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New Time-Space Maps of Europe

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1. Introduction: Space and Time

At the beginning of the era of the railways, Heinrich Heine wrote in Paris: "The railway kills space, so we are left with time. If we only had enough money to kill time, too! It is now possible to go to Orléans in four and a half hours or in as many hours to Rouen. Wait until the lines to Belgium and Germany are built and connected with the railways there! It is as if the mountains and forests of all countries moved towards Paris. I can smell the scent of German linden trees, and the North Sea is roaring in front of my door." (Heine, 1854, 65). The quotation circumscribes the topic of this paper, the relationship between speed and space or, in other words, the relationship between space and time.

Following the theory of time-space geography (Hägerstrand, 1970), increasing speed may be transformed either in a greater amount of free time or in a larger action space. Empirical studies of mobility have shown that the individual daily time budget for transport is relatively constant (Zahavi, 1979). So free time gained by higher speed is often used to travel more frequently or to more distant locations. A constant time budget thus leads to a shrinking of space in the subjective perception of the individual.

Increasing mobility is one of the constituting features of modernity: "The history of modern societies can be read as a history of their acceleration" (Steiner, 1991, 24). Modern society is a society of centaurs, creatures with a human front and an automobile abdomen (Sloterdijk, 1992). Today Europe is facing a new thrust of acceleration: The planned European high-speed rail network (Community of European Railways, 1989) will open up new dimensions of travel speed and so of the relation of space and time.

The topic of the paper is the visualisation of the new relationship between space and time by a new type of maps. These time-space maps do not display spatial distances but time distances between cities and countries. A method for creating time-space maps has been developed which improves current methods and avoids their pitfalls. To demonstrate the method, time-space maps for Europe and selected European countries are presented.

2. Visualisation of Space and Time

There are different methods to display the interrelation of space and time on a map. Three types of maps can be distinguished:

- *Isochrone maps* show temporal relations in space by preserving the spatial distances between map elements.
- *Cognitive maps* visualise the temporal efforts of travel by associative illustrations that are not exact in cartographic terms.
- *Time-space maps* represent the elements of a map in a configuration based on the travel times between them.

Isochrone Maps

Isochrone maps display areas of similar travel time to one selected point on the map. By drawing lines of equal travel times (isochrones) from the selected point, the travel time from all points of the map to the selected point in a given network or transport mode becomes visible. An isochrone far from the next one indicates fast transport; isochrones close to the next one display long travel times. In this way isochrone maps permit to judge the quality of the transport infrastructure. The disadvantage of isochrone maps is that only travel times from one single point can be displayed; travel times between other points of the map cannot be read from the map.

Figure 1 is an example of an isochrone map. The map shows the effects of the Channel Tunnel on rail travel times in western Europe. There are two sets of isochrones on the map: one set for the year 1991, i.e. for current travel times with today's rail and ferry networks, and a second set for the year 2010, i.e. for future travel times with the Channel Tunnel and the high-speed rail network implemented. The map presents travel times of trips from Great Britain and Ireland to Paris and from the European mainland to London. Even in 1991 first effects of the high-speed rail are visible: The French *Train à Grande Vitesse* (TGV) between Paris and Lyon pushes the isochrones south-east of Paris outwards. The future integration of the Channel Tunnel into the European high-speed rail network will halve the duration of most cross-Channel rail trips. Rail becomes the fastest surface transport mode in Europe (Spiekermann and Wegener, 1992).

Travel times and accessibilities can also be displayed in choropleth maps in which travel time categories are represented by different shades or colours. In certain circumstances such a representation can be easier to understand than an isochrone map. Choropleth maps are primarily used if the exact outline of the isochrones is not known. In that case the accessibility of a central point of an area is taken as the accessibility of the total area filled with the same shade or colour. Figure 2 illustrates this type of map by displaying average travel time savings of rail transport between all counties and twelve cities in Germany through the transport projects 'German Unity'. As expected, the new German Länder benefit from the rail improvements, with the exception of Mecklenburg-Vorpommern. The decrease of average travel times in Bavaria and Baden-Württemberg might be less apparent on an isochrone map.

Cognitive Maps

Another way of visualising space and time is by cognitive maps. Cognitive maps are subjective interpretations of reality (Downs and Stea, 1977). A cognitive map reflects the world in a way a person believes that it is like; the map does not need to be exact. The probability of distortion is high. The shape of coast lines and borders may change, proportions between different areas may not be exact, topological relations of places may differ from reality. Because cognitive maps represent subjective perceptions of the world, they are often used for advertisements. By exaggerating certain elements, a positive effect can be achieved, for example by exaggerating the speed of transport modes or changing spatial relations in favour of certain places (see Figure 3).

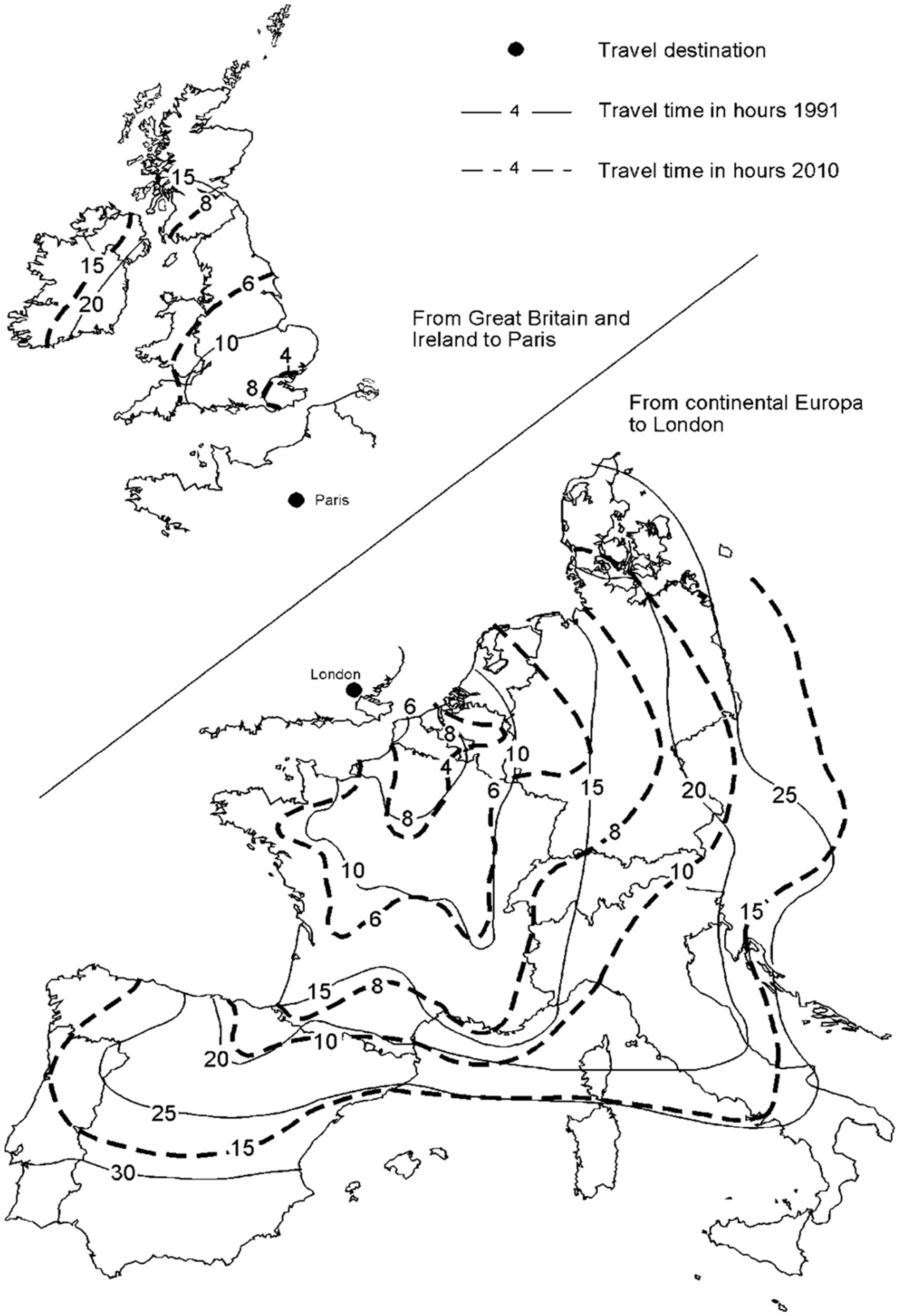


Figure 1. Rail travel times in western Europe, 1991 and 2010. The integration of the Channel Tunnel into the European high-speed rail network has halved the travel time of most rail trips across the British Channel

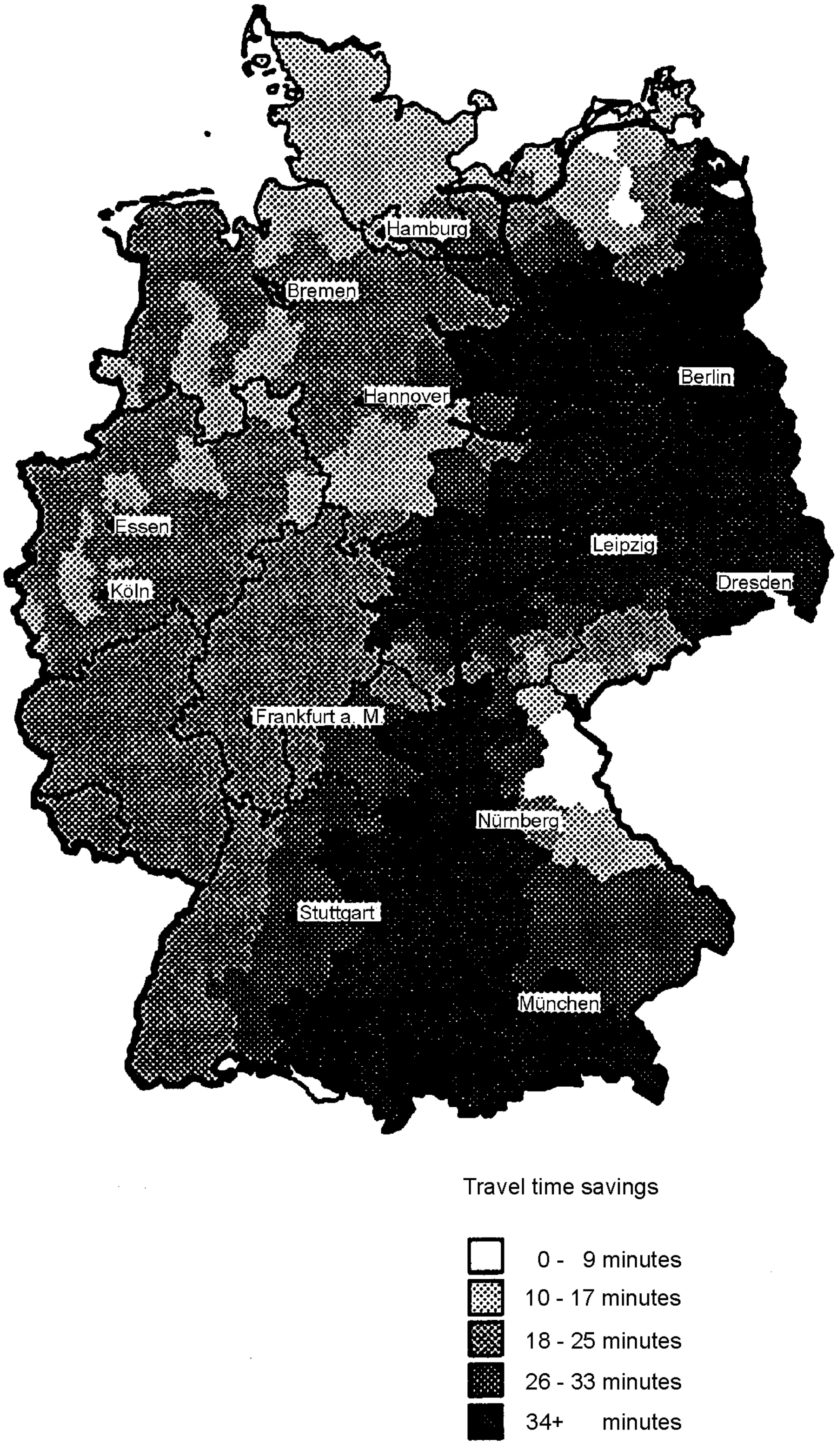
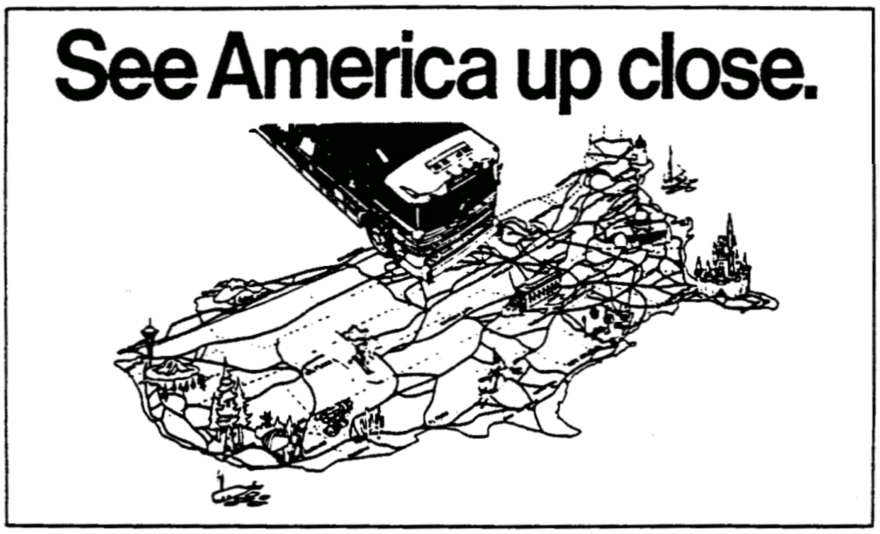


Figure 2. Improvement of travel times between counties and selected cities in Germany by the transport projects 'German Unity' (Source: BfLR, 1992).



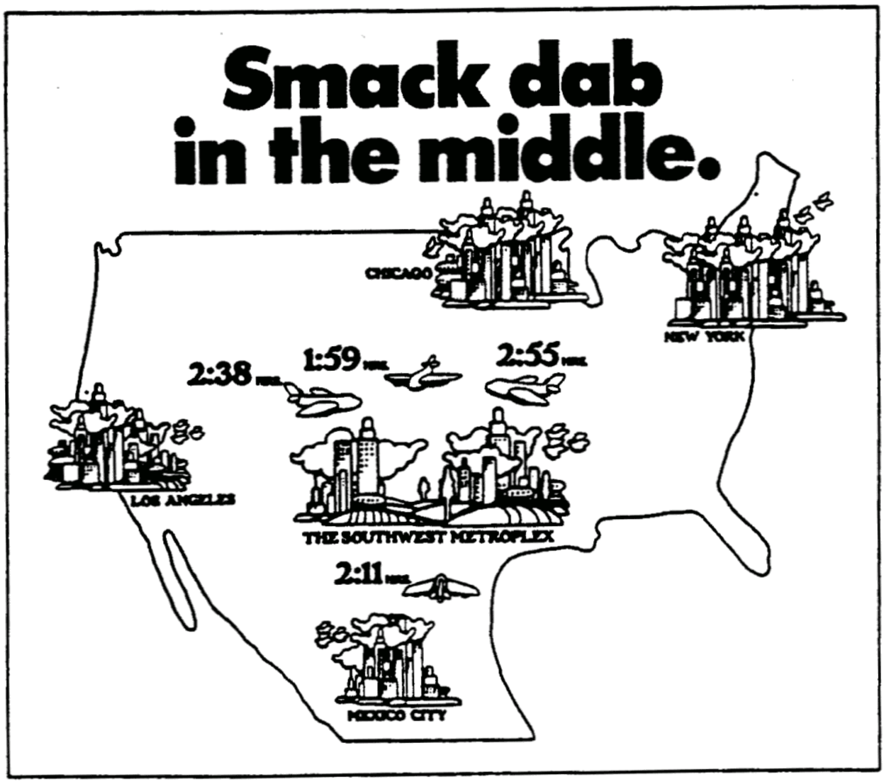


Figure 3. Cognitive maps for advertisement (Source: Downs and Stea, 1977).
Time-Space Maps

Time-Space Maps

Time-space maps represent the time space. The elements of a time-space map are organised in such a way that the distances between them are not proportional to their physical distance as in topographical maps, but proportional to the travel times between them. Short travel times between two points result in their presentation close together on the map; points separated by long travel times appear distant on the map. The scale of the map is no longer in spatial but in temporal units. The change of map scale results in distortions of the map compared to physical maps if the travel speed is different in different parts of the network.

