Visual Analytics of Multi-sensor Weather Information
Georeferenciation of Doppler Weather Radar and Weather Stations

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Abstract: This work presents a geovisual tool which integrates and georeferences data coming from some of the weather instruments installed in the Basque Country: a Doppler weather radar and the weather station network composed of around 100 multi-sensors stations (temperature, precipitation, wind...). The visualization of the raw data coming from the weather radar is based on the generation of a set of 3D textured concentric cones (one per elevation scan). The resulting 3D model is then integrated in the 3D digital terrain of the Basque Country. For the weather stations, we have provided a Kriging based interpolation method to produce textures from the scalar data measured at the weather stations. These textures are then mapped in the same 3D digital terrain as before. The integrated visualization of the weather information enhances the understanding of the data. To illustrate the proposed methods a use case is provided: matching the precipitation measured at ground level with the radar scans.

1 INTRODUCTION

The combination of Geographic Information Systems and Computer Graphics is the main characteristic of the Geovisual Analytics (Andrienko et al., 2010). The geovisual tools have a considerable potential in environmental monitoring and in the decision making process (Tomaszewski et al., 2007). For years, the utilization of weather 2D maps has helped to present the data collected in the weather networks to the users with a great success (Kraak and Ormeling, 2002). The presentation of animated sequences introduces the time to show the historical or predicted evolution of a measured variable.

This paper presents the work carried out in the 3D geovisualization of the weather multi-sensor network installed in the Basque Country (Spain) by the Basque Meteorology and Climatology Agency.

The presented geovisual 3D and interactive tool helps to centralize and to enable the analysis of large amounts of data collected from weather sensors, spread around the territory. These sensors are aimed to monitor the temperature, pressure, humidity, wind, solar radiation, etc. There are other type of weather devices, like a Doppler weather radar, a wind profiler and several oceanic probes.

The first section of this work introduces the Basque Country weather network, including the Doppler weather radar. The second section of this paper presents the 3D visualization of raw data coming from the Doppler weather radar. The nature of the radar scans is volumetric, so we provide mechanisms to produce a 3D model with the scanned 3D information. These 3D models are integrated with the 3D digital terrain, constructed from the available geographic information in the area.

The third section presents the tools to create interpolated images given a *timestamp* and a target instrument (temperature, precipitation, etc.). The produced images are overlaid over the same 3D reconstructed digital model of the Basque Country territory.

The forth and fifth sections present how the geovisual interactive applications can help to handle all the available information from the multi-sensor weather network (radar or weather stations) and to combine them to produce more helpful meteorological products.

Finally, the paper ends with the conclusions and the future work.

2 BASQUE COUNTRY WEATHER NETWORK DESCRIPTION

The Autonomous Community of the Basque Country is a territory in northern Spain bordering with south-

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ern France. It spans an area of 7234 km^2 and is crossed by a few mountain ranges. Established 1990, the Basque Meteorology Agency, Euskalmet, has deployed a large network of weather stations, including a long-range radar, and provides past, present and forecast meteorological information.

The physical data collected by the sensors in the network are stored, managed and retrieved to provide meteorological products. The weather forecast to the public is one of the most common ways to use the meteorological products (in TV or in a web page).

The acquired information from the network is also used to help in the decision making process in two different ways. Firstly, the information is used to analyze high risk potential hazard zones, especially, to improve the flood awareness in the territory, so preventive actions can be performed. Secondly, the historical analysis of the available data is used to study the evolution of the climate. The analysis of past singular events is also important to extract important knowledge and conclusions from the data and to help to improve the numerical weather models.

2.1 Weather Radar

The Basque Weather service operates a dual Doppler Weather Radar, located on top of Mount Kapildui, 1000 m. high and 100 km. away from the coast. It is a Meteor 1500C model from Selex-Gematronik. Among other variables, the radar computes the reflectivity (dBZ), radial velocity (V) and spectral width (W) fields every 10 minutes through two volumetric and two elevation scans.

2.2 Multi-sensor Weather Stations

A weather monitoring network is composed of a set of weather stations. Each one can be considered a multi-sensor device, which provides periodical measurements to the control center.

In the Basque Country, this weather station network is composed of around one hundred network stations, each one with a variety of measurement instruments. Some of them have thematic instruments, normally associated to the stations near the sea (currents, salinity...) and the top of the main mountains. As for the time resolution of the installed instruments, the automated station delivers a new data package (which includes all the measurements of all the installed instruments in the station) to the control center every 10 minutes.

