An Alternative Raster Display Model

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Abstract: In this paper we present an alternative, vector based coverage model, which could extend the traditional raster model. As the coverage model only changes the representation model behind rasters, it needs minimal effort to implement, mitigates current raster limitations, and has minimal performance impact due to modern computers' increased computing capacities. Moreover, coverages could still get the benefits of the traditional raster model. As the data model remains the same, traditional raster based operations can still be applied on rectangular coverages, while other patterns can still benefit at least from matrix algebra. Finally, not only current raster operations could be kept, but there would not be any limitations of developing new ones optimized for different coverage patterns (e.g. hexagonal operations).

1 INTRODUCTION

It is basic knowledge, Geographic Information Systems (GIS) work with two distinct data types: rasters and vectors. There are essential differences between the two models, converting them into each other results in data loss most of the time. These models are still used in parallel since not only their characteristics, but their typical use cases also differ. A fundamental attribute of the 2D raster model (hereafter raster model) is it can be created and used without interpreting the represented phenomenon. That is, a raster – for example a land cover image – can be created without excessive knowledge of the surveyed area. On the other hand, the vector model requires interpretation. Vectors can only be created, if one can choose and delimit the mapped entities, while the effective use of attributes also requires being familiar with the mapped phenomenon.

Additionally, the two models differ in the types of mapped phenomena. Usually, rasters are used for continuous data (e.g. temperature), while vectors are used for discrete entities (e.g. administrative divisions, infrastructure). This duality in GIS caused by the distinct characteristics of– and use cases for the two specific data models create a seemingly irresolvable disagreement when both of them are needed. In this study we argue, this duality is not really necessary, and the conversions between the two models can be neglected. Furthermore, by loosening the restrictions of the traditional raster model, new, interesting raster-vector cross products could be developed, which might be more appropriate for a given task than choosing a traditional model.

2 THE RESTRICTIVE RASTER MODEL

Since our current raster model is a heritage of an old computing era (Lim, 2008), it is still burdened with technological limitations of those times. No matter how those limitations are eased or vanished (Chrisman, 1987), our raster model still consists of a strongly coupled data–, and representation model. That is, rasters are matrices seamlessly filling a rectangular extent in a projected raster space (Ritter and Ruth, 1997). As common GIS software suggest, they must be represented with rectangular, coincident cells.

2.1 Strengths and Weaknesses

Despite of the limitations, the benefits of the raster model make it a useful, and widely used data model even in modern GIS analyses. However, by grouping some of its major characteristics (Huisman and De By, 2009; Bolstad, 2016; Farkas, 2017) by the level of conceptuality (i.e. data and representation), one can see, most of its strongest, most enduring merits are coming from the data model (Table 1).

Most of the strengths are coming from the model's simplicity. Since the majority of a traditional raster

Table 1: Characteristics of the raster data model without being exhaustive.

Data model	
Advantages	Continuous coverage Small size, good compressibility Simple data structure Good for parallel computing Easy to overlay when aligned
Disadvantages	Quadratic growth in raster size
Representation model	
Advantages	Easy to create textures Fast rendering (textures, pyramids) Easy to resample and interpolate Georeferencing is unequivocal
Disadvantages	Hard to reproject Rotation needs resampling Precision depends on latitude Sampling bias

file consists of cell values, rasters have good compressibility, as matrices can be easily encoded in a binary format. Furthermore, as subsetting a matrix is trivial, tiling up a raster layer for saving bandwidth, making operations faster, or parallelizing an analysis is easy.

On the other hand, advantages bound to the representation model are not huge, while the disadvantages are severe. Most of the restrictions of the raster model are coming from its disadvantages, and can be originated to the shapes of individual cells. As they are restricted to be rectangular and coincident, reprojection needs resampling and interpolation in most of the time. Furthermore, if cells are used for representing their centroids (i.e. sampling), a bias is unavoidably introduced, as diagonals are longer than sides.

2.2 Evolution of the Raster Model

In order to overcome a few disadvantages of the raster model, it has undergone some changes. First, when the raster model was introduced to aid plotting and visualization on digital displays (Lim, 2008), cells had a good reason to be squares. This initial property is still carried by some of the old, but popular formats, like the ArcInfo ASCII Grid (Yu and Custer, 2006).