If one assumes equal speed for all parts of the network, the result is the familiar physical map. Time-space maps with equal speeds can be used as reference for the interpretation of other time-space maps. They are called *base maps* here. All base maps in this paper use a homogenous travel speed of 60 km/h and have the same time scale as their associated time-space maps.

Time-space maps may include all elements of normal maps such as coast lines or borders, transport networks or single buildings. In practice only elements relevant for understanding the map are displayed. The emphasis is on the distortions of time-space maps compared with physical maps or with other time-space maps.

3. Current Methods for Creating Time-Space Maps

Time-space maps are created by transforming physical coordinates of a physical map into time-space coordinates. This can be expressed in global terms as follows:

$$u = \mathrm{f}\,(x, y) \qquad v = \mathrm{g}\,(x, y) \tag{1}$$

Here (x,y) are the coordinates of a point on the physical map, (u,v) the coordinates of that point on the time-space map, and f and g are transformation functions. The functions are calibrated in such a manner that the distance between points i and j on the time-space map,

$$d_{ij} = \sqrt{(u_i - u_j)^2 + (v_i - v_j)^2} \tag{2}$$

is in as close agreement as possible with the time distance t_{ij}. Figure 4 explains the principle of time-space mapping using a simplified example.

Because there are different speeds in the network, it is not possible to exactly reproduce the time distances of a time-space map in two dimensions. This would require a coordinate space with more dimensions. Time-space maps therefore can only be approximate.

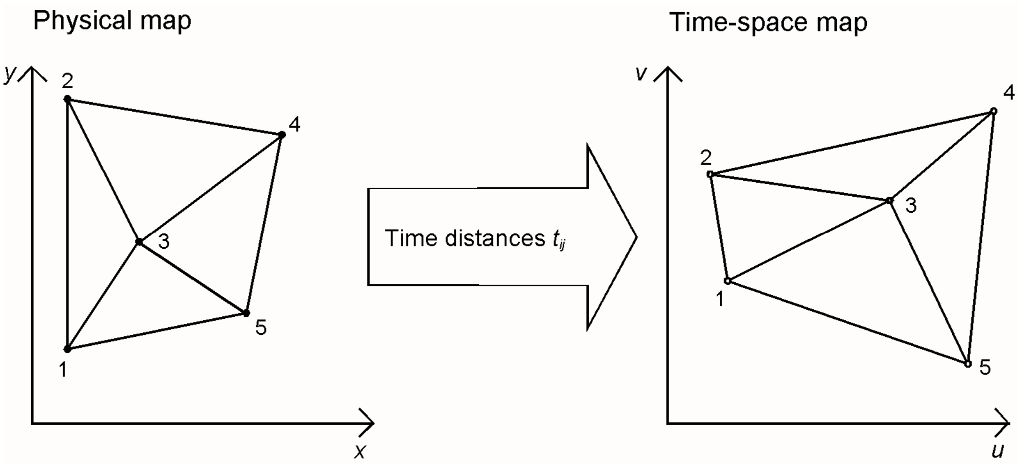


Figure 4. Principle of time-space mapping.

3.1 Multidimensional Scaling (MDS)

Usually the technique of multidimensional scaling (MDS) is used for generating time-space maps. If the differences between a set of phenomena in one dimension (in metric or non-metric units) are known, the MDS technique generates a spatial configuration in multidimensional coordinate space of additional attributes of the phenomena such that the distances between the items are as close as possible to the known distances. The MDS approach was developed in psychometrics in order to analyse, for instance, similar or different reactions of persons on multiple stimuli through visualisation in multidimensional space.

Time-space mapping is an example of applying metrical MDS. If t_{ij} is the travel time and d_{ij} the distance between two points i and j, all points are configured in two-dimensional space such that

$$\min_{u,v} = \sum_{i<j} (t_{ij} - d_{ij})^2 \qquad (3)$$

The principle of MDS for the generation of time-space maps is illustrated in Figure 5. The simple example shown can be solved by manual iteration (see Haggett, 1983; Gatrell, 1983).

At the beginning of the first iteration, the physical coordinates of the points to be calibrated are taken as initial values of the time-space coordinates $\{(u,v) = (x,y)\}$. It is not necessary that a travel time is known for every pair of points. The known travel times, which for practical reasons are scaled to the dimension of the physical coordinates, are drawn as lines which are centred between two points (top left).

If a line extends beyond the two points, the map distance between the points is too small and is increased. If the line is shorter, the map distance is decreased. The interim result are displacement vectors (offsets in X- and Y-direction) for each calibration point. They indicate the location of the points after the first iteration (top right). The new coordinates are the initial coordinates of the next iteration.

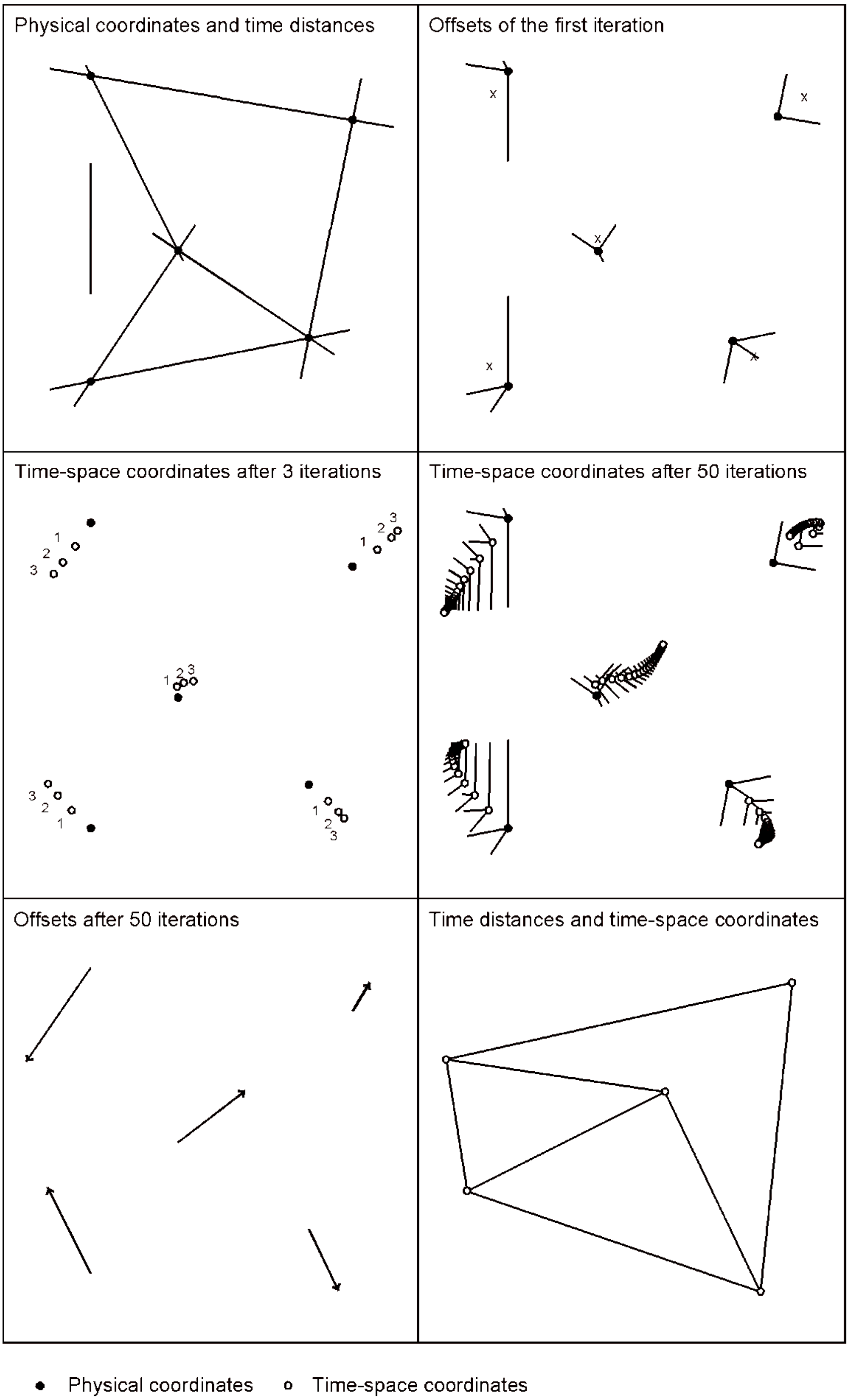


Figure 5. From physical coordinates to time-space coordinates.

The middle part of the figure shows the location of the calibration nodes after the first three iterations (left) and after fifty iterations with their displacement vectors (right). The final time-space coordinates are derived from the final displacement vectors (bottom left). The procedure continues until there is no more improvement, i.e. until a high correspondence between travel times and map distances has been achieved (bottom right).

There are several MDS algorithms differing by the optimisation procedure used. The transformation functions of equation (1), however, always have the form

$$u_i = x_i + a_i \qquad v_i = y_i + b_i \tag{4}$$

i.e., the time-space coordinates are calculated by adding point-specific offsets to the physical coordinates.

3.2 Interpolation

The result of MDS is a configuration in which the distances between the calibration nodes correspond as closely as possible to the known travel times. The calibration points may represent cities or other places, but they do not represent a complete map. Other map elements such as coast lines or borders have to be added. The time-space coordinates of the additional elements are not generated by MDS but by interpolation.

As shown in Figure 5, the transformation of physical into time-space coordinates can be represented by displacement vectors or offsets in X- and Y-direction. These vectors indicate for each calibration node the transformation from physical to time-space coordinates. Offsets of additional map elements can be calculated by interpolation between the offsets of adjacent calibration nodes. This is normally done by calculating the mean of the offsets of the closest calibration nodes weighed by their distance (see, for instance, Ewing and Wolfe, 1977).

A time-space map so generated is based on a number of calibration nodes, their offsets are determined by MDS, and the coordinates of additional map elements are calculated by interpolation. Figure 6 shows a time-space map for Toronto that is created applying this method. The effects of different speeds in the network become visible on the time-space map through the distortion of the grid that is right-angled on the physical map. The time-space increases in the congested inner city areas and decreases at the urban fringe.

However, there are two problems associated with this method, which are not visible in the map of Toronto (see Tobler, 1978 and Shimizu, 1992):

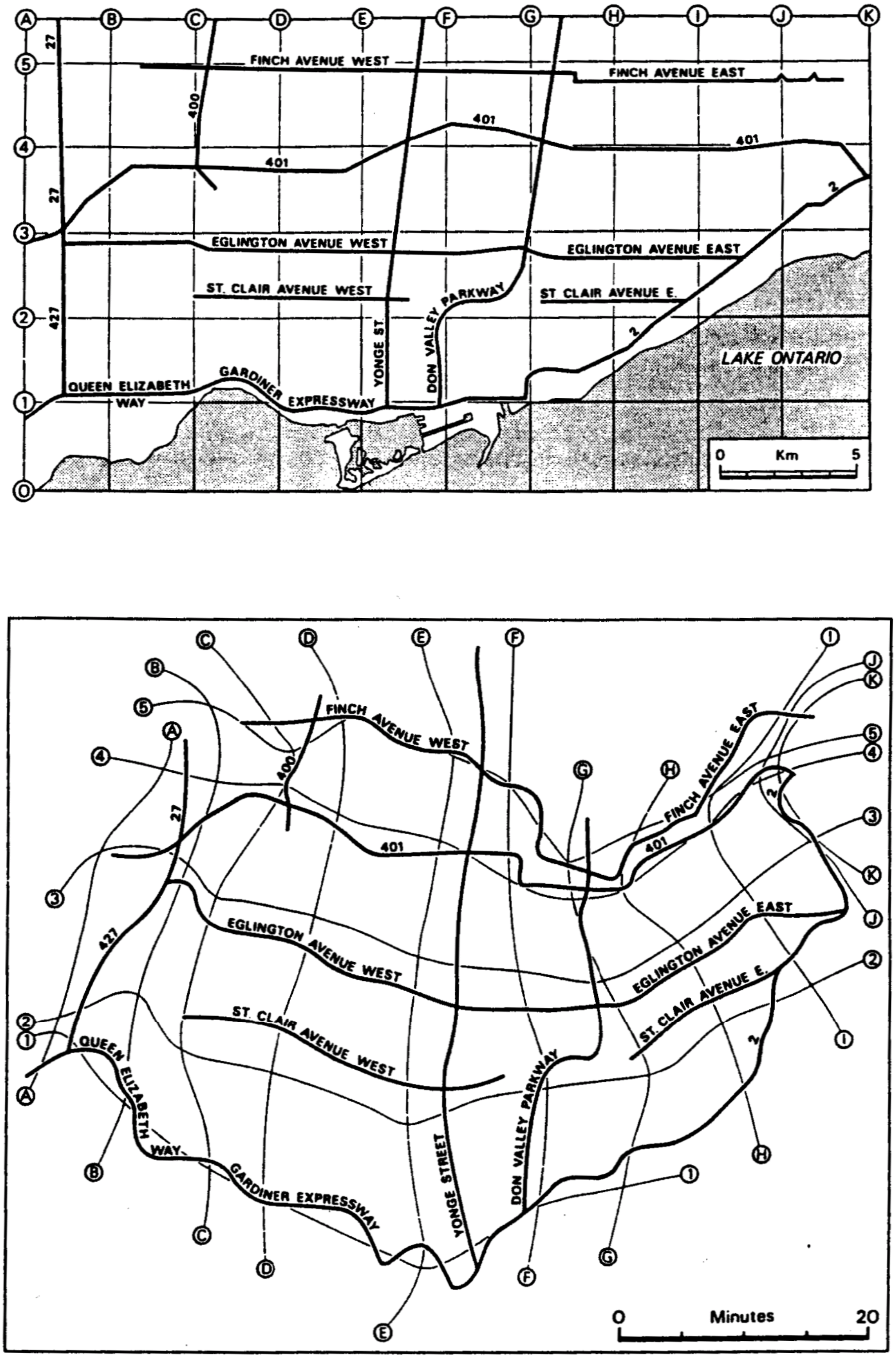


Figure 6. Physical map (top) and time-space map (bottom) of the Toronto road network (Source: Ewing and Wolfe, 1977).

- MDS locates calibration nodes only on the basis of travel times and does not take the topological features of the map into account. Therefore MDS may result in a distortion of the topology. For instance, it is possible that two streets which in reality are parallel, cross on the time-space map, or that certain areas are mirrored or folded over other areas, even though the map may represent an excellent solution of the objective function of the optimisation.

- The second problem is caused by the interpolation method, in which a weighted mean of offsets of nearby calibration nodes is calculated. This can lead to sudden discontinuities in the transformation. For example, if along a coast line one calibration node is replaced by another with a different offset, a jump in the coast line may occur. Such leaps may lead to faults in the map, which may be misinterpreted as large time distances between points.

To illustrate these problems, Figure 7 displays a series of time-space maps of western Europe generated by the above method. The number of adjacent calibration nodes used for the interpolation of coast lines and borders was increased stepwise from three (top) to nine (bottom). In each case the topology is distorted. Even on the most stable map (bottom) a 'new island' is drawn in the western part of the British Channel. In the other two maps the distortions of topology are aggravated. Jumps generated by the interpolation method can be observed, for instance, at the north-eastern border of Portugal. For this part of the border one or more calibration nodes are substituted by other nodes. The inclusion of more nodes reduces the effects of single nodes. However, this results in the elimination of local features so that the time-space map becomes more and more similar to the physical map. So a new problem arises, the selection of an appropriate number of nodes for the interpolation.

3.3 Topological Transformations

As stated earlier, there is no optimum solution for the location of the calibration nodes in two-dimensional time space but an unlimited number of possibilities performing equally well in mathematical terms. How to select a solution that is satisfying from a cartographic point of view? Shimizu (1992) proposed an extension of the MDS technique that solves the problem of preserving the topological properties and eliminates the interpolation step.

The method integrates a topological transformation into the MDS technique. The same optimisation criterion as in equation (3) is applied. While standard MDS generates time-space coordinates (u,v) directly, here instead the parameters of a transformation function are calibrated. This function is then used to calculate the time-space coordinates of the calibration nodes. It is not necessary to interpolate the coordinates of additional map elements, because the coordinates of all map elements can be transformed using the calibrated function.