The historical data from the Basque Country network can be consulted and retrieved in the Euskalmet web site [1].

3 WEATHER RADAR DATA

Radar scans are typically represented as 2D images in the form of either PPI (plan position indicator) or CAPPI (constant altitude PPI) products.

In this work we don't use these products. Since we are aiming to visualize the complete radar volumes in 3D (not just individual slices from it), we use the raw output from the weather radar, containing the whole volume scan.

The process to construct a 3D model from the raw data of the radar is addressed in the following subsections. Firstly, the raw output is processed and a set of gray-scale images is created. From the metadata of the volume scan, a 3D geometry is generated, composed of a set of concentric cones. Then, the gray-scale images are colored using a transfer function and they are mapped as textured in the 3D cones, creating the final 3D model for the given volume scan. The 3D model is integrated with the digital terrain of the Basque Country, resulting a 3D visual Geographic Information System (Peuquet and Marble, 1990).

3.1 Volumetric Data Processing

The volumetric datasets acquired by the radar are composed of 14 scans at increasing elevations (from -1° to 35°). Such scanning process results in a discrete sampling of the sky volume in which each sample has elevation, azimuth and range coordinates. Thus, samples can be addressed by spherical coordinates.

The volumetric information is converted into a set of gray-scale images, one per elevation. The scanned values (dBZ, V or W) provided in the raw binary file are not the actual values and some transformations have to be applied to the raw values to get the actual values. Then, the range of interest (window level) in the values is mapped to the byte range (128 values) to create the gray-scale image pixels.

The Figure 1 shows a composition of the 6 lowest levels of a given volume scan. The left side of each one is the closer side to the center of the volume (the radar location) and all the pixels in the first column correspond to the same physical location due to the nature of the polar coordinates.

The produced individual images require additional metadata to decode the information (encoded

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[1] Euskalmet web site (Basque Meteorology and Climatology Agency): http://www.euskalmet.euskadi.net/

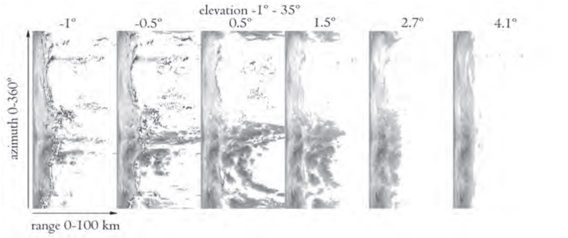

Figure 1: A composition of 6 gray-scale images corresponding to the lowest elevation levels of a given radar scan.

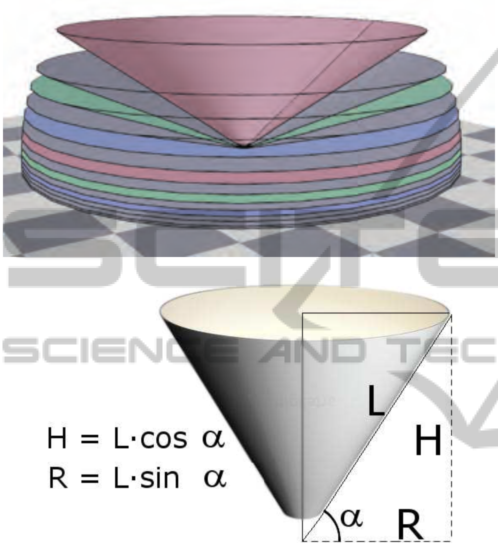

Figure 2: A 3D model of the scanned volume is created as a set of concentric cones. The radius and height of each cone is calculated from the metadata of the radar scan.

variable, window level used in the byte range accommodation, numerical transformations, etc.) which can be encoded in the filenames of the images. Any additional information could be still loaded from the original raw data files.

3.2 3D Representation and Visualization

Previous works have dealt with the visualization of the volume scans acquired from a weather radar. We can see an extensive classification and review of the main techniques and methods in (Ernvik, 2002).

The geometry of the radar scans can be seen as a set of conical sweeps at different elevations. The work of (Sundaram et al., 2008) et al. adds a rectification step to convert the conical grid into a rectilinear grid. This approach suits better for the traditional methods of volume visualization: indirect (isosurfaces, marching cubes...) or direct (volume rendering).

