Remote Sensing Technologies and Virtual Reconstruction of Archaeological Landscapes: New Developments of the Aksum Project

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Abstract. The Aksum Project is a joint research program of the Istituto Universitario Orientale (Naples – Italy) and Boston University (USA) who are conducting an archaeological investigation in Aksum, Ethiopia. The general goal of the project is to study the development of complex societies in Tigrai from late prehistoric (3rd-2nd millennia BC) to medieval times (14th century AD). Since 1998, the Institute of Technologies Applied to Cultural Heritage of the Italian National Research Council has been collaborating in developing a program for the creation of a virtual reconstruction of the ancient archaeological landscape of Aksum through the application of OpenGL technology. The creation of interactive 3D virtual models of the landscape, connected to a GIS spatial databases will offer new perspectives on the development of the Aksum state through immersion in the virtual world.

Key words. Virtual Reality, Immersion, OpenGL, Virtual Theatre.

1 Introduction

The Aksum Project, established in 1993, is conducting a broad range of research activities that utilise various investigative techniques, from archaeological fieldwork practices to spatial technologies. The main digital activities of the project include:

- Remote sensing multispectral classifications (supervised, unsupervised, data fusion).
- DGPS surveys for the construction of micro-DEMs and micro-scale cartography.
- GIS spatial analyses.
- DVR (Desktop Virtual Reality) applications for the reconstruction and the simulation of the archaeological landscape.

All these sources of spatial data and processing are important for a cognitive interpretation of the landscape (Forte et al. 2001; Forte 2002a).

The large and diverse database of information that has been collected provided the opportunity to develop a program of visualisation, aiming at utilising techniques of virtual reality to enhance understanding of the landscape through immersion in virtual spaces, a compelling way of accessing information. The ability to generate new data, inaccessible through standard archaeological investigative approaches, is a fundamental criteria of this research. The possibility to obtain original perspectives of the ancient landscape through digital reconstructive archaeology is offered through the application of virtual reality technology, where immersion in a reconstructed environment will allow exploration of the sense of being within the landscape. Through the modelling of ancient structures and symbols, such as palaces and sacred areas, we attempt to acquire a greater cognitive understanding of the ancient interaction with the landscape.

Whilst virtual reality is not the only avenue of research, it is a technique that has the potential to revolutionise the way in which we engage with and re-present the past (Forte 2000; Gillings and Goodrick 2000). Its application as a research tool in this project has been guided by two principles. Firstly, the emphasis of the model should be spatial, in that all data should be correctly located and fully referenced to an underlying archive, which in this project comprised of several connected relational databases. This awareness of the spatial element of the data may improve the accuracy of the reconstruction and allow a two-way process in the interrogation of the data, in that data may be simply recalled, deleted, queried or updated. The second has been on utilising virtual reality as a form of reconstructive archaeology, as it is a medium that can be intuitively understood and rapidly updated or changed to reflect new opinions and ideas.

The creation of a virtual reality application is important for the presentation of the projects data as, it is believed that through the application of virtual reality a cognitive landscape or "mindscape" can be created (Forte et al. 2001: 247; Forte 2002a).

2 Virtual Reality Technology

Prior to discussing the elements that were chosen to create the virtual landscape, a short discussion may be useful explaining the choice of method that was used to create the virtual reality application (Forte 2000). A majority of recent work that has involved the application of virtual reality has been based upon the reconstruction of buildings and objects, rarely is it attempted to simulate a landscape. Therefore, few precedents existed to guide the research program, as terrain modelling differs greatly from that of reconstructing buildings. The main requirement was that a framework was needed in which

a user could freely move around, in order to experience a feeling of immersion.

An alternative to using a modelling program is to create a virtual reality file format, such as VRML. Experimentation with VRML was conducted through the 3D Analyst Extension of ESRI ArcView, however results quickly showed that the program has difficulties in managing detailed complex terrains. A further alternative suggested was the application of bubble-worlds, but whilst offering the degree of immersion that was required it has fewer possibilities for user interaction, particularly in the form of free navigation.

The decision was therefore taken to use a specifically designed terrain modelling package with the requirement that it allow complete user documentation and population of its terrain database. A program of scientific cooperation was therefore established between the Institute of Technologies Applied to Cultural Heritage (ITABC) of the Italian National Research Council (CNR) and the software company Terrex for the investigation of their software for application in archaeological reconstructions. The choice of using Terra Vista was specially guided by its use of the OpenGL working environment and its close connection with GIS software packages. Standard file formats used by the most widespread GIS softwares can be readily imported into the terrain builder, maintaining both their spatial location and associated attribute data. Finally, the format that the terrain is exported in, discussed in section 6, is a widely supported industry standard that can be easily modified and updated in other software programs as no propriety format is used.

