Metrics of scale in remote sensing and GIS

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ABSTRACT

The term scale has many meanings, some of which survive the transition from analog to digital representations of information better than others. Specifically, the primary metric of scale in traditional cartography, the representative fraction, has no well-defined meaning for digital data. Spatial extent and spatial resolution are both meaningful for digital data, and their ratio, symbolized as L/S, is dimensionless. L/S appears confined in practice to a narrow range. The implications of this observation are explored in the context of Digital Earth, a vision for an integrated geographic information system. It is shown that despite the very large data volumes potentially involved, Digital Earth is nevertheless technically feasible with today's technology.

INTRODUCTION

Scale is a heavily overloaded term in English, with abundant definitions attributable to many different and often independent roots, such that meaning is strongly dependent on context. Its meanings in "the scales of justice" or "scales over ones eyes" have little connection to each other, or to its meaning in a discussion of remote sensing and GIS. But meaning is often ambiguous even in that latter context. For example, scale to a cartographer most likely relates to the representative fraction, or the scaling ratio between the real world and a map representation on a flat, two-dimensional surface such as paper, whereas scale to an environmental scientist likely relates either to spatial resolution (the representation's level of spatial detail) or to spatial extent (the representation's spatial coverage). As a result, a simple phrase like "large scale" can send quite the wrong message when communities and disciplines interact – to a cartographer it implies fine detail, whereas to an environmental scientist it implies coarse detail. A computer scientist might say that in this respect the two disciplines were not *interoperable*.

Many comprehensive reviews of scale can be found in the literature. Lam & Quattrochi [1992] discuss the many meanings of scale in geography and environmental science. The collection of chapters edited by Quattrochi & Goodchild [1997] includes perspectives from many of the environmental disciplines.

Goodchild & Proctor [1997] have discussed the problems associated with the widespread adoption of digital technology. Definitions of scale were largely established in a pre-digital era, and have been adapted through a series of somewhat arbitrary conventions to fit the new world of digital databases. The cartographer's representative fraction (*eg*, 1:25,000, meaning that 1 cm on the map corresponds to 25,000 cm on the Earth's surface) is widely used to describe digital databases that have been built by digitizing or scanning paper maps, even though there are no distances in a digital database (distances between the locations of bits on the hard drive?) to compare with distances on the ground. Instead, by convention a digital database inherits the representative fraction of its paper source—but then what "representative fraction" should one use to characterize the detail in a digital database that had no paper source, such as a digital image of the Earth's surface captured by a satellite?

In this paper I examine the current meanings of scale, with particular reference to the digital world, and the metrics associated with each meaning. The concern throughout is with *spatial* meanings, although temporal and spectral meanings are also important. I suggest that certain metrics survive the transition to digital technology better than others.

The main purpose of this paper is to propose a dimensionless ratio of two such metrics that appears to have interesting and useful properties. I show how this ratio is relevant to a specific vision for the future of geographic information technologies termed Digital Earth. Finally, I discuss how scale might be defined in ways that are accessible to a much wider range of users than cartographers and environmental scientists.

FOUR MEANINGS OF SCALE
LEVEL OF SPATIAL DETAIL

As suggested earlier, to most scientists scale implies level of spatial detail, or spatial resolution, often defined as the shortest distance over which change is recorded, and

thus having units of length. The symbol S will be used here to denote this measure. Unfortunately several of the standard representations of a field (a variable conceived as a continuous function of the spatial variables x and y) do not have suitable well-defined metrics of spatial resolution. A square raster (Figure 1A) provides the simplest instance, because in this representation of the spatial variation of a field the spatial resolution is clearly the length of a cell side, all variation within cells having been lost. A slight complication occurs because it is impossible to cover the Earth's curved surface with square cells of uniform dimensions, so specifications of spatial resolution can be at best approximate. In remote sensing spatial resolutions are often termed *nominal* for this reason, and it is common to cite the most detailed spatial resolution, often the resolution of the image directly below the satellite, as its nominal value, even though this resolution is achieved over only a small part of the image. A square array of sample points (Figure 1B), often the basis for digital elevation models, also leads to a straightforward interpretation of spatial resolution.