As the rectification process is very time consuming, our approach do not create such rectilinear grid.

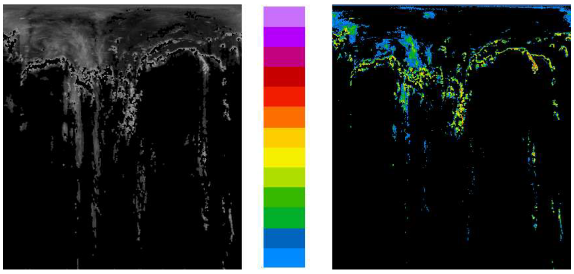

Figure 3: Color mapping of the first level of a scanned volume by the weather radar. The images are given in polar coordinates, with the weather radar located in the upper side of the images.

Instead, a set of geometrical and concentric cones (see Figure 2), centered in the radar location is created (Peng and Lingda, 2007). The height and radius of each of the cones are determined by the elevation angle of such scan.

Each of the images is then used as texture of the corresponding cone. As the images are gray-scale, a coloring function (transfer function) is used. The Figure 3 shows how a colored RGBA texture (on the right) is created by applying a transfer function (shown in the middle) to the gray-scale image (on the left) (Ginn, 1999). The black area in the final colored texture corresponds to the alpha channel, allowing a proper 3D visualization of the scene when all the textures of the set of concentric cones are rendered together.

3.3 Ground Clutter Removal

Given the topography of the Basque Country, the lower scans are affected by the surrounding mountains and other topographical elements, adding almost constant noise to the data, which should be ignored. This constant noise is known as ground clutter.

In Mount Kapildui clean scans can be obtained at elevations greater than 1°. The elevations between -1.0° and 0.5° contain noticeable ground clutter, but they can not be discarded since they provide valuable information.

As the ground clutter is in theory constant in time, its effects in the lowest scans can be reduced by subtracting a fixed mask to the retrieved data.

However, given the variability of radar echoes caused by topography, a single scan of a clear sky is not enough to create a reliable clutter filter. In order to avoid this problem, the final clutter mask was created as the average image of 6 radar scans taken at different times with a clear sky.

The resulting mask effectively removes the ground clutter from the volume scans, but it may not filter correctly all the ground echoes due to the inherent variability of the radar echoes in the topography.

3.4 GEOREFERENCED 3D VISUALIZATION

A fully interactive viewer requires the presentation of a virtual scene to the users, which is composed of two main elements: i) a model coming from the weather radar data and ii) the terrain where the weather radar is located. The most common techniques to integrate terrain and radar data involve the overlapping of 2D images: i) the terrain image or map, where colors represent the height and ii) the image of the weather radar (Toussaint et al., 2000). Usually, the radar images are typically represented as 2D images in the form of either PPI (plan position indicator) or CAPPI (constant altitude PPI) (James et al., 2000).

In our work, we aimed to a 3D visualization of the volume scans and the terrain where the data has been acquired. As presented before in the subsection 3.2, the visualization of the weather radar data is achieved by creating a 3D model composed of the textured 3D cones. The resulting 3D model correspond to the 3D visualization of the given volume radar data and it can be used in interactive 3D applications.

For the 3D digital terrain, we have constructed a 3D model of the whole Basque Country. It was created as a combination of highly detailed digital elevation data and a set of properly adjusted high resolution orthophotographs (Jenson and Dominque, 1988), provided by the Basque Government. This large amount of data has been prepared and transformed into a *PagedLOD* model, ready to be loaded and rendered by the *OpenSceneGraph* graphics library at interactive frame rates.

The terrain data and the radar scans are correctly georeferenced, since the radar data includes the corresponding UTM coordinates and therefore, a seamless visualization of the 3D terrain model and the radar information at the same time is achieved without major inconveniences. The union of radar and topographic data clearly highlights the presence of ground clutter around the highest mountain ranges (see Figure 4).

The Figure 5 shows some visualization examples of volume scans with different variables. Each measured variable has its own transfer function, following the standardized coloring functions used by the commercial products (like Rainbow 5, from Gematronik). The left column shows the reflectivity (dBZ) of two different timestamps and viewpoints using the trasfer function shown in Figure 3. The right column shows the velocity (V) in the same timestamps and viewpoints. They use a custom transfer function (a gradient from blue to red).

