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CREATING SOUND SYMBOLS
FROM DIGITAL TERRAIN MODELS:
AN EXPLORATION OF CARTOGRAPHIC COMMUNICATION FORMS

by

STEPHEN JOHN GLAVIN, B.A. (HONS.)

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Arts

Department of Geography

Carleton University

Ottawa, Ontario

March 9, 1987

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AN EXPLORATION OF CARTOGRAPHIC COMMUNICATION FORMS"

submitted by Stephen John Glavin, B.A. (HONS.)

in partial fulfilment of the requirements for

the degree of Master of Arts

Thesis Supervisor

Chairman, Department of Geography

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April 1987

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INTRODUCTION

Dynamic Cartography

The use of computer-assisted map production techniques has allowed cartography to become dynamic. Because these new map products can be displayed on film or video rather than paper, they can depict temporal changes in the graphic image. These visual dynamics will enhance the representation and perception of the mapped phenomena during the presentation and reading of the map information. Dynamic maps differ from static maps in their ability to be interactive with the user and to change the display accordingly. The differences between conventional cartographic methods and dynamic displays can be grouped into four major types of applications.

- (i) A map can be actively explored by the user and the image changed to reflect the area of interest (See FIGURE 1A).
- (ii) Dynamic maps can present information in an ordered sequence, i.e., a progression of different data values (See FIGURE 1B).
- (iii) Animated maps can show the change of a feature through time (See FIGURE 1C).

(iv) Dynamic displays also allow for the movement of map images to provide a perspective similar to that of viewing the subject in three-dimensional space (See FIGURE 1D).

Now that maps can be dynamic and not restricted by the limitations of a static paper sheet, auditory information which is fundamentally dynamic can be added to the visual information. The two sensory dimensions of sight and sound could be used in conjunction with one another to display change through time. Dynamic maps would benefit from the corresponding use of sounds, either in the form of speech or coded tones, to create a truly audio-visual display. Aural information has been used with some types of cartographic displays. Narration is commonly used in films depicting geographic phenomena with maps. Similarly, symbolic tones are used in association with radar navigation displays to signal the presence of objects within the image.

The most simplistic example of a visual map image being supported with audible information is when a conventional map is used in a seminar or classroom situation. The speaker places a map on the overhead projector for the audience to view (See FIGURE 2A). It is a standard choropleth map designed with three different visible components, text, data and graphics (See FIGURE 2B). Rather than make the audience read the map without assistance, the speaker chooses to explain the visual image with words. By acting as a guide and leading the audience's attention through a specific sequence of map features,

the visual information is being presented through time and the map becomes a simple example of a dynamic display.

The speaker starts by pointing at the study area and saying, "This is the Ottawa-Carleton region divided into census tracts". This action, and the corresponding words spoken are the speech equivalent of geographic labelling. It reinforces what would otherwise be the purely visual association between the printed text and the geographic outline (See FIGURE 3A). The speaker continues by pointing at the legend and saying, "The map shows population distribution for the year 1985 using five classes from 10,000 to 100,000". This is the speech equivalent of data description. It is reinforcing the association of the text and the data map components (See FIGURE 3B). Pointing out the shaded boxes in the legend, the speaker explains, "The population figures varying from low to high are represented with five textures ranging from light to dark". This is the speech equivalent of symbol definition. It associates the data values with the visual variation of the symbols used (See FIGURE 3C). Returning to the mapped area to analyse the population distribution, the speaker points out the darker census tracts and says, "High population", and then points out lighter areas and says, "Low population". Pointing at an area of middle-grey texture the speaker, who seems lost for words, says, "Ah... a moderate population... um... lower than... but higher than...". At this point the speaker resorts to waving arm gestures to supplement the analysis of the various levels of grey found on the map.

This simple example of a map being presented shows how the use of speech can augment, or even replace, the use of text on a map. However, this application is limited to the purposes of labelling and data description. Speech is quite restrictive for the analysis of the actual data values and the relationships between different areas (See FIGURE 4). Yet this is the most important aspect of the map reading process. The disadvantages of speech as compared to the visual symbols used in this case are to be expected. This is because the visual symbolism was specifically designed to take advantage of the visual variation of texture, but language was not necessarily developed to be able to represent data values.

This does not mean that graphic images must remain silent. Speech can be informative and useful in guiding the map reader's attention. However, different types of aural information could be designed which would also be able to strengthen the association between the data and graphic components of a map (See FIGURE 5). For sound to be used to aid the analysis of map features other than just text, something other than speech must be used. Encoded, symbolic tones can provide a range of audible sound symbols which would reinforce or replace the conventional use of visual symbols.

With some radar navigation systems a "beep" tone is used to signal the presence of an object on the display. This is a simple

correspondence between the visual information and the audible symbol. The sound has two possible states, on or off, to represent presence or absence of objects. Many map displays and visual symbols are more complex than this and would also benefit from the addition of sound symbolism. However, the audible attributes of sounds must be more fully explored and utilized to produce a more extensive range of detectible symbols as compared to a simple On/Off signal. Just as visual symbolism uses a range of visible characteristics, i.e., texture, size, color, et cetera, a set of coded tones can be created by manipulating the corresponding attributes of sound, i.e., frequency, duration, loudness, et cetera. By linking sound symbols with the mapped data an extra sensory dimension can be added to the display. In the previous example, a speaker pointing to areas on a map could perhaps represent the data by raising and lowering the voice appropriately.

The creation of an audio-visual map display is dependent on the use of automated techniques. The synthesis of visual information with sound symbols to allow the simultaneous displaying of graphics and playing of tones is now possible with the available computer technology. Recent advances have made both sound generation and dynamic map display devices more commonly accessible. As well, an increased number of applications using these technological developments has prepared map users for this type of combined information display. Research must now be carried out to investigate these new display capabilities and new map user skills.

The creation and audition of sound symbols can be seen as an addition to the conventional visual communication model.² The three components of this expanded audio-visual map system would be:

- (i) the map;
- (ii) the map user;
- (iii) the sounds.

Rather than providing the map user with just visual information, the auditory channel allows for the corresponding transfer of aural information (See FIGURE 6A).

The proposed communication model capitalizes on the recent developments which have occurred within each one of these components. Advances in map display techniques, increased user familiarity and faster computer sound software now make the creation of a sound map possible (See FIGURE 6B). A sound map system would assist the map user in the analysis of a mapped phenomenon. New techniques to add information to map displays are becoming increasingly necessary as cartographic images become more complex. The desire to map multiple data sets and increase the amount of visual information is limited by the possibility of the visual channel becoming overloaded. The sound-channel could expand the sensory limits of information overload by acting as a replacement for one of the visual symbols in a complicated

data display. Even with simple, single purpose thematic maps, the addition of sound symbols to reinforce the display would strengthen the map reader's ability to differentiate between data values. With dynamic perspective views and animated maps, the sound symbols generated could correspond to the changing visual image and aid the map user in the perception of the type and rate of change occurring.

For this research, the mapping of relief form is used to investigate the potential of creating sound symbols and adding them to a dynamic display. The representation of terrain relief with contours provides the means for creating continuous data surfaces, or Digital Terrain Models, which can then be converted to sound symbols. The Digital Terrain Model is a statistical surface which can represent an actual landscape or a thematic topic, i.e., population. The sound symbols generated by the Digital Terrain Model should aid the map reader in the description, recognition and comparison of different landforms on the undulating surface. To do so, the sound symbols must correspond to the physical attributes of the relief, i.e., elevation (See FIGURE 7).

How can sounds be generated to describe a landscape or a cartographic representation of a three-dimensional surface? There are various ways that sound can represent a particular landscape. The most obvious method is through the natural sounds the landscape creates. The sounds heard would be produced by the actual environment and would not

be altered, or reorganized in any way as one listened, i.e., birds, wind, water flowing (See FIGURE 8A).

There have also been various artistic attempts to evoke the experience of a landscape. Some classical music compositions have been scored to represent a particular type of landscape. The sounds used in this case are those created with conventional instruments and they are heard as they were ordered and arranged by the composer (See FIGURE 8B). A second type of artistic landscape representation using sound is the "Found Sounds" method of music composition. With this modern technique the actual environmental sounds are recorded directly from the landscape, i.e., buses, people but then they are altered and rearranged by the composer to create a collage of sounds which would not have occurred naturally (See FIGURE 8C).

A scientific method of analysing a landscape or physical form is the use of physics of sound principles to describe the creation and modulation of sounds in the environment. By measuring the sound wave characteristics of natural noises or artificially generated tones, the effects of distance and form can be seen in the loudness and reverberation or echo of the sounds, i.e., room acoustics analysis (See FIGURE 8D).

Compared to these sound products, the type of sound symbols created by a Digital Terrain Model of the landscape should be more scientific than artistic. The attributes of the sound symbols should correspond with the relief and be derived from the actual surface elevation values (See FIGURE 8E). The composition or ordering of the sounds heard should not be based on artistic ideals, but be consistent with the spatial distribution of values across the surface. The individual notes should not be created by conventional instruments but with simple sound waves so that they remain symbolically "value-free" like shades of grey on a choropleth map.

At what level of symbolic correspondence can a Digital Terrain Model of a landscape be used to create sounds which will describe the relief? The possible linking of the terrain with sound attributes can be conceptualized at four different scales, the whole earth, a defined landscape, the Digital Terrain Model, and a single polygon.

The whole natural world emits a broad range of different sounds. Some of these sounds are created by natural forces and many are generated by human activity or machines. This is the realm of physical correspondence between visual events and sound occurrences (See FIGURE 9A). If we focus only on a particular landscape area, there is a much smaller set of sounds which are created by the specific environment. At this scale, artistic compositions try to describe the

landscape with a limited number of sound generators, i.e., conventional instruments. These musical pieces are created by an individual composer's concept of the landscape and rely on the unpredictable interpretation of the sounds by the audience (See FIGURE 9B). Because the audience's understanding of the music is based on socially-defined associations of sight and sound, it can be referred to as the realm of social correspondence.

If we focus on a single aspect of the landscape, i.e., elevation, a Digital Terrain Model can be created to represent the relief. We can also select just a single sound generator which produces a range of different tones. At this point, there is the ability to make an association between the terrain data and the tones. The correspondence between the visual image, i.e., one variation of relief, and the sounds, i.e., one variation of tone, can be called a symbolic correspondence (See FIGURE 9C). The linking of these sight and sound variations can be performed at the scale of the individual units of each dimension.

The smallest visual component is the single polygon. Similarly, the smallest audible sound event is the single note. The polygons represent the relief form with different characteristics of elevation, slope and orientation. The individual notes of a series can vary in frequency, duration and timbre (modulation). By matching the polygon variables with the sound variables, a single note can be defined

for each polygon. The sound symbols can now be created by associating elevation with frequency, slope with duration, and orientation with modulation (See FIGURE 9D). These data transformations define the symbolic correspondence between the terrain and the notes. By mapping the sound attributes to each polygon of a surface, the landscape now has a continuous set of notes which symbolize the relief (See FIGURE 10).

Although the Digital Terrain Model surface creates a large number of notes they cannot all be heard simultaneously. The terrain relief must be actively explored to create sequences of individual notes. The ability to use sound symbols to represent relief is dependent on the use of dynamic map displays to show the polygons creating the notes. It is also beneficial to the map user's perception of more complex terrains which are changing through time. The terrain can be explored dynamically by the user specifying a simple path to be traversed. The sequence of sound symbols heard will correspond to the polygons which were visited along this path (See FIGURE 11A). A multiple-level path can be defined by the user to move across the terrain and also jump to other surfaces representing the same relief with different levels of generalization (See FIGURE 11B). As with a simple path, the notes heard would represent the polygons which were visited by the user.

If the terrain being explored is undergoing changes in relief, the notes heard will represent the amount and rate of the polygon mutation occurring (See FIGURE 12A). If the user wants to analyse the

movement of the terrain relative to the user's viewing position the notes heard will represent the changes in the polygon's position, distance and rotation characteristics (See FIGURE 12B).

These methods of terrain exploration and note generation were performed to test the limits of the proposed sound map system. The ultimate sound map would allow the real-time, interactive exploration of the Digital Terrain Model. However, the limitations of the computer systems and software used in this research to create the sound maps permitted only the simulation of the full capabilities proposed. The simulations were carried out by creating Digital Terrain Models of relief, performing the necessary data transformations to generate sounds, and then recording the results on video (See FIGURE 13).

This thesis introduces the reader to the sensory capabilities of the sound map user's visual and aural perception systems and defines a set of variables which can be used to create sound symbols. The methods used for creating the Digital Terrain Models and converting the polygonal data into sound surfaces are fully documented. The results of the different terrain exploration techniques are reported and the potential of further applications is also discussed. The thesis concludes that the creation of sound maps was successful and suggests that it is only one possible application of sound within cartography.

FIGURE 1

MAP DYNAMICS

A. MAP EXPLORATION

B. ORDERED PRESENTATION

C. FEATURE CHANGE

D. MAP MOVEMENT

FIGURE 2**MAP COMPONENTS****A. CHOROPLETH MAP** **B. SEPARATED COMPONENTS****TEXT**

OTTAWA-CARLETON
CENSUS TRACTS
POPULATION

DATA

1985
10,000
25,000
50,000
75,000
100,000

GRAPHICS

FIGURE 3

15

ORAL MAP PRESENTATION

A. NARRATION TO LABEL AREA

TEXT

GRAPHICS

A
S
S
O
C
I
A
T
I
O
N

B. NARRATION TO DESCRIBE DATA

TEXT

DATA

A
S
S
O
C
I
A
T
I
O
N

C. NARRATION TO DEFINE SYMBOLS

DATA

GRAPHICS

A
S
S
O
C
I
A
T
I
O
N

FIGURE 4 CAPABILITIES OF NARRATION

A. SPEECH CAN REPLACE MAP LABELS

B. LIMITED DATA DIFFERENTIATION

FIGURE 5

**APPLICATIONS OF SOUND
IN
CARTOGRAPHY**

FIGURE 6

AUDIO-VISUAL COMMUNICATION

A. SYSTEM COMPONENTS

B. SYSTEM DEVELOPMENT

FIGURE 7

SOUND MAP PRODUCTION

FIGURE 8

SOUNDS AND THE LANDSCAPE

FIGURE 9**SIGHT AND SOUND CORRESPONDENCE****A. PHYSICAL CORRESPONDENCE**

ALL SOUNDS

WHOLE EARTH

D
E
C
R
E
A
S
I
N
G**B. SOCIAL CORRESPONDENCE**

SELECTED SOUNDS

LANDSCAPE

S
C
A
L
E**C. SYMBOLIC CORRESPONDENCE**

SPECIFIC RANGE

D.T.M.

D. SYMBOL DEFINITION

SINGLE NOTE

F
R
E
Q
U
E
N
C
Y
D
U
R
A
T
I
O
N
M
O
D
U
L
A
T
I
O
N

SINGLE POLYGON

E
L
E
V
A
T
I
O
N
S
L
O
P
E
O
R
I
E
N
T
A
T
I
O
N

FIGURE 10**CREATING SOUND SURFACES****A. SOUND SURFACE**

NOTES VARY IN FREQUENCY DURATION MODULATION

DATA TRANSFORMS **B. DIGITAL TERRAIN MODEL**

POLYGONS VARY IN
ELEVATION SLOPE ORIENTATION

FIGURE 11

TERRAIN EXPLORATION I

A. SIMPLE PATH

NOTES
GENERATED

SOUND
SURFACE

DEFINED
PATH

D.T.M.

B. MULTIPLE LEVEL PATH

P
A
T
H

O
N

L
E
V
E
L
S

D
I
F
F
E
R
E
N
T

N
O
T
E
S

FIGURE 12**TERRAIN EXPLORATION II****A. CHANGING SURFACE** **B. MOVING SURFACE**

FIGURE 13

SOUND MAP SIMULATION PROCESS

Visual and Aural Capabilities

A display system which is to synthesize visible and audible symbols must be sensitive to the sensory capabilities of the map reader. The successful communication of information will depend on the reader's eyes and ears being able to detect and identify the symbolism. Both the visual and aural senses have physical limits of detection which must not be exceeded in the design of symbols. They also each have recognizable, variable components that can be used to symbolize a series of data.

The Visual System. Map reading involves the viewing of an image with either reflected or emitted light. The visible information is processed by the brain and analyzed for meaning. This results in a judgement being made concerning the mapped information (See FIGURE 14A).

To be visible an object must be within the sensible limits of size, wavelength and brightness (See FIGURE 14B). The visible range of object size extends from a minimum of approximately 0.3 mm to a theoretically infinite size, usually only limited by the size of the paper or map display device.

The visible range of an object's spectral characteristics extends from wavelengths of approximately 400 to 700 nanometers. Within

these limits objects are visible and appear to have color attributes ranging from violet-blue (shorter wavelengths) through green to red (longer wavelengths).