From a geostatistical perspective, spatial resolution is related to the ability to estimate the variogram or correlogram at very short distances. In principle, direct estimation of variance or correlation over distances less than S is impossible since nothing is known about variation over such distances, and instead the variogram or correlogram must be modeled in this region, without benefit of empirical data. In turn, any variation estimated by kriging or simulation over such distances, for example in the immediate vicinity of data points, is purely speculative since it depends on the validity of the modeled spatial correlation function.

Much more problematic are the vector representations of a field illustrated in Figure 1. In Figure 1C, spatial variation is represented by capturing the value of the field at irregularly spaced points. This approach is commonly used in atmospheric science, where the sample points are irregularly spaced weather stations, and in soil survey, where the sample points are soil pits. The shortest distance over which change is recorded is the shortest distance between neighbors, but this implies a variable spatial resolution, ranging from the shortest to the longest distance between any point and its nearest neighbor. From a geostatistical perspective, estimates of the variogram or correlogram at short distances comparable to the distances between nearest neighbors may be based on very small numbers of pairs of points. Similarly in Figure 1D all variation between adjacent contours is lost, although contours place upper and lower bounds on variation. In the triangulated irregular network (TIN) model (Figure 1E) variation is represented as a mesh of planar, triangular facets, but the irregular size of the triangles fails to lead to a simple metric of spatial resolution.
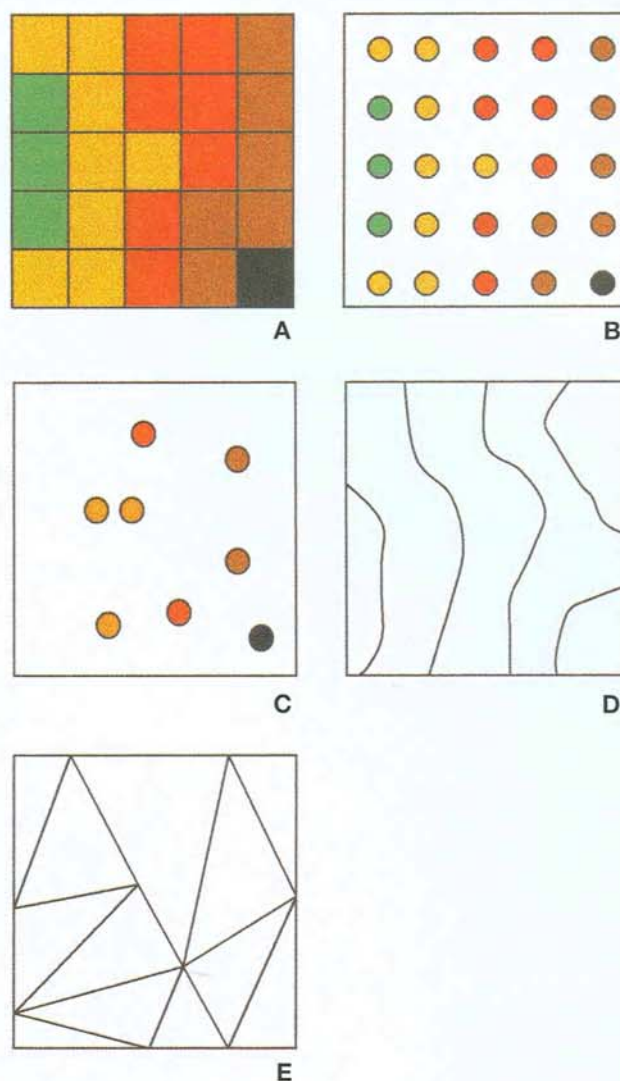

FIGURE 1 Five of the representations of a field commonly used in GIS. The spatial resolution of a square raster (A) is defined by the length of a cell side, and of a square grid (B) by the point spacing. Spatial resolution is not obviously defined for irregularly spaced sample points (C), contours (D), or triangulated irregular network (TIN) model (E).

