

MAPPING ON THE FLY: THE INTEGRATION OF USER-DEFINED MAP PROJECTION WITHIN DIFFERENT EXISTING PROJECTIONS IN AN INTERNATIONAL CONTEXT

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Abstract

The potentiality of digital era allows to face and definitely solve the map-related problems in designing great infrastructures (like railways, highways etc.) crossing different countries where different geodetic datums and different map projections are used. Designers require a projection able to minimize linear deformation and to make it possible direct use of field observations, avoiding post-processing of data. Regional mapping authorities, responsible for GIS managing, require that information are geocoded using official datum and projection. Digital techniques allow “mapping on the fly”, i.e. the ultimate solution for projection problems between cartographers and designer, making transformations easy and fast: L2G and G2L (local to global and global to local) datum and projection transformations become user-friendly. User can easily pass from a regional GIS to a local “ad hoc” system, useful for designing and construction, then come back to update regional data set and transform the data in the bordering system.

INTRODUCTION

The paper illustrates the solution offered by digital technology to the different approaches that designers and cartographers show in the two fundamental phases of the realization of a civil infrastructure, i.e. the design and the construction.

The design is firstly developed on a base map, transferring on it the geometric constraints that the work will have to respect on the ground. Secondly, an appropriate surveying is performed and a special map is set up, on which geometric details of the future infrastructure are put. The construction is then carried out transferring on the ground, by geodetic methods, the geometric properties and the characteristics extracted from the map. In both phases input data should be pre-processed to take into account the cartographic distortions.

In the operational context, it often happens that the designer neglects the reduction of the constraints to the reference surface and to the cartographic plane; moreover, during the phase of construction, people involved often neglect the reduction of the geometric information extracted from the map to the physical surface on which they are operating. Such simplifications are acceptable only if the cartographic projection has been developed ad hoc, so that the differences between the used data and those ones theoretically correct are negligible.

In addition to these common problems, when the work involves different countries characterized by different map projection and different datums, it is necessary to define a strategy to integrate different requirements in an user-defined solution. From one hand, designers require a projection able to minimize the linear deformations and to make it possible a direct use of field measurements, avoiding geodetic reductions and post-processing of data. On the other hand, regional mapping authorities, responsible for GIS managing and updating, requires that information are geocoded with reference to their official datum and projection. The surveying process during designing (at the beginning) and construction (final phase) need to be revisited taking into account GPS potentiality and global system opportunities, but usually local systems are requested and still used.

DATA PROCESSING

For better understanding the problems involved in data processing, the treatment of the distances is exemplary: in fact three typologies of distances exist and should be considered. They are:

1. spatial distance between ground points, which is observed and reduced to the horizon on the base of the gradient; it should be consistent with the project requirements (fig. 1);
2. ellipsoidal distance, that is the length of the arc of geodesic between the projection of the points from the physical surface to the reference surface (i.e. the ellipsoid);
3. cartographic distance, i.e. geometric distance between the projection of the points from the reference surface to the map plane; it depends of course on the chosen map projection.

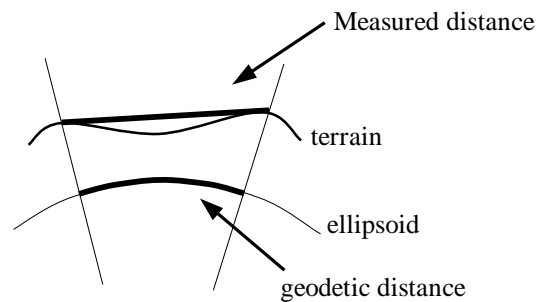


Figure 1: spatial distance and geodesic line

The spatial distance depends on the morphology and the characteristics of the work and cannot be modified. The difference between the spatial distance and the ellipsoidal distance depends on the mean ellipsoidal height of the points and can be reduced by an appropriate choice of the local reference surface, i.e. an ellipsoid of such size to approximate in the best way the physical surface.