To be visible an object must have an appropriate level of brightness. This is provided by the amount of reflected light, or in the case of C.R.T. displays, the emitted light. The brightness of an object can range from light to dark but its visibility is also influenced by the brightness of surrounding objects and background.₃

The Aural System. The sensation of hearing results from the ability of the ear to sense vibrations in the air. A vibrating source emits waves, or rapid changes of air pressure. These vibrations are received by the ear and processed by the brain. By analysing the characteristics of the sound heard, judgements can be made about the source of the sound (See FIGURE 15A).

To be audible a sound must be within the sensible limits of duration, frequency and loudness (See FIGURE 15B). The audible range of tone duration extends from only a fraction of a second to an infinite length of time.

The audible range of tone frequency extends from a minimum of 20 cycles per second (Hz) to a maximum of 20,000 cycles per second. This is the optimum range detectible by the human ear and with age or hearing damage a decrease in the range, especially the high frequencies, is experienced.

The audible range of tone loudness extends from soft, quiet sounds to beyond the threshold of pain. The loudness of sounds is usually measured in decibels. On this scale the audible range is from 0 dB (soft) to 140 dB (loud) but the ability to hear a particular tone will also depend on the loudness of other sounds occurring simultaneously and the amount of background noise.⁴

To create sensible sound symbols the characteristics of the tones generated must be within these limits of duration, frequency and loudness, just as visual symbolism must remain within the limits of size, wavelength, and brightness.

Maps and Visual Variables

If an object is visible then its graphic characteristics can be used to represent a series of data. The recognizable visual variables of a graphic object are its location, size, value, texture,

color, orientation and shape (See FIGURE 16A). Cartographic displays use symbols which attribute one or more of these variables to the data values being mapped. In addition to graphic symbols, maps also use text and numbers to label geographic areas, describe the map subject, and quantify the symbols.⁵

Pseudo three-dimensional perspective views can be made by deforming the shape and size characteristics of graphic elements in two dimensions. The association of size with distance and shape with the focal center creates the illusion of depth on a flat surface (See FIGURE 16B). Terrain relief can be modelled in this manner using a continuous surface deformed into a perspective view.⁶ A computer-generated Digital Terrain Model uses a surface of regular triangular polygons to represent three dimensional space (See FIGURE 16C).

By displaying the landscape relief, the Digital Terrain Model provides information about surface elevations, slopes and orientation (See FIGURE 17). Although it successfully synthesizes this information into a single image, it also loses the advantages of having an orthogonal map view. The Digital Terrain Model can be rotated to a map view but the deformation of the polygon shapes is not significant enough to show the physical form. Although the Digital Terrain Model can provide a valuable "like being there" point of view it has several

disadvantages. Because the size and shape of the polygons change with distance, it becomes hard to quantify spot heights or even make comparisons of elevation between two different points. It is also difficult to measure the distance between the viewer and points on the model, or compare distances between different points on the surface. Because the Digital Terrain Model provides a single point of view there will always be parts of the surface out of view due to its relative orientation, and blocking or interposition of other areas.

Dynamic Displays. A dynamic image can show motion or change on a map by manipulating the data and symbols in time. Animation of map data can be achieved with corresponding temporal changes in the visual variables used. The visible symbol characteristics which can change through time are position, size, value, texture, color, orientation and shape (See FIGURE 18A). The introduction of time to the graphic image creates a new variable, the rate of change. The amount of visual change per temporal unit can be fast, slow, accelerating or decelerating.

Dynamic perspective views can manipulate shape and size characteristics in time to create the illusion of changing position and rotation in three-dimensional space relative to the viewer (See FIGURE 18B). Dynamic Digital Terrain Models can provide multiple views of the same relief being rotated about its center or translated to different positions, to the left or right and near or far (See FIGURE 19A).

The actual elevation data being represented by the Digital Terrain Model can be changed through time to give the visual impression of relief mutation (See FIGURE 19B).

The ability to explore dynamically the Digital Terrain Model surface compensates for the disadvantages of having a single point of view from one position.⁷ A series of images can provide a visual simulation of travelling across the terrain (See FIGURE 20). By exploring the relief in three dimensions the viewer can see areas of the surface which were previously out of view or blocked.

Auditory Displays and Variables

The ability to hear sound is an important part of sensing the environment. People communicate with speech by using the voice to create words. The vocal sounds are received by the ears, and if the language is understood, meaning can be derived from the sequence of vibrations. Included in language are more symbolic, non-verbal, vocal gestures. Laughing or crying and sneezing or coughing can indicate the emotional or physical state of the person emitting the sound. The realm of aural communication is vast and complex but people can successfully interpret each other's vocal gestures if the meaning of the sounds is understood.

Modern devices, such as radio receivers and telephones, rely exclusively on the use of sound transmission for information communication. There are also devices which are designed to interact with human speech. An electrical switch can be activated with the appropriate "On" or "Off" command. Security systems and computer data entry systems use voice recognition and decode the spoken words to permit access or store data.

High rates of data transmission can be achieved with devices such as the phone line communications MODEM. The MODEM modulates and demodulates sound to encode, transfer and decode many pieces of information per second. Of course, this method of communication is not intended to be decoded directly by the human auditory system. An older system of information transfer using sound signals which was developed to be within the capabilities of human hearing is the Morse code. By symbolizing letters of the alphabet as combinations of long and short tone bursts, words and numbers can be communicated as sequences of sounds. Although the Morse code system works, the actual rate of information encoding, transfer and decoding is quite slow. The use of speech to communicate data values orally is also quite cumbersome. Vocalizing the numbers "3, 25 and 4759.648", produces the complex phrase "three, twenty-five and four-thousand seven-hundred fifty-nine point six, four, eight". Similarly the use of language to make statements of quantity is very restrictive, e.g., many, few, high, low, greater than, less than.

However, within the range of human hearing are several audible variables which can be used to generate sound symbols. These recognizable characteristics of sound can be manipulated to produce meaningful series of signals to communicate data. The sound variables which can be sensed are the location of a tone's source, the tone's loudness, its frequency, timbre, and duration (See FIGURE 21). Like the visual variables used to create map symbols (location, size value, color, texture, orientation and shape) these audible characteristics of sounds can represent data values and convey information. Just as visual symbols allow better representation of relative quantities than does text, audible tones can provide a more sensible representation of values than does speech. Both the visual and aural senses have better abilities for detection and discrimination of symbols than can be provided by language and text. A simple use of an audible symbol is the ringing of a telephone. In this case, a loud tone bursts on and off at a set time interval. The frequency and timbre of the sound heard is produced by the bell and hammer inside the phone. The sound signals to the listener that someone wants to speak to them through the phone line. Using the capability provided by binaural hearing (having two ears) the listener can locate the source of the sound and respond. This is a simple on/off signal that commences when the number of the phone is dialed and ends when the receiver is picked up or when the caller cuts the request by hanging up.

More complex use of sound symbolism can communicate information about a particular system's operation, its present status or other special events. The sounds a car or elevator engine naturally produces can inform the user of its condition. The frequency, loudness and timing variations of the sound heard represents the engine's revolutions per minute and its workload. The sound "symbols" created by the engine can then aid mechanical diagnosis and maintenance. Other systems use artificially generated tones to symbolize operating status. Most often these coded sounds are used to signal a dangerous situation. The audible symbol can correspond to the importance of the event by increasing the loudness, frequency or duration of the tone heard as the necessity of a response becomes more crucial. This is more than just an on/off signal because the characteristics of the sound vary in relation to changes in the system. The range of coded tones (i.e., low to high frequency) is directly proportional to the information (i.e., low to high importance) to be communicated.

This type of coded tone generation has been used in a device that aids visually impaired people to navigate safely around physical objects. The device gives information about the distance ahead to objects by measuring the distance with sonar and then converting the value to an audible tone. The frequency of the tone heard is proportional to the distance so that close objects generate high

frequency tones and distant objects generate low frequency tones. This type of sound symbolism can be applied to data other than distance and is not restricted to use only by the visually impaired.

Applications of Sound. Sound should be used to convey information when:

- (i) there is a lack of visual information;
- (ii) the visual sense is already overloaded;
- (iii) attention is needed; or
- (iv) it simplifies complex events.

If there is no visual information or method to send and receive it, as would be the case with a blind person or a telephone conversation, it becomes advantageous to use sound transmission. Speech and audible signals can be used as a replacement for the visual communication of text and events (See FIGURE 22A). If visual communication is possible but the visual display is overloaded, as would be the case with a complex map, then audible information can be sent and received without adding to the visual work. Speech and tones can be used in combination with visual information because of the brain's ability to simultaneously "look" and "listen" (See FIGURE 22B).

Auditory signals also have superior attention-gaining capabilities compared to visual stimuli. If sufficiently loud, speech or tones will always be detected by the ear. Map readers may close their eyelids or look away from a visual display, but they can never close their ears (See FIGURE 22C).

In some cases auditory information can simplify complex events. An operating engine is too complex to be analysed visually but the sound it creates can represent minor variations of all its separate moving parts (See FIGURE 22D). Sound symbols can be generated that represent multiple data sets because the separate variable attributes of the tone, its frequency, duration, and timbre can be heard simultaneously. This is similar to being able to interpret visually the separate size, shape and color characteristics of a single pictorial symbol simultaneously.

The addition of sound symbols to terrain reading exercises is now possible because the display of animated Digital Terrain Models and the audition of sounds are both dynamic and can change correspondingly through time.

This research uses tones to symbolize the terrain relief qualities of selected Digital Terrain Models because the sound symbols can provide an additional model dimension without adding to the visual display. By using the frequency duration and modulation (timbre)

variables of sound the audible symbols can compress the terrain elevation, slope and orientation data into a series of tones. The attention-gaining qualities of the generated sounds will enliven the dynamic exploration of the Digital Terrain Model surface.

Audio-Visual Displays

The natural environment is experienced by people as a series of events in physical space. Natural occurrences are sensed as corresponding visual and aural events, i.e., lightening and thunder. The ability to capture both these sensory dimensions on film was a great advance from the silent film era. Silent movies quickly passed into obscurity because the picture, supplemented with only "cue card" dialogue and incidental live music did not provide the reality and simultaneity of the new "talkies". Now television and video (visual and audio) are widely available and used to display all types of information (See FIGURE 23). Most television programs broadcast "real" images with the "real" associated sound, e.g., a mouth moves and generates words. These are natural occurring events captured with cameras and microphones and when viewed appear "real". Another recent use of this technology is the production of music videos. Like television in general, music videos use largely natural sights and sounds; but unlike T.V. programs it is usually the music which guides the progression of the images. The

sounds are the primary sensory dimension and the visual images are selected and edited to correspond to the music. Animated cartoons use generated pictures and dubbed sounds to imitate and add humour to real experiences. Although "Bugs Bunny" may seem to walk and talk as a person would, the image is not real in the sense that one could see him walk down the street. The sounds used in cartoons are a combination of both real and artificial ones. An animated character may have an actual recorded human voice, but when struck over the head with a baseball bat, a resounding, comical "GONG" is heard, rather than the more disturbing real sound of the actual narrator being struck. Other common types of audio-visual displays include video simulations and games. Both of these use artificially generated sounds to support the visual events. Simulations usually attempt to provide sounds which mimic the real experience. A flight simulator might use a "drone" sound to represent engine noise, and although not real, the sound heard will change in response to the operator's actions much the same as it would in an actual cockpit situation.

Video games use different sounds to signal and symbolize events occurring on the visual display. In this case the use of sound symbols to represent successful scoring and game progression is advantageous because the game player can concentrate on the visual task at hand.

Types of Correspondences. All these audio-visual displays use a range of sight and sound correspondences which can be roughly grouped into physical, social and symbolic correspondence. A physical correspondence between a visual image and an audible sound results from natural events. An actual bus driving up a hill would produce the sound of a large diesel engine under stress (See FIGURE 24A). This correspondence is physical in that the sight and sound are generated by an actual object and the meaning attributed to the information is intrinsic to the situation. Even without seeing the bus the sound heard could still be identified correctly as "a large engine under stress".

Social correspondences of sight and sound describe those events which, although occurring simultaneously on a video display, are not physically related. An animated cartoon of the same bus driving up a hill would be accompanied by a "Vrooom" sound. Although most viewers would understand this event, the sound heard is not that of an actual engine, but a socially defined convention which represents motion. If one closed one's eyes and heard just "Vrooom", it is unlikely that the visual information "a bus" could be identified without also seeing the corresponding visual image (See FIGURE 24B). The use of background music in films is also a good example of socially defined correspondences of sight and sound. The sound of a string orchestra is not generated naturally by a romantic scene between actors. However, this musical score convention has created a social correspondence

between the image and the sound heard. Although not related in any manner other than occurring simultaneously in the film, they are not perceived to conflict with one another, and the meaning is understood.

A symbolic correspondence between sights and sounds describes the association of generated sounds with particular visual occurrences. As with any use of symbols, the meaning of the different symbols must be understood before any information can be read from them by the viewer. If in the model of a bus driving up a hill, a relationship between bus height and tone frequency is established, then the visual image would be accompanied by a tone sweeping from a low to a high frequency (See FIGURE 24C). This symbolic correspondence is similar to the socially defined type because the tone is not actually created by the visual object but simply occurs simultaneously. However, it is also like a physical correspondence, because having defined the symbolic association between the visual and aural information, the sound heard by itself can still be identified as a bus moving upward. Having established this symbolic relationship, a tone sweeping from a high frequency to a low frequency could be correctly interpreted as representing the bus going down the other side of the hill. The simultaneous display of the visual image with the corresponding sound symbolism creates a truly audio-visual display in which both the senses can be utilized. By sensing the display with both the visual and aural systems the viewer can gain a better understanding of the event than is possible with either sense individually.

Films and videos that are concerned with geographic phenomena have been produced which use "live" sound, narration and musical soundtrack material to support the visual image. These types of audio-visual products use only the physical and social correspondence of sights and sounds. The creation of a sound map will explore the capability of using a symbolic correspondence between the image seen and the sounds heard.

FIGURE 14**THE VISUAL SYSTEM****A. MAP READING** **B. VISIBLE LIMITS**

FIGURE 15

THE AURAL SYSTEM

A. HEARING SOUNDS

B. AUDIBLE LIMITS

FIGURE 16**MAPS AND VISUAL VARIABLES****A. VISUAL VARIABLES** **B. PERSPECTIVE VIEW** **C. DIGITAL TERRAIN MODEL**

FIGURE 17

PERSPECTIVE VS. MAP VIEWS

FIGURE 19

DYNAMIC DIGITAL TERRAIN MODELS

A. CHANGING ROTATION AND DISTANCE

B. CHANGING RELIEF

FIGURE 20**PERSPECTIVE VIEW EXPLORATION**

CHANGING RELATIVE POSITION

FIGURE 21

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AUDIBLE VARIABLES

POSITION

LOUDNESS

FREQUENCY

MODULATION

DURATION

FIGURE 22**APPLICATIONS OF SOUND****A. REPLACE VISUAL INFORMATION** **B. ADDITION TO VISUAL** **C. GAIN ATTENTION** **D. COMPLEX EVENTS**

FIGURE 23

AUDIO-VISUAL DISPLAYS

TELEVISION

MUSIC VIDEOS

CARTOONS

SIMULATIONS

VIDEO GAMES

FIGURE 24**TYPES OF CORRESPONDENCE****A. PHYSICAL CORRESPONDENCE**

ACTUAL SOUND

BUS MOVING

B. SOCIAL CORRESPONDENCE

INVENTED SOUND

CARTOON BUS

C. SYMBOLIC CORRESPONDENCE

PROPORTIONAL SOUND

MODELLED BUS

Sound Maps

The intention of creating sound symbolism for map data is not to replace the visual information but to use them in conjunction with the visual display to enhance the map reading experience. The addition of sound to a cartographic image is useful for communicating information which cannot be represented visually. A speaker presenting a map in a seminar situation, or the narration on a film can use speech to guide the viewer's attention and discuss related concepts. In some cases the use of sound, either speech or tones, is crucial to the success of a display. With an automobile dashboard street map display a voice speaking the words "Turn at next right" communicates the necessary navigational information without distracting the driver from the visual task of maneuvering the vehicle. In this example, forcing the map user to look constantly at the display to read the information could have disastrous results.

The combined use of visual and aural information takes advantage of a person's capability to watch and listen simultaneously. The human brain has the ability to divide its attention between the two senses. The conventional map reading process is a silent experience but would benefit from the addition of sound symbols. Both the visual and

aural dimensions have their own strengths which can be used to support each other. Sounds can provide information without having the map user sense it visually. Conversely, the visual sense is better at locating spatial information than is the aural. Together, the sound symbols provide aural information which can be placed visually at the appropriate location on the map.

