Mass Storage Estimates for the Digital Mapping Era*

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ABSTRACT: Modern computer technology offers cartographers the potential for transition from conventional film-oriented methods to digital techniques as the way of mapping in the future. Traditional methods utilizing silver halide aerial and lithographic films for storage are time proven, and film is a very high density archival storage media. In view of this, proponents of the digital era recognize that a break-through in mass storage technology may be required to attain a reasonable degree of computerization of the cartographic mapping and data management process. One major question in the transition is: How much mass storage is needed to handle the mapping problem, and further, what technology is on the horizon that may have potential for handling such large volume? This paper provides the rationale for estimating that about 10^{14} bits of digital mass storage are needed for developing a digital 1:24,000-scale topographic data base of the United States. Also, it will discuss the optical disk as a leading candidate for handling the mass storage dilemma.

INTRODUCTION

TRADITIONALLY, the data base for topographic maps has resided on photographic film and been stored in flat files. Film is a very high capacity storage media with time-proven archival qualities that has several advantages attractive to the conventional cartographer: reliability, human readability, long life, cost effectiveness, and compatibility with other parts of the mapping process.

Over the years, cartographers have recognized the trends in the computer industry, where computing hardware costs have decreased while storage capacity has increased with a significant decrease in cost per bit stored. Considering this trend, along with space age remote sensors and the concurrent developments in computerized data management systems, cartographers are envisioning very large computer-aided mapping systems where the data base resides online in a digital mass storage media.

In essence, the transition away from film media to digital magnetic storage media has been slow, largely due to the massive volume of disks or tapes that would be required. Another factor is that magnetic media's shelf life is probably limited to less than three years, at best.

In recent years, a new technology, the laser optical disk, has emerged. This technology appears to offer a solution looking for application. Optical disks have a very high capacity, and their shelf life is estimated at ten years. In short, it now appears feasible to begin an orderly transition to the digital mapping era by means of this new breakthrough in storage technology.

In view of this opportunity, this paper will address the problem of a digital data base to store the content of 1:24,000-scale topographic maps for the lower 49 States. It will provide the rationale and concept for estimating the amount of storage needed. It will also briefly review laser optical disk technology and systems, compare them with magnetic storage media, and discuss the potential that optical disk offers for the digital mapping era. Finally, it will review some of the problems anticipated in the transition.

ESTIMATING CELL SIZE

For this project assume that

- Approximately 54,000 7.5-minute standard topographic quadrangle maps at 1:24,000 scale cover the lower 49 States; and
- Digital computer technology in the 1980's may permit these 54,000 quads to be stored online as an archive for digital mapping systems.

Considering these 54,000 quads, two different approaches will be demonstrated to estimate the cell size and, therefore, the amount of digital storage needed for a raster (array) oriented data structure.

Method #1, Smallest Map Feature 0.25 mm (0.010 in.)

- Assume the smallest feature that is *depicted* on a standard quadrangle, image, or line map has a dimension of 0.25 mm (0.010 in) on a side.
- In order for an object, 0.25 mm in size, to be photographically identifiable on an image map, it should be imaged by about five line pairs per millimetre. Accepting that 1 line pair is approximately equiva-

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* A follow-on to this article, "Planning for Optical Disk Technology with Digital Cartography," will appear in the April 1986 issue of this Journal.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 52, No. 3, March 1986, pp. 419–425.

0099-1112/86/5203-419$02.25/0

lent to 2.5 pixels, it follows that 12.5 pixels sufficiently represents five line pairs. Using this rationale, it seems reasonable to assume that the object's area (0.25 mm by 0.25 mm) must be divided into 12.5 subareas to permit identification.

