaller likelihood of obstruction by high buildings. The Medical Research Council in Durban, South Africa, for example, used GPS to record the location of about 30,000 homesteads in northern KwaZulu-Natal for which medical, demographic and social data are recorded (LeSueur *et al.* 1997). The same approach would also be appropriate for a census database or a sampling frame in demographic analysis. Using GPS in tracking mode – i.e., readings are taken automatically at regular intervals – EA boundaries that coincide with roads can also be captured from a vehicle.

2.2 Aerial photography and satellite remote sensing

Remotely sensed imagery can provide an alternative to cartographic fieldwork using GPS or more traditional field techniques. EA boundaries can be delineated on air photos or satellite imagery provided that the resolution of the image is sufficient to distinguish significant features such as roads or individual houses. Where up-to-date maps are unavailable, remotely sensed information can be used to detect changes such as new squatter settlements in large cities (see Paulsen 1992) or new road and settlement construction in remote areas.

Aerial photography

Aerial photography is obtained using specialized cameras on-board low flying planes. The camera captures the image on photographic film which still provides a far superior resolution (i.e., the ability to distinguish small details) compared to digital sensor systems. Although, given the rapid developments in this area this may change in the near future. Traditionally, the end products of an aerial photography project are overlapping printed photos of an area on the ground which can be used to produce a mosaic covering the entire region. More and more of this process, however, is done digitally.

A standard approach today is to scan printed aerial photographs using very high resolution scanning devices in order to produce a digital image that can be processed further on a computer. This gray-scale or color image is a regular array of pixels (picture elements) that can be manipulated in image processing or GIS packages. Standard processing steps include corrections for distortions due to camera attitude and lens characteristics. These corrections are greatly facilitated by in-flight GPS control which provides parameters required for the removal of distortions and for georeferencing in order to relate the image elements to true positions on the ground.

A digital elevation model (DEM) – a raster image corresponding to the air photo, where each pixel value indicates the elevation of that point on the ground – can be derived using stereo pairs of air photos. This DEM can then be used to remove distortions due to terrain elevation. The end product of this process is an *orthophoto* which combines the geometric accuracy of a conventional topographic map with the large detail of a photograph. The resulting orthophoto maps are usually produced at map scales of 1:2,000 to 1:20,000 depending on airplane altitude and processing (for more information see Michael 1997).

Rather than creating hardcopy prints of the orthophoto maps, orthophotos are now often delivered in digital form. A database for a city, for instance, may consist of a mosaic of several images which are contained on a CD/ROM and can be displayed seamlessly on a computer screen. Since the images can be obtained in standard graphics formats (such as TIFF or JPEG), no specialized image processing software is required. In fact, any graphics package could be used to extract features from the images, although the georeferencing information will be lost. This information is usually contained in a small header file, which is used by desktop mapping packages to register the images with other GIS data sets. Further processing is based on visual interpretation such that staff do not need to be trained in advanced image processing techniques. Features can be delineated directly on the digital orthophotos (see Figure 1) or the images can serve as a backdrop to provide a context for the display of GPS derived locations or digitized features such as health facilities or transport networks.

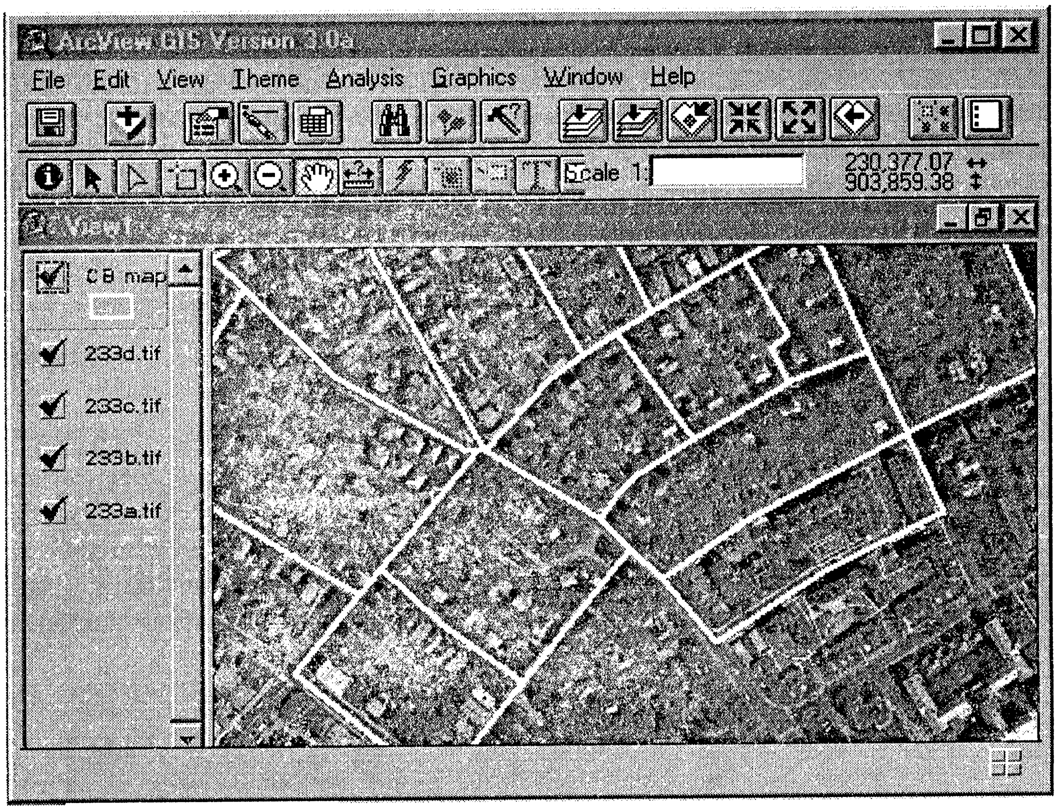


Figure 1: Interactive delineation of census block boundaries on a digital orthophoto (Data source: MIT/MassGIS Digital Orthophoto Project - http://ortho.mit.edu)