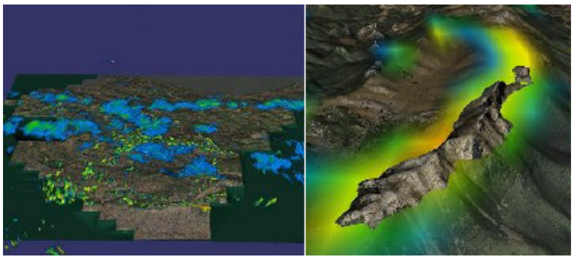

Figure 4: Unfiltered Kapildui radar volumetric information visualization using a reflectivity color map. In the left image, the rain areas can be seen in blue as well as ground clutter. In the right image, a close up of the ground clutter is shown, matching the mountain causing it, which proves that the georeferenciation of the volume radar and the 3D terrain is accurate.

3.5 Animation support

The interactive visualization of a single radar volume merged with the 3D geographic model enhances the understanding of the radar data. The users can navigate through the 3D world and visually inspect the volume and its relationship with the terrain (mountains, valleys). With the visualization of a sequence of consecutive radar volumes, the users' knowledge is increased dramatically, since the temporal axis gives additional visual information. Hidden information in the full set of sequential 2D slides, which compose the radar scans, emerges when several data are visualized in an animated way. Some of most appealing retrieved information refers to the evolution of the rain clouds, the visual inspection of the trajectories of the storms and the effect of the mountains in the evolution of the rain clouds.

The animation support requires to have a quite large amount of consecutive radar data, which will be loaded in runtime. As the data amount could be randomly huge, it is not feasible to precalculate all the 3D model of the radar scans. Therefore, a fast on-demand construction of the 3D models is required.

4 GEOVISUALIZATION OF SCALAR FIELDS

This section introduces the visualization techniques used to display the information acquired from the instruments installed on the weather station network.

Since the values of temperature and precipitations are known only in the points where the weather stations are, an interpolation method has to be set in order to color the whole map. Kriging methods (Cressie, 1993) and its variations are widely used (Mair and Fares, 2011) (Hartkamp et al., 1999) to interpolate the measurements from the weather net-

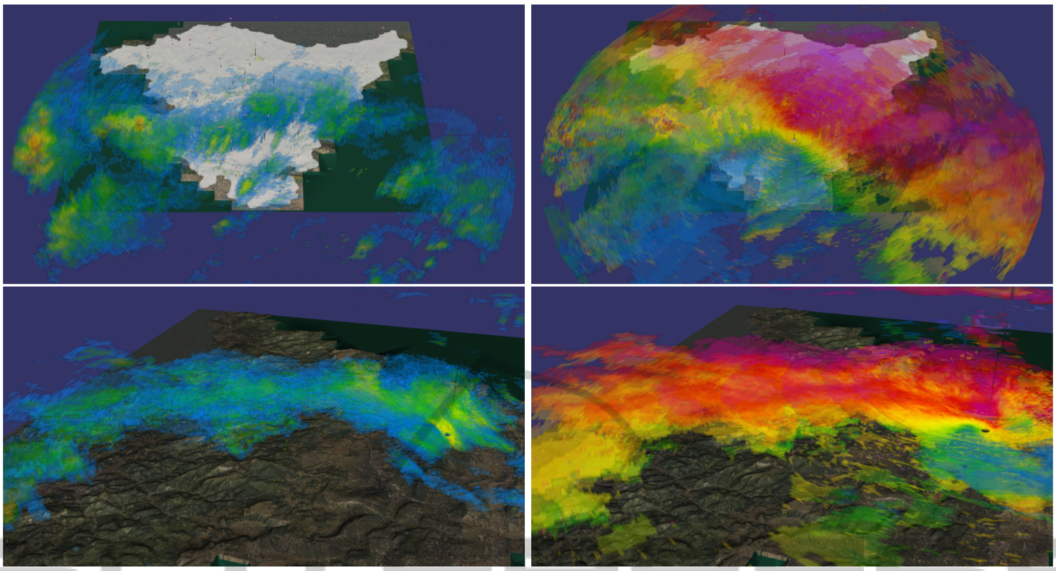

Figure 5: Weather radar 3D visualization over the Basque Country 3D digital terrain. Reflectivity (dBZ) in the left column and Velocity (V) in the right column.

work. These methods obtain the value in a point combining the values of the neighbor known values and the distances to those points.