- Therefore, the cell size (*Cs*) on the ground required to portray the Earth's features corresponding to a 0.25-mm (0.010-in.) square spot on the map can be written as follows:

$$Cs\ (\text{mm})^2 = (0.25\ \text{mm})^2 = 0.0625\ \text{mm}^2$$

Subdividing the area into 12.5 parts and multiplying by the Map Scale Number (MSN),

$$Cs = (0.0625)^{1/2}\ \text{mm} \times 1\ \text{m}/1{,}000\ \text{mm} \times \text{MSN}$$

$$Cs\ (\text{m}) = 7 \times 10^{-5}\ \text{MSN}$$

For example, at a map scale of 1:24,000

$$Cs\ (\text{m}) = 7 \times 10^{-5} \times 24{,}000$$

$$Cs = 1.7\ \text{m}$$

It is informative to recognize that the computed cell size is analogous to a square on the ground of 1.7 m on a side, and this amount of terrain is to be represented by a number (actually binary bits) which is the radiometric reflectance value (brightness in the visible spectrum) representing that cell. For a digital remote sensor, this number could be the value sensed by each detector in the image plane of the sensor. For film, this number represents the density value or shade of gray of the pixel. For map linework, shades of gray are not involved; the presence of a line can be a "1," and the lack of a line can be a "0." In this project, the digital value is to be stored in the mass storage system, and it represents the cell's radiometric reflectance value or shade of gray for that pixel. As a point of interest, a *Cs* of 0.07 mm in the image is equivalent to 1.0/0.07, which is 14 lines/mm, or 7 line pairs/mm. Seven line pairs/mm are equivalent to a 147 line/inch screen used by lithographers for high-quality printing. The point is that a *Cs* of 1.7 m is consistent with what cartographers conventionally expect from quality printing for image maps.

To add additional credibility to the 1.7-m cell size estimate, a second method utilizing a different criterion follows.

Method #2, Spot Size (Cell Size) From Digital Stereophotogrammetry and Contouring Criteria

This method utilizes national map accuracy requirements for contouring by stereophotogrammetric methods. The method chooses the proper cell size to permit stereocontouring from the data, and that cell size will be represented digitally in the storage media.

Assume 1:24,000-scale maps with a requirement for a 10-ft (3-m) contour interval. The rationale for computing the proper cell size (spot size) from this criterion follows.

Assuming sufficient transformation capability for bringing corresponding images into approximate congruence, the error σ_{Px} to be expected in image parallax clearance when employing electronic or digital correlation techniques is described by the following equation:

$$\sigma_{PX} \leq K\ (\text{spot size}) \tag{1}$$

where values

$$0.2 \leq K \leq 1.5$$

are generally accepted. (Itek, 1981; Murai and Shibasaki, 1982).

K is a nondimensional number which expresses the degree to which stereocorrelation can be achieved.

The parallax clearance error may be converted into the height domain (*h*) through use of the base-to-height ratio inherent in the well-known parallax equation which, when $\sigma_{Py} = 0$, expresses the precision of a single height observation (Doyle, 1963) as

$$\sigma_h = \frac{H}{f} \cdot \frac{H}{B} \cdot \sigma_{Px} \tag{2}$$

where

σ_{Px} represents the total error in parallax measurements in the image plane;

f is the sensor focal length;

H is the flying height of sensor above the ground; and

B is the base distance between exposure stations.

It is convenient to express the parallax units of Equation 2 in ground coordinates; then, the scale factor multiplied by the parallax in the image plane yields

$$\frac{H}{f} \cdot \sigma_{Px} = \sigma_{Px'}, \text{ and Equation 2 becomes}$$

$$\sigma_h = \frac{H}{B} \cdot \sigma_{Px} \tag{3}$$

Substituting Equation 1 into Equation 3,

$$\sigma_h = \frac{H}{B} \cdot K \cdot (\text{spot size}). \tag{4}$$

Solving Equation 4 for spot size yields the equation of interest:

$$\text{Spot Size} = \frac{l}{K} \cdot \frac{B}{H} \cdot \sigma_h \cdot \tag{5}$$

In order to meet the criterion that 90 percent of elevations be correct within one-half the contour interval (CI), National Map Accuracy Standards imply that

$$\text{CI} = 3.3\ \sigma_h$$

where σ_h = error in determination of height in a stereointersection. Then, for 10-ft (3-m) contour interval, which is common for 1:24,000-scale maps,

$$\sigma_h = \frac{CI}{3.3} = \frac{3.0\ m}{3.3} = 0.91\ \text{m}.$$

Invoking the heighting requirement of $\sigma_h = 0.91$ m, spot size requirements for mapping at 10-ft (3-m) contour intervals can be derived for digital ster-

