



## Scale factor and image resolution: some cartographic considerations

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### Abstract

The preservation of our cartographic heritage has long advocated the transformation of historical maps or, more generally, of paper maps produced by analogue methods into digital format. The development of GIS techniques and cartographic databases has allowed increasingly rapid georeferencing of scanned maps into global datums like WGS84. The prerequisite for good georeferencing is, however, good digital transformation of the paper map format. This is of course a technical issue, but it also has some mapping implications connected to cartographic generalization theory.

The subject of this paper is to connect the well-recognized cartographic generalization concept (the graphicism error) to the resolution of the scanned image (measured in SPI). The core of this paper's issue must be of course clear to all the technicians that are involved in map digitalizations, for instance at the several public cartographic archives. Not only: because of the fact that most of the current maps are in digital format, we think that the given concept should also be taught to medium/high level students of Cartography and to base level GIS students.

After a short introduction on some technical features linked to the scanning process (DPI, PPI, SPI), the scale factor of a map is briefly recalled. Then the numerical relation between the scanning resolution and the scale of the paper map is given. Awareness of this relation is useful to avoid scanner accuracy superseding the accuracy of the scanned map.

**Keywords:** SPI, Scale Factor, Image Resolution, Graphicism Error, Georeferencing

### 1. Introduction

Currently, the digital format is the predominant type of map produced in the world. Moreover, most digital maps are drawn “by query” (on demand) from geographic databases and are displayed only momentarily on the users' monitors (Dodge et al., 2011). It has been generally recognized that GIS (Geographical

Information Systems) have profoundly changed cartographic methods and Web 2.0 has had even further technical and social implications (see e.g. Gartner, 2009; Goodchild, 2007). However, it is also true that we have a large number of older paper maps that constitute a veritable heritage.

To preserve and cherish this cartographic heritage, the transposition from paper into digital

format has been adopted. This has been facilitated by some IT developments like advances in scanning technologies and the refinement of compressed image formats (jpg). Mass insertion of paper cartography into digital format in the mass storage of the computer followed. Sometimes the scanned raster layers have been simply memorized in the various files of the computer or “at other times they have been organized into structures of relational-type databases, accessible via geographic queries and/or attribute” (Favretto, 2012).

Unfortunately the scanning process of a paper map is not a neutral operation. Back in 1959 Tobler conceptualized the map as a data storage medium and, consequently, as a computer input element. Considering the direct transfer of the map into a computation system, Tobler warned that “an offset camera can change the scale of the map and, to a limited extent, the projection”.

The aim of this paper is to give some technical information on the digital transformation of a paper map. After a short introduction on some technical features linked to the scanning process (DPI, PPI, SPI), the scale factor of a map is briefly recalled. Then the numerical relation between the scanning resolution and the scale of the paper map is given. Awareness of this relation is useful in avoiding scanner accuracy exceeding the accuracy of the scanned map. Some concluding remarks are then given.

## 2. DPI, PPI, SPI

Occasionally there is some confusion with digital image resolution. Acronyms are often used incorrectly: one replacing another although they are not the same. The following are some basic definitions:

- DPI (Dots Per Inch) refers to printer resolution i.e. how many dots of ink or toner the printer uses in order to reproduce on paper the text or graphics with reference to one inch (2.54 cm). Of course, a higher number of dots endows the print with a sharper aspect.
- PPI (Pixels Per Inch) refers to the display resolution, and is the number of

pixels<sup>1</sup> an image fills when displayed on a monitor or other device. Every monitor has its own PPI, usually given by the factor of width by height (for instance: 1366 x 768 pixels). Therefore, PPI is connected to the monitor, not the image. A high resolution monitor has a larger number of pixels available than a lower one.

- SPI (Samples Per Inch). The digital format of an image is composed of samples, which is the information the monitor uses when displaying the picture. So, when a paper format graphic element is passed under a scanning device, SPI refers to the amount of scanned samples per inch. SPI is therefore both the scanner and the digital image resolution. The more scanned the samples are, the closer the scanned file is to the original paper format image.