The difference between the ellipsoidal distance and the cartographic distance depends on the linear deformation generated by the cartographic projection and can be reduced by an adequate choice of the projection itself as well as by an appropriate definition of the application conditions.

In the case of a project crossing the border between two countries, the problem may be complicated (and often it is) by the existence of two different national geodetic datums and two different national cartographic systems. Let's call them R1GD (Region 1 Geodetic Datum) for the former country, R2D for the latter one, R1CS (Region 1 Cartographic System) and R2CS respectively. As far as the geodetic datums are concerned, we have to consider for each national realization a Horizontal Datum and a Vertical Datum, so we have R1HD, R1VD, R2HD and R2VD. In R1HD and R1VD the geodetic networks of levelling, triangulation and GPS of the former country are defined, while the networks belonging to the second country are defined in R2HD and R2VD.

In the first phase of project analysis, jointly carried out by designers and cartographers, the fundamental common requirement consists in ensuring:

- the highest practicable degree of precision, accuracy and reliability of geometric data;
- an easy updating process of the data
- an easy integration with data coming from different sources.

To satisfy these requirements the strategy consists in defining a local geodetic reference system, split in a Horizontal Datum and a Vertical Datum (LHD and LVD) and a local cartographic system (LCS), suitable for the specific application.

Taking into account that GPS is the most common survey technique in use, the local geodetic system is of course a special realization of the WGS84; R1HD and R2HD could be (and often are) national realizations of the same system, but in some cases they could be earlier national datums still in use. As far as the vertical data are concerned, generally we have a geoidal undulation model per each country, with different accuracy level and two national levelling networks, based on different m.s.l. datums and playing the role of realization of the vertical datum. Even if a connection between the two levelling networks physically exists, the observed data are often relevant to largely different epochs; thus no one of the nets could play the role of base vertical net, but the monumentation.

In conclusion, the local systems have to play the double role of:

- high accurate and reliable frame for the specific task of designing and building up the infrastructure;
- effective and reliable link between the different national (regional) systems.

To this goal, unambiguous transformations between local and regional systems should be modelled in order to set up a specific software able to treat the relationships between LHD, LVD, LCS and the correspondent R(i)HD, R(i)VD, R(i)CS, for $i = 1, 2$.

Nowadays it is possible taking correctly into account the designer needs as well as the mathematical aspects of cartographic data: geometric constraints on the field could be adequately transferred on the map and vice versa. Any computation involved by the transformation procedure can be performed using CartLabOtF software developed by the authors. It can treat the main datums used in Europe, as well as the associated cartographic systems and can easily integrate any other datum or map projection.

LOCAL GEODETIC DATUM

As stated earlier, the local horizontal geodetic datum is generally a special realization of the WGS84 system. In fact no doubt that any survey carried out at present takes profit of the incomparable advantages of GPS technology. As far as the vertical datum is concerned, we need to make use of orthometric or normal heights; in both case a reliable model of geoidal undulation is needed, to transform the ellipsoidal height derived by GPS observations into physically meaningful data.

The necessary surveys oriented to the production of a detailed and updated digital map are thus carried out by GPS and spirit levelling observation linking the GPS network to the levelling network. In performing this last operation, special attention should be paid to the selection of the fixed height benchmark, chosen as local origin for the orthometric or normal heights. The basic assumption is that the local levelling network should be as consistent as possible with the regional networks, but it has firstly to ensure the highest internal consistency and the maximum degree of suitability for the project. In case the regional networks run in proximity of the interested area, or at least one of them does it, the local origin could be coincident with one existing benchmark, provided it can ensure sufficient stability for the future. A detailed and deep analysis of the geological history and characteristic of the site could help the geodesists, as well as the analysis of available repeated observations made in the past.