Let $(x_1, x_2, ..., x_N) \subset \mathbf{X} \subset \mathbb{R}^2$ be the points where the temperature is measured. In the probabilistic model used by ordinary kriging, the temperature in a specific point, $t(x)$, is considered the realization of a random variable $T(x)$ and two degrees of stationarity are assumed. This implies that the mean of all random variables $T(x)$ is the same and that the correlation between two random variables depends only in the distance between the points and not in their positions.

$$\begin{array}{ll} E\{T(\mathbf{x})\} = m & \forall \mathbf{x} \in \mathbf{X} \\ \gamma(T(\mathbf{x_i}), T(\mathbf{x_j})) = \gamma(\mathbf{h}) & \forall \mathbf{x_i}, \mathbf{x_j} \in \mathbf{X} \end{array}$$

Where $\mathbf{x_i} = \mathbf{x_j} + \mathbf{h}$ and $\gamma(T(\mathbf{x_i}), T(\mathbf{x_j})) = VAR(T(\mathbf{x_i}) - T(\mathbf{x_j}))$ is the variogram function.

In ordinary kriging, the random variable $T(\mathbf{x})$ is estimated by $\hat{T}(\mathbf{x})$. It is the linear combination of the random variables referred to the known points and the weights $w_i(\mathbf{x})$ are obtained from the stationarity assumptions.

$$\hat{T}(\mathbf{x}) = \sum_{i=1}^{N} w_i(\mathbf{x}) * T(\mathbf{x_i})$$

In our case, universal kriging (Huijbregts and Matheron, 1971), also known as regression kriging (Goovaerts, 2000), has been implemented. In this method, the variable $t(\mathbf{x})$ is divided into a deterministic component and the residual, that is treated as a random variable.

$$t(\mathbf{x}) = m(\mathbf{x}) + r(\mathbf{x})$$

Then, the deterministic component is approximated by a plane using least squares method and the residual is computed with ordinary kriging. For this latter, since the variogram function needed for the kriging method cannot be computed, a spherical variogram model (Cressie, 1993) is used.

Once prediction for the values at random locations are obtained, the interpolated numerical values have to be visualized somehow. A transfer color function is used to predicted values to a specific color. In this way, anyone can take visual indications about the warmer zones or the areas where the precipitation has been higher. The 2D colored images break the link with the actual terrain. One way to solve this issue is to generate a 3D scene. A reconstructed 3D terrain, textured with the colored image, georeferences the weather data and the terrain where they have been measured (see Figure 6). As the texture is overlaid over the terrain, the resolution of such textures is important. A balance between the computational effort (the interpolation method has be called for each pixel in the image) and the quality of visualization output has to be found.

The Basque Country can be embedded in a 150 km. × 150 km. square. Provided a 1024 × 1024 texture, we have approximately a 150 m. per pixel resolution, which is enough to get high quality visual representation of the scalar field. In a commodity computer, the computational time is below 2 seconds.

The interpolation techniques also predict values outside the Basque Country territory, as the square texture covers parts of the neighboring provinces. For those outer regions, the number of near weather sta-

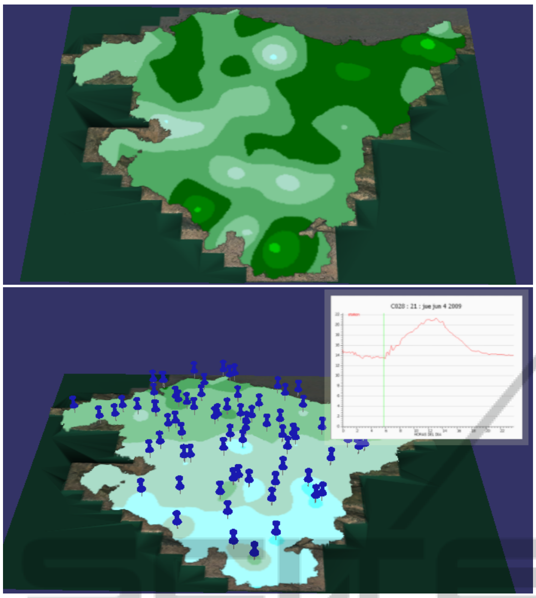

Figure 6: Temperature (°C) rendered in an overlay texture and fitted to the Basque Country administrative boundaries. In the bottom figure, the pins show the location of the weather stations and a 2D graph is attached to the selected station showing the evolution of the temperature within the selected day.

tions is very limited and therefore, the interpolated values are less accurate. In fact, in the corners of the texture, the method can be perceived as an extrapolation method. To limit the impact of such undesired behavior, an alpha mask with the Basque Country shape is used to limit the texture to the correct boundaries. This technique also has an impact in the performance, since the pixels out of the mask are not calculated using the interpolation method.