The purpose of this research is to explore the potential of using sound as an aid to terrain analysis. The ultimate terrain experience would be the actual physical exploration of the relief. The perfect visual display of the relief would be the real landscape covered with map symbols at a scale of 1:1 to represent the characteristics of the terrain. Similarly, the ultimate sound would be the landscape covered with "Hi-Fi" speakers each playing an appropriate tone symbolizing the nature of the relief beneath it. A landform reader could then walk about the surface and see, as well as hear the changing elevations, slopes and orientations of the relief (See FIGURE 25A). These examples are unrealistic and could never actually be carried out, but they do indicate the purpose of developing a sound map.

The forte of cartography is the ability to model reality or provide a different view which is not obtainable by any other means. By reducing the scale of the landscape, classifying the data, and

symbolizing it, a model of the ultimate landscape experience can be created. Because this model can be dynamic it is a good substitute for exploring the actual terrain.

For this research, a contour representation of the terrain will serve as the initial stage in the creation of an audio-visual map. The contour map can then be converted into a Digital Terrain Model which explicitly represents the elevation, slope and orientation characteristics of the terrain in three-dimensional space. From this Digital Terrain Model sound symbols can be created which correspond to the characteristics of the terrain relief (See FIGURE 25B). To perform this symbolic association of three-dimensional space and sound, the visual attributes of the Digital Terrain Model surface need to be statistically transformed into aural variables. This process will generate an audio-visual display which simulates the ultimate experience of exploring a landscape covered with map symbols and speakers.

Symbolic Correspondence. The goal of this research is to define a logical symbolic correspondence between the qualities of sound and the nature of physical relief. The landscape itself does not, of course, emit natural sounds which symbolize its shape (See FIGURE 26A). There is no possibility of having a physical correspondence of sight and sound. A whole range of instruments and sound generators exist which could be used to create sounds symbolizing the relief. However,

conventional instrumentation, musical composition and orchestration techniques cannot be used. These methods would affect the perception of the sound map because of the social conventions already established concerning the correspondence of these types of sounds with particular visual images (See FIGURE 26B).

The Digital Terrain Model represents the relief as a continuous surface of polygon facets which are mutated in shape and size to represent differences in elevation. This surface can be associated with a corresponding continuous scale of tones. The smallest visual element of the Digital Terrain Model is the individual triangular polygon. The equivalent audible sound object is the single note. At this point a symbolic correspondence between the polygon characteristics and the qualities of the note can be defined (See FIGURE 26C).

The single polygons making up the surface vary in elevation, slope and orientation. A series of individual notes can vary in frequency, duration and timbre (or modulation). By matching the attributes of the polygons with those of the tones, a meaningful set of sound symbols can be created to represent the undulating relief. However, which attributes of the aural and visual dimensions should be paired together and made proportional to each other?

Variable Matching. The most logical symbolic correspondence is the note frequency varying with the polygon elevation, duration varying with slope and modulation varying with orientation (See FIGURE 26D).

Frequency is associated with elevation because they are both the fundamental variables of their respective symbol systems. Just as frequency is the most distinguishable aspect of a tone, elevation above the flat plane is the most noticeable property of a polygon. If the frequency of a tone was not within the audible range of 20 to 20,000 cycles per second there would also not be a detectable duration or modulation. Similarly, if there was no detectable polygon elevation, e.g., a perfectly flat surface, there would also be no slope or orientation characteristics. Both the elevations of a Digital Terrain Model and the audible range of frequencies have minimum and maximum limits which can be related to each other. Thus, low frequency tones are associated with low polygons and high frequency tones with high polygons (See FIGURE 27B). There is no good explanation for people's natural association of low notes with valleys and high notes with peaks. The relationship seems to be a cultural norm and reversing the definition is likely only to cause confusion.

The duration or length of a tone provides a second audible variable which can be related to a polygon's slope. If a tone has an audible frequency, then its duration can be sensed as well. Similarly,

if a polygon has a visible difference in elevation across its surface, then it also has a slope. Because the Digital Terrain Model is created with consistently spaced data points, variations in elevation cause the polygon facets to be stretched between their three corner points. The amount of area represented by a single polygon is a function of its slope. The size of polygons on a surface can vary from a minimum area, i.e., a flat polygon, to an infinite amount, i.e., a polygon stretched between two points of infinitely different elevations. Similarly, a series of tones can vary in duration from the minimal amount of time necessary to be detected, (a fraction of a second) to an infinite amount (a continuous tone can last forever). Thus, short note durations are associated with low polygon slopes (small areas) and long, sustained notes with high slopes (large polygon areas) (See FIGURE 27C). Although tone duration and polygon size are both infinite variables they are limited in practice by the physical size of the display device and the monotony of extremely long sounds. The symbolic correspondence between duration and slope (area) is easily understood because the length of the tones heard is proportional to the time necessary to visually explore polygons of different sizes.

The third aspect of sound symbolism is the correspondence of tone modulation with polygon orientation. If a polygon has a slope greater than zero, then it also has an orientation, i.e., the polygon faces a particular direction. This orientation can be specified as the

number of degrees east or west of 0° north that the polygon faces. The orientation of polygons on a Digital Terrain Model can vary from 0 to 180 degrees east and west of north. Similarly, the modulation of tones is achieved by varying the pure, fundamental frequency of the note up and down a number of cycles per second (Hertz, or Hz) at a very fast rate. Different modulation values produce sounds with different texture characteristics. A pure tone, i.e., 60 Hz, has a clear sound but as the modulation amount is increased from ± 0 Hz to ± 10 Hz the sound becomes audibly "muddy", i.e., a fundamental frequency of 60 Hz modulated ± 10 Hz would generate a tone which varies quickly between 50 to 70Hz. The orientation values of the polygons can be related to the modulation values by making the number of degrees east or west of north proportional to the number of cycles per second (Hz) added or subtracted from the fundamental frequency (See FIGURE 27D). A polygon facing due north would generate a pure tone, and as the orientation east or west varied, so would the amount of modulation. A polygon facing due south would have the maximum amount of modulation applied to its fundamental frequency. This correspondence of orientation and modulation is similar to the effect produced by hill shading since the surfaces facing towards the light source would be bright and generate clear tones, while surfaces facing away would be dark and generate muddy tones.

When all the notes representing the separate polygons are brought together they create a layer of sound symbols corresponding to the terrain relief (See FIGURE 28A). Each tone has frequency, duration

and modulation characteristics which symbolize the elevation, slope and orientation of each polygon (See FIGURE 28B).

Variables Not Used. Although there are five possible audible variables (location of source, loudness, frequency, duration and timbre or modulation) the location and loudness of sounds cannot be used in this system of sound symbol creation. Both the location of a tone's source and its loudness are perceptible qualities of sound but they are affected by the listening situation. The environment in which the sounds are heard influences these two variables unpredictably once the tones have been produced and released into the room. Frequency, duration and modulation are more consistent and controllable for communicating aural information.⁹

The apparent location of sounds generated by an audio display is dependent on the number and placement of speakers within the room relative to the listener. The apparent loudness of the sounds heard will also be influenced by the listener's location in the room relative to the speakers (See FIGURE 29A). For these reasons, the location of the sound's source and its loudness must remain external to the definition and creation of sound symbols. This is similar to the design of visual symbols because the cartographer cannot control the angle of the viewer relative to the map or the amount of light present while map reading.

Although uncontrollable at the design stage, minimum limits of sensation must be satisfied in the delivery of the audio-visual information. The visual image must be within the visible gaze angle and have a sufficient amount of reflected or emitted light (See FIGURE 29B). The source of the sound symbols should be in or near the same horizontal plane as the ears. This requirement can be ensured with the use of headphones. The sound source must generate a reasonable loudness of tones to permit the audition of subtle variations in frequency, duration and modulation. However, the loudness of the sound generator should be adjustable to the user's personal preference just as different map readers prefer various amounts of light.

Visual Location. The association of a sound with the location of its source polygon on the Digital Terrain Model surface must be established visually. The defined sound symbol once generated is only valuable when "seen" in relation to its visual counterpart, the corresponding polygon it represents. With a conventional map image the visual symbols must be displayed in their appropriate locations to allow the spatial extent of the data to be seen. The map user can then read the image through time with a sequence of eye motions and fixations (See FIGURE 30A). Similarly, the sound map user must be able to read a sequence of simultaneous sound symbols and terrain locations (See FIGURE 30B). The symbolic correspondence of the tones with the appropriate polygons depends on the temporal coincidence of the aural and visual information.

Sound and Shape. The basic triangular shape of the polygons, like their locations, must also be established visually. Sounds by themselves cannot represent shape characteristics. A set of tones cannot be manipulated in either location, loudness, frequency, duration or timbre to intrinsically symbolize a square, circle, star or geographic shape (See FIGURE 31A). However, if the shape of the visual variable is consistent, as is a regular grid of triangular polygons, sounds can symbolize the relative mutation of these similar shapes rather than attempting to differentiate the common shape from other shapes (See FIGURE 31B). Having established visually that the Digital Terrain Model is constructed with similar shaped triangular polygons, the frequency, duration and modulation characteristics of the tones heard can be interpreted as representing differences of elevation, slope and orientation, not differences in basic shapes. The visual illusion of three-dimensional space is achieved by the subtle mutation of polygon shapes. The sounds generated symbolize the amount and type of polygon mutation present as compared to a perfectly flat plane with no variation of elevation, slope or orientation.

Waveform Shape. The one aspect of sound which has a shape characteristic is the waveform of a tone. A waveform represents the "shape" of a tone by plotting the changing voltage of the wave in milliseconds of time. A pure tone can be represented in this manner as a sine wave. The number of cycles (+/- Voltage) per second of the wave

defines the frequency of the tone heard. The human hearing system is very sensitive to the frequency of a tone but cannot differentiate between wave shapes very well. A square wave, triangular sawtooth wave and a sine wave of the same frequency all sound the same (See FIGURE 32A).¹⁰

The change in a waveform through time is often drawn in a perspective view which creates a terrain-like surface (See FIGURE 32B). Although there is an apparent graphic similarity between this type of waveform specification and a digital terrain model there is no way of relating the two systems of representation. The initial waveform shape and any changes in it through time are not recognizable characteristics. Even if minor variations in wave voltage were detectable the variation occurs in milliseconds of time and would still not be a practical means of representing changes in elevation across space. The three dimensional appearance of the waveform graphic is produced by having two dimensions of time and one variation of voltage. The first of the time dimensions displays one cycle of the wave while the second shows a repetition of this cycle as it changes through time. If one was to link these dimensions to the three dimensions of a Digital Terrain Model (2 planar dimensions and one variation of elevation) the sound generated would be that of regularly spaced cross sections from the terrain put end to end and played extremely fast (See FIGURE 32C). Although this is possible, the resultant sound would not aid perception

of the relief because the elevation values of the visually continuous terrain surface have been displaced in time to create a single cyclical waveform.

Computer Sound Generation. The realization of the sound map concept is dependent on the use of computer-assisted techniques. The ability to generate dynamic Digital Terrain Models and manipulate the audible characteristics of tones to create a truly audio-visual display is a recent development. The increased availability and use of computer technology is expanding the possibilities for new symbol designs and applications.

It must be stressed that the only sound computer hardware actually makes is the whirring and klunking of the disk drives or an electronic "zap" when the system is turned on. It is the software that allows the technology to produce a wide range of sounds. Sound software is a set of executable instructions which can specify the frequency, duration and modulation of the sounds created. The computer hardware and software can generate tones which are both more precise and flexible than the types of sounds which can be produced with conventional instruments. The major advantage of this new technology is the ability to use a set of numerical data as the drive for sound generation.¹¹ For sound map creation, the production of sound symbols which represent polygons can be achieved by transforming the elevation, slope and orientation data into the frequency, duration and modulation values of the tones.

The tones generated by the software used for this research are simple square waves with few overtones or harmonics. Although these sounds are less pleasant to the ear than most, and not very musical, they benefit from also not having any socially learned, preconceived definition of what they mean, as do the tones produced by conventional instruments.

The sound symbols created are consistent with the terrain data and represent the values in the same manner that a series of visual textures are used to symbolize a range of data on a choropleth map. The black and white textures on a map and the tones produced by a sound map are similar in that they have no intrinsic meaning other than that attributed to them by the map maker. With conventional maps the symbolic association between the visual variable, i.e., textures and the data values, e.g., population, is communicated to the map reader through the use of a legend. Similarly the sound map user must be made aware of the symbolic correspondence of sight and sound for the symbols to have meaning.

The simplicity of the square wave sound allows the listener to concentrate on the perception of the tone's frequency, duration and modulation characteristics. The ability of the computer software to generate tones of slightly different qualities provides a full range of audible symbols to differentiate polygon properties and represent the form of the relief.

Terrain Exploration. Now that the terrain relief has been translated into a set of notes, which particular notes should be played and in what order? The playing of the different sounds representing the relief will be based on the exploration of the relief through time and/or the changes in the relief over time. A single tone is meaningless if the viewer cannot attribute it to the corresponding visual element which created the sound. Because a sequence of notes is temporally ordered the associated polygons must also be perceived as a visual sequence.

The simultaneous displaying of the visual image and playing of the tones creates a synthesized audio-visual display in which the different senses can support each other.

The provision of dynamic visual information is necessary for the viewer to be able to locate the sources of the sound symbols. This is a situation similar to that of a seminar map presentation because the speaker must visually point out the particular areas being discussed for the verbal description to be perceived in the proper sequence. Consequently, a sound changing through time can aid in the perception of a dynamic visual image. If an animated map displayed the increasing values of the mapped data over a period of time, a corresponding tone sweep from low to high frequency would reinforce the viewer's perception of the rate and amount of change.

There are four different ways of exploring the terrain relief. Each of these takes advantage of the way the dynamic visual and aural information support one another. A simple path can be traversed visually across the digital terrain model and a sequence of sounds generated. The tones heard would be those created by the polygons which were visited along the path (See FIGURE 33A). A multiple-layer path can be traversed across separate surfaces and each will represent the Digital Terrain Model with different amounts of generalization. As with the simple path, the sequence of tones heard would be that of the polygons visited, but the terrain "traveller" could also jump from one surface to another (See FIGURE 33B). Both these methods of terrain exploration generate tones based on the changing location of the viewer through time relative to the whole surface.

A terrain which is undergoing relief changes through time can generate tones that represent the amount and type of surface mutation. If the viewer selects a polygon to listen to the changing elevation, slope and orientation characteristics of the polygon will be reflected in the dynamic frequency, duration and modulation attributes of the tone heard (See FIGURE 33C).

If the terrain is not actually changing, but is moving in three dimensions relative to the viewer, sound symbols can be generated to represent this motion. By making the frequency, duration and

modulation characteristics proportional to the physical limits of the display device, the changing position, rotation and distance (size) of the terrain will affect the tones heard (See FIGURE 33D). The tone created by a selected polygon will now represent the polygon's vertical position on the display (not elevation) with frequency, its absolute size (not slope) with duration, and its aspect relative to the viewer's position (not orientation from north) with modulation.

These active terrain reading methods will provide sequences of simultaneous visual and aural information. The definition of paths across the surface uses the visual dimension to reinforce the audition of the tones. The exploration of changing and moving surfaces uses the audible variation of the tones to reinforce the dynamic visual image.

The exploration of a sound map could be performed interactively or be recorded and used as additional soundtrack material on films which present information with cartographic images. The use of sound symbols on films would provide a more meaningful audio track than the conventional use of incidental, orchestrated music. Most composed music uses the sounds of instruments being played by musicians. These sounds are then arranged and ordered in time by the composer. A sound map system creates the notes from the actual terrain relief values, and the composition or sequencing of the tones is based on the dynamic exploration of the relief. This method produces a symbolic

correspondence between the visual and aural information. Conventional soundtrack material relies on the social correspondence of particular sights and sounds and the audible information does not relate directly to the visual image (See FIGURE 34).

The proposed system of sound map creation generates notes which are within the aurally detectable limits of frequency, duration and timbre (modulation). The separate notes each represent the elevation, slope and orientation values of the single polygons making up a Digital Terrain Model. Because of the acuity of the hearing system, the sound symbols can make subtle variations in the shape of the polygons a more distinguishable model characteristic. By exploring the Digital Terrain Model dynamically and simultaneously displaying the visual and aural information, the viewer can better evaluate the terrain relief.