LOCAL CARTOGRAPHIC SYSTEM

All map projection methods cause some distortion and various methods are selected to best fit the shape of the specific area to be mapped and to minimize the effects of particular distortions. Locations on the earth are represented by meridians of longitude, λ , and parallels of latitude, φ . On the map these are represented by scaled linear distances, X and Y, using the dimension of the Earth ellipsoid and selected criteria that the specific map projection must satisfy (the so-called application conditions). The map coordinates are obtained from transformation equations taking the general functional form of:

$$X = f_x(\lambda, \varphi)$$

$$Y = f_y(\lambda, \varphi)$$

Nowadays, the most common family of map projection is that one of conformal projections. Conformal or orthomorphic projection results in a map showing the correct angle between any pair of short intersecting lines, thus making small areas appearing correct in shape. Among them our attention has been focused on the Lambert conic conformal projection (LCP) and on the transverse Mercator projection (TMP). The fundamental application condition is the scale factor on the central parallel for the former one and the scale factor on the central meridian for the latter one; it could be 1 (in the so-called tangent mode), less than 1 (secant mode) or even greater than 1 (external mode in the geometric interpretation). In some cases oblique Mercator projection (OMP) could be of interest.

In order to select the most suitable map projection for the project and the subsequent operation, the attention should be concentrated on the following points:

- Analysis of the shape of the area

For areas with greater extent North-South than East-West, we know that the most suitable projection is the TMP, while in the opposite case (i.e. greater extent East-West than North-South) the LCP is preferable. Figure 2 shows a typical case for which the conic conformal projection is the most correct choice.

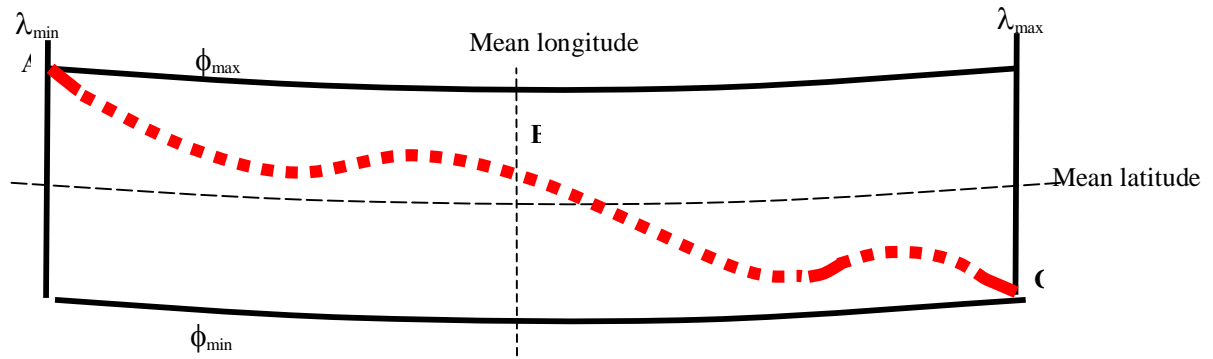


Figure 2: planimetric layout

- Analysis of the topography of the area

From the altimetry point of view, the topography of the interested area plays an important role, increasing with the mean ellipsoidal height along the profile. When this value is of the order of many hundreds or thousands of metres, the difference between observed distance (on the field) and ellipsoidal distance become significant and not negligible. Such differences should be algebraically added to the distortions produced by the map projection when one makes use of cartographic distances. As above said, we have to take into account the three categories of distance involved, i.e. the observed ones (corrected for the gradient), the geodesic lines and the cartographic distances. They are theoretically different and only the last one can be modified according to the application conditions in order to minimize the difference with reference to the geodesic line. Figure 3 shows a study case of variable profile for which we have to consider that a height-related deformation of approximately 100 ppm occurs every 600 m of ellipsoidal height.