The upper image in the Figure 6 shows an scalar field (temperature) mapped in a 3D model of the Basque Country. The texture resolution is 1024 × 1024 and an alpha mask has been added with the administrative boundaries. The bottom image shows the location of the weather stations as 3D pins. Although the network is composed of almost 100 stations, not all of them have the same instruments. And additionally, at a given time, some stations can be out-of-service or their data could have been discarded due to the quality control over the data and the electronics in the weather station. In the shown case, the number of available stations for the temperature instrument is 68 at that precise instant.

5 GEOTOOL USER INTERFACE

This section introduces the visual geotool implemented to seamlessly visualize the weather radar volume scans and the weather station network.

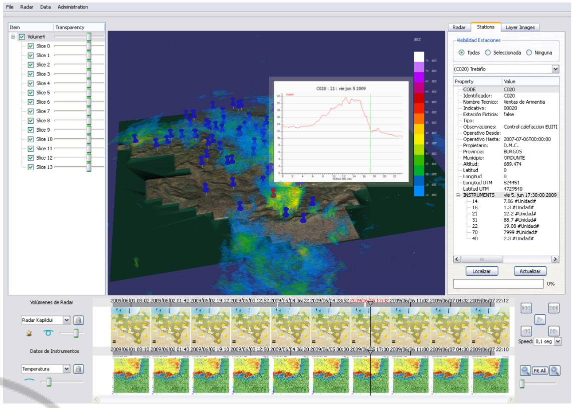

Figure 7: The user interface of the geotool. In this case, a weather station is selected and the evolution of the temperature during the selected day. Also, the weather radar data is displayed in the 3D environment.

The amount of available data is stored in a PostgreSQL DataBase, queried from a QT application. The temporal nature of the data requires to arrange a scroll panel where the available timestamps are shown (see bottom part of the Figure 7).

There are two main timelines: the weather radar and the weather station network. The timeline for the weather radar configures which one of the available variables is shown, i.e, reflectivity (dBZ), velocity (V) or spectral width (W). In a similar way, the timeline for the weather stations configures which instrument is shown in the overlaid texture over the terrain.

Some zooming functionality is added to the timelines to allow the user to inspect and navigate the database. The available data in the database spans for 7 consecutive days in our tests (around 1000 samples) but it could be extended to the whole existing database in the Euskalmet meteorological agency (several years for the weather station network).

The 3D virtual terrain is centered in the geotool. The selected volume data coming from the weather radar can be configured: global and per cone visibility / transparency. The textures interpolated from the weather station network have similar options: visibility and transparency. There is also a selector to choose the instrument to visualize: temperature, precipitation, solar radiation, pressure or any other available instrument in the database.

An additional panel is added to show metadata. For the weather radar, the metadata embedded in the raw files is shown which included useful information for the meteorologists. For the weather station network, information about the selected instrument and the selected station (if any) is shown. The user can inspect the installed instruments on a given station and show in a 3D panel the evolution of a variable along the selected day (see Figure 7).