Unfortunately, PPI, DPI and SPI are often considered synonyms when specifying image resolution.

The focus now passes to the scanner image acquisition process. To create a digital image, its continuous data<sup>2</sup> has to be transformed into digital form. This is achieved via two processes: sampling and quantization. Sampling is the digitizing of the coordinate values and is done by overlaying a sample grid onto the continuous image data. Every cell of the grid becomes a pixel and its color is the mean of the samples that are inside the cell. Quantization is the digitizing of the amplitude values, which is the conversion of every pixel of the sampled image into a numerical value. It is easy to understand that the quality of a digital image is determined by the density of the grid and by the number of the discrete values used in the quantization process. The density of the grid sets the image resolution (which is measured by SPI).

<sup>1</sup> As is well known, pixel stands for “picture element”. It is the smallest component of a monitor. Every pixel on the screen is identified by a specific x, y coordinate with the origin of the coordinate system in the top-left corner of the screen.

<sup>2</sup> The image data are continuous with respect both to the position and amplitude of the samples which compose it.

Thus, when scanning a paper format map, SPI has to be adjusted to the required level. If the map is transformed into digital format only for display purposes, the chosen SPI will condition the successive printing DPI (in the sense that it is not possible to print a map image at a higher DPI level than the SPI of the scanning process).

If the digital map is then later georeferenced, it also is necessary to take into account the scale factor of the original map before setting the SPI in the scanning procedure.

### 3. Scale Factor

The Scale Factor (SF), which is the well-known denominator in the scale ratio, is at first glance an easy concept. SF is obtained from the scale ratio. It is an a-dimensional quantity which states how many units of measurement on the ground correspond to one unit of measurement on the map.

Nevertheless, sometimes a little confusion may arise, especially when the SF is considered in relation to the distortions connected to the projection of a curved surface on a flat one.

Iliffe (2000, p. 60) defines the SF as a ratio between distances. It is:

$$SF = \frac{\text{distance on the projection}}{\text{distance on the sphere}} \quad [1]$$

Iliffe's definition of the SF [1] is however referred only to the distortion caused by the projection transformation, not to the dimension of the map graphic elements with respect to the earth geographic element they represent.

There are in fact two different SF values associated to every map. One is related to distortion and one to scale. To grasp this concept, map projection must be considered as a two-stage process (Robinson et al., 1995).

The first stage is the reduction of the Earth to a sphere (or a spheroid) of the size chosen for the flat map. This is the stage in which only the dimension of the Earth is changed, not the type of geometry (from a curved surface to a flat one). The size of the reduced sphere (or

spheroid), is proportional to a parameter, known as scale factor and is specified in the scale ratio.

The second stage is the mathematical transformation, point to point, of the curved surface of the sphere (or spheroid), into the flat surface of the map. Here we have no reduction in size but only in the geometry. The equation [1] assumes values around 1 (it depends on the distance from the tangency point between the sphere/spheroid and the flat surface/cylinder/cone).

For the scope of this paper, the "dimensional" aspect of the SF (the first stage of the map projection process) will be considered. This can in fact be connected with the scan resolution.

### 4. Image resolution and scale factor

As is well known, one important factor that affects cartographic generalization is the so-called graphic limits. These can be further split into two: physical limits (imposed by the equipment and materials used by the map maker), and the limits connected to "the map user perceptions and reactions to the primary visual variables" (Robinson et al., 1995, p. 459).

Connected to the first class of limits (the physical ones), one well-known mapping rule is the so-called graphicism error. It can be explained by the following:

$$\varepsilon_g = \varepsilon_{gm} * SF \quad [2]$$

where

$\varepsilon_g$ : ground graphicism error (mm)

$\varepsilon_{gm}$ : map graphicism error (if the map has been produced with analogue methods, this is conventionally equal to 0.25 mm; if the map has been produced by fully automated methods, this is conventionally equal to 0.1 mm)

SF: scale factor.