Measures based on the spatial structure of a representation are also problematic because of the ease with which modern geographic information systems (GIS) can resample, interpolate, and otherwise change the apparent spatial resolution of data. Many methods exist to take the representation shown in Figure 1C and to create a square raster with a user-defined cell size, including a wide range of geostatistical methods. The apparent spatial resolution is now the length of the cell side. But suppose this length is less than the shortest distance between any pair of observations. As noted earlier, in such circumstances the form of the variogram or correlogram at short distances is determined entirely by the choice of the fitted mathematical function, since there are no actual observations of variance or correlation at

these distances. Thus the apparent refinement of the data has been achieved through what amounts to little more than guesswork. If a metric of spatial resolution is to be useful, it must be robust against such manipulations of the data, except where manipulations are based on sound model-based predictions supported by empirical data.

REPRESENTATIVE FRACTION

A paper map is an analog representation of geographic variation, rather than a digital representation. All features on the Earth's surface are scaled using an approximately uniform ratio known as the representative fraction (it is impossible to use a perfectly uniform ratio because of the curvature of the Earth's surface). The power of the representative fraction stems from the many different properties that are related to it in mapping practice. First, paper maps impose an effective limit on the positional accuracy of features, because of instability in the material used to make maps, limited ability to control the location of the pen as the map is drawn, and many other practical considerations. Because positional accuracy on the map is limited, effective positional accuracy on the ground is determined by the representative fraction. A typical (and comparatively generous) map accuracy standard is 0.5 mm, and thus positional accuracy is 0.5 mm divided by the representative fraction (eg, 12.5 m for a map at 1:25,000). Second, practical limits on the widths of lines and the sizes of symbols create a similar link between spatial resolution and representative fraction: it is difficult to show features much less than 0.5 mm across with adequate clarity. Finally, representative fraction serves as a surrogate for the features depicted on maps, in part because of this limit to spatial resolution, and in part because of the formal specifications adopted by mapping agencies, that are in turn related to spatial resolution. In summary, representative fraction characterizes many important properties of paper maps.

In the digital world these multiple associations are not necessarily linked. Features can be represented as points or lines, so the physical limitations to the minimum sizes of symbols that are characteristic of paper maps no longer apply. For example, a database may contain some features associated with 1:25,000 map specifications, but not all; and may include representations of features smaller than 12.5 m on the ground. Positional accuracy is also no longer necessarily tied to representative fraction, since points can be located to any precision, up to the limits imposed by internal representations of numbers (eg, single precision is limited to roughly 7 significant digits, double precision to 15). Thus the three properties that were conveniently summarized by representative fraction – positional accuracy, spatial resolution, and feature content – are now potentially independent.

Unfortunately this has led to a complex system of conventions in an effort to preserve representative fraction as a universal defining characteristic of digital databases. When such databases are created directly from paper maps, by digitizing or scanning, it is possible for all three properties to remain correlated. But in other cases the representative fraction cited for a digital database is the one implied by its positional accuracy (eg, a database has representative fraction 1:12,000 because its positional accuracy is 6 m); and in other cases it is the feature content or spatial resolution that defines the conventional representative fraction (eg, a database has representative fraction 1:12,000 because features at least 6 m across are included). Moreover, these conventions are typically not understood by novice users – the general public, or children – who may consequently be very confused by the use of a fraction to characterize spatial data, despite its familiarity to specialists.

SPATIAL EXTENT

The term scale is often used to refer to the extent or scope of a study or project, and spatial extent is an obvious metric. It can be defined in area measure, but for the purposes of this discussion a length measure is preferred, and the symbol L will be used. For a square project area it can be set to the width of the area, but for rectangular or oddly shaped project areas the square root of area provides a convenient metric. Spatial extent defines the total amount of information relevant to a project, which rises with the square of a length measure.