Five transformation functions analysed by Shimizu are listed below, where a,b,c,... are parameters to be calibrated. With the exception of the polynomial transformation (9) all transformations preserve the topological properties.

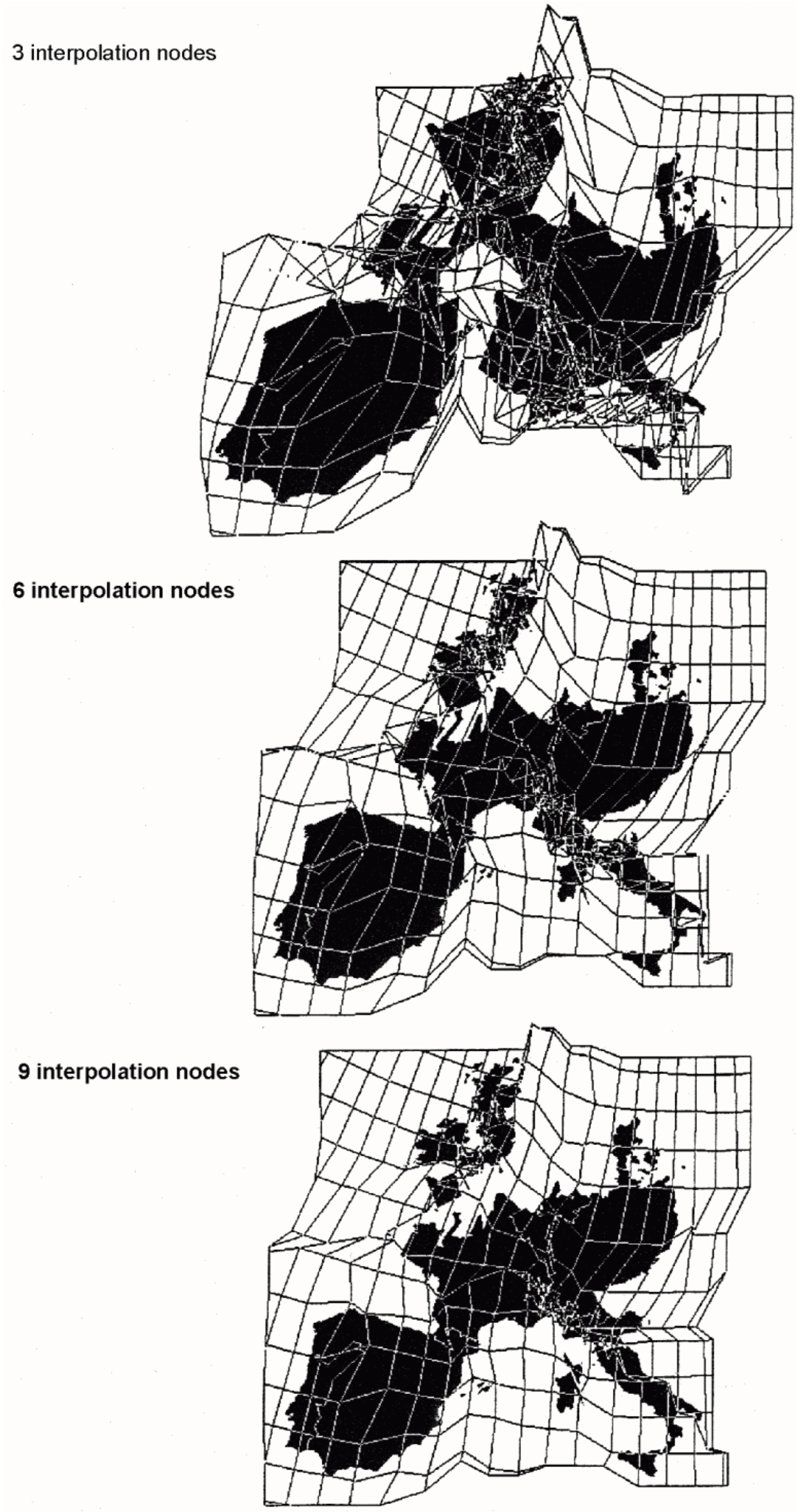


Figure 7. Problems of multidimensional scaling (MDS).

a) Affine transformation

$$u = ax + by + c \qquad v = dx + ey + f \qquad \begin{vmatrix} a & b \\ d & e \end{vmatrix} \neq 0 \tag{5}$$

b) Quadratic affine transformation

$$u = a(x-b)^2 + c(y-d)^2 \qquad v = e(x-f)^2 + g(y-h)^2 \tag{6}$$

c) Cubic affine transformation

$$u = a(x-b)^3 + c(y-d)^3 \qquad v = e(x-f)^3 + g(y-h)^3 \tag{7}$$

d) Projective transformation

$$u = \frac{ax + by + c}{px + qy + r} \qquad v = \frac{dx + ey + f}{px + qy + r} \qquad \begin{vmatrix} a & b & c \\ d & e & f \\ p & q & r \end{vmatrix} \neq 0 \tag{8}$$

e) Polynomial transformation

$$u = ax + by + cxy + dx^2y + exy^2 \qquad v = fx + gy + hxy + ix^2y + jxy^2 \tag{9}$$

Table 1 compares the performance of these transformations with standard or metric MDS. Using a simple map with only five calibration nodes, Shimizu calculated correlation coefficients between the known travel times and the distances on the time-space map and analysed the impact on the topology. The table indicates that relatively high correlation coefficients can be achieved only by transformations that do not preserve the topological properties, i.e. topological transformations imply a loss of similarity between the known travel times and their representation on the map.

Table 1. Accuracy of time-space mapping methods.

Method	Correlation coefficient	Topology
Metric MDS	0.942	not preserved
Affine transformation	0.771	preserved
Quadratic affine transformation	0.873	preserved
Cubic affine transformation	0.866	preserved
Projective transformation	0.806	preserved
Polynomial transformation	0.941	not preserved

Source: Shimizu (1992)

Shimizu showed that the application of the topological transformation method can lead to impressive results (see Figure 8). A cubic affine transformation was used for creating these time-space maps of Japan. The correlation coefficients for the maps are between 0.956 and 0.971, i.e. are much higher than in Table 1. The extension of the Japanese high-speed rail network Shinkansen leads to a continuous shrinking of the country with the exception of the Hokkaido island, which will be only partly included in the new network.

However, attempts to apply topological transformations to a time-space map of France revealed a number of problems (see Figure 9). The two topology-preserving functions at the top of Figure 9 are too continuous, i.e. no significant distortions compared with the physical map are visible. The inclusion of the grid of latitudes and longitudes shows how much local distortions are levelled off. One may compare these two illustrations with the time-space map of Figure 15 (top), which is based on the same data. The third map at the bottom of Figure 9 is an extreme application of the polynomial transformation, which does not preserve topological properties.

4. Our Own Approach

The deficiencies of the MDS technique are the weak control of the optimisation and the instability of the interpolation. The topological transformation approach by Shimizu avoids these problems, but results in a levelling-off of local distortions of the time-space map. To overcome these deficiencies, modified methods for calibration and interpolation were developed.

4.1 Stepwise Multidimensional Scaling (SMDS)

MDS achieves an optimal configuration of calibration nodes in two-dimensional time space, i.e. a configuration in which the map distances between the calibration nodes are as proportional as possible to the known travel times.

However, there exist many configurations which are equally optimal, yet each of them may result in a totally different map. As demonstrated in Figure 7, there may be serious distortions of the map topology in the form of faults and wrinkles of the map surface. Two kinds of topological distortions can be distinguished:

- 'True' topological distortions may occur if the transport network between the calibration nodes has great variations in speed. For example, a high-speed train link may make a remote town appear closer than a nearby town connected by slow trains.

- 'False' topological distortions are artefacts of MDS or of the subsequent interpolation. They appear particularly where fast and slow elements of the network meet.

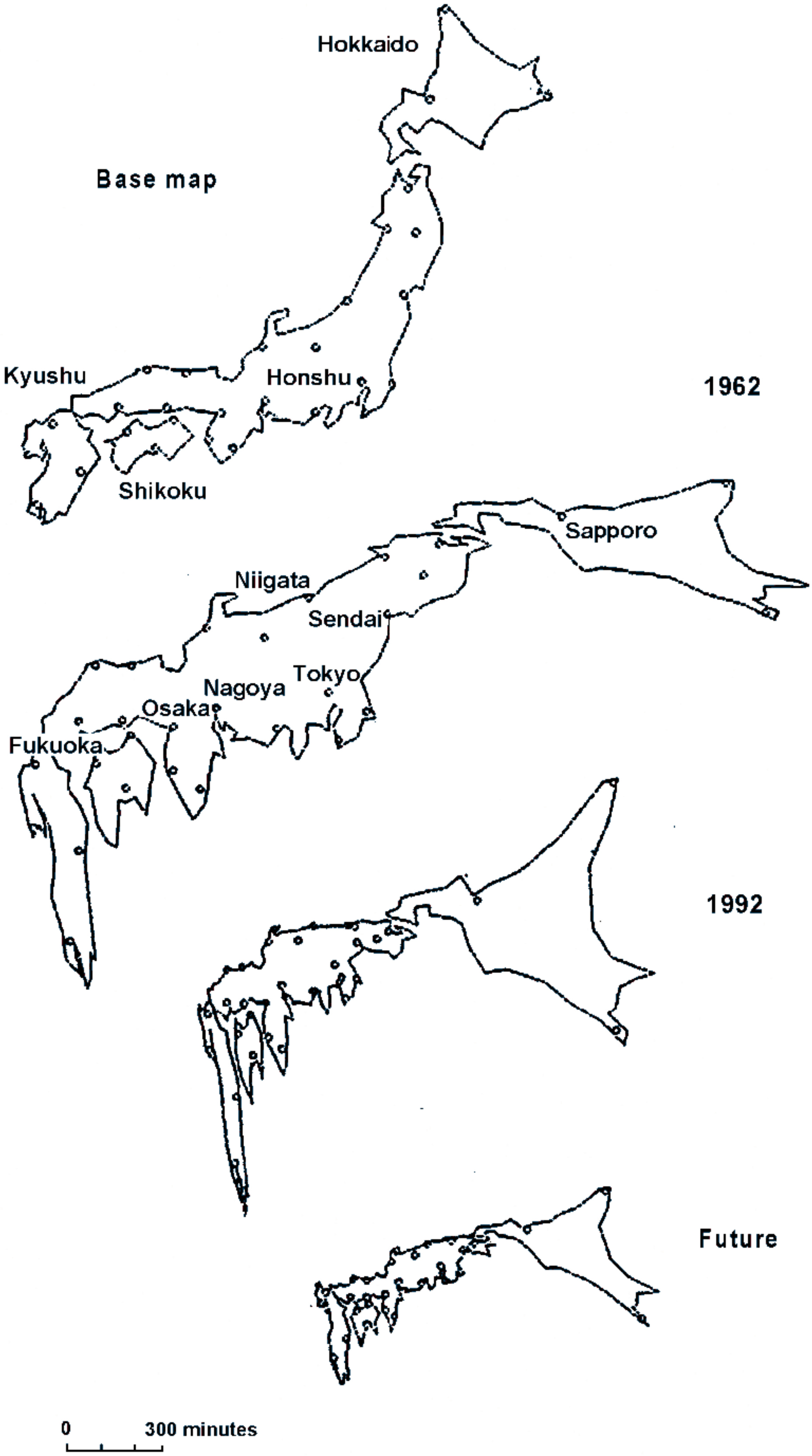


Figure 8. Japan, physical map (top) and time-space maps for different stages of the Shinkansen high-speed rail network (Source: Shimizu, 1992).

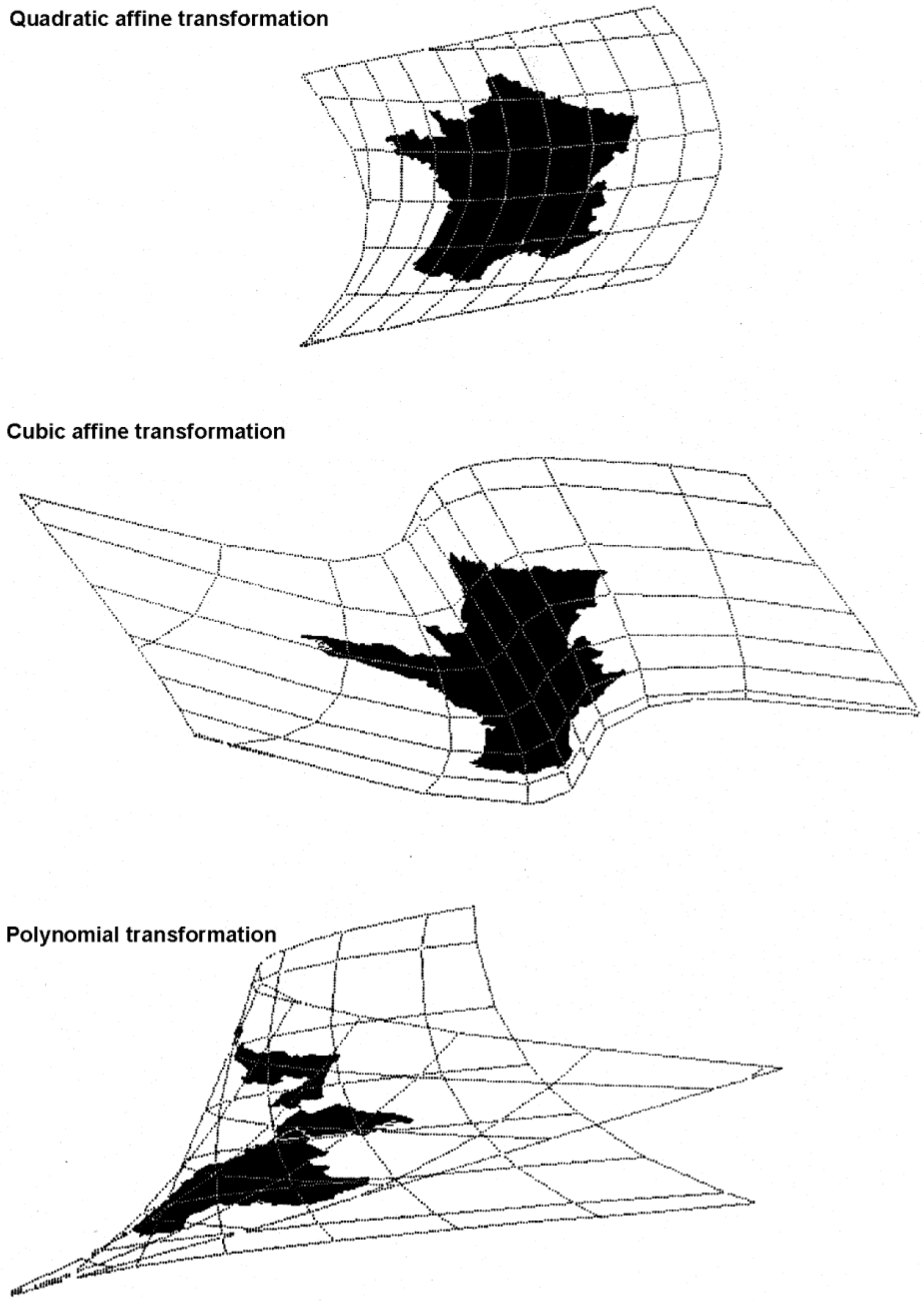


Figure 9. Problems of topological (quadratic affine and cubic affine) and non-topological (polynomial) transformation functions.

The slow ferry links between Ireland and Wales are an example of 'false' topological distortions. Because the ferry links have to be represented by a much longer distance on the time-space map than on the physical map, the MDS procedure tries to push their end points, Dublin and Holyhead, outwards on either side. This may result in Holyhead moving east and being located in the middle of England or even in the North Sea. In other words, the east coast of England becomes the west coast on the time-space map. Dublin, however, and the rest of Ireland move to the west, as one might expect.

'True' topological distortions are of potential interest. But they are irritating if one is mainly interested in changes of international accessibility. It is rather easy to avoid this kind of topological distortions by deleting slow routes from the network. It is more difficult to avoid 'false' topological distortions, as the optimisation algorithm of MDS cannot be influenced. For example, in the case of the ferry lines across the Irish Sea there is no way of telling the optimisation procedure that the extension of the ferry lines on the time-space map should go to the west.