3 The Aksum Digital Project

The field research of the project has been focused on the hill of Bieta Giyorgis, which lies to the northwest of Aksum in northern Ethiopia, as illustrated in figure 1.
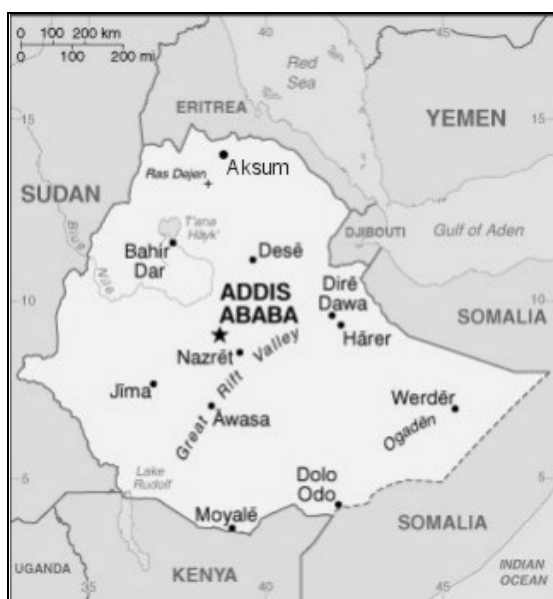

Fig. 1. Location of the research area.

The general goal of the expedition is to study the rise and development of the Aksumnite state through from the late 1st millennium BC to the early 1st millennium AD. An important goal of this project is to investigate the origins and development of Aksum within its environmental setting and this has involved research in many fields, from archaeology through to anthropology and geology. Another field of research introduced was the investigation of the data archive collated by the project through virtual reality, which lead to the establishment of the Aksum Digital Project being undertaken in collaboration with ITABC. This research covers many areas in the use of spatial technologies, from field survey using GPS to the classification of satellite imagery (see Forte 2001: 243). However, this paper focuses on one particular area of investigation, that of the application of virtual reality tools for the generation and visualisation of an ancient archaeological landscape: Virtual navigation through the reconstructed landscape including vegetation, paleoenvironmental data, architectonic and 3D models.

4 Data Preparation for Virtual Reality

The diverse activities of the research program of the Aksum project, ranging from topographic surveys to excavation and anthropological studies, has lead to the creation of a large archive of information. For application within a VR system, certain technical criteria have to be met, which therefore dictates a period of data definition, refinement and processing. A range of sources were drawn upon to develop the virtual model, in particular the spatial data held within the project GIS and the photographic archive established throughout the years of fieldwork. The decision of which data to include within the VR model is usually defined by the choice of VR system and the types of raster and vector data it will include. The project's use of Terra Vista as the terrain modelling software was particularly influenced by the close links of this software with GIS, therefore allowing the simple passage and exchange of spatial data. This concept was of importance as it has been an aim of the work to maintain the spatial element of the data rather than a synthetic world with little context outside the virtual model. Terra Vista allows the user to work in a similar fashion to a GIS, maintaining point (location), polygon (definition of areas for the stitching of textures) and polyline (rivers, tracks) layers.

Whilst a standard procedure had been defined for the inclusion of the GIS data, other forms of archaeological data required significantly more processing prior to entering the VR system. The broad range and complexity of archaeological data means that few software programs are designed to incorporate these different data formats therefore some preliminarily processing must first be undertaken.

In order to recreate the terrain around Aksum it was necessary to collect data concerning the topography of the area. This data was firstly extracted from cartography of the area in the form of 10 meter contours. However, the accuracy and amount of cartographic data available for this area in Ethiopia meant that, in order to create a more precise terrain it would be necessary to undertake topographic field survey in the hinterland of Aksum. Therefore a program of differential GPS survey was initiated and has been undertaken during two field seasons (see Bard 2000). These two datasets have thus provided two possibilities with which to build digital elevation models (DEM) of the region. Due to their differences in scale and accuracy the datasets have been maintained separately in

order that two virtual terrains could be created, the first covering Aksum and its territory and the second a more localised model where the topographic surveys were conducted on top of the hill of Bieta Giorgis.