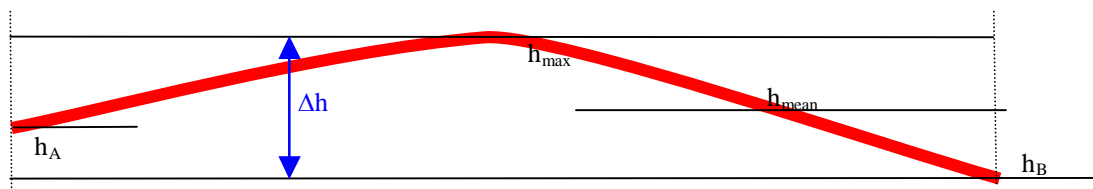


Figure 3: vertical profile along the path - (ellipsoidal heights)

- Linear deformations due to the projection and topography-related deformations

When the mean ellipsoidal height and its variation is not negligible, we can introduce a proper expanding factor for the coordinates, that is equivalent to a scale factor greater than 1 on the central meridian of longitude or on the central parallel of latitude. In fact in such a case the ellipsoidal distance is significantly shorter than the spatial distance observed on the ground (and corrected for the slope).

The resultant constant scale variation puts the cartographic distances in a reasonable agreement with the observed ones. This is the reason of setting up a local cartographic system, allowing to balance as much as possible the height-related deformations and making negligible the remaining distortions.

Obviously the projection-related distortions cannot be eliminated by definition, as they vary point by point, but we can minimize them in the local cartographic system. As far as the relationship with the official cartographic systems is concerned, the flexibility of digital techniques as well as the reversibility of map projection equations make it easy and fast a projection transformation: L2R and R2L (local to regional and regional to local) transformations become user-friendly not only between geodetic datums, but also between cartographic systems. User can easily pass from a national GIS to a local “ad hoc” system, useful for designing and construction, then come back to update national data set and transform data in another bordering system.

- Computation and analysis of the residual distortions for different application conditions

In order to examine the residual linear distortions and their variation as function of the chosen scale factor on the central line (parallel of latitude or meridian of longitude), a simulation software has been produced, which accept as input the latitude or longitude (for LCP or TMP respectively) of a test parallel or meridian and the relevant scale factor. As output the software provides, for each critical point of the area of interest (e.g. the points A, B and C of fig. 2), the height-related distortion, the projection-related distortion and the residual distortion (see Tab. 1 as generic output example and table 2 as a real case of study applied to LCP). The last column value represents the final difference, expressed in ppm,

between the cartographic distances and the observed ones (corrected for the slope), i.e. what we would like to minimize. Finally the software allows to find the “optimum” for the specific problem.

Position (fig. 2)	Ellipsoidal heights (fig. 3)	HLD Linear deformations due to heights [ppm]	PLD Linear deformations due to projection [ppm]	RLD residual linear deformations [ppm] = PLD-HLD
A	h_A	HLD_A	PLD_A	RLD_A
B	h_B	HLD_B	PLD_B	RLD_B
C	h_C	HLD_C	PLD_C	RLD_C

Table 1: linear deformations

Position (fig. 2)	Ellipsoidal heights (fig. 3) [m]	HLD Linear deformations due to heights [ppm]	PLD Linear deformations due to projection [ppm]	RLD residual linear deformations [ppm] = PLD-HLD
A	+ 700	+110	+ 125	+ 15
B	+ 800	+ 126	+ 99	- 27
C	+ 400	+63	+ 76	+1 3

Table 2: linear deformations in a study case

- Application conditions

The application conditions to be defined for the local cartographic system (LCS) are shown in the Tab. 3. The first column lists the conditions relevant to the Transverse Mercator projection and the second column displays the equivalent conditions for the Lambert conic conformal projection.

Transverse Mercator Projection	Conic Conformal Projection
Mode: tangent/secant/external	Mode: tangent/secant/external
Longitude range	Latitude range
Longitude origin	Latitude origin
Scale factor on central meridian	Scale factor on central parallel
False East	False East
False North	False North

Table 3: application conditions of the LCS

DATUM TRASFORMATION AND COORDINATE TRASFORMATION

On the base of what has been illustrated, we can now list the geodetic datums of interest, as well as the associated cartographic systems.