Next, the classical raster model took the opportunity to extend rasters in the only possible way: permitting different resolutions on different axes. The GeoTIFF data exchange format is a prime example for this. It creates a raster grid with rectangular cells from a regular TIFF image with a tie point and an affine transformation matrix (Ritter and Ruth, 1997).

Since there were demands for various new raster capabilities, and the current, restrictive raster model could not incorporate them, theoretical and practical raster concepts parted. Now the theoretical concept capable of filling an extent with different shapes, called regular–, and irregular tessellation (Huisman and De By, 2009), is taught as GIS theory. Rasters, on the other hand, are the widely implemented subset of regular tessellations using rectangular grids.

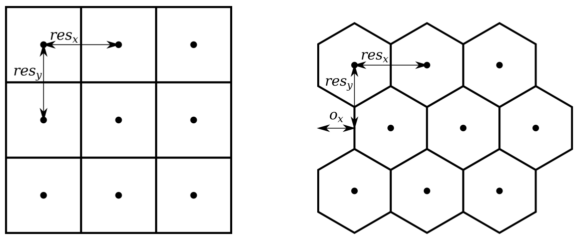
Some of the more popular demands, like the hexagonal grid (Birch et al., 2007) are slowly making their way into various GIS software in form of tools (Ramakrishna et al., 2013; Esri, 2017), however they are generated and stored as polygon layers. The problem with this approach is almost every advantage of the raster data model is lost. For example, after the grid is generated, the continuity is not enforced anymore, making space for a variety of user errors. Another potential concept for geomorphologists, the Multiresolution Image Format (Bugya and Halmai, 2013) does not have a straightforward way of getting implemented, as it relies on the raster data model.

3 DISPLAYING RASTERS AS VECTORS

Since most limitations of the raster model are coming from the representation model, we propose an alternative display model for rasters, and other regular tessellations: the coverage model. Rendering raster grids as vectors would need minimal modifications to popular data exchange formats, and minor modifications in GIS software. On the other hand, it would mitigate current raster limitations, making space for improvement.

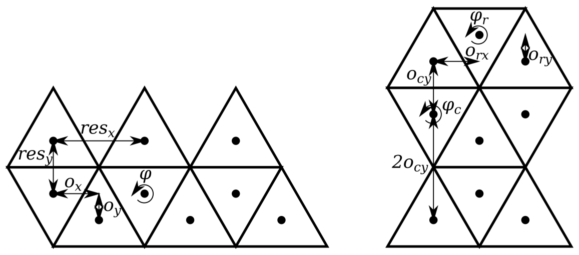
3.1 A Permissive Coverage Model

The main aspect in defining our coverage model was making it as permissive as possible. That is, its sole requirement is continuous coverage in a spatial extent. Specifically, elements of the coverage must not have gaps between them, nor overlap each other. We realize that such a strong criterion should be enforced by the model itself. Consequently, having an unequivocal, direct mapping between the coverage pattern and the data matrix is unavoidable. If no such mapping could be established in a practical way, the coverage should be treated as an irregular tessellation (e.g. TIN



(a) (b)

Figure 1: Required attributes for describing rectangular (a) and hexagonal (b) coverages. Vertical and horizontal resolution (res_x, res_y), and horizontal offset (o_x), which can be negative.



(a) (b)

Figure 2: Two different matrix mapping techniques in a $3x3$ triangular tessellation. In row-to-row mapping (a), the horizontal resolution (res_x) is constant in a row, while the vertical resolution (res_y) and offsets (o_x, o_y) are periodically changing in new rows. The rotation (φ) is always applied on a new row. In element-to-cell mapping (b), there are offsets and a rotation for cells in a row (o_{rx}, o_{ry}, φ_r), and for cells in new rows (o_{cy}, $2o_{cy}$, φ_c). The vertical offset for new rows is periodically changing.

model). Using such a model could enable an implementation to apply more heuristics as the regularity of the pattern increases. This way, traditional rasters would be treated in a more flexible way; as an edge case of the vector model.