Other data that was captured in the field and is of importance in the construction of a virtual model is the photographic record. This has two particular applications within a VR model. Firstly, textures captured in the field lend authenticity and reality to the virtual model. Therefore photographs were taken of textures ranging from stone used to build stele, to the type of stonework visible in archaeological ruins, to the differing soil colours. The second function of the photographs taken was to provide the correct vegetation within the virtual model. Through scientific excavations conducted throughout the region it has been possible to study the fossilised pollen record and thus have an indication of the type of vegetation to create and its correct location within the virtual landscape. Whilst Terra Vista is supplied with an extensive library of different species of vegetation, both as textures and 3-D models, the orientation of this library is towards vegetation found in North America or Central Europe. Therefore those species of trees found in the territory of Aksum and present in the pollen record were photographed to be used as 'billboard' themes in the virtual terrain.

In addition to the digital archive of images collected in the field, Terra Vista also has the provision to include geospecific imagery within the virtual terrain. This provides the opportunity to use air photographs or satellite images to provide the texture for the terrain skin, either combined with other texture data or independently as an overlying image.

The final data set necessary to build a virtual terrain are the objects within it, such as monuments and habitation, which are inserted in the form of 3D models. The virtual terrain builder Terra Vista is supplied with a complex library of generic building types, typically of the architectural style seen in North America. For an archaeological reconstruction of an ancient archaeological landscape in North Africa these models have little functionality. Therefore the opportunity was provided to import within the landscape 3-dimensional reconstructions of some of the archaeological sites within the area and further to increase the realism by including features such as stele fields. Drawing on excavation records, literature sources and field observations it was possible to locate accurately using a GPS these buildings and then create simplified 3-D models of these structures based upon their ground plans.

The purpose of this short section has been to define data types required to create a virtual landscape and the type of information that must be gathered in order to lend some authenticity. The aim here is not the definition of a data process which should be followed, for access to software may vary greatly, but to define the data types required and the format necessary in order to create an OpenGL model. The transition of the data of this project was guided by the choice to maintain a strong link between the virtual landscape created through Terra Vista and the GIS of the project.

5 Virtual Model Data Sets

The preliminary stage in the creation of a virtual landscape is the documentation of a database of information from which can be drawn the desired elements. The subsequent step then requires decisions to be made as to which data to omit and which presents the most accurate reconstruction of the landscape in question. A brief discussion is therefore useful of some of the data which was chosen for an individual flight file that was created during this research.

A fundamental element within the creation of a virtual landscape is the accuracy of the terrain reproduced using a DEM. As mentioned in the previous section, two sets of data were available to create the basis of the model, and in this instance it was chosen to build a fly-through that covered the region of Aksum rather than a localised walk-through for the main project site on the hill of Bieta Giorgis.

Overlain over this DEM was a georectified aerial photograph. The application of an image meant that the flight would need a maximum ceiling and floor imposed in order for the textures to have clarity. If a walk-through flight were required, it would be necessary to remove this image as the texture and instead apply textures captured through photographs taken of the terrain and soil types.

The following stage in the construction of the flight was the insertion of vegetation. Analysis of the faunal remains data collected during the IUO/BU excavations at Aksum has revealed that in areas where Ecliptic trees now grow (which not native to this area) there had previously been Acacia and Sycamore trees, although the latter grew more at the foot of the hills. Through the joint analysis of recent satellite images, field survey data collection and the pollen data collected through soil sampling during the excavations, it has been possible to identify some of the plant types seen in the ancient archaeological faunal remains. The terrain building software Terra Vista offers a number of modes in which to build the vegetation coverage. The first method requires the individual insertion of plants through the creation of a point file, either within a GIS package or Terra Vista. Each point is then ascribed a code which is unique for each specie of vegetation. It is further possible to specify the individual height, span and width of each plant therefore creating some diversity. This form of illustration for vegetation is particularly useful when creating walk-through flights as the viewer is much closer to the vegetation and is able to see individual plants and their textures. The drawback of this form of representation is the greater amount of time and processing that is required to build the vegetation, as well as the time required to insert individually each plant. An alternative method to simulate vegetation in Terra Vista is through the use of billboards. These are created through closed polygons which define an area of vegetation, such as a woodland. Then a choice of image is made which represents a view of the side of a piece of woodland, which is repeated around the edge of the polygon. This image is set at a chosen height and a canopy placed over the top of the polygon, thus simulating the effect of a closed woodland. The advantage of defining vegetation in this manner is the low cost this has on the performance of the flight in runtime. The drawback of this system is the viewer must be kept at a certain

distance and altitude from the defined area as the effect when viewed at close proximity is unrealistic. Whilst it is possible to include both representation methods in one flight, it is apparent that one should be used for high fly-through models and the other when the viewers interaction on the surface is greater. A fundamental aspect of Terra Vista is the ability to control the levels of detail within the flight file, which in turn will control the file size of the flight and how smoothly it can be run.