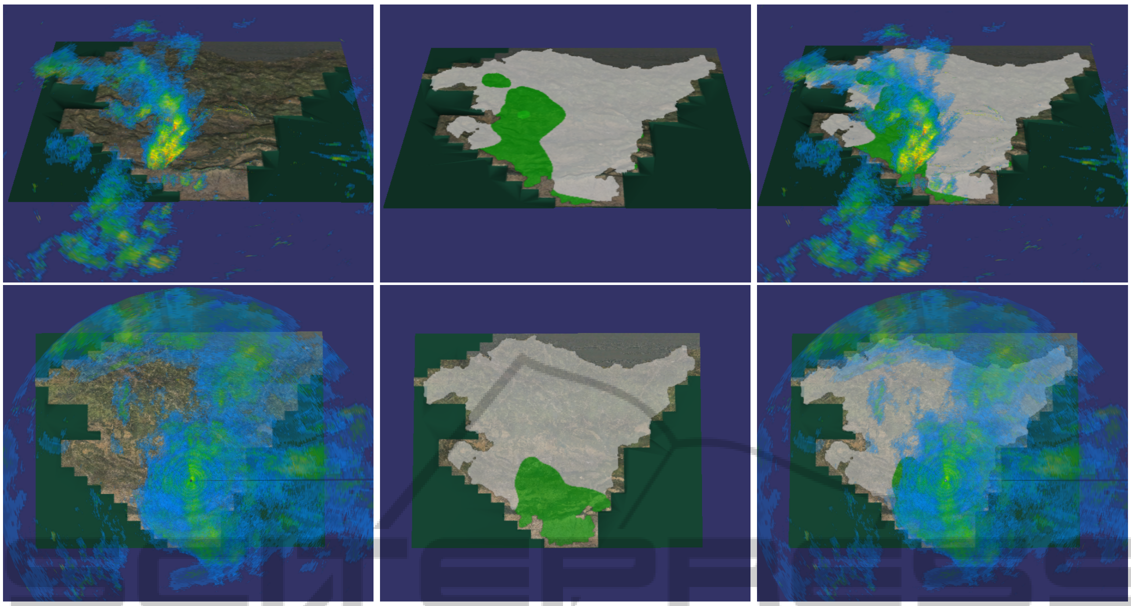

Figure 8: Two examples of georeferenciation between the weather radar and the precipitation measured at the ground level. In both cases, the location of the water in the atmosphere matches the pattern obtained by the Kriging interpolation.

As the nature of the data is inherently 4D, we have provided animation support for some of the typical VCR functionality on the data: Play and stop with some speed up functionality, go to the next data or to the previous data. The interactive visualization of the 3D environment is kept while the animation is running, which is useful to inspect freely the evolution of the weather in the region.

6 GEOVISUAL ANALYSIS: PRECIPITATION

Having multiple monitoring devices produces lot of information for the meteorologists. Analyzing all the data using long tables is not efficient, or at least, it is difficult to globally understand the data. The utilization of textured maps with the scalar fields helps to visualize in a concise way all the existing data in a given timestamp.

The weather radar monitors the atmosphere and thus, it detects the amount and type of the meteors (ultimately, the water in the atmosphere). This information is related to the measured amount of precipitation by the weather stations. The correlation of such variables should show that fact. But it is difficult to analyze the raw data from the weather radar and cross-reference the values with tabular data of the precipitation measured by the weather stations.

The presented geotool can load a 3D representation of the weather radar and visualize the precipitation measured at the ground level by the weather station network as a texture on the 3D terrain. The Figure 8 shows that the composition of both datasets fits perfectly. The shape produced by the precipitation matches the shape of the meteors in the atmosphere. Although the acquisition time is almost identical, there is a 10-20 minutes delay since the weather data is measuring the meteor in the atmosphere and the weather stations are measuring the water already fallen to the ground.

The georeferenciation of both datasets can be seen clearly in an animated loop. The volume captured by the weather radar advances towards the East and we can see the same pattern in the shape of the interpolated texture from the stations.

7 CONCLUSIONS

Meteorologists receive tons of data coming from multiple sources. It is important to provide tools to help them to analyze such amount of data. Visual Analytics has been proved to provide concise thematic visual outputs from large datasets.

This work has provided a geovisual tool to help in the integration and georeferenciation of the data coming from the weather instruments installed in the Basque Country: a weather radar and a weather station network composed of around 100 multi-sensors stations.

The generation of the 3D models from the raw radar information provides a pseudo volumetric visualization at interactive rates. Users can analyze visually where the meteors are located in the atmosphere and where it is expected to rain. Additionally, cross-referencing the radar information with the precipitation measured in the weather stations provide a unique visualization and understanding of the process.

As future work, the massive introduction of devices like the smart phones or tablets makes interesting to port the presented geovisual tool to the Web (Van Ho et al., 2012).

Additionally, the utilization of volume rendering techniques can provide further analysis methods to the meteorologists, even in the Web environment (Congote et al., 2011).

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