The solution to this problem is to apply MDS stepwise on ring-shaped segments of the calibration network and to permanently fix the nodes of each round. This modification of MDS is called stepwise multidimensional scaling (SMDS). Stepwise multidimensional scaling starts with an origin node specified by the user. The coordinates of this node remain unchanged. In the first round all nodes of the calibration network directly connected to the origin node are processed. The X- und Y-coordinates of these nodes are the parameters to be optimised. The calibration network of the first round consists of all links between the origin node and these nodes and all links between them.

After completion of the first round the time-space coordinates of the nodes of the current calibration network are permanently fixed. The calibration nodes of the second round are all nodes which are directly connected with the nodes of the previous round. The calibration network of the second round consists of all links between the nodes of the first round and the new nodes and all links between the latter. Before entering the optimisation, the new calibration nodes are relocated so that their direction from the node of the previous round they are connected with and their distance from that node (in terms of travel time) remain unchanged. In other words, the initial values of the coordinates of the new round are set in such a way that the extension of the time-space network follows the direction of its extension on the physical map. In this way the probability of 'false' topological distortions is minimised. After the optimisation, the new calibration nodes of the second round are also fixed.

The subsequent rounds are processed correspondingly until all nodes of the calibration network are fixed. In this way the calibration network is processed from the inside out in ring-shaped segments. The advantage of the stepwise approach is that by choosing the origin node it can be decided which parts of the map should be stable and in which direction the distortion should take place. This avoids undesired topological distortions but does not level off 'true' distortions of topology.

Figure 10 displays the stepwise processing of calibration nodes in ring-shaped segments for the rail network of western Europe.

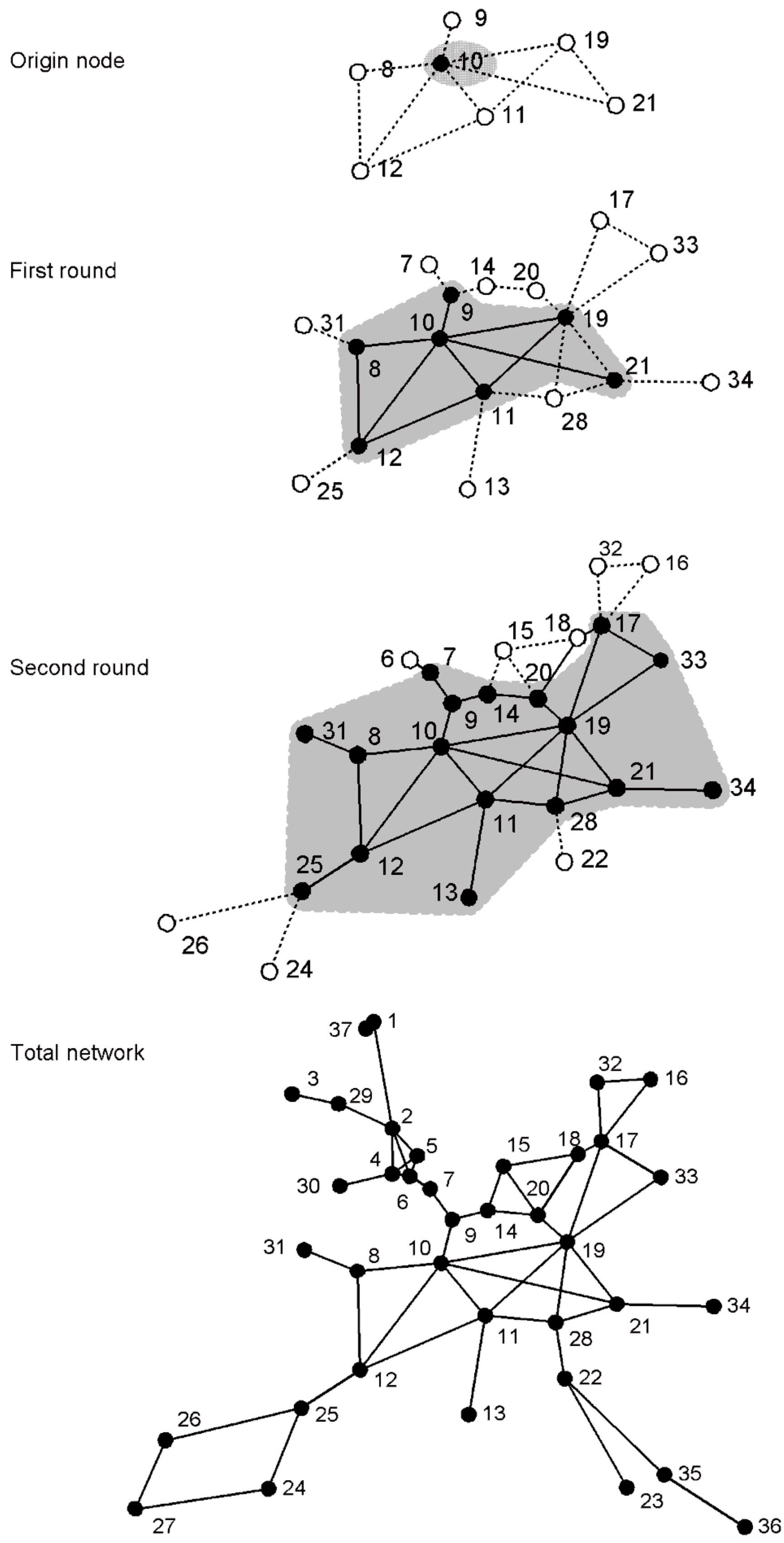


Figure 10. Principle of stepwise multidimensional scaling (SMDS).

Figure 11 displays the complete network in physical (black) and time-space (white) coordinates. The origin node is Paris (node 10).

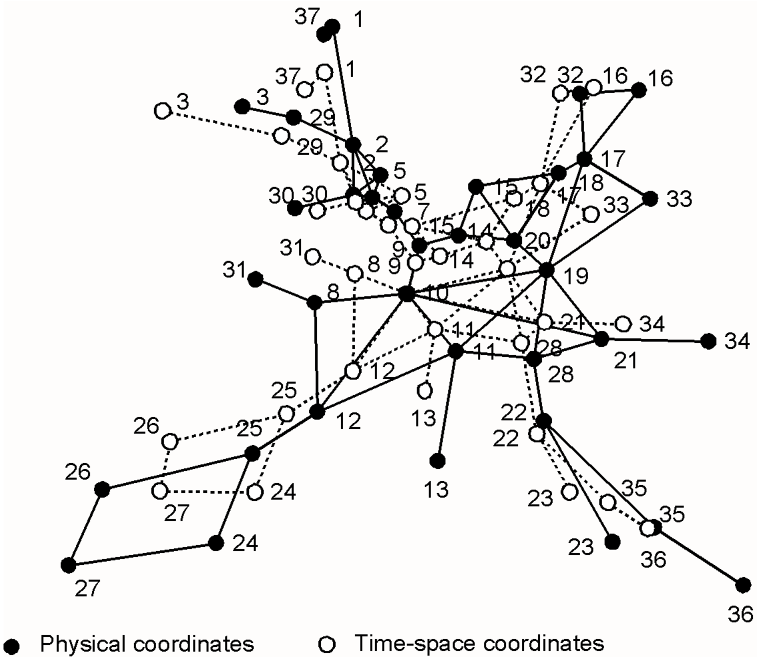


Figure 11. Calibration network in physical and time-space coordinates.

As it will be demonstrated in the next chapter, SMDS results in a much more easily understandable map representation. However, SMDS does not guarantee that there will be no topological distortions. If 'true' topological distortions appear, the map editor has to decide whether they are to be kept or be removed by deleting slow links of the network. In the case of 'false' topological distortions it is sometimes possible to improve the result by selecting a different origin node.

One disadvantage of SMDS is that the optimisation is not applied to the complete network in one single step, but to several ring-shaped segments separately. One has to expect that the deviation from the theoretical optimum is larger than with standard MDS. However, the loss in accuracy is small compared with the gain in cartographic quality. The correlation coefficients for time-space maps of western Europe created with SMDS were between 0.938 and 0.994, and so of similar magnitude as with standard MDS and clearly better than the correlations achieved with topological transformation functions (see Table 1).

4.2 Interpolation with Triangulation

The second reason for the jumps in the coast lines and borders of time-space maps created by MDS (see Figure 7) was the instability of the interpolation method, in which the displacements of linear map elements are calculated as weighted means of the offsets of adjacent calibration nodes. Jumps in the lines may appear where one calibration node is substituted by another node with a different offset.

The interpolation method developed here avoids this problem. It is based on triangulation as applied in digital terrain modelling. A triangulation of a group of points is a triangular mesh with the points as corners and minimum total length of edges. In digital terrain modelling triangulation is used to interpolate contour lines between irregularly spaced points with known elevation. In analogy to this, triangulation is applied here for the interpolation of points between calibration nodes with known offsets.

For the triangulation, ACM algorithm 626 (Preusser, 1984) is used. The algorithm starts by sorting the air-line distances between the calibration nodes by ascending distance. It then constructs from the sorted distances the triangular mesh with the calibration points as corners and minimum total length of edges. The offsets of the corners, i.e. the displacement vectors of the calibration nodes, are provided by the SMDS procedure. In order to cover the whole map area, the four corner points of the map and the midpoints of each map edge are treated as calibration nodes and are given fictitious offsets calculated as weighted averages of the corners of adjacent triangles. Figure 12 illustrates the triangulation for western Europe.

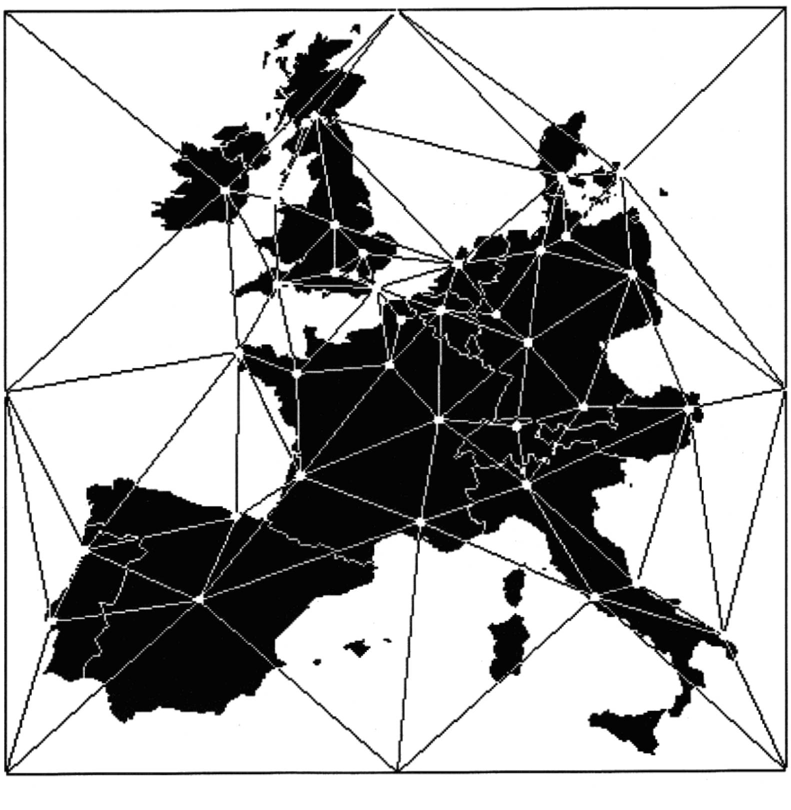


Figure 12. Triangulation of the calibration network.

Because the triangulation covers the entire map area, each point on the map, i.e. each point of the coast lines and borders and of the geographical grid, can be allocated to a triangle, for which the offsets of the corners are known. The offsets of a point are calculated as the weighted average of the offsets of the three corners of the triangle in which it is located. The averaging is done for the X- and Y-directions separately. If the X- and Y-offsets of the three corners of the triangle are considered as 'elevations', the averaging consists of determining the intersection between the triangle surface and a vertical line at the point in question. This method avoids jumps in the interpolated lines.

Figure 13 displays the interpolated offsets of coast and border lines (top) and of the intersections of the geographical grid (bottom) in western Europe. It can be seen that due to infrastructure improvements travel times in most parts of Europe are getting shorter, whereas Ireland, which can only be reached by ferry, moves outwards. The two illustrations give a first indication of the shrinking of the continent and the peripheralisation of Ireland.

5. Results

This section presents time-space maps of Europe and of selected European countries produced with the method described above. The time-space maps visualise the impacts of recent and future improvements of the road and rail networks in Europe, in particular of the evolving high-speed rail network, on the time space of the continent using four examples:

- The first example is France because the first high-speed train was the TGV, and the French high-speed rail plans are the most ambitious in Europe.

- The second example is Germany. The German high-speed train, the Intercity Express (ICE), has been in operation since 1991. Germany is also of interest because of the reintegration of the formerly separated rail networks of west and east Germany.

- The third example shows the evolution of the road and rail networks of western Europe, i.e. of the European Community plus Austria and Switzerland.

- In 1992 the International Union of Railways (UIC) outlined a high-speed rail network including eastern and northern Europe. The consequences of this network for the time-space of Europe are shown in the last example.

5.1 France

Figures 14 and 15 show the effects of different stages of implementation of the French TGV network. Origin of the stepwise multidimensional scaling of these maps is Paris. Figure 14 (top) is the base map with a speed of 60-km/h. The lower part shows a time-space map of France based on travel times between seventy French cities and Paris in 1988/89 (SNCF, 1991). The contraction of the hexagon along the TGV Paris-Lyon is visible. The difference in size compared with the base map indicates that even without the TGV the average speed is higher than 60 km/h.

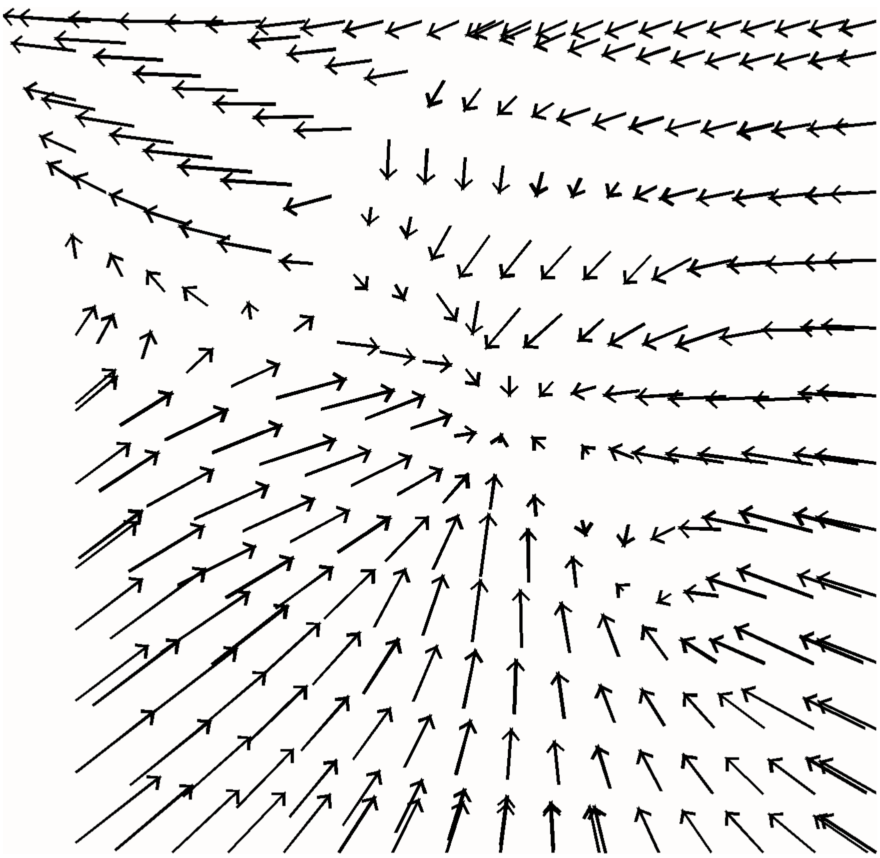


Figure 13. Interpolation of coast lines and borders (top) and of the intersections of the geographical grid (bottom).