The focus until this point has been the generation of the landscape, correctly detailing topography and vegetation. The next stage is the addition of the habitation, bring the historical and human elements into the territory. Whilst the landscape was undoubtedly changed by agricultural practices and other human interaction, it is the addition of the 3-D models that begins to transform the landscape from something abstract to that which begins to represent and recreate the ancient landscape. As previously discussed, the 3-D resources provided by Terra Vista to generate a landscape are focused towards modern North America, so it has been necessary for the project to establish its own library in order to simulate the type of structures witnessed in the archaeological record.
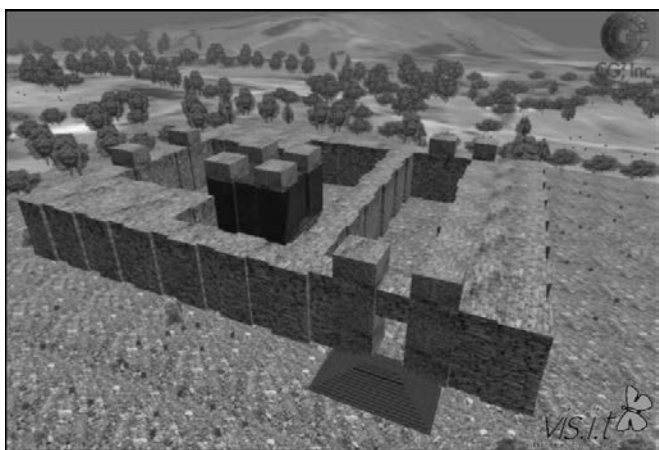

Fig. 2. The reconstructed palace of Mika'el, spatially positioned in the reconstructed landscape.

Through the research of the Aksum Project and scholars' extensive studies of the territory, in particular by Phillipson (1997), it has been possible to individuate the type of monuments that existed around Aksum. The area is characterised by a number of stele fields, both of royal and of lower status. Despite the removal throughout history of these impressive obelisks, a number still remain, both standing and fallen. A majority have been carefully studied, and from these records the dimensions and stone type were extracted and 3-D representations made within a CAD system. Two different forms of stele existed at Aksum, the royal monument which is usually carefully worked, carved stone which may have stood at a maximum height of 20 meters. The lower status stele consist of rough, uneven stone which were simply moved and then placed in an upright position[1]. In total, four different forms of royal stele were selected and nine diverse forms of lower status stele. These simpler stele required more diversity as each stone

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[1] A fuller discussion and drawings of these monuments may be found in Phillipson (1997).

should be different in shape, size and sometimes textures as they represent un-worked stone.

The same procedure is also used by Terra Vista to import more complex models within a virtual terrain. At the current stage of the research, three different sites have been studied in order to generate a reconstruction. The structure of the work has been to establish the ground plan of the major structures through study of both literary sources and ruins as now seen in the field. From these plans, walls are extruded up to the believed height of the structure. This methodology was followed for the palaces of Enda Sem'on, Mika'el (Fig.2.) and Ta'kha Maryam which all lay within close proximity to the ancient town of Aksum.

A similar process was also followed in order to recreate the type of habitation, drawing heavily on the generic ground plans seen in the excavations. Investigations have shown that there is much continuity seen between the type of structures witnessed in the archaeological record and those seen in the current landscape.