On paper, conventionally, it is not considered possible to draw a line thinner than 0.25 mm. This, multiplied by the scale factor becomes a length on the ground. This length, named ground graphicism error, is the smallest dimension of a

geographic element to be drawn on the map at the chosen scale<sup>3</sup>.

The equation [2] can also be applied to the raster layers and it is generally used to connect the spatial resolution of the remotely sensed images to a certain scale (see e.g. Favretto, 2006, p. 135).

The equation [2] can also be used to connect SPI and SF. It must be remembered that, from a cartographic point of view, the SPI scanner accuracy should not be much higher than the original accuracy of the map. This is especially true when the digital format of the map has later to be georeferenced and inserted into a GIS. In fact, if SPI is much greater than the original accuracy of the map, then all paper imperfections and all possible sudden changes of tone in pixels of the same color could be interpreted by the rectifying algorithm (re-sampling method) as different land cover, instead of an accidental change of color, due to the imperfect status of preservation of the paper map.

In order to connect SPI and SF we have to calculate the pixel ground resolution in cm (or also, the pixel precision) connected to each SPI. This can be done via the following equation:

$$\frac{SF * 2.54}{SPI} = \text{pix\_prec} \quad [3]$$

where:

SF is the scale factor of the map to be scanned

2.54 is one inch in cm

pix\_prec is the pixel ground resolution (in cm)

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<sup>3</sup> With regard to this it must be remembered that “Clarity demands geometric generalization because map symbols usually occupy proportionately more space on the map than the features they represent occupy on the ground” (Monmonier, 1996). Certain important geographic elements (streets, for instance), especially at medium scales (1:20000/30000), should be symbolized by very thin lines according to the graphicism rule. These elements should even disappear at lower scales. In order to draw these important features even at lower scales, the generalization procedures use the so-called “exaggeration”, which is the intentional enlargement or alteration of a feature “in order to capture its real world essence” (Robinson et al., 1995, p. 454).

SPI is the Samples Per Inch at which the scanner acquired the image.

We have calculated pix\_prec by [3] using several SF and SPI values. The results are shown in Table 1. Each table column shows the scale factor of the paper map to be scanned. Each table row is instead the samples per inch at which the scanner device can be adjusted in order to acquire the paper map.

Each cell of the table shows the pixel precision (cm) in correspondence to each different value of SF and SPI (column and row, respectively).

Then each pix\_prec value (at each SPI) has to be compared with its corresponding ground graphicism error (the graphicism error connected to the same SF).

Table 2 shows some different SF ground graphicism errors ( $\epsilon_g$ ), calculated with equation [2] and transformed in cm. The first table column shows the different scale factor values of the paper map. The second column shows the corresponding ground graphicism error (it is the smallest dimension of the object that can be drawn at each scale).

From a cartographic point of view a certain SPI should only be chosen if its corresponding pixel precision (from Table 1) is not greater than the ground graphicism error connected to the SF of the paper map to be scanned (Table 2). That is if scanner accuracy is desired not to exceed original map accuracy.

Observing Tables 1 and 2, it can be seen that there is only one row in Table 1 which meets the condition set down: it is the row corresponding to SPI equal to 100 (check the values in cm at each SF).

This seems to suggest not exceeding 100 SPI when scanning a paper map drawn with analogue methods, whatever the SF of the original map. This is, of course, only from an exclusively cartographic point of view, to avoid a high SPI making the scanner acquire paper imperfections that the successive georeferencing algorithm could interpret as geographic variability.