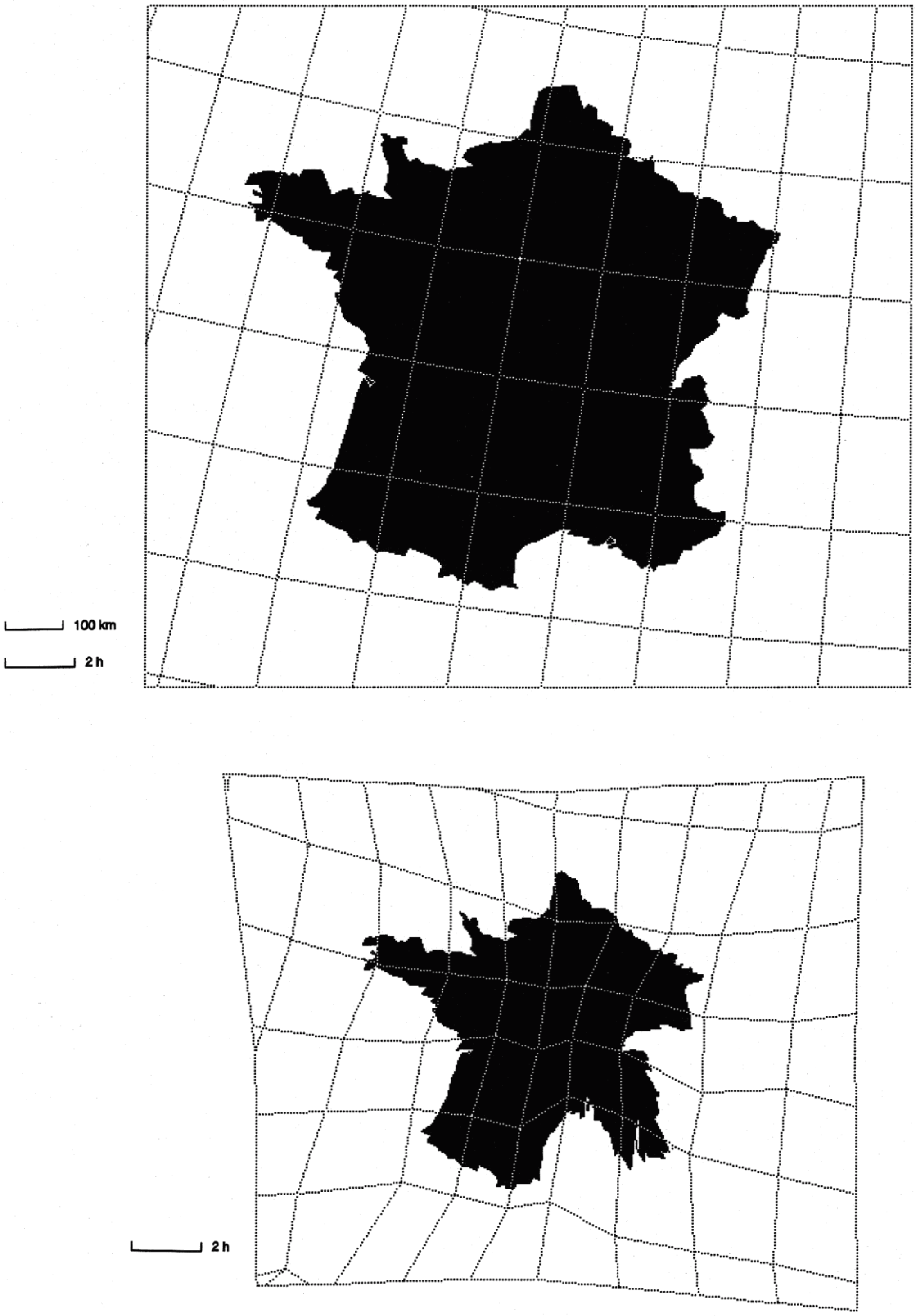


Figure 14. Time-space maps of the rail network in France, 60-km/h base map (top) and for journeys to Paris, 1988/89 (bottom).

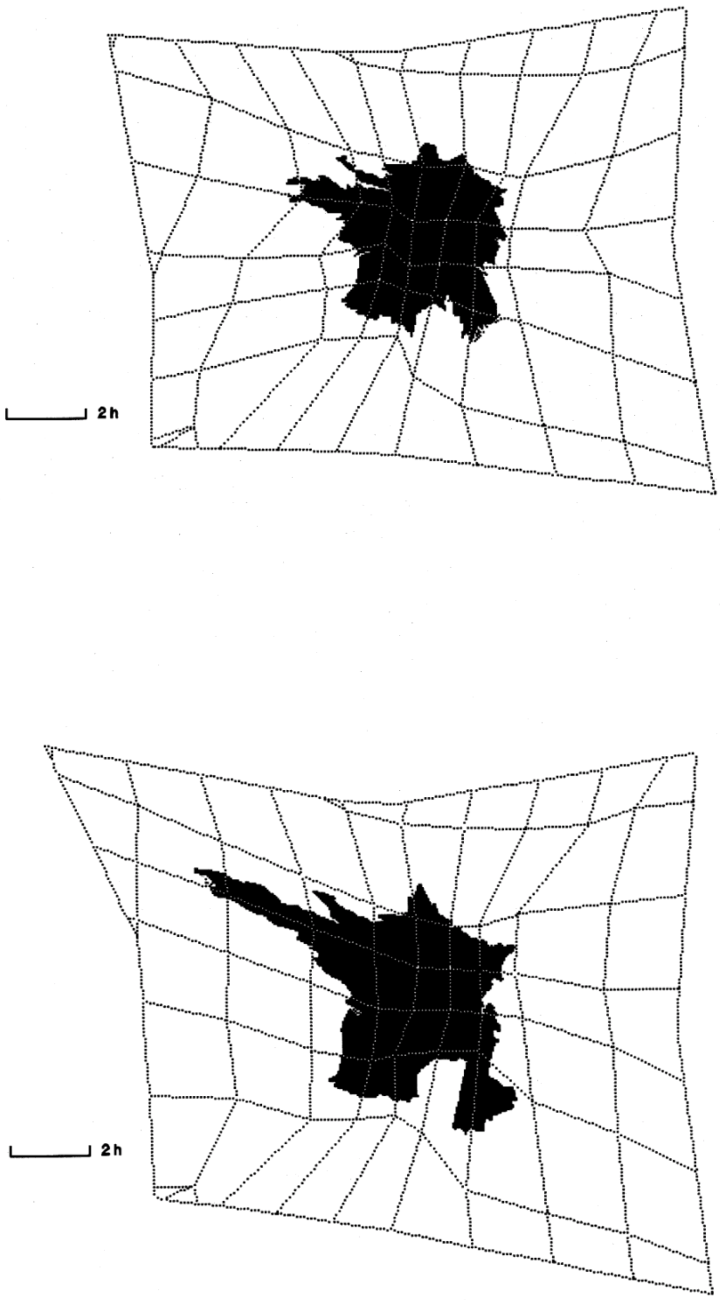


Figure 15. Time-space maps of the rail network in France for journeys to Paris, 2010 (top) and between regional centres, 2010 (bottom).

When the plans of the French government for the TGV (SNCF, 1991) will be implemented, the shrinking of the hexagon will be much more dramatic (Figure 15, top). This plan contains 4,700 km of high-speed lines, of which 700 km are currently in operation. After implementation of the scheme, all important regional centres will be reached from Paris in less than three hours, all borders in less than four hours. Return trips on the same day to London, Amsterdam, Cologne, Frankfurt, Munich, Zurich, Milan or Barcelona will become feasible with a maximum travel time of four and a half hours one way. The future TGV network, which originally was mainly oriented towards Paris, will also enable quick journeys between regional centres through the Paris bypass and TGV lines such as Rhin-Rhone (Mulhouse-Lyon) or Grand Sud (Bordeaux-Narbonne).

Figure 15 (bottom) presents a time-space map for France based on 28 such regional links. With the exception of parts of the Bretagne and the far southeast of France, all regional centres are linked to each other in less than five hours. This might lead to a reduction of the dominance of the French capital.

5.2 Germany

Figures 16 to 18 present the calibration network, the triangulation, the topographic map and three time-space maps for the German rail network. Origin node of the stepwise multidimensional scaling of these maps is Frankfurt.

Figure 16 (top) shows the base network of the German IC and ICE lines and the most important links to neighbouring countries. The lower part of the figure displays the triangulation of the calibration nodes.

Figure 17 (top) is the base map representing an air-line speed of 60 km/h. Figure 17 (bottom) is based on the rail travel times of 1985. It becomes visible that in 1985 train journeys in the GDR were much slower than in West Germany and that the links between East and West Germany were slowed down by long stops at the intra-German border. Due to the long travel times between Bavaria and the GDR the whole territory of the GDR is pushed towards the northeast.

Figure 18 (top) shows the current situation. The operation of the first ICE line between Hamburg and München since 1991 has led to a further shrinking of west Germany. The new Länder have come somewhat closer because of the elimination of stops at the former border and the restoration of east-west rail links. However, the rail network in the former GDR has not yet been accelerated so that the time-space disparity between the western and eastern parts of the country has become even more pronounced.

This will change when, as assumed in Figure 18 (bottom), the planned rail improvements will be implemented in the next century. Then rail speeds in east and west Germany will be equal so that the time-space map of Germany will again look like the base map, though much smaller.

It is interesting to note that the French time-space maps (Figure 14, bottom, and Figure 15) are shrinking more than their German counterparts. This indicates that the German railways are slower than the French railways and that this difference will continue to exist in the next century.

The time-space maps of Figures 17 and 18 can also be regarded as visualisation of a fusion of two time regimes (Stiens, 1992; Baier, 1990). The wall not only separated the population of East Germany from the world, but at the same time protected a zone of relaxed time. West Germany, in contrast to this, was a zone of compressed time. By the transport projects 'German Unity' the new Länder are 'elevated' to the zone of compressed time.

5.3 Western Europe

Figures 19, 20 and 21 illustrate the impacts of infrastructure improvements in the road and rail networks on the time space of western Europe. Both networks were reduced to the base network of Figure 19 (top) used already in Figures 10 to 13. For this network travel times were collected from time tables and forecast for different points in time (ACT Consultants et al., 1992; Fayman et al, 1992). The following four infrastructure scenarios were considered:

- Road network 1991: The road network of the year 1991 is represented by the most important European motorway and ferry links.

- Road network 2010: Road improvements will occur primarily in France. The most important change is the opening of the Channel Tunnel in conjunction with the coastal motorway along the Dutch, Belgian and French coast.

- Rail network 1991: In 1991 the European high-speed rail network consists only of one link, the TGV between Paris and Lyon. All other parts of the network are operated at lower speeds.

- Rail network 2010: The rail network in 2010 will contain the high-speed rail links already in operation since 1991, the TGV Atlantique in France and the ICE Hamburg-Munich in Germany, and future links such as the TGV Nord, the TGV Mediterrané, the TGV Est and the new ICE links Cologne-Frankfurt and Berlin-Hamburg as well as links to and within Spain and Italy. The most important changes in the European rail network are the opening of the Channel Tunnel in 1994 and the direct high-speed rail links from Paris and Brussels to London.

The impacts of these four scenarios on the time space of western Europe are presented in Figures 20 and 21; Figure 19 (bottom) shows the base map as reference. The base map refers to an air-line speed of 60-km/h and has the same time scale as the following time-space maps.

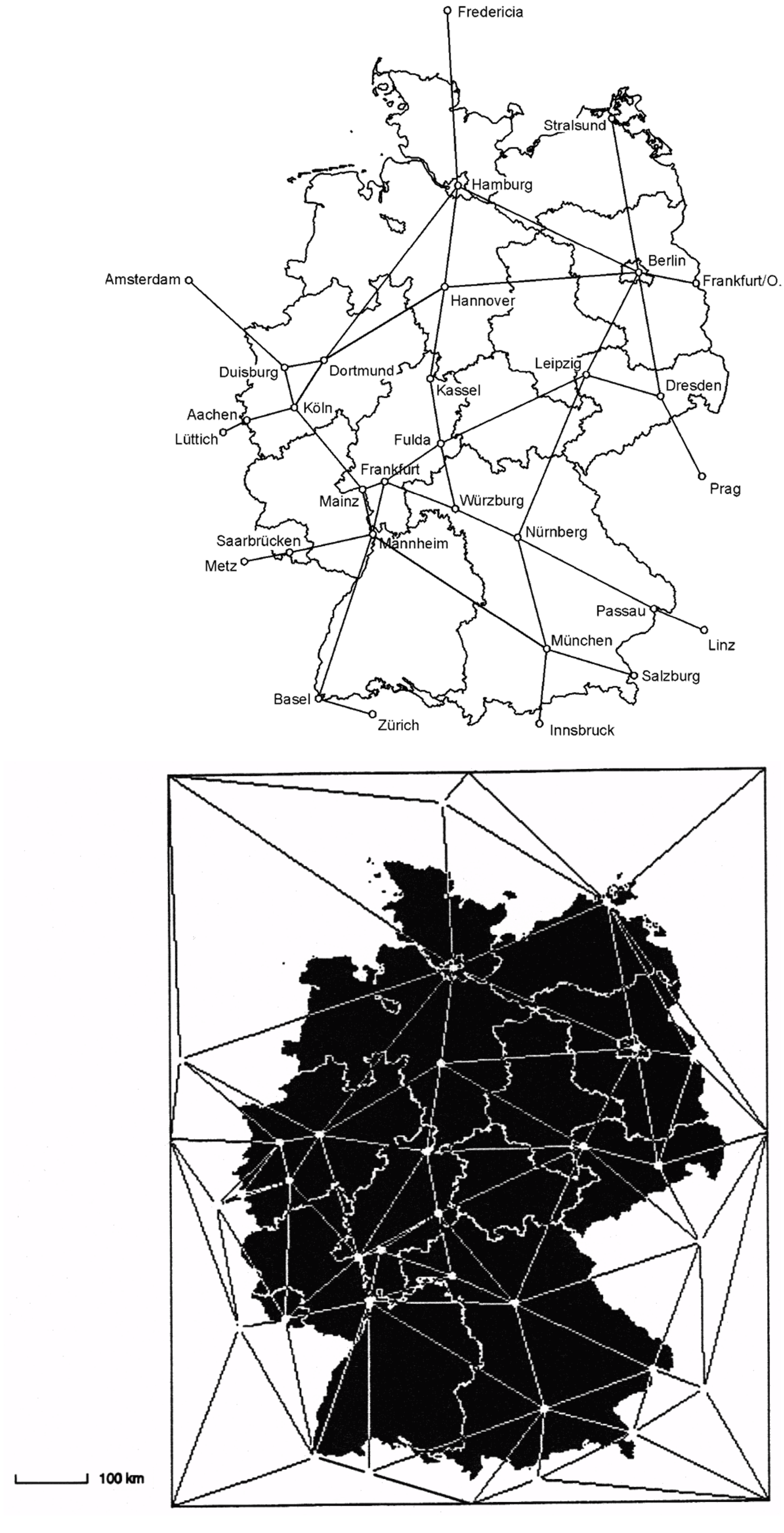


Figure 16. Calibration network (top) and triangulation (bottom) of the German rail network.