FIGURE 25**ULTIMATE VS. SOUND MAP MODEL****A. ULTIMATE TERRAIN EXPLORATION**LANDSCAPE WITH
AUDIO SPEAKERSLANDSCAPE WITH
VISUAL SYMBOLISMACTUAL
LANDSCAPE **B. DISPLAY MODEL SUBSTITUTES**CONTOUR
MAPDIGITAL
TERRAIN
MODELSOUND
SURFACE

FIGURE 26

SYMBOLIC CORRESPONDENCE

A. NO PHYSICAL CORRESPONDENCE

B. NO SOCIAL CORRESPONDENCE

C. SYMBOLIC CORRESPONDENCE

D. ATTRIBUTE MATCHING

FREQUENCY
DURATION
MODULATION

ELEVATION
SLOPE
ORIENTATION

DECREASING

SCALE

FIGURE 27

POLYGON-NOTE ASSOCIATION

A. PERCEPTION SYSTEM

B. ELEVATION TO FREQUENCY

C. SLOPE TO DURATION

D. ORIENTATION TO MODULATION

FIGURE 28

SURFACE OF NOTES

A. COMBINED NOTE ATTRIBUTES

NOTE 1 NOTE 2 NOTE 3 NOTE 4 NOTE 5

NOTE
SURFACE

B. SEPARATE NOTE ATTRIBUTES

FREQ.	40	120	537	1425	2370
DURA.	5.2	6.4	9.1	10.4	13.3
MODU.	+/-3	+/-2	+/-4	+/-5	+/-6

POLYGON #1 #2 #3 #4 #5

DIGITAL
TERRAIN
MODEL

FIGURE 29

FACTORS INFLUENCING AUDITION

A. VARIABLE LOUDNESS-LOCATION

B. OPTIMUM SITUATION

FIGURE 30

LOCATING SOUND SYMBOLS

A. VISUAL MAP READING

B. SOUND MAP READING

FIGURE 31

SOUND AND SHAPE

A. SOUND CANNOT REPRESENT DIFFERENT SHAPES

B. SOUND CAN REPRESENT DIFFERENCES BETWEEN SIMILAR SHAPES

FIGURE 32

WAVEFORM SHAPE

A. WAVEFORM SHAPE IS NOT RECOGNIZED

60 HZ SINE WAVE

FREQUENCY IS
DOMINANT
ATTRIBUTE

60 HZ SAWTOOTH WAVE

60 HZ SQUARE WAVE

EAR
SENSES
60 HZ

ALL WAVES
SEEM THE
SAME

B. 3-D WAVEFORM IMAGE

C. IMPERCEPTIBLE ASSOCIATION

A 3-D SURFACE IS NOT SENSED VISUALLY
AS A SERIES OF LINEAR CROSSECTIONS

FIGURE 33**POSITION AND SOUND ASSOCIATION****A. SIMPLE PATH** **B. MULTIPLE LEVEL PATH** **C. TERRAIN MUTATION,** **D. TERRAIN MOTION**

FIGURE 34**SYMBOLIC VS. CONVENTIONAL SOUND**

METHOD

The creation of sounds to symbolize physical relief is the result of a process of terrain representation and data transformation. The physical relief, as represented in map view with contours, is sampled at regular intervals and the elevation values are transferred into the three-dimensional Digital Terrain Model format (See FIGURE 35A). The Digital Terrain Model provides a representation of the relief as a continuous surface of polygons which have individually detectable qualities of elevation, slope and orientation (See FIGURE 35B). By quantifying these physical attributes and translating them into the audible variables of frequency, duration and modulation, a sound surface of separate notes representing the relief is created (See FIGURE 35C). Because the sound symbols are temporal, i.e., sensed through time, the sound map must be actively explored in time to order the tones generated. The sequence of tones heard will be the result of exploring the Digital Terrain Model surface and the simultaneous displaying of the notes and their source polygons (See FIGURE 35D). The following sections will describe the creation of dynamic Digital Terrain Models, the transfer of the polygonal data from physical to sound characteristics, and the ways in which the terrain can be explored to generate sequences of sound symbols.

Creating Digital Terrain Models

To test the ability of sound to represent relief, three different terrains were used in this research. This ensured that the system of data conversion and sound generation was consistent and applicable to a variety of relief types.

The contour maps used as the initial stages of sound map production are different hypothetical surfaces created by the author. These can be described as representing low relief (See FIGURE 36A), mixed relief (See FIGURE 36B) and high relief (See FIGURE 37 A). To create Digital Terrain Models of these landforms each map was sampled spatially at a regular interval (See FIGURE 37B). A 10 by 10 grid of sample points yields 100 elevation values representing the surface (See FIGURE 38A). This type of data table can be used to create perspective views of the relief represented as a series of cross sections (See FIGURE 38B). However, to create individual areal facets, or polygons, each group of 4 neighboring points were averaged to create a new center point with an appropriate elevation value. This center point serves as the shared corner of the 4, three-sided polygons formed (See FIGURE 39A). When this process is repeated for all the elevation values a sheet of triangular polygons is created (See FIGURE 39B). These Digital Terrain Model surfaces are now in a suitable format to be displayed as perspective views and dynamic images on the computer graphics screen. The three different contour maps can now be seen as

three dimensional models of high relief (See FIGURE 39B), low relief (See FIGURE 40A), and mixed relief (See FIGURE 40B). These Digital Terrain Models display a wide range of different landform characteristics. The Digital Terrain Models can be displayed in the normal manner, with hidden polygons removed (See FIGURE 41A), with the individual polygons separated (See FIGURE 41B) or with all the polygons shown, including those behind others (See FIGURE 41C).

Definition of Polygonal Data

The Digital Terrain Model representation can now provide the necessary elevation, slope and orientation data for the creation of sound symbols. By contouring the three dimensional relief (See FIGURE 42A), the elevation of each polygon can be specified as its average elevation above the flat plane. The slope can be defined as the change in elevation across the polygon's extent. The polygon's orientation with respect to north can be derived from the angle of a line drawn perpendicular to the contours in the down-slope direction (See FIGURE 42B).

These different qualities of the relief can be mapped in a conventional manner by shading the polygons with an appropriate range of textures. This is similar to the mapping of spatially continuous data, but the values are plotted for the separate polygon areas. Compared to

the conventional mapping of surface elevation, slope and orientation the representation of discrete polygon values produces a more coarse image (See FIGURES 43, 44 and 45).

Although these three different attributes cannot be visualized simultaneously with visual symbolism in map view, label maps of the polygon data can be created. This type of representation documents the actual elevation, slope and orientation values of the individual polygons of each of the different terrain types (See FIGURES 46, 47 and 48). The high, mixed and low relief terrains were all created within the equal limits of elevation at the same relative scale. The polygon elevation values can range from a minimum of 0 units to a maximum of 9 units. The slopes of the polygons (defined as change in elevation) can also range from 0 to 9 units. For simplification, the orientation of polygons with respect to north is represented as 20 aspect sectors of 18 degrees each. The possible range of polygon orientations from 0 to 360 degrees corresponds to the values ranging from 0 to 19. The 20 sectors are numbered counter-clockwise from north (0) through due west (5) to the south (10), to due east (15), and then back to north through the values 16 to 19. It is these values of elevation, slope and orientation which will be transferred into the sound variables of frequency, duration and modulation to create a tone for each polygon.

2

Microl

FIGURE 37

88

CONTOUR MAP AND SAMPLING

**A. HIGH
RELIEF**

MIN.=0 UNITS

MAX.=9 UNITS

B. 10 X 10 SAMPLE GRID

YIELDS
100 ELEVATION
POINTS

The different sound symbols generated by the generalized surfaces create a wider range of tones to describe the relief of a particular terrain and also to compare the terrains to each other.

FIGURE 35

STAGES OF SOUND MAP CREATION

A. REPRESENTING LANDSCAPE B. CREATING D.T.M. C. CREATING SOUNDS

CONTOUR MAP

SAMPLED MAP

D. EXPLORATION

NOTE SEQUENCE

FIGURE 36

CONTOUR MAPS

A. LOW RELIEF

MIN.=0 UNITS

MAX.=3 UNITS

B. MIXED RELIEF

MIN.=0 UNITS

MAX.=6 UNITS

FIGURE 37

88

CONTOUR MAP AND SAMPLING

A. HIGH
RELIEF

MIN.=0 UNITS

MAX.=9 UNITS

B. 10 X 10 SAMPLE GRID

YIELDS
100 ELEVATION
POINTS

FIGURE 38

CREATING PERSPECTIVE VIEW

A. SAMPLED DATA

B. PERSPECTIVE VIEW

FIGURE 39**CREATING POLYGONAL SURFACES****A. NEW CENTER POINTS**

CENTER POINT
IS AVERAGE OF
NEIGHBOURS

**B. D.T.M. MADE
OF POLYGONS**

SUITABLE FOR
3-D MODELLING

FIGURE 40

91

DIGITAL TERRAIN MODELS

A. LOW RELIEF D.T.M.

B. MIXED RELIEF D.T.M.

FIGURE 41

DISPLAY MODES

A. HIDDEN
LINES
REMOVED

B. SEPARATED
POLYGONS

C. ALL POLYGONS
TRANSPARENT

FIGURE 42**DEFINING POLYGON DATA**

A. CONTOURED
DIGITAL
TERRAIN
MODEL

HIGH
RELIEF
D.T.M.

B. SEPARATE POLYGONS

DATA FOR
EACH
POLYGON

AVE. ELEVATION

SLOPE
(CHANGE IN ELE.)

ORIENTATION
(W.R.T. NORTH)

FIGURE 43

MAPPING ELEVATIONS

A. SHADED
ELEVATION
RANGES

HIGH

LOW

B. POLYGON
ELEVATION
VALUES

HIGH

LOW

HIGH RELIEF
D.T.M.

FIGURE 44

MAPPING SLOPES

A. SHADED
SLOPE
RANGES

HIGH

LOW

B. POLYGON
SLOPE
VALUES

HIGH

LOW

HIGH RELIEF
D.T.M.

FIGURE 45

MAPPING ORIENTATIONS

A. SHADED
ORIENTATION
RANGES

0 DEGREES (N)

+/-180 (S)

B. POLYGON
ORIENTATIONS

0 DEGREES

+/-180 (S)

HIGH RELIEF
D.T.M.

FIGURE 51

DIFFERENT LEVELS - LOW RELIEF

FIGURE 47

DATA VALUES - MIXED RELIEF

LABELS

1 = ELEVATION (0-9)

#2 = SLOPE (0-9)

#3 = ORIENTATION (0-19)
(N=0 W=5 S=10 E=15)

FIGURE 48

99

DATA VALUES - LOW RELIEF

LABELS

#1 = ELEVATION (0-9)

#2 = SLOPE (0-9)

#3 = ORIENTATION (0-19)
(N=0 W=5 S=10 E=15)

FIGURE 49

100

CREATING GENERALIZED LEVELS

A. LARGER SAMPLING INTERVALS

B. FEWER POLYGONS 36 POLYGONS

4 POLYGONS

C. GENERALIZED D.T.M. SURFACES

FIGURE 50

DIFFERENT LEVELS - HIGH RELIEF

FIGURE 51

DIFFERENT LEVELS - LOW RELIEF

FIGURE 52**DIFFERENT LEVELS - MIXED RELIEF**

FIGURE 53**DEFINING POLYGON DATA****A. CONTOURED POLYGONS**36 POLYGON
SURFACE **B. POLYGON
VALUES**ELEVATION
(0-9)SLOPE
(0-9)ORIENTATION
(0-19)

FIGURE 54**DEFINING POLYGON DATA****A. CONTOURED POLYGONS**4 POLYGON
SURFACE **B. POLYGON
VALUES**ELEVATION
(0-9)SLOPE
(0-9)ORIENTATION
(0-19)

FIGURE 55

**DATA
VALUES
LOW
RELIEF**

**36 POLYGON
SURFACE**

**4 POLYGON
SURFACE**

FIGURE 58

DATA VALUES MIXED RELIEF

36 POLYGON
SURFACE

4 POLYGON
SURFACE

Creating Sound Surfaces

Now that the terrain relief has been represented with polygons and the physical variables of elevation, slope and orientation have been specified, the translation of these quantities into the corresponding sound attributes of frequency, duration and modulation must be carried out.

Elevation to Frequency Conversion

The terrain models used in this research were all created at the same scale within a 9 unit cubic space. The maximum variation of polygon elevations possible in this three-dimensional volume ranges from 0 to 9 units. This range of elevation will be mapped into an audible variation of frequency.

Although the extreme frequency limits of human hearing are between 20 Hz and 20,000 Hz, only a portion of this range is necessary to create a series of recognizable sound symbols (See FIGURE 57A). The detectible range of frequencies is limited in practice to a smaller range. The hearing capabilities of individuals decreases with age and the detection of frequencies begins to fall off above approximately 12,000 Hz (See FIGURE 57B). The usable range of frequency is further limited because tones above 10,000 Hz cause discomfort in most listeners

(See FIGURE 57C). Any music using conventional instruments has notes which are generally under 8,000 Hz frequency (See FIGURE 57D). For example, the highest note a piano creates is 7,900 Hz, middle A is approximately 440 Hz. The highest sensitivity of the aural system to frequency is in the range of 1,000 Hz to 3,000 Hz (See FIGURE 57E). For this research a range of frequencies from 40 Hz to 4,500 Hz is used to represent elevation (See FIGURE 57F).

The ability of a listener to discriminate changes in the frequency of notes will affect the perception of changes in elevation the notes represent. The detection of frequency change varies with the initial frequency of a tone, but the minimum amount of change necessary is generally within the range of 2 Hz to 4 Hz. The variation in physical elevation from 0 to 9 units can be represented with a range of approximately 4,400 Hz ($4,500 - 40$) and provides at least 1,100 ($4,400/4$) recognizable values of frequency (See FIGURE 57G). The variation of frequency chosen for the creation of sound symbols is well within the limits of human hearing and provides an extensive range of tone frequencies to represent polygon elevations.¹²

The elevation values for each polygon of the 10 by 10 sample grid can now be converted into the frequency range of 40 Hz to 4,500 Hz (See FIGURE 58 for high relief example). The 324 polygons each have a frequency value attributed to them corresponding to their relative

elevations above the flat plane. The 4 by 4 and 1 by 1 sample grid terrain surfaces represent the relief with fewer polygons and do not need as large a range of frequencies to create a distinguishable series of tones. These larger sample grid sizes produce coarse representations of the relief and are less capable of capturing the intricate nature of the surface. Correspondingly, the elevation values can be mapped into smaller ranges of frequency. The complexity of the different levels of generalization and their potential to represent the relief is directly related to the frequency limits of the tones they can generate. The 36 polygon and 4 polygon surface values are translated into the frequency ranges of 40 Hz to 1,500 Hz and 40 Hz to 500 Hz respectively. These changes of range represent an even reduction of 1/3 for each level down from the maximum of 40 Hz to 4,500 Hz (See FIGURE 59). These compressed ranges will minimize the extreme jumps in frequency which would otherwise occur between the large polygon areas. This will maintain the sensation of a connected surface of polygons at each level of generalization, as well as ensure that these different levels produce audibly different types of tones. The elevation values for each polygon of these surfaces can now be converted into the appropriate frequency range (See FIGURES 60 and 61 for high relief example).

orientation relative to the north-south axis (See FIGURE 69 for low relief example). This can be performed for all the polygons of all the different levels of generalization (See FIGURES 70 and 71).

The conversion of the physical qualities of elevation, slope and orientation to the sound variables of frequency, duration and modulation creates a sound symbol for each polygon. The notes generated can vary in frequency from 40 to 4,500 Hz, in duration from 3 ticks (1/6 of a second) to 54 ticks (3 seconds), and in modulation from ± 0 Hz to ± 6 Hz (See FIGURE 72). The sound generated by each polygon has all three of these variables encoded in it. A single sound symbol note has a fundamental frequency which lasts for a specified duration and is modulated a particular amount from this frequency throughout its duration. This process creates an extensive range of different notes to represent the polygons.

These three note attributes can be mapped for each polygon of the three different levels of generalization by labelling the actual values (See FIGURES 73 and 74). The different relief characteristics of the high, mixed and low relief terrains can be seen in the actual range of frequencies, durations and modulations generated by the polygons representing the different surfaces (See FIGURE 75).

4 polygon surface which had the maximum slope value (See FIGURE 62B). These limits of minimum and maximum polygon area will correspond to the limits of tone duration.

The computer note generator does not use seconds as the unit of time, but instead is based on a clock which uses "TICKS" of time. One second of normal time is equal to approximately 18 computer ticks (T). Within the computer system a "sixteenth" note of standard musical duration (0.136 seconds) would be represented as approximately 3 ticks. A "whole" note's duration (2.18 seconds) would be equal to 40 ticks. If the minimum audible duration of a tone is set to 3 ticks for the smallest polygon of a 324 polygon surface, then the largest polygon of a 4 polygon surface will have a duration greater than 81 times this value based on its relative size. This would generate extremely long notes with duration values in excess of 243 ticks, or 13.5 seconds (243/18) (See FIGURE 62A).