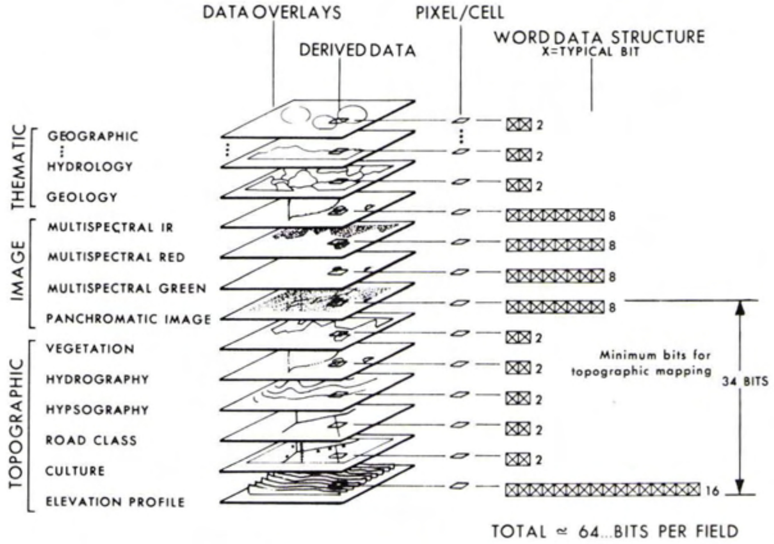


FIG. 1. Multilayered cell structure.

eopixel imagery by evaluating Equation 5 with appropriate parameters.

As an example, let

$K = 0.2$ and $\sigma_h = 0.91$ m.

Also, for standard stereoimagery, $B/H = 0.6$.

Then, from Equation 5,

spot size (SS) = (0.6)(0.91 m)/0.2

SS = 2.73 m on the ground

Because K can range from 0.2 through 1.5, Table shows a range of corresponding values computed with Equation 5.

TABLE 1. COMPUTED CELL SIZE WITH K AND B/H AS VARIABLES

K	B/H	h	Cell Size (Spot Size)	Spot Size** Scale 1:24,000	Spot Size** Scale 1:80,000
0.20	0.6	0.91 m	2.73 m	114 μm	34 μm
*0.40	0.6	0.91	1.36	57	17
0.50	0.6	0.91	1.09	45	14
1.00	0.6	0.91	0.55	23	7
1.50	0.6	0.91	0.36	15	5
0.20	0.8	0.91	3.64	152	46
*0.40	0.8	0.91	1.82	76	23
0.50	0.8	0.91	1.46	61	18
1.00	0.8	0.91	0.73	30	9
1.50	0.8	0.91	0.49	20	6
0.20	1.0	0.91	4.55	190	57
*0.40	1.0	0.91	2.28	95	29
0.50	1.0	0.91	1.82	76	23
1.00	1.0	0.91	0.91	38	11
1.50	1.0	0.91	0.61	25	8

*Values shown in table 2.

**Represents the computed ground cell size at scales of 1:24,000 for mapping and 1:80,000 for imagery flown by high-altitude aircraft.

DIGITAL STORAGE REQUIREMENT

Now that cell size has been established by two different estimating methods, it remains to structure and count the bits required per cell and to calculate the total bit storage requirements for the 54,000 quads covering the lower 49 States. Figure 1 illustrates a vertical overlay structure for a variety of products such as thematic, image, and topographic maps. Notice that line data are allowed two bits, imagery eight bits for 256 shades of gray, and the elevation number is allocated 16 bits, a total of 64 bits overall. Actually, line data would only require one bit but, to be liberal, two bits are assigned. For topographic mapping, including both line and an image map, 34 bits per cell adequately represents the actual arrays of data for each of the six separation overlays and the digital elevation value. No allocation has been made for attribute codes; only the map content is represented by the 34 bits.