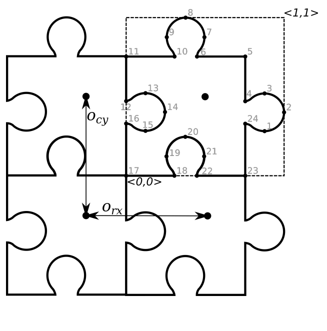
The amount of information needed to describe a regular pattern is minimal, while for more complex patterns it can gradually increase. In case of rectangular coverages, users could not experience any differences. They would look very similar to texture-based representations, while – as the data model behind the coverage model is the same – traditional raster and image tools can be used on them. Furthermore, existing and new compression algorithms for raster data can also be used on every coverage. By considering the rectangular pattern as the trivial one-to-one mapping to the underlying matrix, hexagonal tessellations can be described with only a few attributes (Figure 1), assuming the orientation of individual cells are horizontal (i.e. points-up or honeycomb). Developers could implement another set of tools optimized for hexagonal coverages (and rectangular coverages with an offset), as computations on hexagonal grids are well-founded (Her, 1995), while there are also potential use cases of them in GIS (Birch et al., 2007).

The third regular tessellation in euclidean space – a triangular pattern – has no trivial mapping to a matrix. Such a mapping can be defined in various ways, but grouped into two distinct categories; row-to-row mapping, where each row consist of cells with the same attributes, and element-to-cell mapping, where neighboring cells are changing periodically (Figure 2). No matter which method is used, there will always be a periodicity included, which needs to be considered. Such ambiguous coverages can make little use of traditional raster tools, although the continuity is granted, and matrix algebra can be used on a single coverage, or when the patterns of two coverages match. Furthermore, as they would be treated like vectors, vector tools could be used on such coverages.

In order to describe arbitrary patterns, there is one final consideration left: the way pattern geometries are stored. As there are numerous ways to tessellate an extent with irregular shapes, we do not think the coverage model should be restricted to euclidean regular tessellations (i.e. rectangular, hexagonal, triangular). If one can describe an arbitrary pattern with an unequivocal mapping to the underlying matrix, that pattern should be able to used as a coverage. While there are numerous ways to describe such a shape, we argue, it should be done in a normalized coordinate system enclosing the axis-oriented bounding box of the shape (Figure 3). This way shapes could be automatically scaled with the resolution of the coverage. Shape coordinates should be relative to the anchor point, as it would decrease the number of calculations required for visualizing the pattern, as in the following pseudo-code of a straightforward implementation (assuming hardware-acceleration is used):

```
Input: Cell shape $S$, Pattern $P$, First
centroid $C_0$, Resolution $R$.
Output: Coverage triangulation $T$.
1. Calculate $S_R$ by scaling $S$ with $R$.
2. Calculate triangulation $S_T$ from $S_R$.
3. do
4.   Get current cell's rotation $\varphi$ from $P$.
5.   Calculate cell $S_i$ by offsetting $S_T$ by $C_i$.
6.   Rotate $S_i$ by $\varphi$ around $C_i$.
7.   Add $S_i$ to $T$.
8.   Calculate next centroid $C_i$ using $P$.
9. until There are no cells remaining.
```

Storing the first anchor point or centroid is important, as it serves as the starting point of the pattern, a reference to absolute shape coordinates, and



ID	X	Y
1	0.4	-0.2
2	0.5	-0.1
3	0.4	0
4	0.45	-0.03
5	0.25	0.25
6	-0.05	0.25
7	0	0.38
8	-0.13	0.5
9	-0.25	0.38
10	-0.2	0.25

Figure 3: An arbitrary pattern described with a minimal number of attributes. Coordinates of the shape are stored in a normalized coordinate system, therefore it can be linearly scaled with the resolution of the coverage. As this pattern is based on a rectangular coverage, only one offset is needed for cells in the same row (o_{rx}), and one for new rows (o_{cy}), which also agree with the resolution.

a basis to offset, and rotate the shape in the pattern. On the other hand, storing the topology of neighboring shapes could be also considered, since that way a GIS could validate a coverage more easily and accurately (i.e. without false positives from arbitrary floating point calculations, and without the overhead of calculating the first period of the pattern). Similarly to triangular tessellations, these arbitrary coverages could neither be used for traditional raster analyses, although they would still get the other benefits of the raster data model.