PROCESS SCALE

The term process refers here to a computational model or representation of a landscape-modifying process, such as erosion or runoff. From a computational perspective, a process is a transformation that takes a landscape from its existing state to some new state, and in this sense processes are a subset of the entire range of transformations that can be applied to spatial data.

Define a process as a mapping $b(x,t_2) = f(a(x,t_1))$ where a is a vector of input fields, b is a vector of output fields, f is a function, t is time, t_2 is later in time than t_1, and x denotes location. Processes vary according to how they modify the spatial characteristics of their inputs, and these are best expressed in terms of contributions to the spatial spectrum. For example, some processes determine $b(x,t)$ based only on the inputs at the same location $a(x,t)$, and thus have minimal effect on spatial spectra. Other processes produce outputs that are smoother than their inputs, through processes of averaging or convolution, and thus act as low-pass filters. Less commonly, processes produce outputs that are more rugged than their inputs, by sharpening rather than smoothing gradients, and thus act as high-pass filters.

The scale of a process can be defined by examining the effects of spectral components on outputs. If some wavelength s exists such that components with wavelengths shorter than s have negligible influence on outputs, then the process is said to have a scale of s. It follows that if s is less than the spatial resolution S of the input data, the process will not be accurately modeled.

While these conclusions have been expressed in terms of spectra, it is also possible to interpret them in terms of variograms and correlograms. A low-pass filter reduces variance over short distances, relative to variance over long distances. Thus the short-distance part of the variogram is lowered, and the short-distance part of the correlogram is increased. Similarly a high-pass filter increases variance over short distances relative to variance over long distances.

L/S RATIO

While scaling ratios make sense for analog representations, the representative fraction is clearly problematic for digital representations. But spatial resolution and spatial extent both appear to be meaningful in both analog and digital contexts, despite the problems with spatial resolution for vector data. Both S and L have dimensions of length, so their ratio is dimensionless. Dimensionless ratios often play a fundamental role in science (*eg*, the Reynolds number in hydrodynamics), so it is possible that L/S might play a fundamental role in geographic information science. In this section I examine some instances of the L/S ratio, and possible interpretations that provide support for this speculation.

- Today's computing industry seems to have settled on a screen standard of order 1 megapel, or 1 million picture elements. The first PCs had much coarser resolutions (*eg*, the CGA standard of the early 1980s), but improvements in display technology led to a series of more and more detailed standards. Today, however, there is little evidence of pressure to improve resolution further, and the industry seems to be content with an L/S ratio of order 10^3. Similar ratios characterize the current digital camera industry, although professional systems can be found with ratios as high as 4,000.
- Remote sensing instruments use a range of spatial resolutions, from the 1 m of IKONOS to the 1 km of AVHRR. Because a complete coverage of the Earth's surface at 1 m requires on the order of 10^{15} pixels, data are commonly handled in more manageable *tiles*, or approximately rectangular arrays of cells. For years, Landsat TM imagery has been tiled in arrays of approximately 3,000 cells × 3,000 cells, for an L/S ratio of 3,000.
- The value of S for a paper map is determined by the technology of map-making, and techniques of symbolization, and a value of 0.5 mm is not atypical. A map

sheet 1 m across thus achieves an L/S ratio of 2,000.
- Finally, the human eye's S can be defined as the size of a retinal cell, and the typical eye has order 10^8 retinal cells, implying an L/S ratio of 10,000. Interestingly, then, the screen resolution that users find generally satisfactory corresponds approximately to the parameters of the human visual system; it is somewhat larger, but the computer screen typically fills only a part of the visual field.

These examples suggest that L/S ratios of between 10^3 and 10^4 are found across a wide range of technologies and settings, including the human eye. Two alternative explanations immediately suggest themselves: the narrow range may be the result of technological and economic constraints, and thus may expand as technology advances and becomes cheaper; or it may be due to cognitive constraints, and thus is likely to persist despite technological change.