The range of minimum and maximum duration values must be reduced to shorten the longest notes. Because the change in polygonal area does not increase linearly between the different levels of generalization, the ranges of duration values which will never be used can be removed from the specification of sound symbols. This compensates for the fact that a single polygon of a 324 polygon surface

can increase in area by a factor of 9 as the slope varies from 0 to 9 units, whereas a single polygon of a 36 polygon surface can increase in area by a factor of only 3 for the same range of slope. Similarly, a single polygon of a 4 polygon surface can only increase in area by a factor of 1.4. Because the occurrence of polygonal slopes greater than 6 units are quite rare, the total range of tone durations can be further compressed by removing the unused portions that would have represented high slopes (See FIGURE 63).

The slope values for the 10 by 10 sample grid terrains were converted into the duration range of 3 ticks to 18 ticks. The slope values for the 4 by 4 and 1 by 1 terrains were converted into the duration ranges of 18 T to 36 T and 36 T to 54 T respectively (See FIGURE 64). The variable durations of the tones generated will represent the relative areal extent (slopes) of the polygons within a particular terrain surface. Also, the different generalized surfaces will have increasingly longer notes which correspond to the larger polygonal sizes (See FIGURES 65, 66 and 67 for mixed relief example).

Orientation to Modulation Conversion

The orientation of the polygons on the terrain surface will be converted into the amount of modulation in the tones generated. The purity of the note will correspond with the direction the polygon faces with respect to north.

The polygon orientations were divided into 20 sectors of 18 degrees each representing the possible range of 360 degrees (See FIGURE 68A). The modulation of a note is defined by the amount of change in the note's fundamental frequency. The perceived purity of a tone can be manipulated by varying its frequency up and down by small amounts. This modulation of the fundamental frequency is done at a very small time interval throughout the total duration of the note. The variable modulation amounts create a series of tones with different sound textures.

The limits of modulation used to create sound symbols cover the range from ± 0 Hz to ± 6 Hz. This range provides a wide variety of tone characteristics as well as ensuring that the audition of the fundamental frequency is still possible. If the initial frequency of a note, as set by the elevation value of the polygon, is modulated too much, i.e., ± 50 Hz then the fundamental frequency value would become imperceptible.

A north facing polygon will generate a pure frequency tone with ± 0 Hz modulation characteristics. A south facing polygon will have the maximum amount of modulation applied to its frequency, ± 6 Hz. Polygons facing due east and west will have equal modulation values of ± 3 Hz (See FIGURE 68B). Each polygon of the terrains can now be given a modulation value corresponding to their east or west

orientation relative to the north-south axis (See FIGURE 69 for low relief example). This can be performed for all the polygons of all the different levels of generalization (See FIGURES 70 and 71).

The conversion of the physical qualities of elevation, slope and orientation to the sound variables of frequency, duration and modulation creates a sound symbol for each polygon. The notes generated can vary in frequency from 40 to 4,500 Hz, in duration from 3 ticks (1/6 of a second) to 54 ticks (3 seconds), and in modulation from ± 0 Hz to ± 6 Hz (See FIGURE 72). The sound generated by each polygon has all three of these variables encoded in it. A single sound symbol note has a fundamental frequency which lasts for a specified duration and is modulated a particular amount from this frequency throughout its duration. This process creates an extensive range of different notes to represent the polygons.

These three note attributes can be mapped for each polygon of the three different levels of generalization by labelling the actual values (See FIGURES 73 and 74). The different relief characteristics of the high, mixed and low relief terrains can be seen in the actual range of frequencies, durations and modulations generated by the polygons representing the different surfaces (See FIGURE 75).

To visualize the three components of the sound symbols simultaneously the values can be mapped with multi-variable point symbols for each polygon. This type of visual symbolism allows the frequency, duration and modulation quantities to be synthesized into a single proportional symbol which is similar to the way these characteristics would be perceived aurally. The frequency of the tone generated by a polygon can be represented as the height of a triangular point symbol (See FIGURE 76A). The duration of the tone will correspond to the width of the triangle's base (See FIGURE 76B). The amount of modulation will be represented as different symbol area shades varying from light (+/- 0 Hz) to dark (+/- 6 Hz) (See FIGURE 76C). The various notes generated by the terrains, at all three levels of generalization, can be seen with this type of visual sound symbolism. The high-relief terrain model creates a large number of long, high frequency notes (See FIGURES 77, 78 and 79). Conversely the low-relief terrain model generates mostly low frequency, short notes (See FIGURES 80, 81 and 82). The mixed-relief terrain exhibits a wide variation of different note qualities (See FIGURES 83, 84 and 85). This type of visual note symbolism will be used in the next section to show the sound qualities of the note sequences generated by the dynamic exploration of these terrains.

FIGURE 57

FREQUENCY RANGES

AUDITORY
ABILITIES

POLYGONS VARY
IN ELEVATION
FROM 0 TO 9 UNITS

FIGURE 58**FREQUENCY
VALUES** **A. POLYGON
ELEVATION** **B. POLYGON
FREQUENCY**

FIGURE 59**GENERALIZED FREQUENCY RANGES**

FIGURE 60

120

**FREQUENCY
VALUES**

**A. POLYGON
ELEVATION**

**B. POLYGON
FREQUENCY**

162	300	429			
154	300	405	567	583	486
283	673	608			
348	721	600			
243	527	608	559	527	405
405	462	324			
364	405	251			
186	421	446	364	316	251
218	405	316			

FIGURE 61

121

**FREQUENCY
VALUES**

**A. POLYGON
ELEVATION**

**B. POLYGON
FREQUENCY**

FIGURE 62**PROPORTIONAL AREA TO DURATION CONVERSION**

FIGURE 63

ADJUSTED SLOPE CONVERSION

FIGURE 64
DURATION RANGES

FIGURE 65**DURATION
VALUES**

**A. POLYGON
SLOPES**

**B. POLYGON
DURATIONS**

FIGURE 66**DURATION
VALUES** **A. POLYGON
SLOPES** **B. POLYGON
DURATIONS**

25	21	19	
23	25	25	21
23	27	23	
23	27	23	
23	22	23	20
22	22	20	
22	23	21	
24	23	24	21
23	23	22	

FIGURE 67**DURATION
VALUES** **A. POLYGON
SLOPES** **B. POLYGON
DURATIONS**

FIGURE 68

MODULATION RANGES

A. ORIENTATION SECTORS

B. MODULATION RANGES

FIGURE 69

MODULATION VALUES

A. POLYGON ORIENTATION

B. POLYGON MODULATION

FIGURE 70**MODULATION
VALUES** **A. POLYGON
ORIENTATION** **B. POLYGON
MODULATION**

	1.8		1.8		3.0	
1.8		1.8	1.8	2.4	0.6	6.0
	1.8		2.4		3.6	
3.6		1.8		0.6		
4.2	2.4	1.8	1.2	0.0	0.0	
	3.0		1.2		0.0	
3.6		5.4		5.4		
1.8	5.4	6.0	6.0	5.4	5.4	
	5.4		5.4		6.0	

FIGURE 71**MODULATION
VALUES** **A. POLYGON
ORIENTATION** **B. POLYGON
MODULATION**

FIGURE 72**COMBINED SOUND SYMBOL RANGES**

FREQUENCY

DURATION

4500

3

1500

18

500

36

40
HZ ± 3 ± 0

HZ

 ± 6

MODULATION

 ± 3 54
TICKS

FIGURE 73**SOUND DATA - HIGH RELIEF****LABELS**

#1 = FREQUENCY (40-4500)

#2 = DURATION (3-18)

#3 = MODULATION (0-6)
(N=0 W=3 S=6 E=3)

FIGURE 74

SOUND DATA HIGH RELIEF

36 POLYGON SURFACE

4 POLYGON SURFACE

FIGURE 83 **MIXED RELIEF:
324 POLYGON
SURFACE****NOTE SYMBOLS**

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 77 **HIGH RELIEF:
324 POLYGON
SURFACE****NOTE SYMBOLS**

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 78 **HIGH RELIEF:
36 POLYGON
SURFACE****NOTE SYMBOLS**

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 79 **HIGH RELIEF:
4 POLYGON
SURFACE****NOTE SYMBOLS**

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 80

TILT PAGE TO VIEW

**LOW RELIEF:
324 POLYGON
SURFACE**

NOTE SYMBOLS

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 81

**LOW RELIEF:
36 POLYGON
SURFACE**

NOTE SYMBOLS

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 82

142

LOW RELIEF: 4 POLYGON SURFACE

NOTE SYMBOLS

FREQUENCY = HEIGHT

DURATION = WIDTH

MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 83

TILT PAGE TO VIEW

**MIXED RELIEF:
324 POLYGON
SURFACE****NOTE SYMBOLS**

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 84 **MIXED RELIEF:
36 POLYGON
SURFACE****NOTE SYMBOLS**

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

FIGURE 85 **MIXED RELIEF:
4 POLYGON
SURFACE****NOTE SYMBOLS**

FREQUENCY = HEIGHT
DURATION = WIDTH
MODULATION = SHADE

COMPLETE SYMBOL DEFINITION ON FIGURE 76

RESULTS

Exploring Terrains

Now that audible symbols have been defined for each polygon of the Digital Terrain Models, a note surface representing the relief has been created. This surface of spatially connected notes cannot be heard all at once, i.e., 324 notes simultaneously, so it must be actively explored to generate a series of individual tones. The sequence of sound symbols generated will correspond to a change in location on the terrain and/or changes in the terrain relief. The association between the tones heard and the polygons they represent remains primarily a visual task. If no visual information is given then the sounds cannot be related to the polygons which they represent (See FIGURE 86A). However, if a coordinated sequence of visual and aural information is displayed, the symbolic correspondence of the data is maintained (See FIGURE 86B).

The sound symbols were not created to replace the visual images but to reinforce the analysis of relief elevation, slope and orientation with an additional perceptual dimension (See FIGURES 87A and 87B). The ability to use sound symbolism, which is fundamentally dynamic is both dependent on the simultaneous use of dynamic map displays and beneficial to the perception of these more complex dynamic

map images. There are four types of display dynamics studied in this research to test the use of corresponding visual and aural information (See FIGURE 87C).

- (i) The terrain can be explored by walking on it, or defining a path to be displayed.
- (ii) A multiple level path allows the major trends in the relief to be explored at one or more levels of terrain generalization.
- (iii) The terrain can be explored while it is undergoing changes in relief through time.
- (iv) The exploration of the terrain can involve its motion and change of position relative to the viewer's perspective.

In all these cases, the tones heard which symbolize the relief elevation, slope and orientation will be those generated by the series of locations specified. In the first two instances, changes in notes will be the result of changing positions from one polygon to another. The third and fourth methods of terrain exploration will generate notes which change according to the temporal variation in the specified polygon's characteristics, i.e., change in elevation, or location on the display device. The complexity of the symbolic correspondence between

the aural and visual information presented increases from the simple path exploration technique (i) through to the relative motion application (iv). Each of the four methods of terrain exploration can now be performed on the three different terrain types. The descriptions that follow are from a terrain reader's point of view and present the aural and visual experiences that would occur while exploring the sound map surfaces.

Simple Path

The terrain reader starts by standing on a particular polygon of a surface (See FIGURE 88A). The elevation of this polygon can be seen in relation to how high or low it is relative to the flat plane. A tone is heard which has a frequency proportional to this elevation (See FIGURE 88B). The terrain reader can sense the slope, and areal extent, of the polygon by having to compensate for this to maintain his balance. The tone heard will last a certain length of time based on the size and slope of the polygon (See FIGURE 88C). The direction of this slope can be sensed by the reader through orienting himself with respect to north. The tone heard modulates accordingly (See FIGURE 88D).

To start walking, the terrain reader must first decide which one of the neighbouring polygons should be explored next (See FIGURE 89A). Having decided in which direction to go, the reader leaves

the first polygon and steps onto the next. A pause, or rest, is heard between the two polygons, and then a new note is sounded. The frequency, duration and modulation attributes of this tone represent the new polygon's relief characteristics (See FIGURE 89B). The reader can continue the walk by again deciding which neighbouring polygon to step on next (See FIGURE 89C) and after a brief pause listening to the tone generated (See FIGURE 89D). Taking walks on the different terrain types produces paths with various sound qualities (See FIGURES 90, 91 and 92).

This is the simplest application of the sound map system. The single notes are generated in response to the motions of the reader across the relief. The reader can explore and compare different spot elevations on the surface, or compare the change in elevations along different cross sections of the relief. By cutting across the change in elevations, the reader can concentrate on the slope values. By maintaining the same elevation along a path, the orientation changes can be analysed. In either case the sequences of tones heard will aid the terrain reader in the evaluation of the relief form that created those sound symbols (See FIGURE 93).

Multiple Level Path

Having fully explored the terrain surface and establishing the relationships between elevation and frequency, slope and duration, and

orientation with modulation, the terrain reader still wants to know more about the surface and its trends. While standing on a surface of 324 polygons the reader notices a more generalized surface appear under foot. This new surface represents the same relief but with a fewer number of larger polygons (See FIGURE 94A). The reader jumps down onto this 36 polygon surface and hears a note which is lower in frequency, longer in duration and which also has a more noticeable modulation component because it is heard for a longer period of time (See FIGURE 94B). The reader can now walk around on this more generalized surface and cover more ground with each step because the polygons are approximately 9 times larger. As with a simple path, the sequence of tones heard is based on the reader deciding which polygon to step on next and listening to the sound produced (See FIGURES 95A, 95B and 95C).

Just as the terrain reader's legs (and ears) are getting too tired to continue, an even more generalized surface appears below the reader's feet (See FIGURE 96A). The reader jumps down onto this new 4 polygon surface which represents the same terrain with polygons which are at least 9 times larger than the previous level and 81 times larger than the initial surface (See FIGURE 96B). As with the preceding two levels the reader can decide where to walk, but now with a much larger step size (See FIGURE 97A). The notes produced by this surface are lower in frequency and longer in duration and only represent the major trends of the original surface relief (See FIGURES 97B and 97C).

Taking walks on these generalized levels of the different terrains produces sequences of notes exhibiting an extensive range of sound qualities to represent the relief at various amounts of detail (See FIGURES 98, 99 and 100). The terrain reader can explore any single surface individually as described above, or can listen to all the levels' notes simultaneously. By activating all the layers below the reader, the sound heard is the polyphonic combination of all the polygon notes directly beneath the reader's position (See FIGURE 101A). Now when walking a path across the relief the notes heard change at different times (See FIGURE 101B). This makes identification of any particular note's qualities more difficult but the synthesized tones give a qualitatively better sound which represents the corresponding changes in all three levels simultaneously.

With the multiple-level path technique the terrain reader can analyse the relief at any one level of generalization or make comparisons between the trends shown by the different amounts of polygon coverage. The provision of different levels also allows the reader to make comparisons between the different terrains (high, low and mixed relief) at each level of generalization. The wide range of tones that are generated by a multiple-level path will aid the terrain reader in the evaluation of the relief form and its major trends (See FIGURE 102).

Changing Relief

If the terrain which the reader is exploring is in the process of changing then the sound symbols will represent the amount and type of surface mutation occurring through time.

When standing on a static, unchanging polygon the reader senses the elevation, slope and orientation of this position by the frequency, duration and modulation characteristics of the note heard. If the terrain surface changes, then the physical attributes of the polygon change correspondingly. A change in just the orientation of the polygon would be reflected in the changing modulation of the note (See FIGURE 103A). If the slope of the polygon changed, the duration of the tone generated would increase or decrease accordingly (See FIGURE 103B). Similarly, a change in elevation of the polygon would be sensed as a corresponding change in frequency through time (See FIGURE 103C). Most often the process of relief mutation causes changes in all three polygon attributes simultaneously. So, if the terrain reader stands on a polygon of a changing surface the notes heard will vary in frequency, duration and modulation throughout the duration of the event (See FIGURE 104). When the terrain reader walks across a changing surface the various notes generated by each step represent the extent of the relief transformation which has occurred at that time interval between its initial and its final states (See FIGURE 105). Changes of the

physical relief will be reflected in all the different levels of generalization. The notes produced by polygons of these surfaces will also change according to the amount and type of terrain mutation occurring (See FIGURE 106).

The sound symbols generated by a changing relief aid in the reader's perception of the complex dynamic visual image. As a Digital Terrain Model is transformed between two physical states in three-dimensional space, the amount of relief change and the rate at which it is occurring complicates the visualization of the surface. The aural information provided by exploring the sound map gives the reader additional sensory variables to analyse the changing surface attributes (See FIGURE 107).