Table 2 shows that the 49 States have an area of 7.84×10^{12} m² and illustrates a tabulation of cell size from both methods for comparison. Note that cell sizes of 1.7 (method #1) and 1.36, 1.82, and 2.28 (method #2) are extended in the right-hand column. It is established that a cell size ranging from 1.4 to 2.3 m emerges as the requirement. From observing the right-hand column of Table 2, it is clear from both methods that the estimated mass storage requirement for the lower 49 States is on the order of 10^{13} to 10^{14} bits.

The 10^{14} bit estimate is based on considering the data as arrays of pixels, as in "raster technology." The ultimate digital mapping system will probably be a combination of raster and "vector technology." It is generally accepted that vector data require less

TABLE 2. CELL SIZE AND STORAGE ESTIMATES

B/H	Cell Size (Meters) on Ground	Cell Area (Meters²)	Total Cells Required	Bits Required • Five Overlays × 2 = 10 Bits Imagery = 8 Bits	Total Bits • Graphic overlay • Image Data • Elevation	- 10 Bits - 8 Bits - 16 Bits 34 Bits/ Cell
Approximate Area for Continental U.S. and Hawaii, $7.84 \times 10^{12} M^2$ (3,028,710 SQ. MI.)						
Method #, Smallest Feature 0.25 MM (0.010 IN)						
	1.7	2.89	2.71×10^{12}	4.88×10^{13}	9.21×10^{13}	
Method #2, Contouring Criteria: CI = 10 FT (3 M)						
0.6	1.36	1.85	4.24×10^{12}	7.63×10^{13}	1.44×10^{14}	
0.8	1.82	3.31	2.37×10^{12}	4.27×10^{13}	8.06×10^{13}	
1.0	2.28	5.20	1.51×10^{12}	2.72×10^{13}	5.13×10^{13}	

K = 0.4, Correlation accurate to 0.4 of a pixel

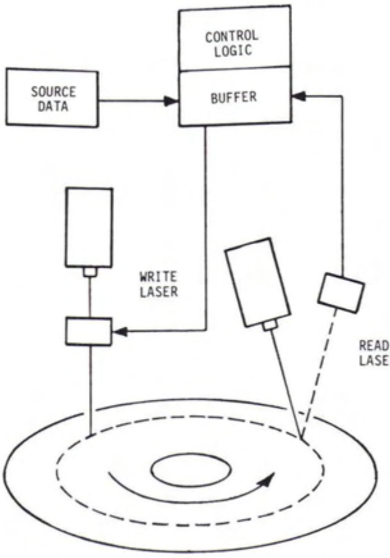


FIG. 2. The direct read-after-write (draw) disk process. Data are written onto a disk by modulating a laser beam. The data, originally digital, are stored in a buffer while being written. Immediately afterward, the same data are read from the disk and compared to those in the buffer. If identical, the next track of data is read in; if not identical, the prior track is rewritten until correct.

storage than raster data, so the 10^{14} estimate is considered to be a liberal estimate.

LASER OPTICAL DISK TECHNOLOGY

Random access memory (RAM), core memory, charge-coupled devices, bubble memory, and the magnetic media of tapes and disks are all applicable to the storage problem, but the laser optical disk appears to be the technology likely to succeed for large mass storage systems on the order of 10^{13} to 10^{14} bits. Every so often a system appears that inspires dreams and whose potential stirs speculation in several disciplines. The transistor was one; the microprocessor another. Now the laser optical disk appears to be a third (Edelhart, 1981).

Optical recording is a new technology using lasers to record and play back information which promises to have many of the desirable characteristics rolled into one media. The basic operational concept of optical disk technology is

- Focus laser beam to a micrometer size spot,
- Selectively "burn" holes in disk surface to record information, and
- Play back recorded pattern (bits) using laser spot at reduced power.

Figure 2 illustrates the laser optical disk recording configuration and the direct read-after-write (DRAW) concept (Moberg and Laefsky, 1982).