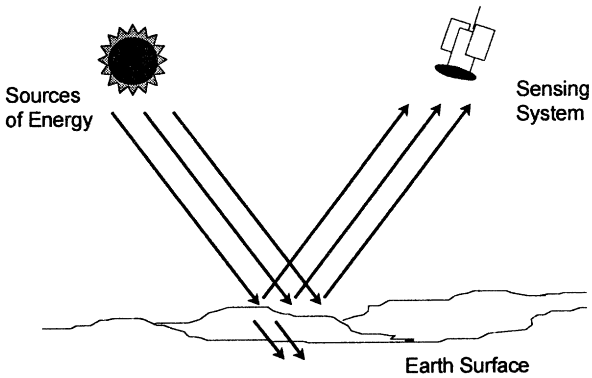
Digital orthophotos generally have very high resolution, with pixel sizes in the centimeter range (usually 5-30 cm). For census operations, resolution requirements are much lower than for topographic mapping or utility and facilities management applications. Pixel sizes between 0.5 and 2 meters are generally sufficient for delineating census blocks and EAs in urban areas. Boundaries can be digitized on the screen, and, since the orthophoto is properly referenced in a standard coordinate system such as UTM, the resulting GIS database of EA boundaries represents an ideal framework for compilation, management, analysis and distribution of geographically referenced census information. It is still important to design EAs so that boundaries can be easily identified on the ground. While a trained air photo interpreter can derive a large amount of information from orthophotos, field enumerators may not be able to relate features on a printed orthophoto to features on the ground without significant training.

Despite the great benefits of orthophotos for census mapping activities, there are two caveats that may inhibit the application of this technology in national statistical offices. The first is that the large data volume involved requires the use of high-end personal computers with storage devices that allow fast access. Secondly, while maps produced using digital orthophotos are generally cheaper than traditional methods for producing topographic maps, given the lower resolution requirements for census mapping, the costs may still be too large for most census projects. Generally it is therefore advisable to follow the example of the Egyptian and Mexican statistical offices and to collaborate with other national or local government departments to share the costs of obtaining such products at least for major urban areas. Since digital orthophotos are also useful for planning of service provision, updating of town maps and many other planning applications, costs can be spread over several projects.

A digital orthophoto database for the city of Boston in the United States is available on the Internet for interactive browsing and downloading (ortho.mit.edu). Orthophoto databases have also been produced for the city of Doha in Qatar (www.gisqatar.org.qa), to update maps for the largest cities in Guinea (Maps Geosystems 1997), for topographic mapping which will support census cartography in Egypt (Ahmed 1996), and for mapping and land titling activities at the Mexican National Institute for Statistics, Geography and Informatics (INEGI, see Espejo 1996). The statistical office of Hongkong has used aerial photography to estimate the number of people living on boats (NIDI 1996). This provides a good example of the use of these techniques for counting populations that are hard to enumerate.

The future of aerial photography is promising a fully digital process, thus eliminating the need to produce intermediate printed photographs. Bossler and Schmidley (1997) describe a university/industry collaboration to develop a system that will use in-flight GPS control and digital charge coupled device (CCD) cameras that can create images of 9,216 by 9,216 pixels with a positional accuracy of 1-4 centimeters. Since the intermediate steps of producing photographic prints and subsequent scanning will be removed, this technology should be considerably cheaper and faster than current technology.

Figure 2: The remote sensing process



Satellite remote sensing

Satellite remote sensing products are derived from space based systems, most of which use so-called passive optical sensors to measure radiation emitted from objects on the earth's surface in the visible and invisible spectrum (Figure 2). Active sensors such as microwave and radar sensors send out pulses of energy and measure the fraction of energy that is reflected back. Since radar remote sensing data have only recently become widely available, their use in census relevant applications has so far been limited (see Short 1997, for an on-line remote sensing tutorial).

The digital data are sent to earth from the satellite and the product delivered by imagery vendors is usually a digital file of a rectified satellite image scene or an image mosaic consisting of several scenes. Alternatively, printed satellite images can be obtained which can be interpreted visually. Most commonly used satellite systems have been developed for natural resources applications and vary in resolution from 10 to 80 meters for the most popular systems such as SPOT's panchromatic sensor – a single band covering a wide range of wavelengths much like a black and white photograph – and Landsat's multispectral imagery. These resolutions allow mapping at cartographic scales of 1:25,000 to 1:50,000 or smaller. Clearly, even 10 meter resolution may not be sufficient for urban applications, although such imagery can be useful for delineating boundaries in rural areas. For the 1991 population census in Nigeria, for example, 150 satellite image maps made from 90 SPOT images covering an area of 110,000 sq. km were produced to support census-related field work and data collection (Satellitbild 1994).