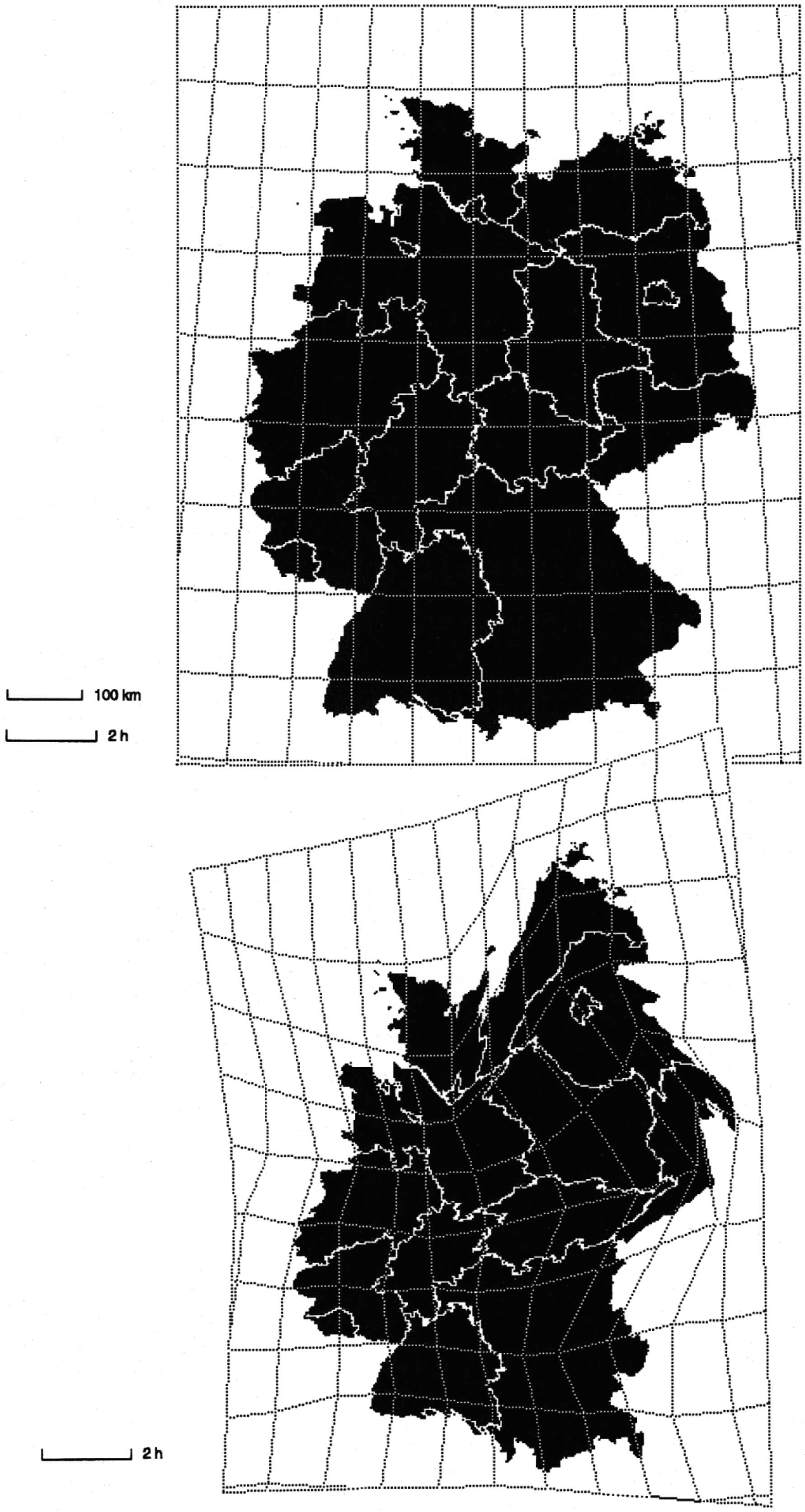


Figure 17. 60-km/h base map (top) and time-space map of the rail network in Germany, 1985 (bottom).

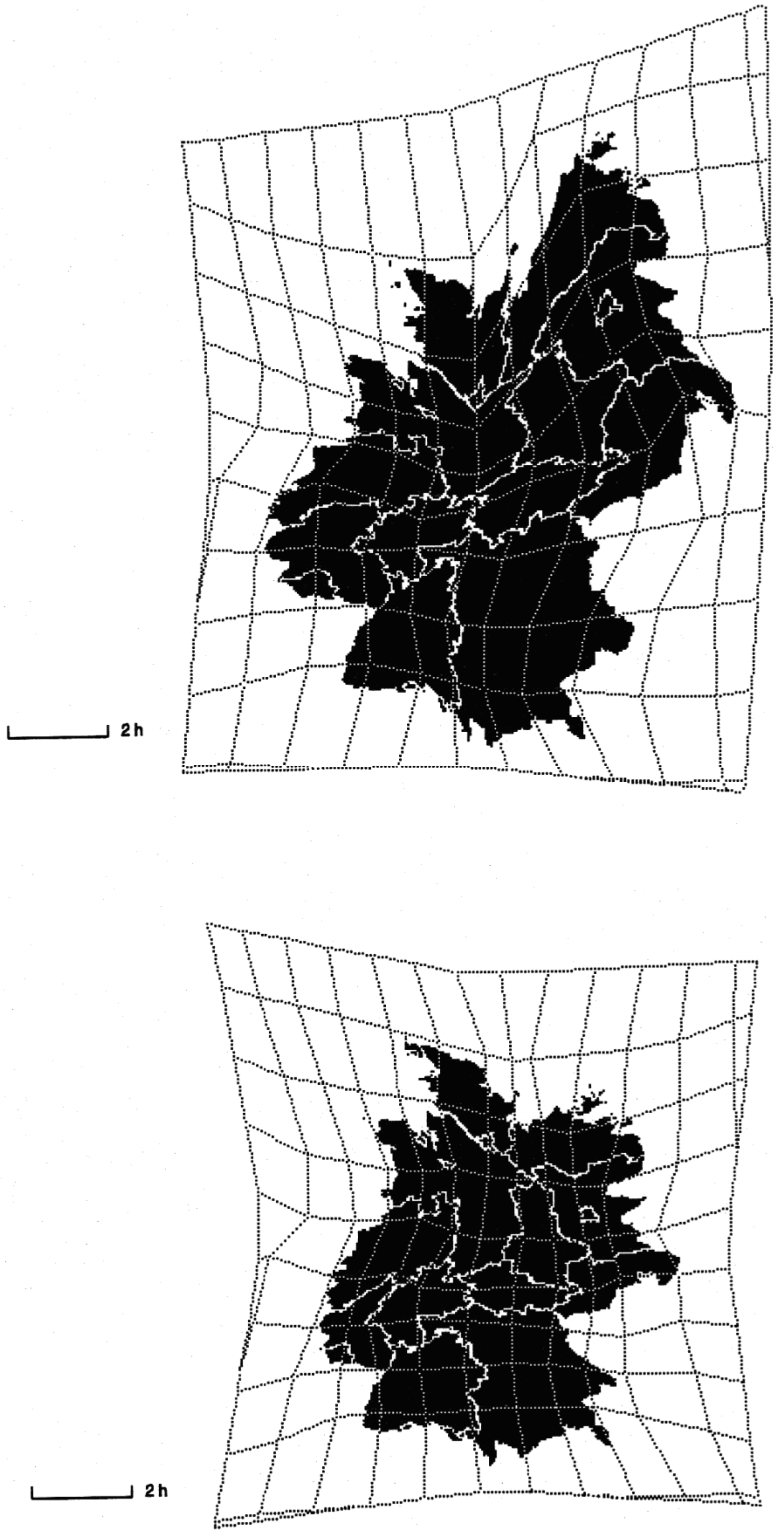
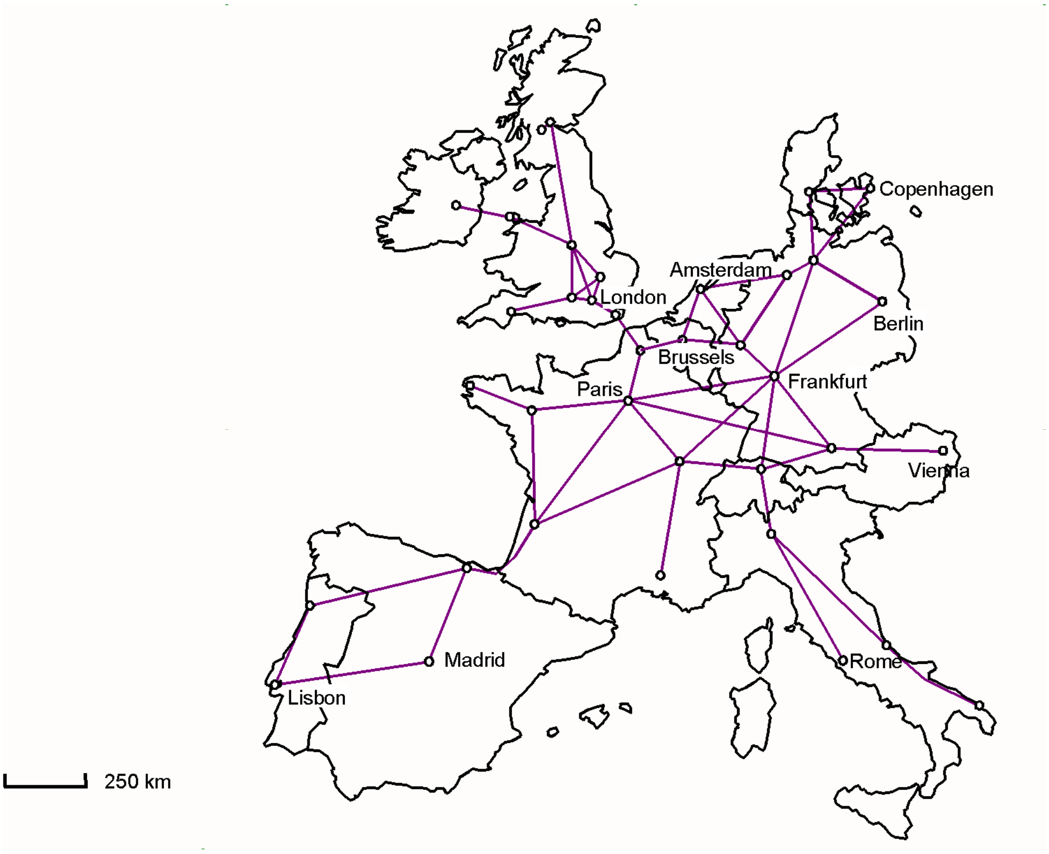


Figure 18. Time-space maps of the rail network in Germany, 1993 (top) and 2010 (bottom).



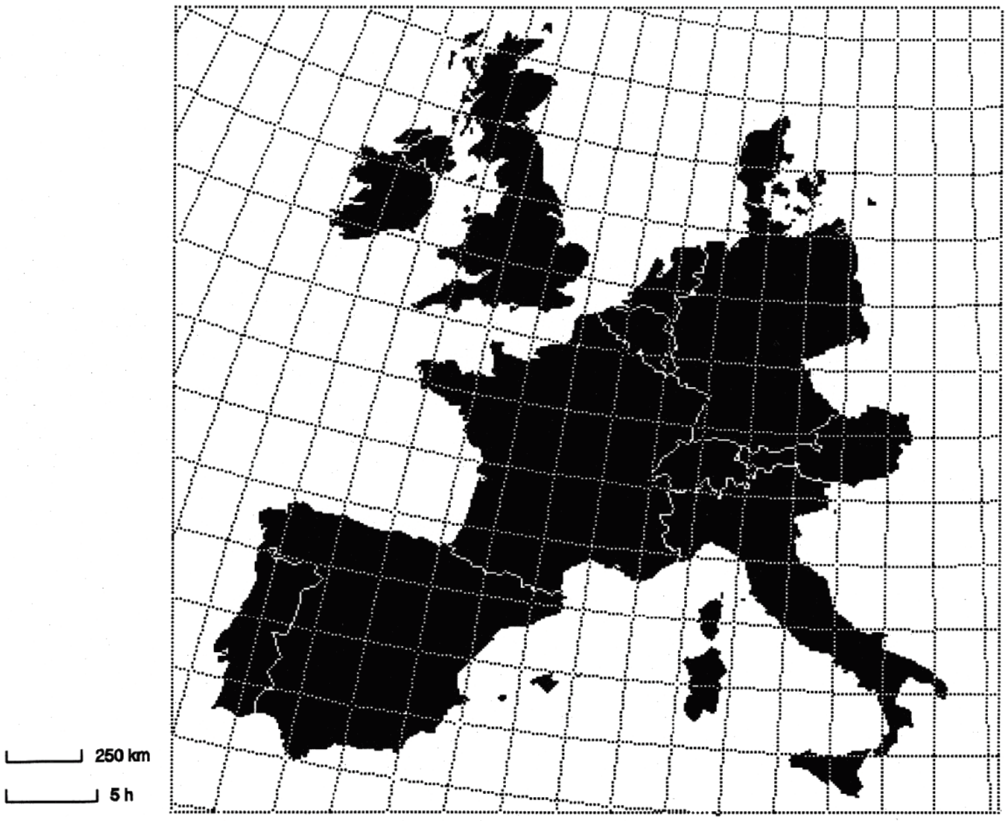


Figure 19. Calibration network (top) and 60-km/h base map (bottom) of western Europe.

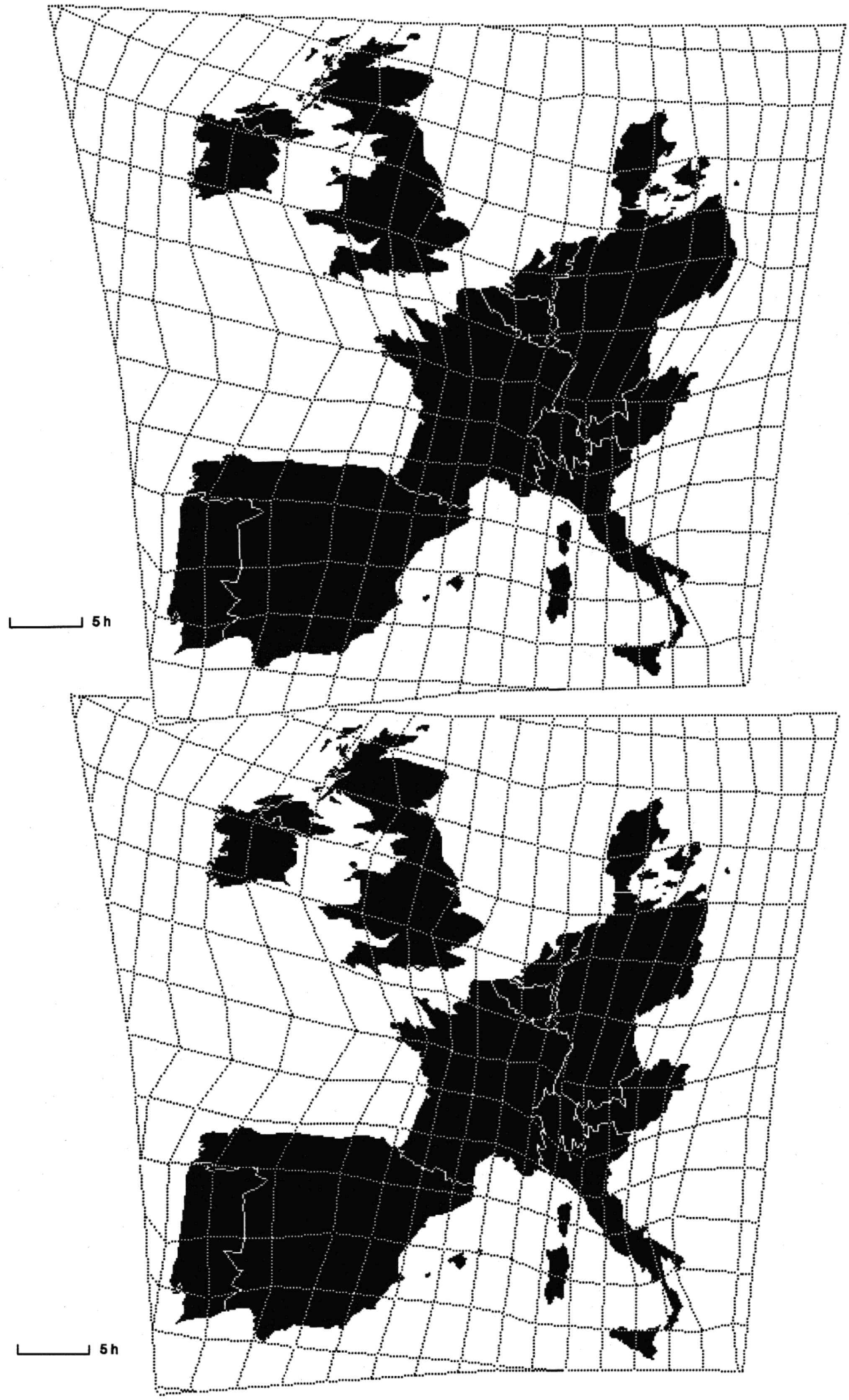


Figure 20. Time-space maps of the road network of western Europe, 1991 (top) and 2010 (bottom).