Performance characteristics for storage media can be broken down into the following categories: capacity, cost, access time, transfer rate, shelf life, and reliability.

Table 3 compares the capacity of other media to optical disk. Because film is not computer compatible, it is disregarded. High-density digital tape (HDDT) at a ratio of 0.38 is high capacity, but magnetic media's short shelf life is undesirable. Plus, HDDT is not computer compatible.

Figure 3 shows optical disk technology to be much less expensive than the others. The literature predicts disk (platter) costs from \$12 to \$150 each. One platter will hold approximately 4×10^9 bytes.

Access time and transfer rates are competitive. Shelf life of the optical disk is not time proven, but estimates are ten years or better. At the present time, there is one significant limitation to optical recording, and that is nonerasability. This nonerasability makes it more difficult to integrate into existing systems using magnetic technology. But, on the other hand, it is precisely this lack of erasability that makes optical recording very attractive for very large, long

TABLE 3. COMPARISON OF VARIOUS STORAGE MEDIA WITH OPTICAL DISK

Storage Media	Capacity (Bits)	Comparison- $\frac{\text{Optical Disk Capacity}}{\text{Other Media Capacity}}$
Optical Disk	32×10^9	1.0
High Density Digital Tape* 27.5 Kb/inch/track 28 Tracks 9200 Ft.	85×10^9	$\frac{OD}{HDDT} = .38$
300 MB Magnetic Disk	2.4×10^9/Pack	$\frac{OD}{MD} = 13.33$
Computer Compatible Mag. Tape 1600 Bpi, 2400 ft.	0.3×10^9	$\frac{OD}{CCT_{1600}} = 106.67$
Computer Compatible Mag. Tape 6250 Bpi, 2400 ft.	1.3×10^9	$\frac{OD}{CCT_{6250}} = 24.61$
Aerial Photo (9×9 inches) Resolution: 25 μm	0.5×10^9	$\frac{OD}{AP} = 64$
Aerial Film Spool (393 ft.)	194×10^9	$\frac{OD}{AP} = 0.16$

*Archive Shelf Life < 2 Years

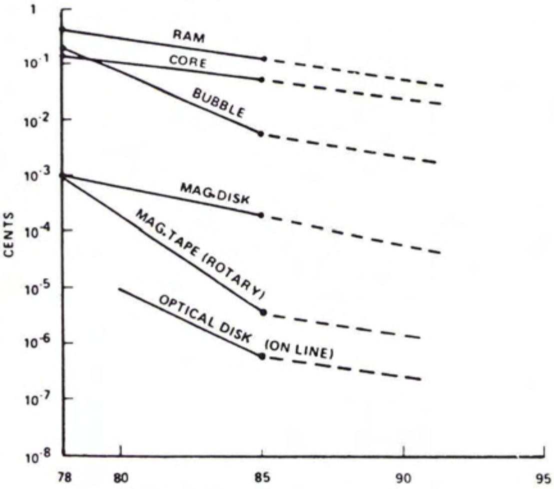


FIG. 3. Cost per bit summary.

life archival data bases (Rothchild, 1982a). Mapping data bases fit this category very well. Currently, the map revision cycle is approximately five years.

Relating the storage capacities tabulated in Table 3 to the requirement for 10^{14} bits, it is clear from Table 4 that optical disk, which calls for 3,100 platters to carry 10^{14} bits, is really the most feasible media. It should be recognized that these are capacity comparisons and do not account for any losses due to recording inefficiency.

A working model of an optical disk drive, courtesy of Storage Technology Corporation, is shown in Figure 4.