Table 1: Selected high resolution satellite sensors

Satellite	**Resolution (meters) /multispectral**	**Channels panchr. / multi-spectral**	**Launch date**	**Company / organization**	**URL address**
EarlyBird	3 / 15	1	1997	EarthWatch	www.digitalglobe.com
QuickBird	0.82 / 3.28	1 / 4	1998	EarthWatch	www.digitalglobe.com
Ikonos (Carterra 1)	1 / 4	1 / 4	1997	SpaceImaging / Eosat	www.spaceimage.com
Lewis	5 / 30	1 / 3	1997	TRW	www.crsp.ssc.nasa.gov/ssti/welcome.htm

Clark	3 / 15	1 / 3	1997	CTA	www.crsp.ssc.nasa.gov/ssti/welcome.htm
Core Software	1.5 / -	1	1997	CST/IAI	www.coresw.com
OrbView-3	1 / 4	1 / 4	1999	Orbimage	www.orbimage.com
IRS-1C	5.8 / -	1 / 4	1995	India RS Program	www.spaceimage.com
IRS-1D	5 / 23	1 / 4	1997	India RS Program	www.spaceimage.com
KVR 1000	2 / -	1	1993	Russian Space Agency	http://www.spin-2.com

Recently, higher resolution imagery has become available from Russian and Indian satellites at 2 meters and 5 meters resolution respectively. In another significant development, several private consortia in the United States are planning to launch commercial satellites in 1997 and 1998 that promise to provide imagery with resolutions as high as 0.82 meters (see Table 1; see also Carlson and Patel 1997). Previous satellite systems were largely funded publicly, so it will be interesting to see whether a commercial product can generate enough revenue to justify the large investments necessary to support the development, launch and maintenance of a satellite system.

Imagery prices are likely to fluctuate until the market has settled. Following are some preliminary figures released by different companies to give an idea of costs involved. Prices differ depending on the degree of processing of the raw data. This may include radiometric correction, geometric correction, and geo-referencing without or with ground control points. Eosat intends to sell one-meter panchromatic data starting in March or April of 1998 for about US$10 per square km for the raw data, while a digital orthophoto map produced from these data will cost about $63/km^2. Products with varying degrees of processing will be priced somewhere between these two. Price comparisons with orthophotos derived from aerial photography are difficult, since the variable costs can be high if such services can not be procured from vendors located nearby. Generally, prices of $100/km^2 or more are quoted for orthophoto maps from aerial photos (Konecny 1997).

Earthwatch's prices for 3-meter resolution panchromatic data will vary between US$2.58 and $3.73/km^2 depending on the total area purchased. Once Earthwatch's satellite has been in operation for some time, archived imagery will be available more cheaply. Processed data (controlled mosaics) will be available for between $4.91 and $8.69/km^2. Data from some of the other sensors may be less expensive but have lower resolution or may not be available for a recent or current date. For example, the Russian camera system KVR 1000 with a resolution of 2 m is not available on a continuous basis. Images from this system which are suitable for mapping at 1:5,000 scale sell for about $30/ km^2 (Konecny 1997).

For census applications, the degree of accuracy and therefore the degree of processing required may not be very high. Still, even the raw data would usually be too expensive for wall-to-wall coverage of an entire country. These satellite data will therefore be most useful to update census maps in rapidly changing urban areas or in remote areas where maps are out-of-date and field work would be time-consuming or difficult. This is a particularly good option if costs can be shared between different agencies with an interest in updated maps.

2.3 GIS as an integrating technology

The previous sections have discussed some new options for collecting the base line information for the generation of enumeration area maps. No matter which method is used – traditional field techniques, use of GPS or remotely sensed data – much of the processing, compilation, operational use and dissemination will be done using a geographical information system. For the purposes of basic census operations, the standard definition applies which sees GIS as a *system for capturing, storing, manipulating, analyzing and visualizing spatially referenced data and integrating it with other computer based information* (e.g., NCGIA 1990). We will later extend this definition.

The United Nations' *Principles and Recommendations* make extensive reference to GIS and digital cartography (see also Suharto and Vu 1996). GIS is considered useful in the production of census maps, for dealing with census logistics, for monitoring census activities, and for data dissemination. The distinction between GIS and desktop mapping is not always clear. While the term *GIS* is often used for high-end systems used by GIS professionals, many mid-range desktop mapping packages provide most of the functions required by the average user. There are probably hundreds of commercial GIS, mapping and related software packages on the market. In addition several public-domain and tailor-made systems exist. UNEP (1995) lists detailed information about more than 60 software companies providing GIS and related products (directories of GIS software and services are also presented in GIS World, 1997). However, of the more than 220,000 installed packages reported in UNEP's survey, more than half represent products from one vendor. So the market is more concentrated than the large number of software products suggests. Of these installations more than half were in North America, one quarter in Europe, 9% in Asia, 6% in South America, 5% in Australia, and 3% in Africa. It should be pointed out that the sample of users and vendors that is the basis of these figures may be somewhat biased since the group that responded to UNEP's questionnaire is probably most active in the natural resources sector.

Digital cartography and GIS have been used for various aspects of census operations by a number of countries in the developed as well as in the developing world (see United Nations 1997b). The approaches reach from simple thematic mapping of census results all the way to in-house development of a data structure and retrieval system for census cartography. Relatively few countries have used GIS in all phases of a census from the preparation of census maps to the dissemination of spatially referenced census data. Yet, the largest benefits of using GIS can be achieved with a fully integrated digital cartographic program.

One fundamental issue that needs to be addressed when using GIS is the level of accuracy that is required in the creation of the database. For basic census enumeration maps, high accuracy is usually not required as long as the maps show the relationships between spatial objects, such as houses, roads or rivers accurately. This *logical accuracy* is maintained even if the map is somewhat distorted or if features are represented some distance away from their true location. This is why many countries base the production of enumeration maps on hand-drawn sketch maps that are produced by field workers and which fulfill the requirements of census data collection.