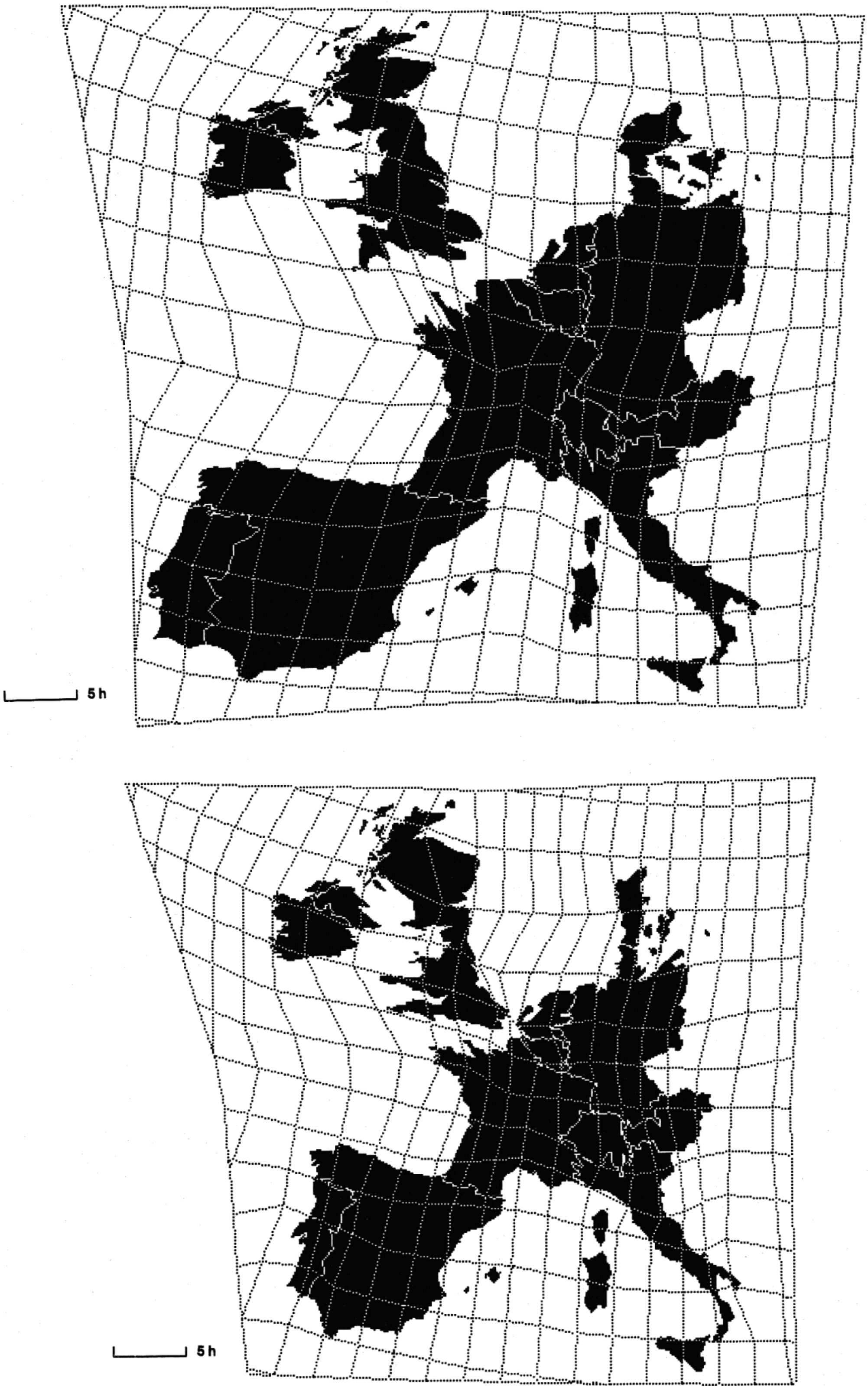


Figure 21. Time-space maps of the rail network in western Europe, 1991 (top) and 2010 (bottom).

The time-space maps based on travel times of the road network (Figure 20) show only a slight distortion compared with the base map. The shrinking of the continent is particularly visible in its core: Frankfurt, Munich and Vienna are more closely located to Brussels, Paris and London than in the base map. In contrast, the Iberian peninsula appears much larger than in the physical map because its road transport infrastructure is less developed than in central Europe. Great Britain and Ireland are pushed outwards due to the slow ferry links across the Channel and the Irish Sea.

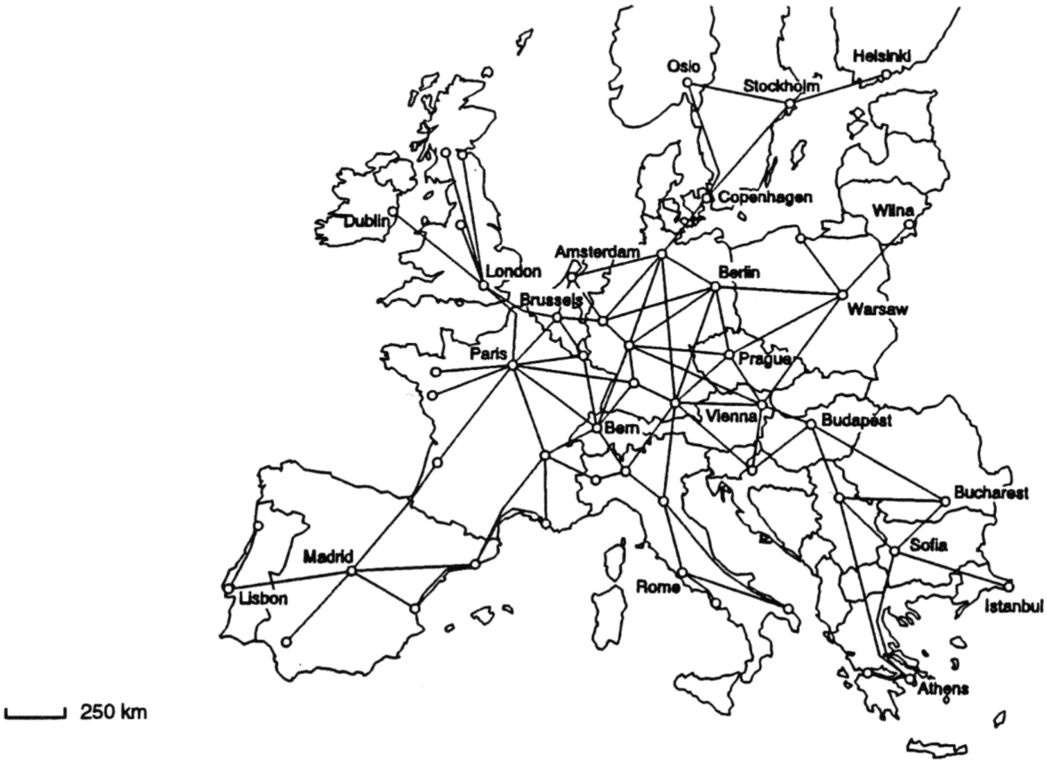
The difference between the two time-space maps for road transport is rather small. This is in line with the relatively small changes in the motorway network until 2010. Only France and the new German Länder are shrinking because most motorway improvements will occur there. The opening of the Channel Tunnel has only a slight effect on the travel times between the United Kingdom and Ireland and the European mainland. The reason is that the time saving for cars using the shuttle trains through the Tunnel is only small compared with current ferry services.

Figure 21 shows that the impacts of the new high-speed rail lines are much larger. Even in 1991 (Figure 21 top), France was contracted by the first TGV between Paris and Lyon, whereas Spain and Portugal appear larger and Great Britain and Ireland are pushed towards the periphery. The full 'space eating' effect of high-speed rail becomes visible with the implementation of the high-speed rail network by 2010 (Figure 21, bottom): The continent has been reduced to half its original size. The southern parts of England are pulled to the continent by the Channel Tunnel, whereas Ireland and the north of Scotland remain peripheral. The Alps remain a major barrier in the core of Europe because in this scenario the Alpine base tunnels are not assumed to be built.

5.4 Europe

Figures 22 and 23 show time-space maps of the whole of Europe (excluding Russia and the Ukraine). Figure 22 shows the calibration network and the 60-km/h base map. Compared with Figure 19, the network is extended to eastern and northern Europe, but is also different in western Europe.

Figure 23 shows time-space maps of the rail network in Europe today and in 2010 as envisaged by the International Union of Railways (UIC, 1992). It becomes obvious that the peripheral location of Ireland in western Europe (see Figure 21) is marginal if eastern Europe is included. The poor quality of the rail network there leads to slow speeds and a large representation on the time-space map. This is particularly true for south-east Europe. In 2010 (if the rail network envisaged by the UIC exists by then) the continent will have shrunk in time space dramatically. However, its shape will become much more similar to the physical map.



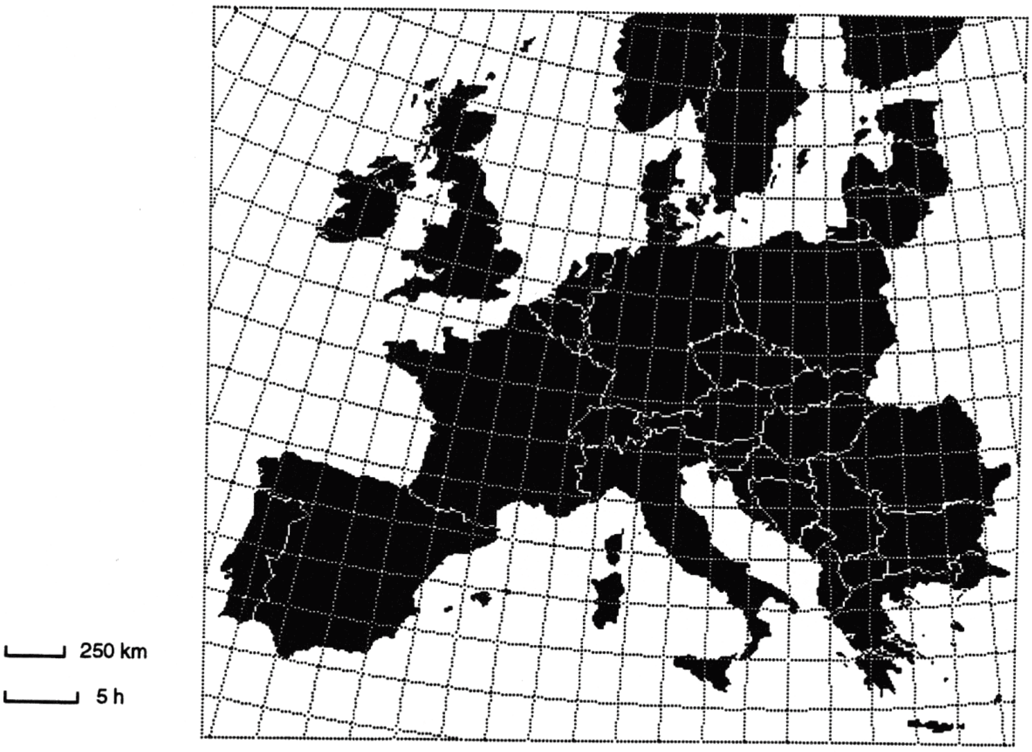
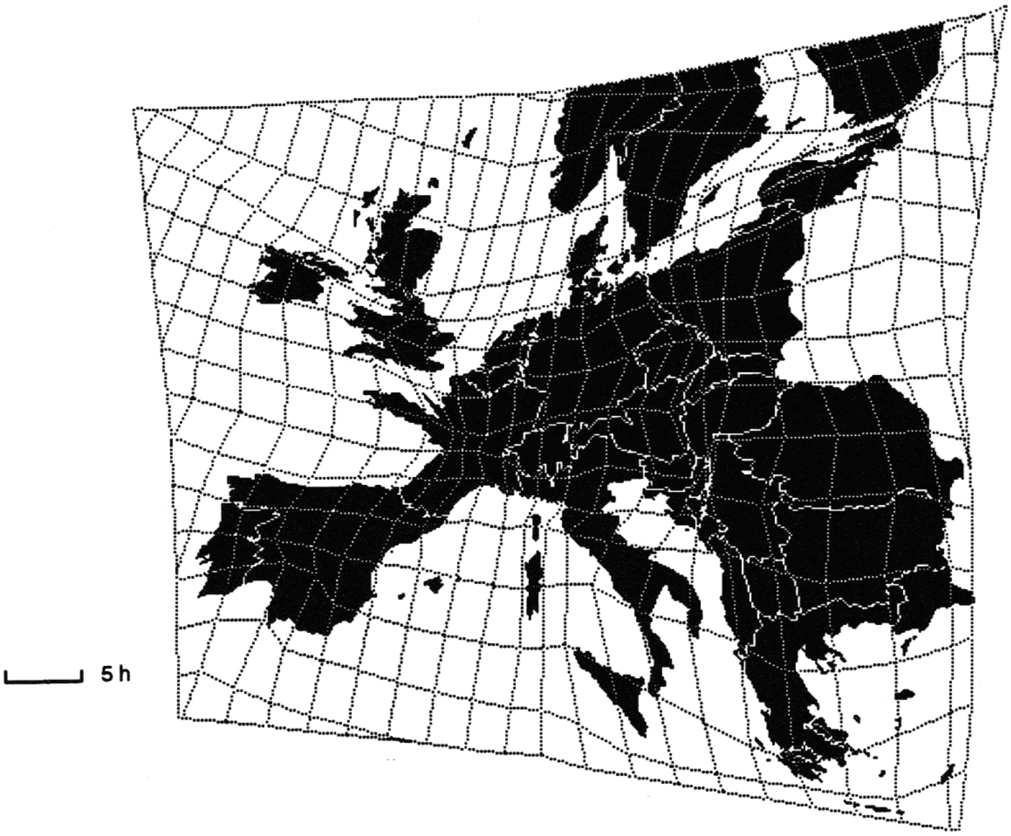


Figure 22. Calibration network (top) and 60-km/h base map (bottom) of Europe.



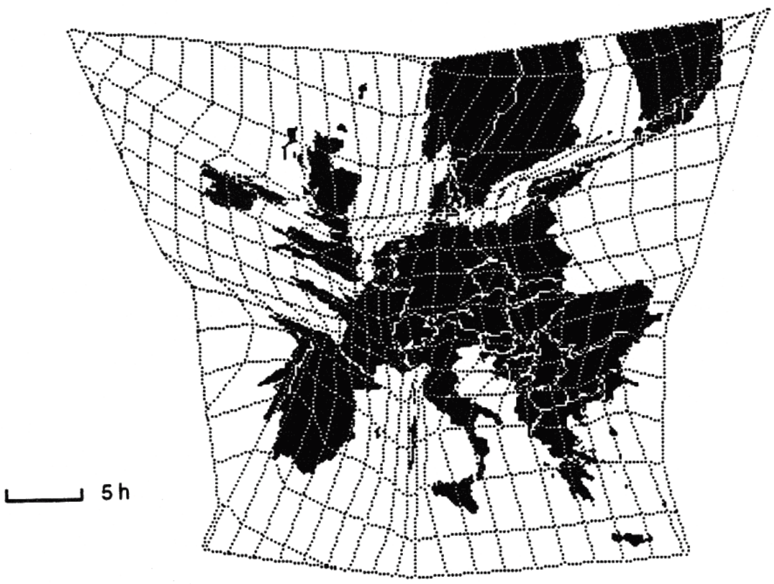


Figure 23. Time-space maps of the rail network in Europe, 1993 (top) and 2010 (bottom).

6. Conclusions

The method of creating time-space maps presented in this paper avoids the disadvantages of current approaches by stepwise multidimensional scaling and interpolation with triangulation. Using this method, time-space maps with a high correspondence between map distances and travel times, yet without undesirable distortions of topology can be produced. By the selection of the origin node the direction of the map distortion can be influenced.

However, because there is no single best solution for a time-space map, the appearance and plausibility of the map depends on the skills of the map editor, who, by adding or deleting links of the calibration network or selecting a different origin node, can influence or even manipulate the results. A comparison between the two time-space maps of Figure 15 and of the time-space maps of France with France within Europe in Figures 21 and 23 indicates that the appearance of time-space maps is significantly influenced by the underlying calibration network.

The visualisation of the effects of new high-speed links in time-space demonstrates the shrinking of the European continent or of countries like France or Germany. However, high-speed infrastructure connects only important cities, but not the space in between them. This generalisation hides that the regions in between might become new peripheralised zones, in which accessibility is decreasing in relative or even in absolute terms through the elimination of interim stops, when high-speed trains are introduced.

Time-space maps, applied with judiciousness and responsibility, are an interesting medium for the visualisation of spatial change. In a period in which new and faster transport modes fundamentally change the relationship between space and time, time-space maps can be used to gain a better understanding of the change processes at work and of the destruction of space by increasing spatial mobility and of its social and ecological costs.

7. Acknowledgements

The authors are grateful to Eihan Shimizu, University of Gifu, Japan, for the permission to use the computer programme for the creation of time-space maps by topological transformation, and to Marcial Echenique and Partners, Cambridge, for providing the travel time data for different transport networks in Europe from the common research project on the Channel Tunnel. The authors are also grateful to Meinhard Lemke, IRPUD, for the digitised base maps.

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9. Appendix: The TIMESPACE Programme

This appendix describes the computer programme TIMESPACE for the creation of time-space maps.