	SF	SF	SF	SF	SF	SF	SF	SF	SF	SF	SF	SF	SF	SF	SF
	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	15000	20000	50000	100000	
SPI 100	25,4	50,8	76,2	101,6	127	152,4	177,8	203,2	228,6	254	381	508	1270	2540	
SPI 200	12,7	25,4	38,1	50,8	63,5	76,2	88,9	101,6	114,3	127	190,5	254	635	1270	
SPI 300	8,467	16,93	25,4	33,87	42,33	50,8	59,27	67,73	76,2	84,667	127	169,33	423,33	846,667	
SPI 400	6,35	12,7	19,05	25,4	31,75	38,1	44,45	50,8	57,15	63,5	95,25	127	317,5	635	
SPI 500	5,08	10,16	15,24	20,32	25,4	30,48	35,56	40,64	45,72	50,8	76,2	101,6	254	508	
SPI 600	4,233	8,467	12,7	16,93	21,17	25,4	29,63	33,87	38,1	42,333	63,5	84,667	211,67	423,333	

Table 1. Matrix table with the pixel ground resolution (pix\_prec) in cm calculated with equation [3], using different SF and SPI values. Each table column shows the scale factor (SF) of the paper map to be scanned. Each table row is instead the samples per inch (SPI) at which the scanner device can be adjusted in order to acquire the paper map.

SF	$\epsilon_g$
1000	25
2000	50
3000	75
4000	100
5000	125
6000	150
7000	175
8000	200
9000	225
10000	250
15000	375
20000	500
50000	1250
100000	2500

Table 2. The ground graphicism error connected to some different SF, calculated with equation [2] and transformed in cm. The first table column shows the different scale factor values of the paper map (SF). The second column shows the corresponding ground graphicism error (it is the smallest dimension of the object that can be drawn at each scale).

### 5. Conclusions

The preservation of our cartographic heritage has long advocated the transformation of historical maps or, more generally, of paper maps produced by analogue methods into digital format. The development of GIS techniques and cartographic databases has allowed increasingly rapid georeferencing of scanned maps into global datums like WGS84. The prerequisite for good georeferencing is, however, good digital transformation of the paper map format. This is, of course, a technical issue, but it also has some mapping implications connected to the carto-

graphic generalization theory.

This paper aimed at connecting the well-recognized cartographic generalization concept (the graphicism error) to the resolution of the scanned image (measured in SPI). In other words, some advice regarding the SPI adjustments of the scanner device was given with respect to the scale factor of the paper map.

It was discovered that there is a trade off between the quality of the digital image (depending on the density of the sampling grid i.e. the number of SPI), and the ground graphicism error (connected to the SF of the paper map). This would suggest maintaining the SPI at a level so that the pixel precision (in cm) is not less than the ground graphicism error.

If this rule is accepted unconditionally, all paper maps should not be scanned at more than 100 SPI, in order to maintain scanner accuracy at the same level as the accuracy of the original paper map (in the sense of the smaller dimension of the drawn elements). It is thus considered that:

1. 100 SPI level may be too small, if the image has later to be georeferenced and maintained as a rectified raster layer in the GIS (low image resolution: possibility of ugly contours or blur effect). In this case it is suggested scanning the map at a level of 250 SPI at the most (furthermore, this SPI level is low enough to keep file sizes reasonable for large maps).
2. 150 SPI could be enough if the rectified raster layer has later to be elaborated to extract some vector feature (considering the map generalization effects, see note 3).

In any case, 100 SPI gives enough detail to recognize the geographic elements in the raster layer and rectify the image. This is because the original map could not be more detailed (due to the calculated ground graphicism error).

Of course, if the only requirement is to scan the map in order to preserve its paper format and it will only be visualized using common image software, it may be desired to scan at 400 SPI or more (for better printing results). However, if the raster layer later needs to be rectified for elaboration and possible extraction of some vector features, it is suggested to follow the above advice, so as to be entirely cartographically correct.

The core of this paper issue must of course be clear to all the technicians that are involved in map digitalizations, for instance at the several public cartographic archives. Not only: because of the fact that most of the current maps are in digital format, we think that the given relationship between data scanning and the scale of a map should also be taught to medium/high level students of Cartography and to base level GIS students. Often it has been rightly noted that GIS experts know the topology concept but ignore even the meaning of the word "Datum". This is the reason for the presence of some elements of the Cartography and Topography disciplines in many GIS course programs. In the same way we think that the basics of graphic data digital acquisition should be taught at all levels of the Cartographic courses, taking into account the relationships between the fields.

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