It is not cost-effective, however, to produce a census GIS database only for the production of enumerator maps. Digital data can easily be duplicated and distributed and will be useful for many other applications. Such applications arise within the statistical office, for example for sample design and analysis, and among outside users, for instance, in the health, education or natural resources sector. In many of these applications, the census GIS data will be combined with other, independently produced data sets. For example, a national household sample survey may have used GPS to record the location of the sample points. Researchers now want to overlay these GPS points on a digital map of census enumeration areas in order to retrieve relevant community-level census data for each sample record. If the census database does not have sufficient accuracy – that is if *positional accuracy* is not maintained – then there will be no guarantee that the sample points will fall into the correct enumeration area. This example is meant to emphasize that a digital approach which can result in a general purpose database will make the accuracy question more prominent compared to the traditional sketch-map approach.

The issue of accuracy also highlights the fact that the advantages of digital spatial data in census operations are associated with significant costs in terms of equipment, training and organizational changes. Thus, while the long-term benefits can make GIS very cost-effective to a census agency, they do not necessarily come cheaply. As real-world examples have shown, there is also a significant risk of failure, if the transition from traditional to digital techniques is not well conceived. The next section of this paper will discuss the direct and indirect costs involved in setting up a GIS program within a statistical office as well as the benefits that can be realized by this technology.

3 Assessing costs and benefits of a digital cartography approach

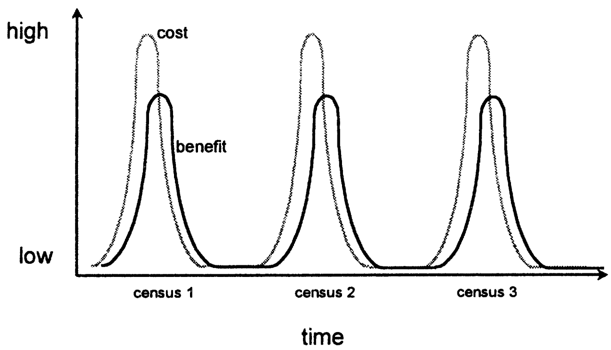
This section will discuss the costs involved and the potential benefits realized in using a digital cartographic or GIS approach in census mapping. The discussion is necessarily general, since there is no "one" approach to census mapping. Rather, there are a variety of options ranging from a fully digital in-house mapping capability to using, for example, desktop mapping for presentation of results and dissemination only. In other words, there is no "one size fits all" solution to the introduction of digital mapping in the census process. In fact, GIS is sometimes criticized as a $500 solution to a $5 problem (e.g., quoted in Batty *et al.* 1995). This is certainly the case when a complex, high-end GIS is introduced where a simple desktop mapping package could have been sufficient. The appropriateness to the task is the overriding principle of any cost-benefit analysis.

For various reasons, it is also very difficult to assess the costs and benefits of using GIS quantitatively. For example, many of the benefits may not be realized by the agency paying for the GIS investment, but rather by outsiders who are gaining access to products of higher accuracy or lower cost, or who may obtain products that were previously not available at all. This also highlights the difference between "cheap" and "cost-effective". The cheapest option, in the short term, for producing census maps may be the traditional manual approach, especially in countries where labor costs are low. From a societal standpoint, however, it may be more cost effective to initially invest more money in a digital approach because the digital output products will realize much larger long-term benefits inside and outside the census or statistical agency.

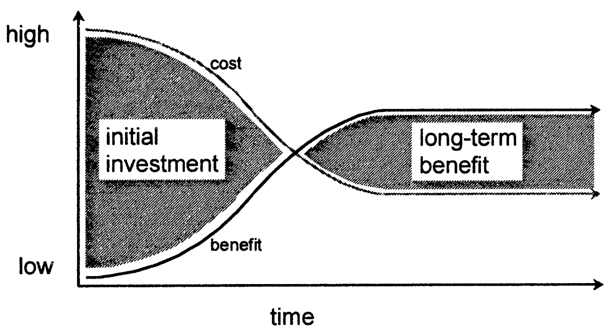
Investments in GIS are also heavily front-loaded. That means that the major costs are incurred early on in a project while tangible benefits may only materialize long into the project cycle. This is illustrated in Figure 3, which contrasts the costs and benefits of a traditional mapping approach with digital cartography. In the first case, maps are re-created manually for each census. The costs tend to be higher than the benefits, since the hardcopy maps are useful for census purposes only. In (b), an initially large investment results in lower maintenance and updating costs and sustainable benefits in the long run. The long-term benefits are significantly higher because the process results in a multi-purpose digital database (see also Deichmann 1996).

Figure 3: Costs and benefits of census mapping options

(a) Traditional mapping approach



(b) Digital mapping approach



This also highlights the importance of a long-term strategy for census mapping. Often, census mapping is purely project based. A few years before the census, a team is assembled to quickly produce census sketch maps by hand which are only used for the enumeration. Several years later the process starts again for the next census. A better approach is to view census cartography as a continuous process with a permanent core staff, regular maintenance of equipment and training.

3.1 Costs

The short-term investment and longer-term maintenance costs of GIS should not be underestimated. Like any new technology or organizational transformation (e.g., management information systems), the introduction of GIS involves a change in routine and significant expenses not only for software and hardware but also for data purchase, training, planning and organizational restructuring. In fact, the significant costs involved are the main reason why the sections on GIS in the *Principles and Recommendations* are very carefully worded. Especially the indirect costs are often underestimated and may lead to the failure of a GIS project.

Following is a list of steps that may be involved in introducing GIS and which incur costs to the introducing agency (see Worrall 1994, Becker *et al.* 1996). Some of the costs are obviously not unique to digital cartography. For example, the costs involved for coordination of decentralized data collection or data conversion are very similar whether the maps are produced in digital form or manually. Not all steps will be required for every project, of course. A census office that wants to use desktop mapping to produce simple thematic maps for a census publication will not need to spend a lot of time or money on a detailed planning process. A comprehensive census mapping project, in contrast, may cost hundreds of thousands of dollars and its success or failure may be a direct function of how rigorously the project was designed.