The figure 4 shows the systems that are involved and the transformations that have been implemented in the CartLabOtF software for horizontal datums and for cartographic systems.

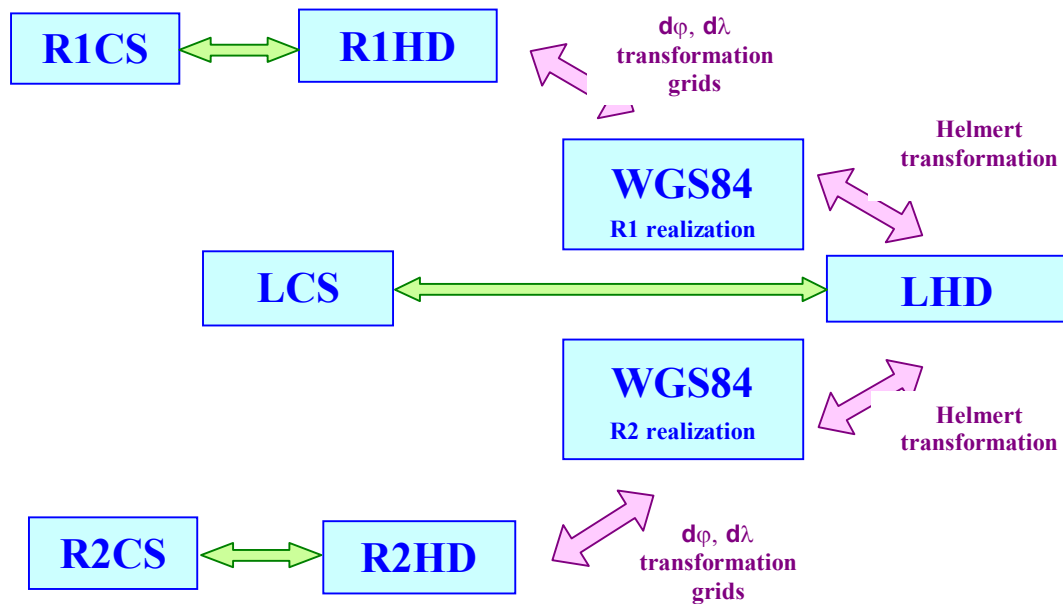


Figure 4: Schema of the transformations between horizontal datums and cartographic systems

The following figure 5 shows the vertical datums and the relevant transformations.

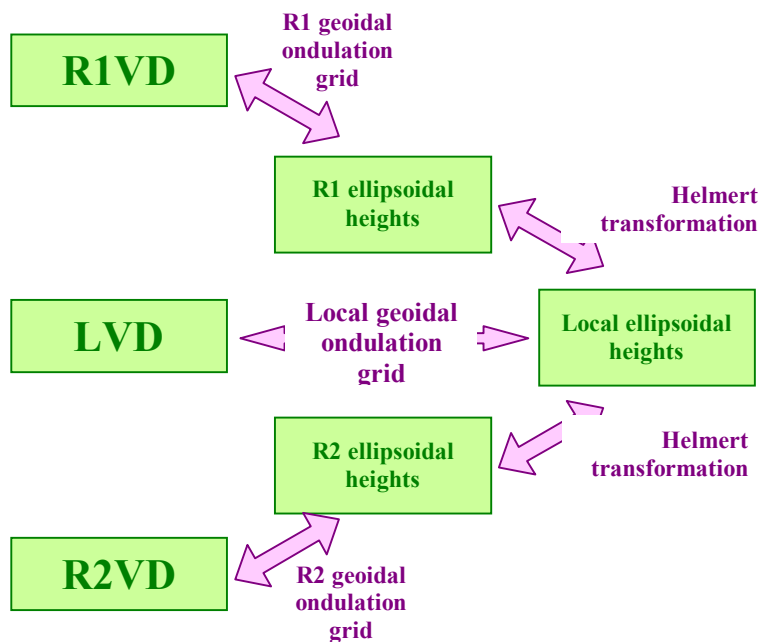


Figure 5: Schema of the transformations between vertical datums

COMPUTATION STRATEGIES

For each defined transformation the most effective strategy of computation has been individuated and tested, separating the horizontal datum transformation procedure from the vertical one. The map coordinates are computed by separate subroutines, depending on the chosen map projection. So the architecture of the system makes it easy any kind of user-oriented modification, as well as a speed partial updating.