This tension between technological, economic, and cognitive constraints is well illustrated by the case of paper maps, which evolved under what from today's perspective were severe technological and economic constraints. For example, there are limits to the stability of paper and to the kinds of markings that can be made by hand-held pens. The costs of printing drop dramatically with the number of copies printed, because of strong economies of scale in the printing process, so maps must satisfy many users to be economically feasible. Goodchild [2000] has elaborated on these arguments. At the same time, maps serve cognitive purposes, and must be designed to convey information as effectively as possible. Any aspect of map design and production can thus be given two alternative interpretations: one, that it results from technological and economic constraints, and the other, that it results from the satisfaction of cognitive objectives. If the former is true, then changes in technology may lead to changes in design and production; but if the latter is true, changes in technology may have no impact.

The persistent narrow range of L/S from paper maps to digital databases to the human eye suggests an interesting speculation: *That cognitive, not technological or economic objectives, confine L/S to this range*. From this perspective, L/S ratios of more than 10^4 have no additional cognitive value, while L/S ratios of less than 10^3 are perceived as too coarse for most purposes. If this speculation is true, it leads to some useful and general conclusions about the design of geographic information handling systems. In the next section I illustrate this by examining the concept of Digital Earth. For simplicity, the discussion centers on the log to base 10 of the L/S ratio, denoted by log L/S, and the speculation that its effective range is between 3 and 4.

This speculation also suggests a simple explanation for the fact that *scale* is used to refer both to L and to S in environmental science, without hopelessly confusing the listener. At first sight it seems counterintuitive that the same term should be used for two independent properties. But if the value of log L/S is effectively fixed, then spatial resolution and extent are strongly correlated: a coarse spatial resolution implies a large extent, and a detailed spatial resolution implies a small extent. If so, then the same term is able to satisfy both needs.

THE VISION OF DIGITAL EARTH

The term Digital Earth was coined in 1992 by U.S. Vice President Al Gore [Gore, 1992], but it was in a speech written for delivery in 1998 that Gore fully elaborated the concept (www.digitalearth.gov/VP19980131.html): "Imagine, for example, a young child going to a Digital Earth exhibit at a local museum. After donning a head-mounted display, she sees Earth as it appears from space. Using a data glove, she zooms in, using higher and higher levels of resolution, to see continents, then regions, countries, cities, and finally individual houses, trees, and other natural and man-made objects. Having found an area of the planet she is interested in exploring, she takes the equivalent of a 'magic carpet ride' through a 3-D visualization of the terrain."

This vision of Digital Earth (DE) is a sophisticated graphics system, linked to a comprehensive database containing representations of many classes of phenomena. It implies specialized hardware in the form of an immersive environment (a head-mounted display), with software capable of rendering the Earth's surface at high speed, and from any perspective. Its spatial resolution ranges down to 1 m or finer. On the face of it, then, the vision suggests data requirements and bandwidths that are well beyond today's capabilities. If each pixel of a 1 m resolution representation of the Earth's surface was allocated an average of 1 byte then a total of 1 Pb of storage would be required; storage of multiple themes could push this total much higher. In order to zoom smoothly down to 1 m it would be necessary to store the data in a consistent data structure that could be accessed at many levels of resolution. Many data types are not obviously renderable (*eg*, health, demographic, and economic data), suggesting a need for extensive research on visual representation.

The bandwidth requirements of the vision are perhaps the most daunting problem. To send 1 Pb of data at 1 Mb per second would take roughly a human life time, and over 12,000 years at 56 Kbps. Such requirements dwarf those of speech and even full-motion video.

But these calculations assume that the DE user would want to see the entire Earth at 1m resolution. The previous analysis of log L/S suggested that for cognitive (and possibly technological and economic) reasons user requirements rarely stray outside the range of 3 to 4, whereas a full Earth at 1 m resolution implies a log L/S of approximately 7. A log L/S of 3 suggests that a user interested in the entire Earth would be satisfied with 10 km resolution; a user interested in California might expect 1 km resolution; and a user interested in Santa Barbara County might expect 100 m resolution. Moreover, these resolutions need apply only to the center of the current field of view.