Cost components

Systems design and planning, consulting services; managerial staff time	Overall planning of a GIS project or a GIS department within an agency will clarify the objectives and anticipate the costs and steps involved. Using outside expertise will often be useful and a large commercial sector offering GIS consulting services has emerged in recent years. For census offices in developing countries it is often useful to visit other offices with significant experience in GIS such as those in Europe, North America, Japan, Mexico or Qatar to learn from their experience (see also Coiner 1997). Also part of the overall system planning are an evaluation of available data and the development of a data conversion strategy which is often the most resource intensive part of a project (see below).
Hardware acquisition or integration	Computers are becoming increasingly powerful while prices are continuously decreasing. However, software packages require increasingly powerful computers, such that the "cost per function" seems to remain fairly constant. If existing equipment is to be integrated, investments in upgrading memory or disk space may be required and the issue of compatibility with newly purchased equipment needs to be addressed. Apart from computers with fast processors and plenty of storage space, GIS applications also require peripherals such as digitizers, scanners and large format color printers which may not be standard equipment in the census office.

Evaluation, and selection of GIS/mapping software	There are now dozens of suitable GIS and desktop mapping software packages on the market ranging in price from a few hundred to tens of thousands of U.S. dollars. In the next few years, many analysts predict a further consolidation of the GIS software market which should lead to lower costs for software since the remaining vendors will benefit from higher volumes. For all practical purposes, the choices can be reduced to a few packages that have emerged as the standard among agencies (see United Nations 1997b). These provide sufficient user support and the functions required to perform all tasks in a census project. Compatibility with other government agencies is an important criterion if data are frequently exchanged or data production costs are shared among agencies. Also, an hierarchical approach may be appropriate where the main GIS unit may uses a powerful software program while regional field units or groups mainly involved in routine tasks rely on cheaper, less powerful software. High-end software vendors often require or encourage the purchase of maintenance contracts which need to be considered in operational budgets. Such services tend to be expensive, but may well be critical to ensure uninterrupted operations.
Prototype development	Before embarking on a census mapping project it is advisable to conduct a prototype or pilot project in a small area of the country. While this requires additional time and resources, the benefits are that problems in the methodology can be detected early. For large projects potential software vendors should be asked to provide benchmark results with a realistic application defined by the client organization.
Hardware/software system configuration/ customization	Since GIS data development is very time-consuming and labor intensive, a distributed approach is usually advisable. This is greatly supported by a networked system where data can be exchanged easily either through a local area network, a special network linking, for example, the national census office with regional offices, or, increasingly, by standard Internet connections. For very large census applications some customization may be required, for example, to develop an interface between the GIS package and a generic database management system that is already in use.
Human resources planning	The implementation of a new technology in an agency may require the addition of new staff. It may, for example, be necessary to bring in a person with experience in digital mapping or GIS to head a new section devoted to this area. Similarly, staff training needs or re-assignments need to be established to ensure a smooth transition from the old to the new mapping system.

Training, skills development, re-training

Besides the costs of hardware, software and data conversion, training is the fourth major expense of any GIS activity. Estimates range from 5 to 10% of the total project costs that should be budgeted for training. Training costs are high largely because of the lack of suitably skilled entry-level job applicants, the complexity of much of today's GIS software and the limited background in geography and spatial analysis of most staff in statistical offices which results in high re-training costs.

It is likely that these issues will become less of a problem in the future. Many universities are now teaching GIS not only in geography departments, but also in computer science, natural resources, business or statistics. Standard core curriculum development for universities and vocational schools (NCGIA 1990) support this development. GIS software is becoming more user-friendly as the Windows platform emerges as a standard and as vendors consider the needs of an increasingly broad and non-specialized user community. For example, many low-cost desktop GIS systems now allow the display of remotely sensed images over which features can be digitized on-screen. Such operations previously required specialized image processing software and training in remote sensing techniques.

Still, training requirements should not be underestimated and a continuous training program is required given the fast changing hardware and software market.

Data base design, data modeling, procedural manual development	Data modeling is the process of defining features to be included in the database, their attributes and relationships, and their internal representation in the database. The result is a comprehensive data dictionary that defines the content of the databases that are produced by the agency. In some instances, such dictionaries can be adopted or adapted from other agencies in the country, for instance where a national digital topographic database exists. In other cases, this data dictionary has to be developed from scratch. The resources required for this will depend on how comprehensive the database will be. It may also be necessary to integrate existing database models which have been developed to manage tabular census information. This is necessary, for example, if data from previous censuses need to be integrated in the GIS data bases. In addition to the data dictionary a procedural manual defines the steps necessary in the development and processing of digital spatial data. Such manuals are important for ensuring consistency in products that are generated by different technicians or units that may perhaps be scattered across the country. They also define recurring analytical work such as the methods used to reconcile past census data with new boundaries after the administrative units have been changed. Accuracy standards should also be defined as part of the overall database design process. While accuracy is often not a very important issue in census mapping – in fact, many countries rely on hand-drawn sketch maps for this purpose – it becomes an issue when the resulting census maps are used in combination with other, higher-accuracy data.
Transitional costs	Additional costs are incurred if old and new systems have to be operated in parallel during a transition period. This is necessary to ensure quality of service while problems in the new system are worked out. For a transitional period, keeping the old system as a backup may be a good strategy if many users rely on the timely delivery of products.
Data acquisition, data purchase	Some of the information required for census mapping may be obtainable from commercial sources or other agencies who charge a fee for their use. Auxiliary geographic data sets describing road networks, hydrology or elevation are useful for census mapping since boundaries should ideally be designed to match features that are identifiable on the ground. Obtaining such data from outside vendors or other government agencies will save both time and money and will also increase the consistency of data products across different agencies. Also, as described in section 2, aerial photography or satellite imagery can be used to support the production of census maps. These are obtained from outside vendors or, in the case of air photos, commissioned from a private company.