6 Data Transition

The form of hyperreal simulation that the digital project has as its goal has required that a careful choice was made concerning the transition of the raw data from the field to the final virtual environment. The preparation and acquisition of the data in particular digital formats, whilst time consuming (as recently noted by Wheatley and Gillings 2002), ensured that the passage to the subsequent phases was smooth. The choice of software with which to create the virtual reconstruction dictated that three phases would be necessary to complete the simulation. The first step was to input all the desired data into the 3D terrain database program 'Terra Vista'.
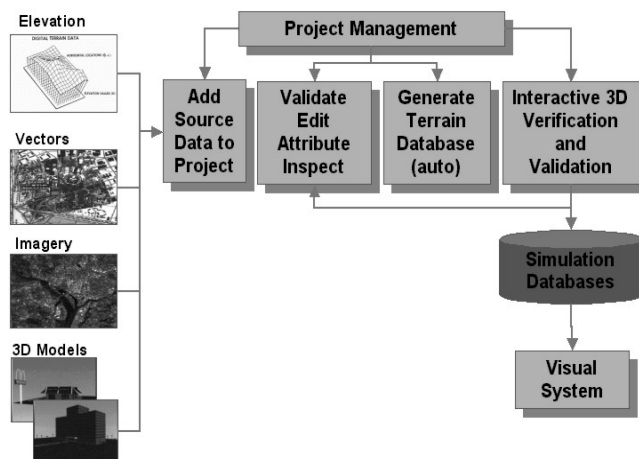

Fig. 3. The managed terrain database generation system of Terra Vista.

This is a software that rapidly constructs digital landscapes through its optimisation for drawing, as such an application must be rapidly updated to trick the viewer that the scene is one continuous uninterrupted landscape. The choice of this software was based on two specific strengths of this system: The first that it allows a high degree of user control over the data through to the creation of an Openflight output; The second that it permits the use of a vast array of spatial data

which is typical of an archaeological data-set. Further, the degree of automation of the program, coupled with an accessible GUI based on a Windows style interface, means that the user does not have to be an expert terrain modeller.

An important aspect of the program that is useful to highlight is its use of Levels-of-Details (LOD). Each LOD represents the tile at a different polygon density: less detailed for when the tile is far from the viewer, more detailed when it is closer (Fig.4). Whether the terrain is displayed in a Virtual Theatre or on a notebook computer, the hardware on which it is rendered will determine some of the parameters for the terrain generation. The number of polygons that can be drawn per second along with the desired frame rate will determine how many polygons can be drawn per frame.

In summary, the structure followed for the passage through this program, as illustrated in figure 3, is as follows:

1. External source data organisation.
2. Import of elevation data, cultural feature data, real-time photo textures, 3D models, geospecific and other imagery to populate the internal database.
3. Assigning of terrain parameters and processing sequence.
4. Finished terrain database output files.

Terra Vista is provided with two forms of data output, Terra Page and Openflight, both of which are transferable to other software but the second of which is the more widely supported industry standard. The OpenGL working environment can provide high quality graphics on inexpensive PCs through the use of accelerated graphics cards. It is the premier environment for developing portable, interactive 2D and 3D graphics applications through its incorporation of a broad set of rendering, texture mappings, special effects, and other powerful visualisation functions. A further advantage important to this project is that Openflight database is relatively simple to modify and update, which was a necessary step once the data were passed through the Terra Vista program.

The subsequent period of post-processing of the data was conducted in MultiGen Paradigm's Creator software, a program particularly suited to working with the Openflight format. Whilst models were optimised for run-time viewing before they were entered into the Terra Vista database, Creator offers the opportunity to manipulate the terrain at the highest level of detail. As the creation of the final terrain Openflight file was an automated function, some errors that visually distort the reality of the terrain were experienced and removal of these was only possible through Creator. For example, the vegetation was inserted into the terrain as individual points which, occasionally, coincided with other cultural data, such as a plant appearing on the surface of a river. Through Creator, these can be simply removed or positioned elsewhere.
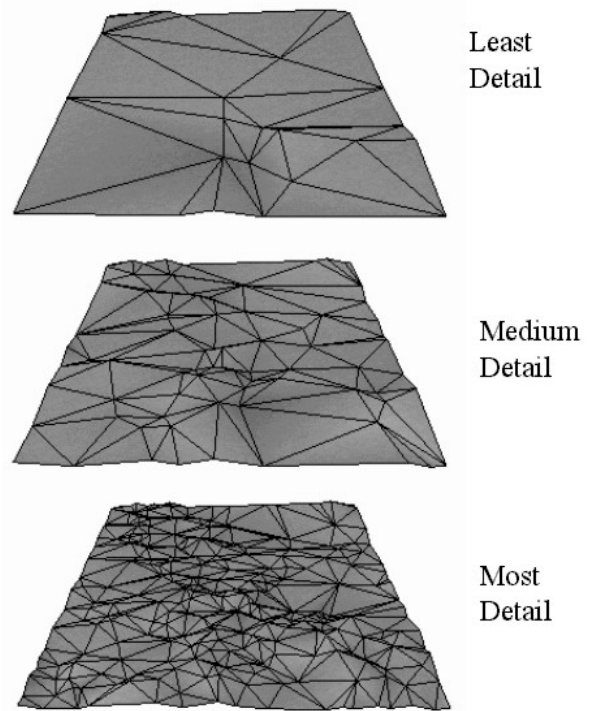