On this basis the bandwidth requirements of DE become much more manageable. Assuming an average of 1 byte per pixel, a megapel image requires order 10^7 bps if refreshed once per second. Every one-unit reduction in log L/S results in two orders of magnitude reduction in bandwidth requirements. Thus a T1 connection seems sufficient to support DE, based on reasonable expectations about compression, and reasonable refresh rates. On this basis DE appears to be feasible with today's communication technology.

DATA VOLUME, PARALLELISM, AND LOG L/S

One of the technical as distinct from cognitive reasons for a limit to log L/S stems from its relationship to data volume. The number of data elements in an uncompressed raster (Figures 1A and 1B) is approximately $(L/S)^2$ or $10^{2 \log L/S}$. Little is known about the general properties of compression, and for most purposes compression rates are expressed as simple percentages, unrelated to the specific characteristics of the data. Again, little is known about the properties of vector data that determine data volume, and their relationship to spatial resolution and extent. If spatial resolution is constant, data volume is expected to rise with the square of extent, such that a doubling of L results in a quadrupling of data volume; and similarly, if extent is constant a halving of S is expected to result in a quadrupling of data volume (although fractal arguments would suggest a more complex relationship). Thus it seems reasonable to assume that the volume of all forms of geographic data is similarly proportional to $(L/S)^2$, with a constant of proportionality that depends on the specific representation and other properties of the data.

In recent years there has been much discussion of the so-called *firehose* problem created by satellite-based sensors. The series of satellites in NASA's EOS program will generate more than 1Tb of information per day, all of which may have to be processed and disseminated through a single data system. But if log L/S is effectively confined to the range 3–4, an application to the entire Earth's surface will be limited to 10^8 data elements, and a spatial resolution of approximately 4 km

(the Earth's circumference times 10^{-4}). Of course applications with greater data requirements are possible. A global climate modeler might conceivably wish to model global atmospheric fields at resolutions of finer than 4 km, but this is well beyond the power of current computing systems.

Applications with S less than 4 km can be expected to cover less than the entire surface of the Earth. Systems that supply data to such applications could be organized in parallel. For example, a single global server could disseminate data at spatial resolutions coarser than 4 km; a network of order 100 servers could disseminate data down to spatial resolutions of 400 m; and a network of order 10,000 servers could disseminate data down to spatial resolutions of 40 m. Arrangements such as these are increasingly common in practice, as local governments establish geographic data servers and clearinghouses for their own jurisdictions.

MAKING SCALE ACCESSIBLE

The use of conventions that are legacies from the era of analog paper maps creates problems for users of geographic data who have little understanding of their basis, such as the general public or children. If L and S are important characterizations of digital geographic data, then such users should have ways of specifying them that make intuitive sense. For example, a user of a major archive of geographic data will need to specify both parameters, in order to search for data relevant to a given problem. With widespread access to such data provided by the Internet and WWW, it is reasonable to assume that such users will include people with very little understanding of cartography or geographic information science.

Currently efforts are being made to provide intuitive ways of defining scale. A request to MapQuest (www.mapquest.com) to provide a map based on a street address returns a map with an L of approximately 2 km, while a request based on a city name returns a map with an L of approximately 50 km. Since these are vector maps there is no obvious basis for inferring S, but pixel sizes are approximately 5 m and 120 m, respectively. Although a map is displayed, no attempt is made to determine its representative fraction, which will depend on the user's screen size, a parameter unknown to the server. Instead, each map shows a bar of length equal to about one tenth of L, labeled according to its length in both metric and U.S. units. Scale can be changed by clicking on a vertical bar positioned next to the map, marked with 10 discrete levels that range in L from approximately 2 km to approximately 12,000 km, with the smallest values of L at the top ("zoom in").

GlobeXplorer (www.globexplorer.com) offers both maps and images. When a city name or street address is supplied, the site displays a MapQuest vector map and alongside it a raster image of the same area. Although S is well-defined for the latter, the display offers no specification of its value for either part of the display.