Data capture, conversion	Initial data development is probably the most expensive part of a GIS project. The share of this element together with data acquisition from outside vendors in the overall project budget is often estimated to be 60-70%, significantly larger than the hardware and software costs. Data capture includes cartographic fieldwork using traditional techniques or new methods that have been discussed earlier. Data conversion or data automation, in contrast, refers to the process of creating digital GIS data layers from hardcopy maps. For this process two options are available. Maps can be traced manually using a digitizing table, or the entire map can be scanned and a data set suitable for input to the GIS is generated through subsequent raster-to-vector conversion. A hybrid option is where selected features from a map are first traced manually on clear sheets which are then scanned and converted to vector format. This approach requires an additional intermediate step, but reduces the time required for editing and labeling of geographic database features (Suharto and Vu 1996).
Validation, quality assurance/quality control (QA/QC)	No matter which data conversion strategy is chosen, data conversion is labor intensive and error prone. Part of the process therefore needs to be a rigorous procedure for checking the resulting data for both positional accuracy and logical consistency. Similar procedures should be implemented to assure the quality of derived output products such as cross-tabulations or GIS overlays. If very high accuracy is the objective, it is not conservative to allocate resources equal to those budgeted for data conversion to the final editing and quality control stage. Quality control also relates to the development of meta-data standards. One major problem of digital data is that documentation is often detached from the actual data and may thus be lost easily. Rigorous procedures are required to avoid loss of accuracy and data quality due to a lack of information about each specific data set. Meta-data should include all information relevant to the data set including source map reference, date, projection and scale, processing steps performed on the digital data set, data lineage and accuracy standards. Meta-data formats for digital spatial data have been developed by many national mapping agencies and can be adapted to the requirements of a statistical office.
System maintenance	System maintenance involves software and hardware upgrades as well as any training that may be required as a result of such upgrades. This component is often estimated to consume about 10% of the initial investment per year, although this figure will vary depending on the scale and scope of the project.

Post implementation review	Even with a detailed planning process and pilot study, there are likely ways in which the system can be improved further after full-scale implementation. It may often be useful to have an in-house or external review of the system to identify weaknesses and to improve productivity. However, the development of a GIS capability within an agency should not be seen as a linear process with a clearly defined ending date, but rather as a continuing process of improving operational procedures. A periodic review of the GIS group's work should thus be part of the regular activities.
Development of data distribution strategies	While anyone can make use of printed census publications and most users of digital, tabular census data will have access to spreadsheet or similar office software, users may not have easy access to mapping or GIS software for using digital census maps. To achieve maximum use of such data, the census office should design a strategy to help users get access to such software. This will not be a large problem in the more developed countries where users will be able to purchase the required software. In less developed countries several options are available to increase use of digital spatial data. These include cooperative agreements with a software vendor to reduce the purchase price or subsidizing software purchase with public funds, in-house development of a data viewer (as for example done by the Mexican statistical office, INEGI), and the use of free or public-domain software such as PopMap (United Nations 1995, Vu 1996) or ArcView 1 / ArcExplorer (www.esri.com).

Cost reduction strategies

A statistical office can reduce or shift the costs involved in setting up a GIS program in several ways. The most effective means is cost sharing with other agencies in the country. The example of statistical offices in Latin America which are often within the same umbrella organization as the national geographic or mapping agency has shown the synergy effects that can be realized from close collaboration. The statistical office benefits from the mapping and GIS capabilities in the geographic division, while the mapping division can integrate spatially referenced census information in its cartographic work and products. Even where such institutionalized links do not exist, close collaboration among agency with similar data needs will be beneficial. For example, a statistical office could coordinate data collection efforts or data purchases with the planning, education or natural resources departments. This can significantly reduce the cost of acquiring remotely sensed data, for example.

Another alternative is to assign the entire cartographic process to another government agency or to a private sector company. For example, the Australian Bureau of Statistics worked together with a private company that produced digital EA maps for the entire country. Agreements between the company and the statistical office guide the use and further commercialization of the data. The advantage for the statistical office is the reduced investment in training and equipment, and the time savings in getting immediate access to extensive GIS expertise. The disadvantages are some loss of control over the cartographic process, the fact that no in-house expertise is developed, and possibly higher costs in the long run as the agency becomes dependent on outside suppliers. In some countries, it may also be difficult to find a domestic company that is able to provide services at the scale necessary to perform a very large census mapping project. In practice, a mix of in-house activities and outside consulting services will usually be the most appropriate approach.