Fig. 4. *Representation of 3 different levels of detail (LOD) used for visualisation by Terra Vista.*

The project has sought to develop models for two different areas of application. An aim of the project is to experiment with and develop the viewers perception of a landscape, best achieved through enhancing immersion within a virtual reconstruction. Therefore, thanks to scientific collaboration with the CINECA Institute (Bologna, Italy), virtual models were developed in Terra Vista and MultiGen Paradigm's Creator to be viewed using the Virtual Theatre facilities of the institute. This is a structure for immersive 3-dimensional computerised visualisation with a surround sound system and a semicircular screen that allows the viewer to experience the illusion of 3-dimensional vision. Further, visualisation obtainable through VR crystal eyes (with stereoscopic view) enhances the level of the viewers perception as generated virtual models can be experienced as holograms (Forte 2002).

The second area of application is to create models for distribution and viewing on desktop PC's. The models were generated in the same manner in Terra Vista then exported in Openflight format to Creator for modification and then saved in Virtual Tree (VT) format to allow simple distribution.

7 Conclusion

The very nature of virtual reality dictates that the most appropriate way to assess the results of the work is through experiencing the landscape that was created. Therefore, the best results witnessed where those seen in the Virtual Theatre of the CINECA institute.

The 3D reconstruction of the ancient Aksumnite landscape through virtual reality has provided a useful contribution to the development of the project and to the construction of cognitive models. This project represents an application of a new tool for understanding the past, through the integration of spatial techniques (GIS) and visual information dynamic sys-

tems (VR). The encouraging results achieved so far, in particular the highly detailed georeferenced terrain created by Terra Vista mean that this avenue of research will continue to be explored, the areas of which are discussed in the next section.

8 Future Research Program

The research conducted in this initial stage of the Aksum digital project has through its development identified areas where the methodology could be expanded and other areas redefined. The clearest demand is for development of the connectivity between the virtual landscape and its underlying GIS spatial database. Currently the user may navigate through the landscape experiencing sight and sound but may not query the features and reconstructions. This has temporary been solved by introducing sound in the form of spoken language which is enabled when the user moves within a certain distance of an object. The future intention is to allow the user to select features which in turn calls a menu and allows other data to be queried, such as alternative reconstructions of 3D models or bibliographic sources. This accessibility to the metadata will allow a greater understanding of the reconstruction and the concepts upon which it was established. This need for greater connectivity with the underlying relational database is coupled with the need to begin to develop the user interface. Currently, work has begun using the C++ programming language to design a specific application within which the model can be interrogated. This environment can also be used to develop a front-end with a GUI that helps the user to navigate around the landscape, for example, the user may request going directly to a monument or being taken on a pre-defined virtual tour of a particular route (such as a ceremonial way). Whilst currently the user is able to experience immersion in the landscape, greater 'unreal' freedom of movement would considerable aid understanding.

Another area where research is beginning to be undertaken is aimed at enhancing the users sense of immersion. It is proposed to greatly develop the use of sound and to offer various representations of the landscape at differing periods throughout the year. Whilst effects such as rain or snow can be easily added to the model, for a greater simulation this will need to be accompanied by a new set of textures that account for the environmental effects that are added. Once completed, those options will be made available to the user in the application menu where the season can be chosen and differing environmental effects added.

The second area of future development away from the user requirements is the exploration of this 3D space with different forms of GIS spatial analyses. An overall aim of the Aksum project is study the development of the Aksumnite state in its territorial context, an avenue of research that would benefit with the introduction of some spatial analyses available within a GIS. Whilst studies of visibility and predictive modelling have been undertaken with GIS tools, rarely are these results combined with the third dimension, perhaps with the notable exception of the recent study around Stonehenge (Exon et al. 2002). A proposed research theme is therefore to explore visu-

ally the output of these spatial analysis techniques in a virtual model, through exporting these as binary raster images and overlaying them in the model as geospecific themes. Testing of output themes such as are achieved from visibility analysis will then become a far more visual and perhaps more accurate form of analysis.

9 Acknowledgements

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