The complexity of a pattern can be gradually increased by defining multi-shape patterns (e.g. euclidean projections of spherical tessellations), however assessing the feasibility of such coverages is out of the scope of this study.

3.2 Required Modifications

For effective coverage storage and retrieval, a standardized set of parameters should be worked out. As mentioned before, a regular pattern can be described with periodically changing translations and rotations, while an arbitrary pattern should contain the shape, and optionally its topological relationship with its neighbors. These are just additional metadata, which need to be stored in a coverage file. Some of the current formats can be extended to hold such information, while for others, it can be safely assumed, their contents are rectangular grids.

Moreover, formats supporting coverages should store the lower left cell's center (or anchor point). While currently it is very popular to store the lower left corner of a raster layer, for non-rectangular patterns it can be ambiguous. Finally, despite of storing the lower left corner of the first cell's bounding box is trivial, a calculation can be saved by not doing so.

A concise description of the triangular pattern in Figure 2b in JavaScript Object Notation could be the following:

```
{
  origin: [46.07, 18.21],
  shape: [[-0.5, -0.5], [0.5, -0.5], [0, 0.5],
    [-0.5, -0.5]],
  row_pattern: {
    rotation: [180deg],
    offset: [
      [0.5, 1/3],
      [0.5, -1/3]
    ]
  },
  col_pattern: {
    rotation: [180deg],
    offset: [
      [0, 4/3],
      [0, 2/3]
    ]
  }
}
```

The second part of the implementation would be a coverage interpreter. As every adequate GIS software is capable of rendering vectors, it would take minimal effort to extend the rendering engine to draw patterns. Besides the pattern drawing algorithm described before, only vector rendering methods need to be used (e.g. drawing cells as polygons, or triangulating and creating vertex buffers). The underlying low-level rendering engine can take care of the rest.

Due to the vector nature of coverages, resampling for display purposes would be rarely needed, although current raster resampling algorithms could be used for rectangular coverages. Pyramids, however, would need to be stored as resampled coverages with different resolutions instead of textures. If pyramids are really needed for arbitrary patterns, a simple approach could be converting the pattern to a rectangular coverage first (rasterization), then building pyramids from the result.

3.3 Advantages and Limitations

While the coverage model only differs from the raster model in visualization, it is easier to see its benefits, if compared directly with the traditional raster model. Since the coverage–, and raster models share their data model, changes can only be found in its representation model. Furthermore, as the coverage model encourages additional heuristics applied to edge cases, the characteristics (Table 2) can depend on the pattern. There are some independent advantages, on the other hand. As coverages are rendered as vectors, ro-

Table 2: Characteristics of the coverage representation model using different patterns.

Common charactersitics	
Advantages	Easy to reproject
	Easy to rotate
	Variable cell size
Disadvantages	Slower than textures
Rectangular coverage	
Advantages	Easily convertible to textures
	Easy to interpolate and resample
	Georeferencing is unequivocal
Disadvantages	Sampling bias
Hexagonal coverage	
Advantages	Easy to interpolate
	Less sampling bias
Disadvantages	Hard to resample
	Slower than rectangular
	Hard to create textures
	No lower left corner
Arbitrary coverage	
Advantages	Pattern can be tailored to use case
Disadvantages	Performance depends on pattern
	Hard to interpolate and resample
	Hard to create textures
	Georeferencing is not trivial

tation and reprojection are trivial operations. Moreover, since no textures are used, cell size can vary in a single coverage, allowing constant precision in projected coordinate systems. The sole common disadvantage is the performance impact. While performance depends on the complexity of the pattern, even rectangular coverages are outperformed by textures.

Rectangular coverages have the most advantages, since they inherit the advantages of the raster model, while most of their disadvantages are mitigated by the vector based visualization of the coverage model. The only disadvantage, which cannot be resolved by the coverage model is the sampling bias, since it is coming from the rectangular cells. On the other hand, this can be solved by choosing a hexagonal pattern. On hexagonal coverages less heuristics can be applied, therefore they have more disadvantages. For example, it is simple to interpolate in a hexagonal coverage, as centroids of neighboring cells can be calculated easily. However, resampling one is hard, as hexagons cannot be partitioned into smaller hexagons. Finally, ass hexagons do not have lower left corners, hexagonal coverages need to supply the centroid of the origin cell, or the lower left corner of its bounding box.