"Soft" factors

Besides the obvious costs that can be quantified for a given GIS project, there are a number of stumbling blocks that may cause a project to fail or to fall short of realizing its full potential. Mostly such problems are connected to a lack of planning, the choice of inappropriate hardware and software, and various organizational mistakes. Surveys of real-world GIS projects can reveal a set of characteristics shared by successful GIS implementations, the absence of which, in turn, also point to possible reasons for the failure of such projects. The following list of critical factors is adapted and expanded from Johnson (1997):

1. A key person to promote GIS development within the organization.
2. High-level management support.
3. Decision to invest in GIS is need-based and problem-driven rather than technology-driven.
4. Detailed strategic, operational and managerial planning based on a realistic assessment of costs and effort involved.
5. Clear goals and objectives defined for the GIS department.
6. GIS education and training for affected employees *and* management.
7. GIS treated not as an independent add-on, but as an integral part of the overall information management strategy.
8. Staff continuity.
9. Completion of a user needs assessment and *a priori* definition of output products.
10. Development of cooperative agreements with other interested parties.
11. Clear implementation schedule.
12. Defined long-term funding plan including cost recovery and data pricing strategies.
13. Accurate estimates for maintenance and associated costs.
14. Explicit operational procedures guiding the use of GIS facilities.
15. Well-established quality control / quality assurance procedures.
16. Well-defined written contracts with vendors, consultants, partners and clients within and outside the government.
17. Completion of a prototype pilot project to test appropriateness of equipment, software and procedures.
18. Outreach and marketing including published successes.

3.2 Benefits

Following Worrall (1994) we can distinguish between *efficiency* benefits and *effectiveness* benefits. The first implies that after a transition period, more or better output can be obtained with the same amount of input, or that the same output can be produced with fewer inputs. Such efficiency effects include cost savings or productivity gains and are mostly realized by the census organization itself which may be able to produce maps faster or with fewer resources than before. Effectiveness, in contrast, refers to the impact of policies or programs that benefit from improved information. These benefits are mostly realized by the users of statistical data derived from a population and housing census. For example, the availability of digital population maps that can be used in combination with environmental information may result in better decision making within the environmental protection agency of a country. Both, efficiency and effectiveness benefits, will now be discussed in turn.

Efficiency benefits

Efficiency effects will largely be realized through cost savings, cost avoidance and productivity gains through reduction in the time required to produce output products. Such benefits are usually measurable, although they may not be realized until well into a GIS project. However, benefits also accrue if higher quality or entirely new products can be generated. For example, if a digital map is produced at a higher accuracy compared with a manually drafted map, no time or cost savings may be involved, but an overall benefit is still realized. The following list contains a mix of measurable "hard" benefits and "soft" indirect effects.

Productivity gain	After the initial investment in creating the digital data base, updates can be produced faster, and more and better output products can be generated with the same number of staff. Digital data also allow a much wider range of applications within the NSO such as sampling frame development or combination with other data layers such as land use information to create new statistical indicators. Copies of updated maps can be printed immediately without tedious manual redrafting. This also enables the NSO to respond more quickly to changing demands and needs by data users.
Cost saving / cost avoidance	The replacement of a technician who is manually re-drafting map data sets with a computer operator can – after a transitional training period – result in lower staff requirements and associated cost savings. For the cartographic work for the 1992 Census of Zimbabwe, a reduction of the number of draftspersons from 70 to 20 was reported by Rundquist (1989). Similarly, digital census maps can be adapted more easily to other purposes such as agricultural or economic censuses or special-purpose sample surveys. Digital mapping using remote sensing can be cheaper than extensive field work, especially in areas of rapid change, where timely maps are difficult to obtain, or in remote areas that are difficult to access. Digital map data provide a more secure archiving system compared to paper maps since multiple backups that can be stored off-site are cheap and easy to produce. Such backups will also require less storage space than a large collection of paper maps.

Better service	Digital data results in faster turnaround times for standard census products. For example, if the enumeration area maps were already created digitally, tabulated census data can immediately be linked to produce thematic maps. Similarly, special purpose products such as tailor-made maps or custom aggregation of census data can be created quickly.
Increased accuracy	Compared to sketch maps, the digital approach encourages higher accuracy which results in better products and supports a wider range of applications. Some digital techniques such as digital orthophotos provide a high degree of "built-in" accuracy.
Improved consistency	Similarly, a digital database is likely to result in a more or less seamless database for the whole country. This will ensure a great degree of consistency which is important, for example, if census units are rearranged. It is also easier to incorporate meta-data in a digital database. For instance, systems have been developed that track operations on digital GIS data bases, so that the end product of such operations will be accompanied by a full description of data lineage and GIS procedures that had been used. Alternatively one could introduce a system where the operator needs to fill in a pre-designed meta-data form whenever changes have been made to a data set or when a new data set is added to the archive. Enforcing such procedures in a traditional, manual system is more difficult.
Income generation	Since digital map data allow for a much wider range of applications, a market for such products has developed in a number of countries around the world. Data users in the private sector include marketing firms, banks, real estate companies, health care providers, non-profit environmental agencies and academic institutions. Moderate pricing of such products increases their widespread application, leads to larger volumes combined with lower production costs, and will support a thriving secondary market in associated mapping services. Attempts to achieve full cost recovery through high prices and strict copyright enforcement, in contrast, prices casual and non-profit users out of the market and limits the accessibility of such data to a relatively few well-off commercial data users. As the experience of various countries shows, the conflict between increasing pressures to generate maximum revenue versus the overall societal benefit of inexpensive, widely accessible data has so far not been resolved.

Effectiveness benefits

Effectiveness benefits reflect the impact of digital GIS data in the work of other government institutions, academic or non-profit organizations and the private sector. User needs vary. Rajani (1996), for example, reviews two market segmentation models used by GIS vendors. In the first, the market is divided into the degree of sophistication of the data user. "Doers" are the people who input, maintain and create digital spatial data, do advanced analysis and modeling and will typically use high-end GIS software on powerful computers. "Users" are in the middle category and will perform basic analysis like combining several map layers to create cross-tabulations. Finally, "viewers" will use spatial data for basic tasks such as making thematic maps and querying an existing database. It is estimated that the number of "viewers" is larger than the number of "users" which outnumber the "doers", each by an order of magnitude. An alternative market segmentation model is based on the software's cost and capabilities which both increase steadily from basic consumer maps to desktop mapping, desktop GIS (which allows data creation and simple analysis) and professional, fully-functional GIS.