9.1 Programme Structure

The programme consists of a control module and three processing modules (see Figure 24). The three modules are described below.

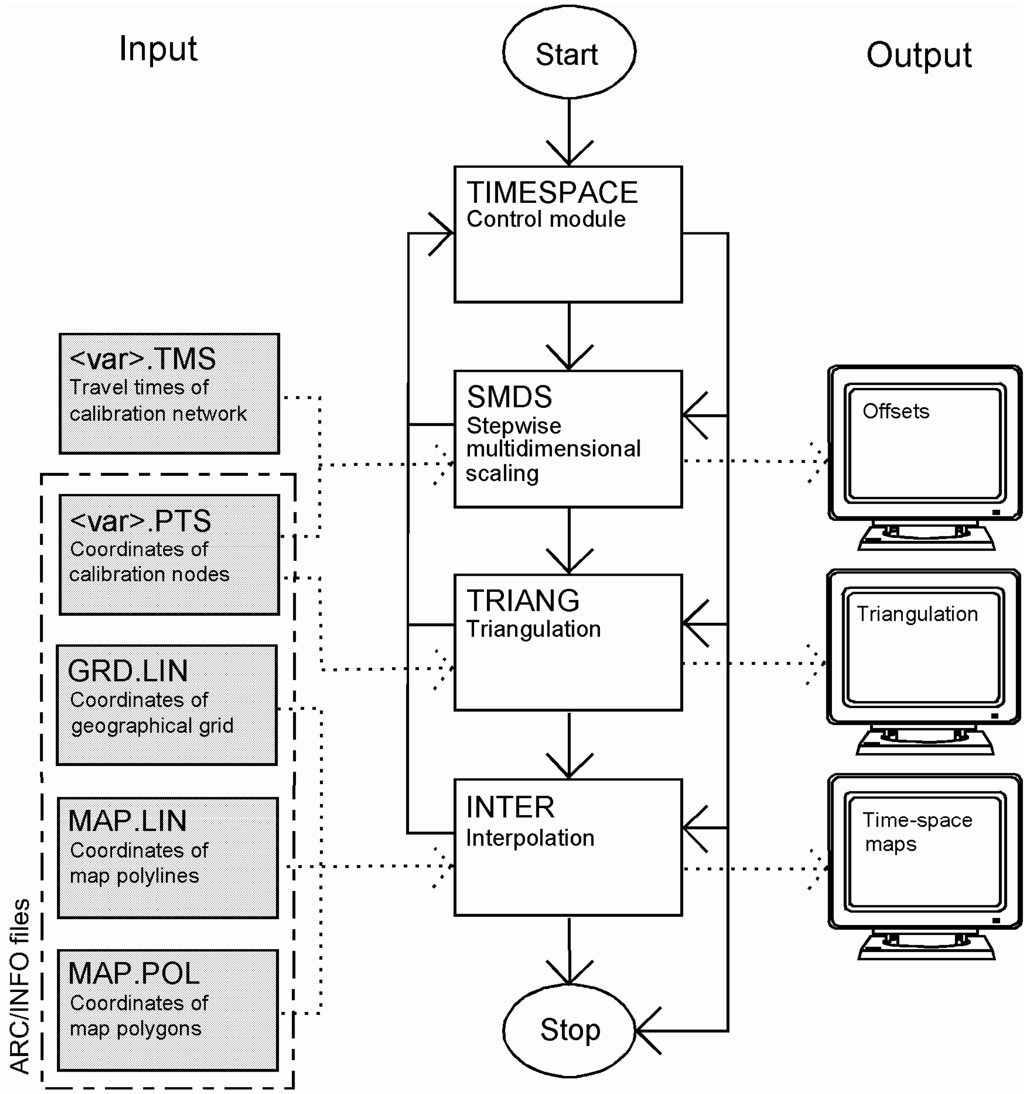

Figure 24. Structure of the TIMESPACE programme.

Control Module (TIMESPACE)

The control module connects between the three processing modules and permits their execution in any sequence. TIMESPACE is called from DOS by entering

timespace

After entering the programme, the user is prompted for the name of the study region <reg> (which is identical to the name of the subdirectory in which the input files for that region are stored (see below), and for the name of the infrastructure scenario <var> for which a time-space map is to be created. Next a menu appears on the screen from which the user can select one option:

Select one:
1 Stepwise MDS
2 Triangulation
3 Time-space map
4 1-3
5 Test origin node(s)
6 New scenario
7 Exit

Options 1, 2 and 3 call the three modules SMDS, TRIANG and INTER, respectively; option 4 causes their processing in sequence. Option 5 assists the user in selecting a suitable origin node. By choosing option 6, the user may change to another region or scenario, or both. Option 7 exits the program. After execution of each processing module, screen output is arrested until the user hits a key. The user may print a hard copy of the current display by entering 'p' (the printer must be in READY status) or return to the main menu by pressing any other key.

Stepwise multidimensional scaling (SMDS)

The module SMDS performs stepwise multidimensional scaling for a calibration network. The programme prompts the user for the following parameters:

sun	Units of space (in kilometres)
tun	Units of time (in minutes)
bas	Speed of base network (km/h)
nop	Optimisation level (0...3)
nod	Origin node of time-space map

The values for the five parameters selected by the user are stored in a file \<path>\<reg>\DEFAULTS, where <path> is the path of the parent directory in which the programme and programme files are stored and <reg> is the name of the study region. If the default file is not present, it is created.

Stepwise multidimensional scaling starts with the origin node specified by the user. Alternatively, two or more calibration nodes are tested as origin nodes. The coordinates of the origin node remain unchanged. In the first round all nodes of the calibration network are processed which are connected with the origin node by a direct link. The X- und Y-coordinates of these nodes are the parameters to be optimised in the first round. The calibration network of the first round consists of all links between the origin node and these nodes and all links between them.

The SMDS procedure minimises the sum of differences between the distances between the nodes of the calibration network and the travel times between them by varying the X- and Y-coordinates of the calibration nodes. Mathematically this is done by an iterative gradient search in n-dimensional parameter space following Newton-Raphson, where n equals twice the number of calibration nodes. The iteration is terminated when no significant improvement of the objective function can be achieved. The stopping point is determined by the optimisation level specified by the user. Higher optimisation levels achieve lower levels of the objective function but require longer computation time. In some cases a lower optimisation level may be preferred to avoid undesirable distortions of the map topology.

After completion of the first round, the coordinates of the nodes of current calibration network are permanently fixed. The calibration nodes of the second round are all nodes which are directly connected with the nodes of the previous round. The calibration network of the second round consists of all links between the nodes of the previous round and the new nodes and all links between these. Before entering the optimisation, the new calibration nodes are relocated so that their direction from the node of the previous round they are connected with and their distance from this node (in terms of travel time) remain unchanged.

After each iteration the new locations of the nodes are displayed on the screen superimposed over the original network. In addition, after the final round, the correlation coefficient between the time distances on the time-space map and the travel times as specified by the user and the final value of the objective function, i.e. the sum of differences between them, are displayed.

The old and new locations of the nodes of the calibration network are stored in a file for later use by module INTER (see below).

If option 5 was selected, the programme prompts the user for a list of origin nodes to be tested. For each of these nodes, the programme displays statistics such as correlation coefficient, objective function and the number of topological distortions, i.e. how many times the edges of the triangulation intersect if the calibration points are relocated to their time-space coordinates. If only one origin nodes was to be tested, the triangulation is displayed in time-space coordinates with the intersecting edges indicated in colour. The user may then select a final origin node for the map and return to the main menu.

The programme draws with each execution of SMDS a map of the calibration network, <var>.NET, in .WPG format. Nodes may carry names appended to their right. To label a node, its name is appended after its coordinates in file <var>.PTS, separated by one or more blanks.

Triangulation (TRIANG)

The module TRIANG performs the triangulation of the nodes of the calibration network. The programme uses ACM algorithm 626 (Preusser, 1984). In order to cover the entire map area, the four corner points of the map and the midpoints of each map border are treated as calibration nodes. The algorithm starts by sorting the $n(n\text{-}1)/2$ air-line distances between the calibration nodes by ascending distance. From these sorted distances it constructs the triangular mesh with the calibration points as corners and the minimum total length of triangle edges. The resulting triangulation is displayed on the screen. For each triangle the numbers and coordinates of its three corners are stored in a file for later use by module INTER.

Interpolation (INTER)

The module INTER calculates the time coordinates for all other linear map elements such as coast lines, national or regional boundaries or geographical grid lines by interpolation between the relocation vectors (offsets) of the nodes of the triangulation.

In a first step the programme determines the relocation vectors (offsets) of the corners of each triangle of the triangulation, i.e. the differences between their space and time coordinates in X- and Y-dimension. The four corners of the map and the midpoints of each map edge are given fictitious offsets as weighted averages of the corners of adjacent triangles.

For the construction of the time-space map, a point-in-polygon routine is used to determine for each point of the map elements to be processed the associated triangle of the triangulation. The offsets of that point are calculated as the weighted average of the offsets of the three corners of that triangle. The averaging is done for the X- and Y-direction separately. If the X- and Y-offsets of the three corners of the triangle are considered as 'elevations', the averaging consists in determining the elevation of the intersection between the triangle and a vertical line at the point in question. The resulting time-space map is displayed on the screen.

It is possible to draw selected nodes of the calibration network in the time-space map labelled with their names. To specify the nodes to be drawn, an asterisk is put in front of the names of the selected nodes in file <var>.PTS. The name will be printed to the right of the node in the time-space map.

9.2 Input Files

All input files for the TS programme are editable ASCII files, most of which can be automatically generated by the ARC/INFO geographic information system. The following input files are used:

\<path>\<reg>\<var>.PTS	Coordinates of calibration nodes
\<path>\<reg>\<var>.TMS	Travel times of calibration network
\<path>\<reg>\GRD.LIN	Coordinates of geographical grid

\<path>\<reg>\MAP.LIN	Coordinates of map polylines
\<path>\<reg>\MAP.POL	Coordinates of map polygons

where <reg> and <var> are defined as above. The string 'bas' for <var> indicates the base network.

The two files <var>.PTS and <var>.TMS contain the calibration network and are required for each scenario. The three files GRD.LIN, MAP.LIN and MAP.POL contain the map image to be displayed and are optional, but one of them must exist. The programmE detects which of them is present.

ARC/INFO Files

Files with extensions .PTS, .LIN and .POL have the format of ARC/INFO export files for point, line and polygon coordinates. This makes it possible to use maps digitised with ARC/INFO without reformatting. Geographical grids, roads, rivers etc. are entered as polylines in GRD.LIN or MAP.LIN. Polylines in GRD.LIN are displayed as broken lines, polylines in MAP.LIN as solid lines. Boundaries may be entered either as polylines in MAP.LIN or as polygons in MAP.POL, but only in the latter case are the areas they contain shaded. Polylines over polygons are shown in inverse colour.

The file with the extension .PTS contains one record for each node of the calibration network with the following format:

Column	Format	Contents
1-10	I10	Number of calibration node
11-25	F18.6	X-coordinate of calibration node
26-40	F18.6	Y-coordinate of calibration node

where the format key 'F18.0' indicates a number of up to 18 digits with or without decimal point and any number of digits behind the decimal point. After the record with the coordinates of the last node there is a record with the string 'END' in columns 1-3.

The files with extension .LIN and .POL have the following format: For each polyline (polygon) of the map the file contains one block of records:

Record	Format	Contents
1	I10	Line type (ignored)
2	2F18.6	X- and Y-coordinates of first point
3	2F18.6	X- and Y-coordinates of second point
...	...	...
n+1	2F18.6	X- and Y-coordinates of n-th point
n+2	'END'	End mark

where n is the number of points of the polyline (polygon perimeter). After the last block of records there is another 'END' record. If the file has the .POL extension and the coordinates of the first and last point of the polygon perimeter are not identical, TS connects these two points by a line.

The coordinates of the .PTS, .LIN and .POL files may be entered in any units of distance (e.g. km, m, 1000 km, etc.), but not in geographical coordinates (longitude and latitude). All files of one application must use the same unit of distance.

If there exists a boundary file with polylines in .LIN format, it may be converted into a polygon file by the utility programme LIN2POL. LIN2POL is invoked by

lin2pol <boundary-file> \time\<reg>\map.pol

LIN2POL identifies polygons only if it finds recursive sequences of polylines with exactly matching end coordinates.

Scenario-Specific Files

Several files <var>.PTS and <var>.TMS for different infrastructure scenarios, i.e. for different strings <var>, can exist at the same time in subdirectory \<path>\<reg>. The .PTS files with coordinates of the nodes of the calibration network are ARC/INFO export files (see above) or are created from ARC/INFO export files by adding or deleting nodes using an editor.

The .TMS files are generally created using an editor. For each link of the calibration network the file contains one record with the following format:

Column	Format	Contents
1-10	I10	Number of from-node
11-20	I10	Number of to-node
21-35	F18.0	Travel time of link

BAS.TMS does not need to contain travel times; if they are present, they are ignored.

Programme Limits

The present version of the programme can accommodate calibration networks with up to 2,000 nodes and 3,000 links. At each iteration, the SMDS module can process a ring-shaped partial network of up to 500 nodes. The triangulation of the calibration network may contain up to 4,000 triangles. The map data may consist of any number of polygons with up to 2,000 vertices each and any number of polylines with up to 2,000 vertices each and up to 20,000 vertices overall.

9.3 Output Files

Each generated time-space map is automatically written to an output file in WordPerfect graphics (.WPG) format named \<path>\<reg>\<var>.WPG. The map can be scaled and printed with WordPerfect 5.1, 6.0 or 7.0 and/or modified or enhanced with DrawPerfect 1.1 or WordPerfect Presentations 2.0 or 3.0 or any graphics programme accepting graphics files in .WPG format.

9.4 Installation

The TIMESPACE programme requires an IBM-compatible PC with VGA monitor. For screen hard copies a HP-compatible laser printer is required. For printing the file \<path>\<reg>\<var>.WPG, any laser printer for which a driver for WordPerfect or WordPerfect Presentations is available may be used.

The TIMESPACE programme and its modules were written in Fortran 77 and compiled with the WATCOM 32-bit Fortran compiler. The programme is executed under MS-DOS using the DOS extender DOS4GW.EXE by Tenberry. It uses graphics commands of a GKS application layer (Wegener and Spiekermann, 1989) adapted to the graphics library of the WATCOM 32-bit Fortran compiler.

The programme and test data are contained in directory \<path>, where <path> is a user-defined directory path. There are two ways to install the programme: either from diskette or via e-mail.

Installation from Diskette

To install the programme from diskette, follow the steps below:

(1) Insert the diskette in drive a: of your computer

(2) Go to the root directory of your computer by typing

**cd **

(3) Start the installation programme on the diskette by typing

a:install

Installation via E-mail

If you have received the TIMESPACE programme and test data via e-mail, follow the steps below:

(1) Create a new directory on your computer with the path <path> and go to that directory by typing

cd \<path>

(2) Copy the file TS.UUE you received via e-mail to directory <path> and decode the file by typing

uudecode timespace

(3) Inflate subdirectories and files of the time-space programme by typing

pkunzip -d timespace

9.5 Execution

Work with TIMESPACE starts by moving to directory \<path>\PROG by typing

cd \<path>\prog

and entering

timespace

All input and output files for study region <reg> are contained in directory \<path>\<reg>. For a new study region, a new directory \<path>\<reg> has to be created.

Source Code

The compiled version of the TIMESPACE programme is contained in directory \<path>\PROG. The directory also contains the source code of TIMESPACE. If the programme is to be modified and recompiled, numerous external references will be unresolved.

Test Files

The TIMESPACE programme is accompanied by test data of three regions: western Europe, France and Germany. Time-space maps of these three regions can be produced by using the following parameters

Directory	Region	sun	tun	bas	nop		nod
EUROWEST	Western Europe	132	1	60	1	(Paris)	10
FRANCE	France	132	1	60	1	(Paris)	1
GERMANY	Germany	.001	1	60	1	(Frankfurt)	20

The above parameters are contained in file \<path>\<reg>\DEFAULTS:

9.6 References

Preusser, A. (1984): ALGORITHM 626. TRICP: a contour plot program for triangular meshes. ACM Transactions on Mathematical Software 10, 473-475.

Wegener, M., Spiekermann, K. (1989): Mikrocomputergraphik. Eine Unterprogrammsammlung für FORTRAN und GKS. Berlin/Heidelberg/New York/Tokyo: Springer Verlag.