One possible solution to the problem of specifying S is to allow the user to identify familiar classes of objects. For example, a user might request sufficient detail to see "the buildings", and the system might respond by providing an image with a resolution of 4 m. A request for enough detail to see "the cars" might result in a 40 cm resolution, whereas "the streets" might be translated into a request for a spatial resolution of 10 m. A request for "the towns and cities" might be satisfied by 1 km resolution. Linking the scale of S to such familiar objects would make it possible for users to provide the necessary specification, without understanding the more abstract notion of spatial resolution expressed in dimensions of length.

CONCLUDING COMMENTS

I have argued that scale has many meanings, only some of which are well defined for digital data, and therefore useful in the digital world in which we increasingly find ourselves. The practice of establishing conventions which allow the measures of an earlier technology – the paper map – to survive in the digital world is appropriate for specialists, but is likely to make it impossible for non-specialists to identify their needs. Instead, I suggest that two measures, identified here as the *large* measure L and the *small* measure S, be used to characterize the scale properties of geographic data.

The vector-based representations do not suggest simple bases for defining S, because their spatial resolutions are either variable or arbitrary. On the other hand spatial variation in S makes good sense in many situations. In social applications, it appears that the processes that characterize human behavior are capable of operating at different scales, depending on whether people act in the intensive pedestrian-oriented spaces of the inner city or the extensive car-oriented spaces of the suburbs. In environmental applications, variation in apparent spatial resolution may be a logical sampling response to a phenomenon that is known to have more rapid variation in some areas than others; from a geostatistical perspective this might suggest a non-stationary variogram or correlogram (for examples of non-stationary geostatistical analysis see Atkinson [2001]). This may be one factor in the spatial distribution of weather observation networks (though others, such as uneven accessibility, and uneven need for information are also clearly important).

The primary purpose of this paper has been to offer a speculation on the significance of the dimensionless ratio L/S. The ratio is the major determinant of data volume, and consequently processing speed, in digital systems. It also has cognitive significance because it can be defined for the human visual system. I suggest that there are few reasons in practice why log L/S should fall outside the range 3 – 4, and that this provides an important basis for designing systems for handling geographic data. Digital Earth was introduced as one such system. A constrained ratio also implies that L and S are strongly correlated in practice, as suggested by the common use of the same term *scale* to refer to both.

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RESUME
Le terme échelle a plusieurs significations, dont certaines survivent la transition de représentations de l'information de l'analogique vers le numérique mieux que d'autres. En particulier, le premier système métrique d'échelle en cartographie traditionnelle, à savoir la fraction représentative n'a pas un sens bien défini pour des données numériques. Une dimension spatiale et une résolution spatiale sont toutes deux pleines de signification pour des données numériques et leur rapport, représenté par le symbole L/S, est sans dimension. En pratique L/S parait confiné dans une étendue étroite. Les implications de cette observation sont explorées dans le contexte de "Terre Numérique", une vision pour un système d'information géographique intégré. Il est montré qu'en dépit des très grands volumes des données potentiellement concernées, une "Terre Numérique" est techniquement réalisable avec la technologie d'aujourd'hui.

RESUMEN
El término escala tiene muchos significados, de los cuales algunos sobreviven mejor que otros la transición entre las representaciones análogas de la información y las digitales. Específicamente, la métrica primária de la escala en cartografía tradicional, la fracción representativa, no tiene significado bien definido en el caso de datos digitales. Extensión espacial y resolución espacial tienen sentido para datos digitales, y su relación simbolizada como L/S no tiene dimensión. La relación L/S parece ser confinada en la práctica a un rango estrecho. Se exploran las implicaciones de esta observación en el contexto de Tierra Digital, una visión para un sistema integrado de información geográfica. Se muestra que, a pesar de los amplios volúmenes de datos potencialmente involucrados, Tierra Digital es tecnicamente factible con la tecnología actual.