It is also important for census offices to keep in mind that "*in many ways, how the data were collected, validated and stored is of nothing more than passing interest to most census users*" (Openshaw 1995, xv). In contrast, many users may not realize the full potential of census data. Since traditionally, census information has mostly been available in very aggregate form in printed publications, many users who may benefit from detailed, small-area statistics in digital form may not have the background to envision how these data can help in their work. Outreach seminars and publications produced or contracted by the census office that focus on the use of the data may help increase the user base and consequently the indirect benefits of census taking. The *Census Users' Handbook* (Openshaw 1995) which covers the 1991 census of the United Kingdom is a good example of such a publication.

Below follows a list of effectiveness benefits that may be realized by data users and, to some extent, of course also by the census agency. Only some of these benefits can be quantified in terms of time or money savings or increased productivity (see also Nordisk Kvantif 1987 and 1990). Mostly, however, the benefits are more indirect. For example, improved visualization or analysis may not necessarily save time or money, but will lead to better insights and understanding and consequently to better decision making.

Improved analysis

The purpose of statistical data compiled and published by a national statistical agency is to support planning and decision making in the country. Thematic maps based on census derived statistics provide an analytical basis for a wide range of public policy applications. Combined with tables and statistical graphics, maps provide an added dimension to data analysis which brings us one step closer to visualizing the complex patterns and relationships that characterize real-world planning and policy problems. Relationships among neighboring regions in the country are explicit in maps which allows for the visualization of spatial patterns that may be determined by some underlying process.

For example, a clustering of high childhood mortality in a number of enumeration areas may point to some environmental condition that has caused this pattern. Higher fertility rates in another set of regions may point to a cultural preference for large families. This information could be used to adapt family planning outreach programs. Visualization of spatial patterns also supports change analysis which is important in monitoring of social indicators. This in turn should result in improved needs assessment.

More advanced spatial analysis may include the combination of different data layers. Health authorities, for example, may be interested in estimates of the number of children in a certain age group that may be exposed to malaria. Climatic and topographic data can be used to determine the range of malaria mosquitoes. This range is unlikely to follow census boundaries, but in a GIS the two data layers can still be combined to derive the number of children living within the affected areas.

In short, the availability of statistical and other information in spatially referenced form and the functions provided by a GIS can allow analyses that were previously too expensive or impossible to perform.

Improved policy making	Improved analysis should in turn improve policy making. For example, statistical GIS databases are useful in site selection for public services such as hospitals, fire stations or schools, or in evaluating different planning scenarios. Auxiliary GIS data layers in combination with small area statistical data can be used for targeting of interventions to alleviate poverty or to reduce economic imbalances in a country. In combination with statistical or simulation models, GIS can also be used to perform "what-if" scenarios and to support resource allocation decisions. For example, after estimating an econometric relationship between some indicator of interest and a number of explanatory variables that can be affected by policies, we can estimate the impact of a number of different policies (such as a given increase of per capita spending on education) on the villages or enumeration areas. The GIS allows us to put the results in a spatial perspective and to determine where the impact will be greatest. This clearly encourages a disaggregated approach to policy analysis. Instead of looking only at overall impacts, the focus is on zooming in on areas of greatest need.
Improved data sharing	Converting data into digital form should lead to improved coordination and data sharing among government agencies (Batty 1992). Data sharing should also result in improved consistency of derived products that are created by other organizations. To realize these benefits, clear collaborative agreements between partner agencies within the government have to be developed. Such agreements should cover any cost accounting that may be required and should also cover issues of data formats, accuracy standards and content definitions.
Improved outreach	Another benefit that should not be underestimated is the fact that graphical representations of data are usually more appealing and generate more interest than tables of numbers alone. One of the main reasons for the success of GIS is undoubtedly the power of pretty maps. This can also help to make the work of a statistical office more accessible, improve outreach and raise awareness of the benefits of census taking among the population.

4 Conclusions

This paper has reviewed some technical developments in the field of GIS that can support the transition from manual to digital mapping within the census process. GPS and remotely sensed data are useful in establishing the cartographic basis upon which a successful census depends. GIS, in turn, provides the framework to put the data to use during census operations as well as for subsequent inventory, monitoring and analysis applications. The successful application of these techniques requires careful planning and a great commitment on the side of the statistical organization. The second part of the paper has therefore discussed the costs and also the benefits associated with digital mapping.

Successful implementation depends crucially on the integration of GIS in overall information management strategy. GIS should therefore not be regarded as an independent activity that is detached from the traditional statistical work. In the absence of an overall strategy, GIS implementation may fail, even if considerable investments in equipment and software have been made.

Lastly, despite of all the understandable excitement about new technological options, one should not forget that the ultimate goal of improving the census data collection process is more wide-spread and improved utilization of census data. Investment in better data collection will only pay off, if it leads to cost reductions, time savings and quality improvements within the agency and among data users outside the agency. This means that statistical offices should combine investments in new technologies with a renewed emphasis on analytical techniques, data dissemination strategies and user support. On that note, it is possible to extend the standard definition of GIS presented in section 2.3 GIS as an integrating technology as

> 'a computer-based system for capturing, storing, manipulating, analyzing and visualizing spatially referenced data and integrating it with other computer based information; a toolkit for the modeling and analysis of complex research, management and planning problems; and, a system to support decision makers by enabling them to structure problems and identify potential solutions for evaluation' (Bond and Worrall 1996).

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