Since arbitrary coverages group patterns which do not have any heuristics applied, those are the most disadvantageous ones. Apart from the common advantages, they have only one; the freedom of choosing the best pattern for the task. However, – depending on the complexity of cell geometries – they have worse rendering performance. Moreover, since a general algorithm for interpolating and resampling must be vector based (i.e. laying down the whole pattern is a requirement), those operations would be hard and slow. As follows, general operations on these coverages could only be written on a vector basis, therefore they would rather act as a large vector layers with many small polygons than a raster layer. On the other hand, operations modifying cell values only (e.g. raster calculator) could still be fast, as they can run against the underlying matrix without considering the pattern.

3.4 Performance Impact

There is only one aspect the current, restrictive raster model excels at: performance. It was created with performance in mind, therefore it offers the quickest representation model possible in GIS. However, the computing capacity of modern computers (even handheld devices) surpassed the need for such optimizations long ago. Since one can enjoy the benefits of hardware-acceleration even in a browser (Nogueira, 2012), there is no reason to stick with the faster model on the expense of usability.

On the other hand, the performance impact of such a change should still be considered. There are – and in the near future there will be – good reasons for such optimizations. There are cases, where the amount of transmitted data or battery life matters (e.g. field devices), or where there is only limited computing power (e.g. embedded systems). In order to take those cases into consideration, the current raster display model should be kept as is. This way, desktop users with more computing power could be granted a permissive coverage model, while developers could still build applications using traditional, texture based rasters.

Another, less trivial implication is due to the flexibility of the vector model. As coverages display cells as polygons, cell geometries can be stored, if needed. This way, one can freely adjust the ratio of stored and calculated data. As spatial Database Management Systems (DBMSs) are optimized for effective storing, and quick retrieval of geometries and attributes, the performance of dynamically subsetting, and even analyzing large coverages could be increased on the expense of disk usage. This grants scalability to users, as they could freely choose tradeoffs. For example, a rectangular coverage can be stored as a GeoTIFF file, in a relational database, or in an array database (Baumann, 2001) as a georeferenced matrix. On the other hand, it can also be stored in a database as vector data by storing the center of each cell, or storing the geometries of the cells. In this scenario – with proper indexing – not only subsetting could be faster, but sparse matrices and multiresolution images could also be stored with ease.

Similarly, developers can choose the best ratio of memory consumption and rendering performance. For example, if hardware-acceleration is used, the triangulation of the whole layer can be stored, gradually increasing performance on the expense of memory consumption. However, additional memory requirement can also be fine-tuned. For example, one must store at least two floating point values per vertex, which can be complemented with four byte values (RGBA colors) for maximum performance. On the other hand, colors can be defined dynamically, on the fly, in order to decrease memory consumption. In cases when memory footprint should be kept at minimum, the tessellation can be triangulated on every drawn frame. Alternatively, if both the rendering engine and the application requirements permit it, the coverage can be rendered on a texture, and reused until the map scale changes.

4 CONCLUSIONS

The raster model is still a dominant, widely used model in GIS, although it has numerous limitations. Its fundamental advantage comes from its matrix nature, as it has well-optimized, fast algorithms, which can effectively be parallelized. On the other hand, its disadvantages – mostly coming from its representation model – are also severe. Its rectangular grid is based on euclidean geometry, therefore it can only map spherical surfaces and volumes with distortions. It is also vulnerable to transformations, and hard to reproject.

On the other hand, the vector data model does not have these limitations; vectors can be arbitrarily and accurately reprojected or interpolated. They require more computing power for those operations, however, modern personal computers have the computing capacity required for a vector-based coverage model. Furthermore, vectors have the unique ability of storing many attributes linked to a single entity, and well-optimized spatial Database Management Systems capable of analyzing them.

The coverage model we are proposing in this paper makes possible to use non-rectangular tessellations similarly to traditional rasters. Its practical implementation seems straightforward, as it does not collide with database standards, and can be integrated into raster data exchange formats with minimal modifications. On the software side, as the simple form of the proposed model would only require affine transformations and a vector rendering engine, thus adding it to modern GIS software would have no conceptual, nor practical limits.

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