TABLE 4. NUMBER OF STORAGE UNITS REQUIRED FOR ^{14} BITS

Storage Media	10^{14} Bits/Unit Capacity	Units Required for 10^{14} Bits
Optical Disk	32×10^9	$3.1 \times 10^3 =$ 3,100
High Density Tape	85×10^9	$1.2 \times 10^3 =$ 1,200
300 MB Disk	2.4×10^9	$4.2 \times 10^4 =$ 42,000
CCT 1,600 BPI	0.3×10^9	$3.3 \times 10^5 =$ 330,000
CCT 6,250 BPI	1.3×10^9	$7.7 \times 10^4 =$ 77,000
Aerial Photo (9 × 9 in)	0.5×10^9	$2.0 \times 10^5 =$ 200,000
Aerial Film Spool (393 ft)	194×10^9	$5.2 \times 10^2 =$ 520

Figure 5 is a multiple-disk-drive/jukebox concept which is typical of the trend in optical disk drive architecture for the post-1985 timeframe (Kenville, 1982). One jukebox may hold up to 500 platters with four gigabytes capacity each (Rothchild, 1982b).

SUMMARY

In summary, 10^{14} bits of storage space are estimated to be needed for a digital mapping system containing 54,000 quadrangles at 1:24,000 scale. A minimum of 3,100 disks would be required to contain the data. A more realistic estimate is 4,000 disks, which is still within economic reason. One big gap in the storage technology appears to be the data base management systems (DBMS) to address such large capacity. Numerous DBMS are available, but none are known to be capable of addressing this large a mass of information. Much work remains to

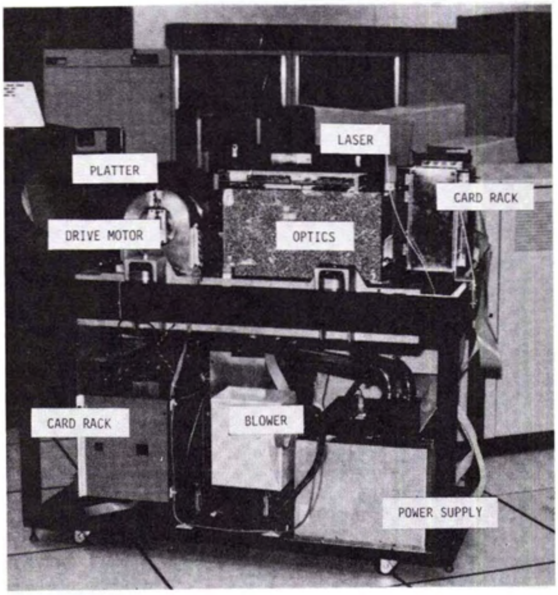
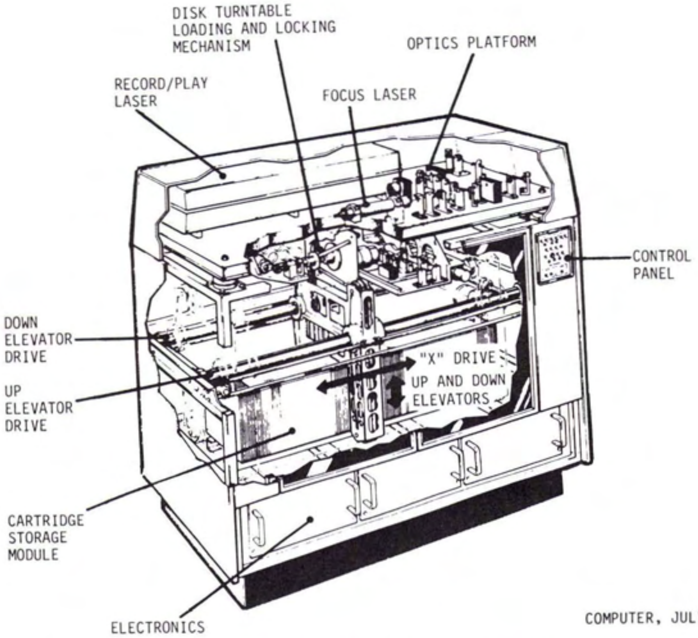


FIG. 4. Optical disk drive, engineering model.



COMPUTER, JULY 1982

FIG. 5. Concept for an automatically fed multiple-disk-drive jukebox.

be done in this area of development. The U.S. Geological Survey plans to begin experiments in digital cartographic applications utilizing optical disk technology in the 1986 and 1987 timeframe.

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(Received 26 November 1983; accepted 12 March 1985; revised 24 October 1985)

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