Terrain Motion

If the terrain reader wants to analyse the motion of the surface relative to their viewing position, the sound symbols must represent the terrain's location, size and rotation on the display. The same sound transforms are used but the elevation, slope (area) and orientation values must be made relative to the physical limits of the two-dimensional graphics screen, rather than being specified as variations in three-dimensional space relative to the flat plane (See FIGURE 108A). Thus, the range of frequencies from 40 to 4,500 Hz will

be proportional to the polygon's height on the screen (See FIGURE 108B). The duration values from 3 ticks to 54 ticks will represent the absolute size of the polygon as seen on the display which varies from the minimum visible to full screen size (See FIGURE 108C). Because the size that a polygon appears on the screen is now a function of its distance away from the viewer and not just the initial size of the sample grid, the duration transform must be applied equally to all the levels of generalization. The modulation range of ± 0 Hz to ± 6 Hz will correspond to the polygon's rotation to the left and right of the viewer rather than being specified with respect to north (See FIGURE 108D).

By selecting a polygon to follow as the surface moves on the display screen, the terrain reader can hear the corresponding changes in the note it generates. If the polygon moves up or down relative to the reader then the frequency of the note will increase or decrease accordingly (See FIGURE 109A). When the polygon moves closer to the reader, its absolute size on the screen increases, and the note will become longer in duration. Conversely, if the polygon moves away from the reader, it becomes smaller, and the duration of the note will decrease (See FIGURE 109B). If the polygon pivots from side to side the modulation of the tone it generates will change. A polygon directly facing the reader would have a modulation value of ± 0 Hz attributed to it. As the orientation of the polygon changes to be facing

180 degrees away from the reader, the amount of modulation applied to the note increases to the maximum of ± 6 Hz (See FIGURE 109C).

Most often the motion of a terrain on the display will change all of the polygon's height, size and rotation attributes simultaneously. If the terrain reader selects a polygon from a moving surface the notes heard will vary in frequency, duration and modulation with respect to the polygon's changing position through time (See FIGURE 110 for mixed relief example).

The terrain reader could also specify a path on the relief surface to be followed and generate a sequence of notes. The sound symbols heard would represent the polygon's different display screen qualities rather than their variations from the flat plane (See FIGURE 111 for mixed relief example). This can be performed on surfaces of any level of generalization (See FIGURE 112).

The sound symbols generated by this method of exploration aid the reader's perception of the terrain motion. As the Digital Terrain Model moves on the display screen, the changing amount and rate of motion creates an increasingly complex visual image. The aural information provided by the sound map symbols reinforces the reader's abilities to analyse this dynamic visual image (See FIGURE 113).

Interactive and Recorded Sounds

The sounds generated by a terrain surface can be used as additional information in two situations:

(i) within an interactive system of map display and user exploration;

(ii) as a pre-recorded soundtrack to emphasize a geographic display.

In an interactive system the sounds heard would be the result of different user actions, as was described in the previous section. These explorations would be carried out in real-time and the notes would be generated immediately to correspond with the map reading task being performed. However, these same methods can be used to generate sounds for produced films and videos of dynamic geographic phenomena. This use of sound symbols which are actually produced by the graphics being displayed would be much more descriptive than the conventional use of borrowed, pre-recorded orchestral music. The use of sound map principles is also more advantageous to communication than simply using a silent graphic image which is the usual method for displaying cartographic information.

The producer of the display could select and play a sequence of notes which relates to the aspects of the visual image that need to be enhanced. For instance, a descriptive sound symbol audio track could include sounds which represent particular cross-sections of the relief displayed. A more qualitative, "musical" type of terrain representation could be composed with notes taken from the different levels of generalized relief and played simultaneously. In either case, the symbolic soundtrack would generate audience interest and guide their attention around the visual image. The addition of sound map symbols to an otherwise silent display provides an extra sensory channel to communicate information about the terrain relief.

This research explored the possibilities of using sound symbols both interactively and as recorded soundtrack material. The sound map examples produced were created by combining graphic images generated on a mainframe computer system and notes generated on a personal computer. Because these are two independent, stand-alone systems, the sound maps produced can only simulate an interactive terrain exploration exercise by editing together the appropriate visual and aural information (See FIGURE 114). However, the sound maps produced in this manner do serve as good examples of how the notes can be recorded and added to a cartographic demonstration. Recent developments in computer hardware and software have made the possibility of real-time, interactive production of animated graphics with simultaneous sounds more of a reality.

An actual interactive sound map system would differ in that it would consist of a single data file representing both the graphic and sound elements. This system would have the capability to produce real-time animation of the terrain rather than the more laborious and time consuming process of frame-by-frame filming of the graphics screen. The corresponding notes would be played instantaneously rather than being recorded and edited onto the film at a later time. The ultimate system would also provide tools such as a cursor for user positioning, a joystick for motion control in three dimensions and set function keys for the automatic selection of different display attributes (See FIGURE 115).

FIGURE 86**AUDIO-VISUAL COORDINATION****A. UNCOORDINATED SIGHT AND SOUND** **B. COORDINATED SOUND MAP**

FIGURE 87

STAGES OF TERRAIN REPRESENTATION

C. EXPLORING THE RELIEF

B. D.T.M. / SOUND REPRESENTATION

A. RELIEF ATTRIBUTES

PATHS

CHANGE/MOTION

FIGURE 88

SIMPLE PATH

A. TERRAIN READER ON SURFACE

B. ELEVATION / FREQUENCY

C. SLOPE / DURATION

D. ORIENTATION / MODULATION

FIGURE 89

POLYGON STEPS

A. DECIDE NEXT STEP

NOTES
HEARD

FIRST NOTE

B. NEXT STEP

NEW NOTE

C. SECOND STEP

NEW NOTE

D. THIRD STEP

NEW NOTE

FIGURE 90

PATH ON HIGH RELIEF

NOTE SEQUENCE

TIME

PATH
TRAVERSED

FIGURE 91**PATH ON MIXED RELIEF**

NOTE SEQUENCE

TIME

FIGURE 92

PATH ON LOW RELIEF

NOTE SEQUENCE

TIME

PATH
TRAVERSED

FIGURE 93
GENERAL MODEL I

166

FIGURE 94**MULTIPLE LEVEL PATH****A. NEW SURFACE**

324
POLYGON
SURFACE

36
POLYGON
SURFACE

B. NEW POSITION

LARGER
POLYGONS

FIGURE 95 LARGER STEPS

168

A. FIRST
NOTE

CONTOURED
RELIEF

1

B. SECOND
NOTE

1

2

C. THIRD
NOTE

1

2

3

FIGURE 96

LOWEST LEVEL

A. NEW SURFACE

36
POLYGON
SURFACE

4
POLYGON
SURFACE

B. NEW POSITION

LARGEST
POLYGONS

FIGURE 97

LARGEST STEPS

170

A. FIRST
NOTE

CONTOURED
RELIEF

B. SECOND
NOTE

C. THIRD
NOTE

FIGURE 98

171

PATHS ON MIXED RELIEF

NOTE SEQUENCE

TIME

36 POLYGON
SURFACE

PATHS
TRAVERSED

4 POLYGON
SURFACE

FIGURE 99**PATHS ON HIGH RELIEF**

NOTE SEQUENCE

TIME

36 POLYGON
SURFACE PATHS
TRAVERSED 4 POLYGON
SURFACE

FIGURE 100**PATHS ON LOW RELIEF**

NOTE SEQUENCE

TIME

36 POLYGON
SURFACE PATHS
TRAVERSED 4 POLYGON
SURFACE

FIGURE 101

SIMULTANEOUS LEVELS

B. NOTES GENERATED

A. PATH TRAVERSED

FIGURE 102

GENERAL MODEL II

FIGURE 103

POLYGON CHANGES

A. CHANGING ORIENTATION

CHANGING
NOTE
QUALITIES

B. CHANGING SLOPE

CHANGING
NOTE
QUALITIES

C. CHANGING ELEVATION

CHANGING
NOTE
QUALITIES

FIGURE 104

CHANGING RELIEF

FIGURE 105

PATH ON CHANGES

POSITION
AT $T=3$

CHANGING NOTE
CHARACTERISTICS

POSITION
AT $T=2$

POSITION
AT $T=1$

NOTES GENERATED

FIGURE 106**CHANGES ON ALL LEVELS**

CHANGE THROUGH TIME
NOTES FROM 324 POLYGON SURFACE

NOTES FROM 36 POLYGON SURFACE

NOTES FROM 4 POLYGON SURFACE

FIGURE 107
GENERAL MODEL III

3 of/de 3

MicroD

FIGURE 108

181

POLYGONS IN PERSPECTIVE

A. RELATIVE TO
SCREEN LIMITS

B. HEIGHT AND
FREQUENCY

C. ABSOLUTE SIZE
AND DURATION

D. ROTATION AND
MODULATION

FIGURE 109

POLYGON MOTION

A. CHANGING HEIGHT

CHANGING
NOTE
QUALITIES

B. CHANGING SIZE

CHANGING
NOTE
QUALITIES

C. CHANGING ROTATION

CHANGING
NOTE
QUALITIES

FIGURE 110

MOVING TERRAIN

FIGURE 111

PATH IN PERSPECTIVE

NOTES GENERATED RELATIVE TO DISPLAY

ORIGINAL NOTES RELATIVE TO THE FLAT PLANE

TIME

FIGURE 112**PATHS ON OTHER LEVELS**

36 POLYGON SURFACE

**NOTES
GENERATED**

4 POLYGON SURFACE

**NOTES
GENERATED**

FIGURE 113
GENERAL MODEL IV

FIGURE 114**RECORDED SOUND MAP SYSTEM**

FIGURE 115**INTERACTIVE SOUND MAP SYSTEM** **INTERACTIVE TOOLS ALLOW PARTICIPATION**

FURTHER APPLICATIONS

An integrated system of visual and aural information display should allow the user to manipulate the ranges of the data and the symbolic correspondence between the sights and sounds. Depending on the purpose of the display, the specifications of the generated sound symbols could be changed to represent better the aspects of the terrain which are of most interest to the user.

Different Conversions

With the proposed system, frequency, the most distinguishable variable of the tones, represents the elevations of the polygons. The slope and orientation characteristics correspond to the secondary qualities of tone duration and modulation (See FIGURE 116A). If the user was more interested in the slopes or orientations of the polygons on a terrain surface then the frequency of the sound symbols could be used to represent these quantities rather than elevation.

The range of frequencies from 40 Hz to 4500 Hz could be substituted for each variable separately, to symbolize either slope variation (See FIGURE 116B) or orientation variation (See FIGURE 116C). Alternatively, the association of elevation, slope and orientation with

frequency, duration and modulation could be maintained as was originally proposed but the variable ranges of the data which were of no interest to the user could be compressed or removed from the symbol definition. If the user was just interested in the polygon elevations then note frequency would be used ~~but~~ duration and modulation would remain at a constant value (See FIGURE 117A). For slope studies, the frequency and modulation of the sound symbols could be held constant and just the variation of tone duration would be heard (See FIGURE 117B). If just polygon orientation was to be examined, the frequency and duration qualities could be suppressed and just the variation of tone modulation would be heard (See FIGURE 117C). Also, the modulations of the tones could be changed by altering the direction which is represented by a pure tone. The orientation values could be expressed with respect to the north-west/south-east axis as is done with conventional hill shading techniques (See FIGURE 118A for high relief example). Similarly, the modulation values could be made relative to a South aspect and would produce the inverse of the original orientation specification (See FIGURE 118B). By suppressing one or more of the audible variables used in the creation of the sound symbols the user can concentrate on a single variable or any combination representing the polygon elevations, slopes and/or orientations.

Automated Explorations

An interactive system would also allow for the terrain relief to be explored in different ways. In addition to defining paths on the terrain at various levels of generalization and following the motion or change, the user could specify that the terrain be explored automatically. The easiest way to perform this would be to have the software generate a path and corresponding sequence of notes by randomly selecting the next polygon to be played (See FIGURE 119A). Another more controlled method of automatic terrain exploration would be based on the user specifying the upper and lower limits of different polygon qualities. This would establish a choice criterion which the software could use to produce a path and a sequence of tones within the specified range which are of most interest to the user. The sound map system would generate different paths depending on whether an elevation range (See FIGURE 119B), slope range (See FIGURE 120A) or orientation range was specified by the user (See FIGURE 120B). The automatic sequencing of a path and tones could also be performed by the user specifying that the next polygon to be selected should have values of elevation, slope or orientation which are the most similar to the present polygon's qualities (See FIGURE 121A) or conversely, the most different (See FIGURE 121B).

Alternatively, the software could generate probability statistics for each polygon of the surface which would represent their individual qualities as compared to the total number of occurrences of polygons with similar elevation, slope or orientation values. These probability values can now be mapped as values ranging from 0 to 1 for each polygon (See FIGURE 122). The probability values can be presented with a series of visual textures to display the relief qualities of the different terrain surfaces (See FIGURES 123, 124 and 125). Having mapped the probabilities of the polygons the software can generate a path and a sequence of tones corresponding to the most likely polygons (See FIGURE 126A) or the least likely polygons (See FIGURE 126B). In this case the exploration of the terrain would be controlled by the variation of the relief itself. A sequence of most probable polygons would guide the listener's attention to those areas of the terrain which reflect the most commonly occurring relief attributes. Conversely, a sequence of least probable polygons would stress the areas of the terrain which have physical attributes that rarely occur on that surface. This type of automatic terrain exploration was tested as part of the research carried out and was successful in generating sequences of tones based on their probabilities. However, once the path traversed enters an area of minimum or maximum probability values for the particular surface, the software selection of the next polygon begins to loop in a circular fashion and plays an endless repetitive series of the same, most likely or least likely polygons.

An interactive system would also allow the minimum and maximum frequency limits of the notes generated by the different terrain types to be changed. The three Digital Terrain Models used in this research, high, mixed and low relief, were all mapped into the same 40 Hz to 4,500 Hz range of frequency. This allowed the sound symbols generated by each surface to be compared to the frequency qualities of the other surfaces. With this consistent application of the elevation to frequency conversion, polygons of the same elevation would create the same frequency note, even if they were from different terrains (See FIGURE 127A). Alternatively, the actual relief variation of a surface could be mapped into the whole frequency range of 40 HZ to 4,500 Hz rather than just using a portion of this range (See FIGURE 127B). This would expand the frequency variation of the sound symbols generated by lower relief terrains, i.e., the low relief Digital Terrain Model with elevations ranging from only 0 to 3 units would correspond to the full frequency range. The effects of this change in symbol definition would be the auditory equivalent of a vertical exaggeration factor being applied to the different terrains (See FIGURE 128).

Creating Terrains from Music

An often suggested application of this system of sound symbol generation is to use the data transformation process in reverse. This would allow the three-dimensional visualization of a musical composition by starting with a music score and building a terrain which physically

represented the notes. To perform this process the proposed sound map system would have to be carried out backwards.

A series of notes would be quantified into values of frequency, duration and modulation (See FIGURE 129A). These sound attributes could then be represented with polygons of corresponding elevation, slope and orientation values (See FIGURE 129B). This group of different polygons defined by the score must now be arranged spatially to create a continuous surface. However, there is no logically intrinsic manner in which the polygons (notes) occur in space. A simple, but arbitrary way to create a continuous sheet would be the placement of the notes (polygons) in the order they occur in the score to create regular cross-sections of relief (See FIGURE 129C). This would produce a three-dimensional model of the musical composition. The original score would be generated by following the same order of polygon placement and variations of the "musical piece" would be heard if any other path was defined (See FIGURE 129D). This reverse process of transforming sequences of notes into surfaces is possible, but because of the arbitrary spatial placement of the polygons relative to their original temporal order, the final terrain relief is ambiguous and could generate many different pieces of music depending on how it is explored. A single terrain shape representing all the notes of the musical scale could theoretically generate every piece of music ever written.

The initial system proposed for generating sound symbols from Digital Terrain Models to represent relief is much more consistent because the original polygon data is intrinsically spatial. The temporal ordering of the notes heard is only a result of exploring the distribution of the different elevation, slope and orientation values on the surface. So, although a series of sounds can symbolically represent data for any specific set of known geographic locations, a sequence of tones which are not intrinsically spatial cannot be used to generate geographic shapes. It would be quite impossible to draw the outline of Canada and the 10 provinces from aural information alone even if given a sequence of tones which correspond to the square kilometre areas of these regions.

Information Overload

The addition of sound symbols to terrain exploration exercises is a new capability of modern computer technology. Although it provides a second sensory variable to communicate information, it also creates a more complex display as compared to a silent graphic image. For the generation of sound symbols to be practical, the benefits of using an aural dimension must outweigh the increased complexity and possible confusion it can create. The successful interpretation of the sound map depends on the symbolic correspondence between the visual image and the sounds heard. However, the simultaneous use of visual and aural symbols combined into a single display creates the potential for information overload. Sensory overload occurs when the rate of the information

being transmitted exceeds the rate at which it can be meaningfully perceived by the map reader.