From a theoretical point of view, the transformation models that have been applied belong to three different categories:

- transformation equation for the direct and reverse transformation between geographic and map coordinates within the same geodetic datum (L, R1, R2);

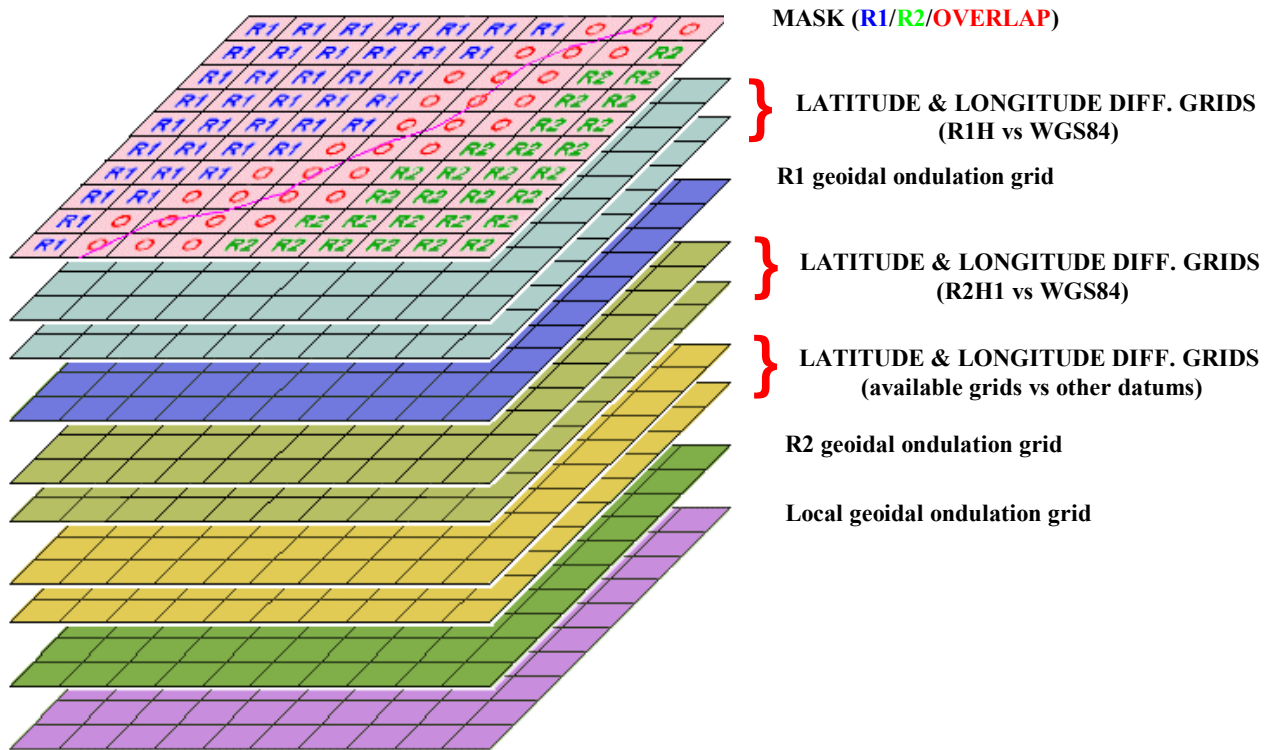


Figure 6: Schema of the grids

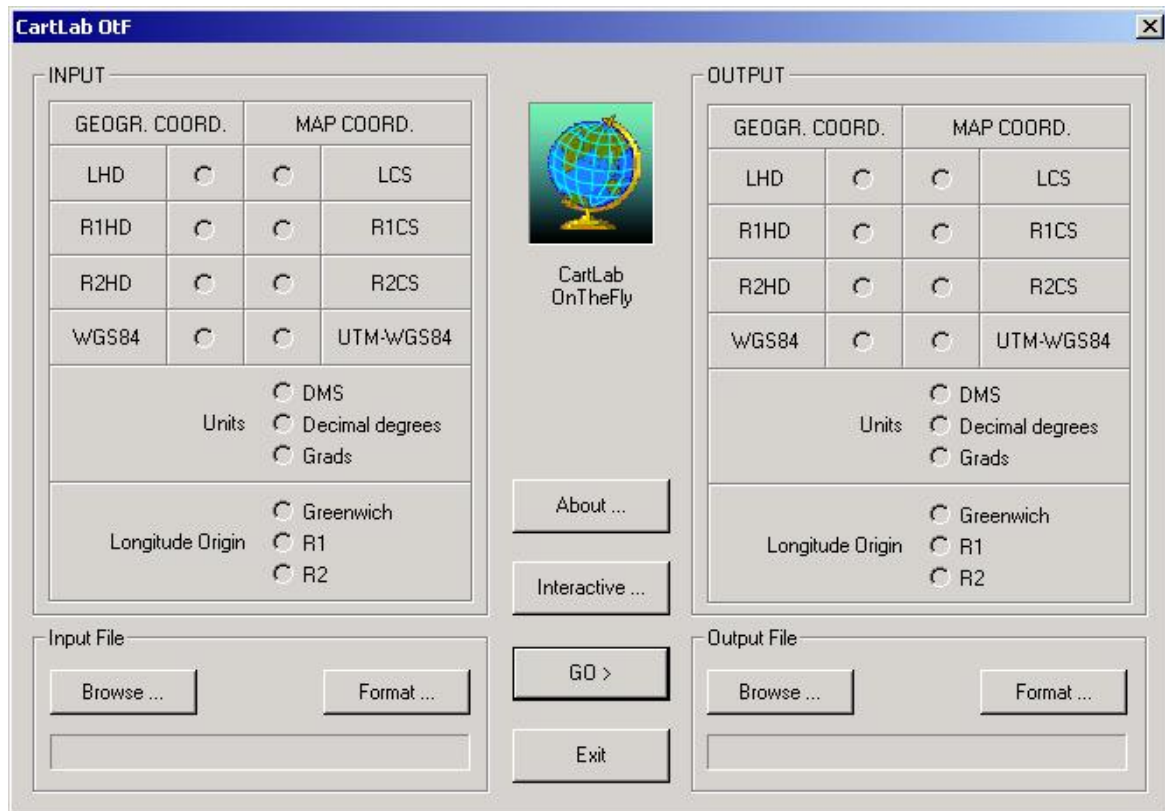


Figure 7: CartLabOtF software interface

- bilinear interpolation based on regular grids for the transformation of geographic coordinates between regional horizontal datums and the WGS84; when several regional datums exist for the same region, the relevant grids could be input to generate the desired coordinates; a mask allows to use of each grid only within the regional sub-area for

which the datum is defined (fig. 6), but an overlapping zone is defined allowing transformation across the boundary;

- bilinear interpolation based on regular grids for the transformation between ellipsoidal and geoidal heights;
- Helmert transformation (seven parameters transformation or simplified three parameters transformation) between WGS84 and LHD;
- Helmert transformation (or simplified model, as in the previous point) between local ellipsoidal heights and regional ellipsoidal heights.

THE GENERAL TRASFORMATION CartLabOtF SOFTWARE

The procedure above described have been organized in a C++ software that allows to operate both in batch and interactive mode, performing the transformation of a single point as well as of a file that could be a text file or a formatted file of common use (such as Shapefile or DXF). The visual interface has been designed to be user-friendly and immediately approachable by any end-user and is displayed in fig. 7.

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