The potential problem of information overload increases with the complexity of the audio-visual dynamics and decreases with user familiarity. (See FIGURE 130). A simple path across a surface presents the user with one polygon and one sound at any time to be interpreted. When analysing the structure of the relief with a multiple-level path, the user must interpret the correspondence between a possibility of 3 polygons (one from each level of generalization) and the three different notes they generate. If the terrain being explored is transforming or moving on the screen, the generation and interpretation of the sounds is further complicated by the amount and rate of the visual change occurring. The complexity of the display and the potential for confusion is directly proportional to the number and rate of symbolic correspondences which must be resolved by the reader. The sensory limit of the rate of information display is quite low for new users of sound maps, but increases with experience.

The proposed system of sound symbol creation from Digital Terrain Models was presented to a group of "untrained" Geography department members at Carleton University in January 1986. Their comments varied from those of confusion and surprise through to enlightened interest (See FIGURE 131). Overall, the response was

positive and confirmed that the sound symbols generated were successful in representing the physical attributes of terrain relief. The reactions of this small sample of viewers stressed the necessity of visually maintaining the source polygons of the notes heard to make the symbolic correspondence between the visual and aural information both sensible and recognizable. The viewer's association of the physical attributes with the corresponding audible variables would be more immediate within an interactive sound map system which actually allowed the viewer to "participate" in the real-time exploration of the relief rather than just "watching" a recorded simulation.

FIGURE 116**FREQUENCY CONVERSIONS** **A. NORMAL ELEVATION-FREQUENCY CONVERSION** **B. SLOPE-FREQUENCY CONVERSION** **C. ORIENTATION-FREQUENCY CONVERSION**

FIGURE 117

SEPARATED VARIABLES

A. ONLY FREQUENCY VARIATION

B. ONLY DURATION VARIATION

C. ONLY MODULATION VARIATION

FIGURE 118

**MODULATION
CONVERSION**

**A. NW-SE
AXIS**

**B. VALUES
W.R.T.
SOUTH**

FIGURE 119**AUTOMATED EXPLORATION I****A. RANDOM PATH SEQUENCE**

● START — ○ FINISH

B. PATH WITHIN ELEVATION RANGE

FIGURE 120**AUTOMATED EXPLORATION II****A. PATH WITHIN SLOPE RANGE** **B. PATH WITHIN ORIENTATION RANGE**

FIGURE 121

AUTOMATED EXPLORATION III

A. PATH OF MOST
SIMILAR POLYGON
ELEVATIONS

B. PATH OF MOST
DIFFERENT POLYGON
ELEVATIONS

FIGURE 122

PROBABILITY VALUES

HIGH RELIEF

PROBABILITY DATA

1 = MOST COMMON POLYGONS
0 = LEAST COMMON POLYGONS

0.19	0.19	0.19	0.29	0.29	0.29	0.29	0.29	0.39	
0.19	0.19	0.19	0.19	0.29	0.29	0.29	0.29	0.39	0.19
0.19	0.19	0.19	0.29	0.29	0.29	0.29	0.29	0.39	0.19
0.19	0.19	0.29	0.29	0.39	0.39	0.19	0.39	0.39	0.19
0.19	0.19	0.29	0.39	0.39	0.19	0.19	0.39	0.39	0.19
0.19	0.19	0.29	0.39	0.19	0.09	0.09	0.19	0.39	0.39
0.19	0.19	0.29	0.39	0.09	0.09	0.09	0.09	0.19	0.39
0.19	0.29	0.39	0.09	0.09	0.09	0.09	0.09	0.19	0.39
0.19	0.29	0.39	0.09	0.09	0.02	0.09	0.09	0.19	0.39
0.19	0.29	0.39	0.09	0.09	0.02	0.09	0.09	0.19	0.39
0.19	0.29	0.39	0.09	0.09	0.02	0.09	0.09	0.19	0.39
0.29	0.39	0.09	0.09	0.09	0.01	0.09	0.09	0.19	0.39
0.29	0.39	0.09	0.09	0.09	0.02	0.09	0.09	0.19	0.39
0.29	0.39	0.09	0.09	0.09	0.09	0.09	0.19	0.39	0.39
0.29	0.39	0.09	0.09	0.09	0.09	0.19	0.39	0.39	0.39
0.29	0.39	0.09	0.09	0.09	0.09	0.19	0.39	0.39	0.39
0.29	0.39	0.19	0.09	0.09	0.09	0.29	0.39	0.39	0.39
0.29	0.39	0.19	0.09	0.09	0.09	0.29	0.39	0.39	0.39
0.29	0.39	0.19	0.09	0.19	0.29	0.29	0.39	0.39	0.39
0.19	0.29	0.39	0.19	0.19	0.39	0.29	0.39	0.39	0.39
0.29	0.29	0.39	0.19	0.39	0.39	0.39	0.39	0.19	0.39
0.19	0.29	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
0.19	0.29	0.29	0.29	0.39	0.39	0.39	0.39	0.19	0.39
0.19	0.29	0.29	0.39	0.39	0.39	0.39	0.39	0.39	0.29
0.19	0.19	0.29	0.29	0.39	0.39	0.39	0.39	0.39	0.29
0.19	0.19	0.19	0.29	0.29	0.39	0.39	0.19	0.39	0.29
0.19	0.19	0.29	0.29	0.29	0.39	0.19	0.39	0.39	0.29

FIGURE 123**HIGH RELIEF PROBABILITIES**

FIGURE 124**MIXED RELIEF PROBABILITIES**

FIGURE 125**LOW RELIEF PROBABILITIES**

FIGURE 126

PROBABILITY PATHS

**A. PATH OF MOST
PROBABLE POLYGONS**

**B. PATH OF LEAST
PROBABLE POLYGONS**

FIGURE 127**CHANGING FREQUENCY RANGES****A. CONSISTENT FREQUENCY CONVERSION**FREQUENCY
RANGE OF
40-4500 HZ

APPLIED EQUALLY FOR ALL TERRAINS

ELEVATION

B. EXPANDED FREQUENCY VARIATIONFULL 40-4500 HZ RANGE
USED FOR EACH TERRAIN

FIGURE 128**AUDIBLE VERTICAL EXAGGERATION****INCREASED EXAGGERATION FACTOR**

FIGURE 129**CREATING TERRAINS FROM MUSIC****A. CONVERT NOTES INTO SOUND DATA** **B. CONVERT INTO PHYSICAL ATTRIBUTES** **C. POLYGON PLACEMENT**

CREATES
CROSSECTIONS

1	5	9
2	4 6	8 10 12
3	7	11
13	17	21
14	16 18	20 22 24
15	19	23
25	29	33
26	28 30	32 34 36
27	31	35

**D. TERRAIN
EXPLORATION**

PATH TO PRODUCE
ORIGINAL SCORE

PATH TO PRODUCE A
MUSICAL VARIATION

1	5	9
2	4 6	8 10 12
3	7	11
13	17	21
14	16 18	20 22 24
15	19	23
25	29	33
26	28 30	32 34 36
27	31	35

REVERSED
SOUND
MAP
SYSTEM

FIGURE 130**INFORMATION OVERLOAD**

FIGURE 131**RESPONSES TO THE SOUND MAP**

COMMENTS OF A GROUP OF GEOGRAPHY DEPARTMENT
MEMBERS: SOUND MAP SEMINAR, JANUARY 1986

SUMMARY AND CONCLUSIONS

This research has documented the creation of sound symbols from Digital Terrain Models. The types of sounds used to represent the relief of these polygonal surfaces are generated from the physical qualities of the individual polygons. The sound symbols produced are within the sensory limits of the human aural system. They use the detectable variables of frequency, duration and modulation to represent the polygon's elevation slope and orientation characteristics respectively. Having defined a set of audible symbols which correspond to the nature of the relief, the terrain can then be actively explored to produce specific sequences of notes.

Four methods of exploring the relief dynamically to generate different tones were performed. Walking a simple path on the terrain surface produced sounds which corresponded to the series of polygons visited. The structure of the relief was represented with three different levels of generalization which each produced various types of notes. These different levels could be explored individually or in combination with one another to produce polyphonic tones representing the three levels simultaneously. The transformation of the relief through time can be used to generate tones which change corresponding to

the amount and rate of terrain mutation. If the terrain moves on the display screen relative to the viewer's position, sounds can be produced which represent the change in the terrain's position, size and rotation.

These terrain exploration techniques and the sound symbols they generated were simulated using frame-by-frame animation of a computer graphics screen and recording the appropriate sounds produced by a Personal computer. The dynamic Digital Terrain Models, drawn with resident three-dimensional solid-modelling software available on Carleton University's mainframe, and the notes generated by custom BASIC sound programs were edited together to create an audio-visual display.

The ultimate sound map system would be interactive and allow the user to specify the type of exploration method desired. The user would receive the corresponding visual and aural information simultaneously. This real-time communication process was not possible with the use of two separate, stand-alone computer systems. However, the video simulation of this type of sound map system does provide a good indicator of how symbolic sounds can be used as meaningful soundtrack material for cartographic displays and demonstrations. In this case, the use of sound symbols which correspond to the dynamic terrain relief is more advantageous for the user's perception of the image as compared to the conventional use of orchestral music or just a silent image. The ability to present aural information is both

dependent on the use of a dynamic image to show the corresponding locations of the source polygons, and beneficial to the analysis of more complex visual images such as terrain mutation and motion.

The creation of sound symbols to represent Digital Terrain Model polygonal data can be seen as just a particular application of aural information within a more extensive sound map system. The use of computer-assisted cartography techniques has allowed map displays to become dynamic. The dynamic presentation of visual information can now be accompanied by aural information which is essentially time-based or dynamic. Conventional cartography has three basic elements; text, data and graphics. The specific design of a map uses these elements in association with each other to communicate visual information (See FIGURE 132). Sound, in the form of speech and symbolic tones can now be used in addition to these elements. Speech can be used, as text would, be, to label geographic areas and describe the data that is being mapped. Symbolic tones, like visual symbols, can be used to represent the data on the map.

Sound symbols can be simple on/off signals to represent the presence or absence of a feature. However, a more complex series of encoded tones can be used to proportionally represent a range of data values. The terrain sound symbols described in this research were created by varying the audible characteristics of frequency, duration

and modulation proportionally with the polygon attributes of elevation, slope and duration respectively. This relationship of the variables to each other defines the symbolic correspondence between the notes heard and the terrain surface. Some special purpose thematic maps, e.g., Amount of Industrialization or Number of Automobiles, could use the actual sounds generated by the phenomena to create a series sound symbols. This would be a physical correspondence between the sounds heard and the mapped data, i.e., increased manufacturing noises, or loudness of car engines.

The sound dimension can be a beneficial addition to map displays because of its various capabilities to convey information which are different than the visual dimension. Sound can represent concepts which cannot be communicated with visual means. Speech, and the oral characteristics of the speaker can communicate emotions (happiness, sadness) or be used to relate language based concepts (Love, God) to the map reader. Even conventional music can be used to create a mood or invoke a particular response from the map reader. However, because these would be mostly socially defined correspondences of sight and sound, the effect on the listener would be unpredictable.

When the map display is already cluttered to the limits of visual overload, sounds can be used to stress a particular aspect of the image or add information to it without increasing the visual complexity.

Words could be spoken to replace the extensive use of labels on a map or to stress important text. An additional set of data could be represented with sound symbols, or one of the visual variables could be removed from the map and replaced with sound to reduce the amount of clutter. Sound also has superior attention gaining capabilities and could be used to reinforce the most important information concerning the mapped subject. Descriptive speech or tones with special characteristics could signal the occurrence of areas with the highest, mean or lowest data values found in the map image.

Sound symbols can represent complex, multiple-variable data sets. A single visual symbol can have simultaneous shape, location, texture, size, color and orientation variation and still be sensed by the eye as having separate qualities, each representing a different data set. Similarly, audible symbols can vary in frequency, duration, modulation (timbre), loudness and location simultaneously and still be detected by the ear as separate variables.

The aural acuity of the human hearing system is at least as sensitive to sound stimuli as the visual system is to a grey scale of tones. The change in a note's frequency can be discriminated at an approximate minimum limit of ± 4 Hz across a wide range of frequencies from 20 Hz to 20,000 Hz. This provides a large set of potential tones

which can be used to represent data variation. A sound dimension added to a display that corresponds to mapped data would allow the differentiation of values which would otherwise not be resolved visually.

To take advantage of these new capabilities further research must investigate the design of dynamic maps. This should include not only the spatial layout of the visual elements but also the possible addition and temporal ordering of aural information. The development of dynamic display techniques has allowed the cartographer to create map presentations which are not static, but change through time. These dynamic maps can now present aural information in the form of speech or symbolic tones that also change through time. The creation of audio-visual maps gives the cartographer a whole new sensory dimension with which to communicate information. The successful use of auditory symbols will generate interest in dynamic images and enliven the map reading process.

FIGURE 132
SOUND AS A MAP
DESIGN
COMPONENT

REFERENCES

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- 3 Ibid., pp. 28-47.
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- 5 Bertin, op. cit., pp. 41-95.
- 6 Bertin, op. cit., pp. 378-379.
- 7 G. Langran, Map Design for Computer Processing (1984), p. 79.
- 8 Kantowitz and Sorkin, op. cit., pp. 232-251.
- 9 Kantowitz and Sorkin, op. cit., pp. 72-83.
- 10 W. Bateman, Introduction to Computer Music (New York, 1980), pp. 102-103.
- 11 Ibid., pp. 10-52.
- 12 Kantowitz and Sorkin, op. cit., p. 71.

```

710 NEXT I
720 REM
730 REM WRITE DATA TO DISK
740 REM
750 OPEN "P",#2,G$,20 : FIELD #2,20 AS Q$
760 LSET Q$=MK$(NP) : PUT #2
770 LSET Q$=MK$(ELMIN)+MK$(ELMAX) : PUT #2
780 LSET Q$=MK$(SLMIN)+MK$(SLMAX) : PUT #2
790 LSET Q$=MK$(A2) : PUT #2
800 LSET Q$=MK$(FMIN)+MK$(FMAX) : PUT #2
810 LSET Q$=MK$(DMIN)+MK$(DMAX) : PUT #2
820 LSET Q$=MK$(MINMOD)+MK$(MAXMOD) : PUT #2
830 LSET Q$=MK$(ELEVSTP) : PUT #2
840 FOR I=1 TO NP
850 PROB(I)=PROB(ELEV(I))
860 LSET Q$=MK$(I)+MK$(FREQ(I))+MK$(DUR(I))+MK$(MODUL)+MK$(PROB(I))
870 PRINT I:FREQ(I):DUR(I):MODUL(I):PROB(I)
880 PUT #2
890 NEXT I
900 PRINT:PRINT"DATA WRITTEN AND READY TO PLAY"
910 REM
920 REM LETS PLAY SOME NOTES
930 REM
940 RANDOMIZE
950 INPUT "ENTER MODRATE=====":MODRATE
960 INPUT "ENTER NUMBER OF STEPS=====":NS
970 FOR K=1 TO NS
980 PRINT "STEP #.":K
990 INPUT "ENTER STEP(POLY#)=====":POLYN(K)
1000 NEXT K
1010 FOR I=1 TO NS
1020 L=POLYN(I)
1030 FOR J=MODRATE TO DUR(L) STEP MODRATE
1040 MODUL=RND(1)*MODUL(L)
1050 SOUND FREQ(L)+MODUL,MODRATE
1060 NEXT J
1070 NEXT I
1080 PRINT:PRINT"ARE YOUR LEGS TIRED?"
1090 END

```

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APPENDIX A

'SOUND MAP VIDEO

"SOUND MAPS", produced by Stephen John Glavin in partial fulfilment of the requirements for the degree of Master of Arts, 1987. A 30 minute, color, VHS video tape.

APPENDIX B

BASIC PROGRAM LISTINGS

```
100 REM SURFACE DATA INPUT PROGRAM (DATAINF.BAS)
110 REM PREPARED FOR STEVE GLAVIN BY STEVE PRASHKER
120 REM © STEVE PRASHKER 1985
130 REM
140 REM THIS PROGRAM PERFORMS MANUAL DATA INPUT FOR POLYGON
150 REM ELEVATIONS, SLOPES, AND ORIENTATIONS
160 REM
170 REM INITIALIZE THINGS
180 REM
190 PRINT CHR$(12);
200 PRINT "SURFACE DATA INPUT PROGRAM" : PRINT
210 REM
220 INPUT "Enter number of polygons =====> ", NP
230 INPUT "Enter filename to store data => ".Fs
240 INPUT "Enter drive =====> ".Ds
250 REM
260 Fs=Ds+":"+Fs
270 OPEN "R",#1,Fs,16 : FIELD #1,16 AS Z$
280 LSET Z$=MK$(NP) : PUT #1 : REM # OF TRIANGLES TO DISK
290 PRINT
300 FOR I=1 TO NP
310 PRINT "Polygon #":I;
320 REM
330 INPUT "Enter elevation =====> ".ELEV
340 INPUT "Enter slope =====> ".SLOPE
350 INPUT "Enter orientation =====> ".ORIEN
360 REM
370 LSET Z$=MK$(I)+MK$(ELEV)+MK$(SLOPE)+MK$(ORIEN) : PUT #1
380 PRINT
390 NEXT I
400 PRINT "Done"
410 END
```

```

100 REM SURFACE DATA PROCESSING PROGRAM (DATAPROC.BAS)
110 REM PREPARED FOR STEVE GLAVIN BY STEVE PRASHKER
120 REM (C) STEVE PRASHKER 1985
130 REM
140 REM THIS PROGRAM PROCESSES FILES CREATED BY 'DATAINP' AND CONVERTS
150 REM THE ELEVATIONS, SLOPES AND ORIENTATIONS INTO FREQUENCY
160 REM DURATIONS AND MODULATIONS. IT ALSO CREATES PROBABILITY VALUES
170 REM FOR EACH POLYGON.
180 REM
190 REM INITIALIZE THINGS
200 REM
210 DIM FREQ(500), DURA(500), MODU(500), PROBU(500), COUNT(20), LUL(20), PROE(500),
ELEV(500)
220 PRINT CHR$(12);
230 PRINT "SURFACE DATA PROCESSING PROGRAM" : PRINT
240 REM
250 INPUT "Enter surface data filename => ", FS
260 INPUT "Enter drive =====> ", DS
270 PRINT
280 INPUT "Enter processed filename =====> ", GS
290 INPUT "Enter drive =====> ", D2S
300 REM
310 GS=DS+":"+GS
320 FS=DS+":"+FS
330 OPEN "R", #1, FS, 16 : FIELD #1, 16 AS Z$
340 GET #1 : NP=CUS(MID$(Z$, 1, 4)) : REM # OF POLYGONS
350 PRINT
360 REM
370 REM INITIALIZE PHYSICAL QUANTITIES TO SOUND QUANTITIES
380 REM
390 INPUT "Enter Elevation min, max => ", ELMIN, ELMAX
400 INPUT "Enter Slope min, max =====> ", SLMIN, SLMAX
410 INPUT "Enter azimuth =====> ", AZ
420 PRINT
430 INPUT "Enter Frequency min, max => ", FMIN, FMAX
440 INPUT "Enter Duration min, max =====> ", DMIN, DMAX
450 INPUT "Enter modulation min, max =====> ", MINMOD, MAXMOD
460 PRINT
470 INPUT "Enter step size for elevations => ", ELEVSTP
480 REM
490 REM COMPUTE CONVERSION STUFF
500 REM
510 FELEV=(FMAX-FMIN)/(ELMAX-ELMIN) : OELEV=FMIN
520 FSLOP=(DMAX-DMIN)/(SLMAX-SLMIN) : OSLOP=DMIN
530 FMOD=(MAXMOD-MINMOD)/10 : OMOD=MINMOD
540 RANGE=(ELMAX-ELMIN)/ELEVSTP
550 LUL(1)=ELMIN
560 FOR I=2 TO RANGE+1 : LUL(I)=LUL(I-1)+ELEVSTP : NEXT I
570 REM
580 REM READ DATA FROM DISK
590 REM
600 FOR I=1 TO NP
610 GET #1 : ELEV=CUS(MID$(Z$, 5, 4)) : SLOPE=CUS(MID$(Z$, 9, 4)) : ORIENT=CUS(MID$(Z$, 13, 4))
620 PRINT "DATA="; ELEV; SLOPE; ORIENT
630 ELEV(I)=ELEV
640 FREQ(I)=OELEV+FELEV*(ELEV-ELMIN) : REM FREQUENCY
650 DURA(I)=OSLOP+FSLOP*(SLOPE-SLMIN) : REM DURATION
660 MODU(I)=ORIENT-AZ : IF MODU(I)<0 THEN MODU(I)=MODU(I)+20
670 IF MODU(I)>10 THEN MODU(I)=20-MODU(I)
680 MODU(I)=OMOD+FMOD*(MODU(I)-MINMOD)
690 FOR J=1 TO RANGE
700 IF ELEV>LUL(J) AND ELEV<LUL(J+1) THEN COUNT(J)=COUNT(J)+1 : ELEV(I)=J :
GOTO 720

```



```

710 NEXT J
720 NEXT I
730 FOR I=1 TO RANGE
740 PROB(I)=COUNT(I)/NP
750 NEXT I
760 REM
770 REM WRITE DATA TO DISK
780 REM
790 OPEN "R",#2,G$.20 : FIELD #2.20 AS Q$
800 LSET Q$=MK$(NP) : PUT #2
810 LSET Q$=MK$(ELMIN)+MK$(ELMAX) : PUT #2
820 LSET Q$=MK$(SLMIN)+MK$(SLMAX) : PUT #2
830 LSET Q$=MK$(AZ) : PUT #2
840 LSET Q$=MK$(FMIN)+MK$(FMAX) : PUT #2
850 LSET Q$=MK$(DMIN)+MK$(DMAX) : PUT #2
860 LSET Q$=MK$(MINMOD)+MK$(MAXMOD) : PUT #2
870 LSET Q$=MK$(ELEVSTP) : PUT #2
880 FOR I=1 TO NP
890 PROBU(I)=PROB(ELEV(I))
900 LSET Q$=MK$(I)+MK$(FREQ(I))+MK$(DURA(I))+MK$(MODU(I))+MK$(PROBU(I))
910 PRINT I;FREQ(I);DURA(I);MODU(I);PROBU(I)
920 PUT #2
930 NEXT I
940 PRINT:PRINT"DATA WRITTEN AND READY TO PLAY"
950 REM
960 REM LETS PLAY SOME NOTES
970 REM
980 RANDOMIZE
990 INPUT "ENTER MODRATE====>".MODRATE
1000 FOR I=1 TO NP
1010 MINFREQ=FREQ(I)-MODU(I)/2
1020 FOR J=MODRATE TO DURA(I) STEP MODRATE
1030 MODU=RN(1)*MODU(I)
1040 FG=MINFREQ+MODU
1050 SOUND FG+MODU,MODRATE
1060 NEXT J
1070 NEXT I
1080 PRINT:PRINT"WASN'T THAT WIERD"
1090 END

```

```

100 REM SURFACE DATA PROCESSING PROGRAM (PREPATH.BAS)
110 REM PREPARED FOR STEVE GLAVIN BY STEVE PRASHKER
120 REM (C) STEVE PRASHKER 1985
130 REM
140 REM THIS PROGRAM ALLOWS THE TERRAIN READER TO DEFINE A PATH OF POLYGONS
150 REM TO BE PLAYED, AS NOTES
160 REM
170 REM INITIALIZE THINGS
180 REM
190 DIM FREQ(500), DURA(500), MODU(500), PROBV(500), COUNT(20), LUL(20), PROB(50)
200 LEV=500
210 PRINT CHR$(12):
220 PRINT "SURFACE DATA PROCESSING PROGRAM" : PRINT
230 INPUT "Enter surface data filename = "; Fs
240 INPUT "Enter drive = "; Ds
250 PRINT
260 INPUT "Enter processed filename = "; Gs
270 INPUT "Enter drive = "; D2s
280 Gs=D2s+";"+Gs
290 Fs=Ds+";"+Fs
300 OPEN "R", #1, Fs, 1 : FIELD #1, 16 AS Zs
310 GET #1 : NP=CUS(MIDS(Zs,1,4)) : REM # OF POLYGONS
320 PRINT
330 REM INITIALIZE PHYSICAL QUANTITIES TO SOUND QUANTITIES
340 REM
350 INPUT "Enter Elevation min. max = "; ELMIN,ELMAX
360 INPUT "Enter Slope min. max = "; SLMIN,SLMAX
370 INPUT "Enter azimuth = "; AZ
380 PRINT
390 INPUT "Enter Frequency min. max = "; FMIN,FMAX
400 INPUT "Enter Duration min. max = "; DMIN,DMAX
410 INPUT "Enter modulation min. max = "; MINMOD,MAXMOD
420 PRINT
430 INPUT "Enter step size for elevations = "; ELEVSTP
440 REM
450 REM COMPUTE CONVERSION STUFF
460 REM
470 FELEV=(FMAX-FMIN)/(ELMAX-ELMIN) : OELEV=FMIN
480 FSLOP=(DMAX-DMIN)/(SLMAX-SLMIN) : OSLOP=DMIN
490 FMOD=(MAXMOD-MINMOD)/10 : OMOD=MINMOD
500 RANGE=(ELMAX-ELMIN)/ELEVSTP
510 LUL(1)=ELMIN
520 FOR I=2 TO RANGE+1 : LUL(I)=LUL(I-1)+ELEVSTP : NEXT I
530 REM
540 REM READ DATA FROM DISK
550 REM
560 FOR I=1 TO NP
570 GET #1 : ELEV=CUS(MIDS(Zs,5,4)) : SLOPE=CUS(MIDS(Zs,9,4)) : ORIEN=CUS(MIDS(Zs,13,4))
580 PRINT "DATA=";ELEV;SLOPE;ORIEN
590 ELEV(I)=ELEV
600 FREQ(I)=OELEV+FELEV*(ELEV-ELMIN) : REM FREQUENCY
610 DURA(I)=OSLOP+FSLOP*(SLOPE-SLMIN) : REM DURATION
620 MODU(I)=ORIEN-AZ : IF MODU(I)<0 THEN MODU(I)=MODU(I)+20
630 IF MODU(I)>10 THEN MODU(I)=20-MODU(I)
640 MODU(I)=OMOD+FMOD*(MODU(I)-MINMOD)
650 FOR J=1 TO RANGE
660 IF ELEV=LUL(J) AND ELEV<LUL(J+1) THEN COUNT(J)=COUNT(J)+1 : ELEV(I)=0 :
GOTO 680
670 NEXT J
680 NEXT I
690 FOR I=1 TO RANGE
700 PROB(I)=COUNT(I)/NP

```

```

710 NEXT I
720 REM
730 REM WRITE DATA TO DISK
740 REM
750 OPEN "R",#2,G$,20 : FIELD #2,20-AS 0$
760 LSET 0$=MK$(NP) : PUT #2
770 LSET 0$=MK$(ELMIN)+MK$(ELMAX) : PUT #2
780 LSET 0$=MK$(SLMIN)+MK$(SLMAX) : PUT #2
790 LSET 0$=MK$(A2) : PUT #2
800 LSET 0$=MK$(FMIN)+MK$(FMAX) : PUT #2
810 LSET 0$=MK$(DMIN)+MK$(DMAX) : PUT #2
820 LSET 0$=MK$(MINMOD)+MK$(MAXMOD) : PUT #2
830 LSET 0$=MK$(ELEVSTP) : PUT #2
840 FOR I=1 TO NP
850 PROB(I)=PROB(ELEV(I))
860 LSET 0$=MK$(I)+MK$(FREQ(I))+MK$(DURA(I))+MK$(MODUL)+MK$(PROB(I))
870 PRINT I:FREQ(I):DURA(I):MODUL(I):PROB(I)
880 PUT #2
890 NEXT I
900 PRINT:PRINT"DATA WRITTEN AND READY TO PLAY"
910 REM
920 REM LETS PLAY SOME NOTES
930 REM
940 RANDOMIZE
950 INPUT "ENTER MODRATE====>".MODRATE
960 INPUT "ENTER NUMBER OF STEPS====>".NS
970 FOR K=1 TO NS
980 PRINT "STEP #."K
990 INPUT "ENTER STEP(POLYN)====>".POLYN(K)
1000 NEXT K
1010 FOR I=1 TO NS
1020 L=POLYN(I)
1030 FOR J=MODRATE TO DURA(L) STEP MODRATE
1040 MODUL=RND(1)*MODUL(L)
1050 SOUND FREQ(L)+MODUL,MODRATE
1060 NEXT J
1070 NEXT I
1080 PRINT:PRINT"ARE YOUR LEGS TIRED?"
1090 END

```

```

100 REM MUSIC GENERATING PROGRAM (COMPRND.BAS)
110 REM PREPARED FOR STEVE GLAVIN BY STEVE PRASHKER
120 REM (C) STEVE PRASHKER 1985
130 REM
140 REM THIS PROGRAM USES PROCESSED DATA FILES FROM DATAPROC AND
150 REM GENERATES A SEQUENCE OF NOTES BASED ON A RANDOM PATH ACROSS
160 REM THE TERRAIN.
170 REM
180 REM INITIALIZE THINGS
190 REM
200 DIM FREQ(500),DURA(500),MODU(500),PROBU(500),NEIGH(3
210 PRINT CHR$(12);
220 PRINT "MUSIC GENERATING PROGRAM" : PRINT
230 INPUT "Enter processed filename => ",Fs
240 INPUT "Enter drive =====> ",Ds
250 PRINT
260 INPUT "Enter output notes file => ",Ms
270 IF LEN(Ms)=0 THEN 300
280 INPUT "Enter drive =====> ",D2s
290 Ms=D2s+";"+Ms
300 Fs=Ds+";"+Fs
310 OPEN "R",#1,Fs,ZO : FIELD #1,20 AS Qs
320 GET #1 : NP=CVS(LEFT$(Qs,4))
330 GET #1,8 : REM DUMMY READ to skip to right place
340 PRINT NP
350 ARW=2*SQR(NP)
360 FOR I=1 TO NP
370 GET #1
380 FREQ(I)=CVS(MID$(Qs,5,4))
390 DURA(I)=CVS(MID$(Qs,9,4))
400 MODU(I)=CVS(MID$(Qs,13,4))
410 PROBU(I)=CVS(MID$(Qs,17,4))
420 NEXT I
430 REM
440 REM SET UP START PARAMETERS
450 REM
460 INPUT "Enter start polygon # => ",POLY
470 INPUT "Enter # of notes to play => ",NOTES
480 INPUT "Enter modrate =====> ",MODRATE
490 RANDOMIZE
500 REM
510 REM PLAY MUSIC
520 REM
530 IF LEN(Ms)<>0 THEN OPEN "O",#2,Ms
540 FOR I=1 TO NOTES
550 PRINT "POLY=";POLY
560 REM MODULATE MUSIC NOTE
570 MINFREQ=FREQ(POLY)-MODU(POLY)/2
580 FOR J=.1 TO DURA(POLY) STEP MODRATE
590 MODUJ=RND(3)*MODU(POLY)
600 FQ=MINFREQ+MODUJ
610 REM PRINT FQ;POLY;FREQ(POLY);MINFREQ;MODUJ
620 SOUND FQ,MODRATE
630 IF LEN(Ms)<>0 THEN WRITE #2,FQ,MODRATE
640 NEXT J
650 REST=MODU(POLY)*(ABS(.9990001-(19/SQR(NP))))
660 FOR RT=.001 TO REST STEP MODRATE
670 SOUND 32767,RT
680 NEXT RT
690 IF LEN(Ms)<>0 THEN WRITE #2,32767,REST
700 GOSUB 750 : REM GET NEIGHBOR
710 POLY=NEIGH(INT(RND(5)*3)+1)
720 NEXT I
730 END
740 REM

```

```

750 REM  NEIGHBOURS RULES
760 REM
770 REM  ARW IS ARRAY WIDTH DEFINED AS 2*((NP)-.5)
780 REM
790 PS=POLY MOD 4 : REM  0-RIGHT; 2-LEFT; 1-TOP; 3-BOTTOM
800 REM  PRINT PS
810 ON PS+1 GOTO 1030,850,910,970
820 REM
830 REM  TOP
840 REM
850 NEIGH(1)=POLY+1 : NEIGH(2)=POLY+3
860 NEIGH(3)=POLY-ARW+2 : IF NEIGH(3)<0 THEN NEIGH(3)=POLY
870 GOTO 1050
880 REM
890 REM  LEFT
900 REM
910 NEIGH(1)=POLY+1 : NEIGH(2)=POLY-1
920 NEIGH(3)=POLY-2 : IF POLY MOD ARW=2 THEN NEIGH(3)=POLY
930 GOTO 1050
940 REM
950 REM  BOTTOM
960 REM
970 NEIGH(1)=POLY+1 : NEIGH(2)=POLY-1
980 NEIGH(3)=POLY+ARW-2 : IF NEIGH(3)>NP THEN NEIGH(3)=POLY
990 GOTO 1050
1000 REM
1010 REM  RIGHT
1020 REM
1030 NEIGH(1)=POLY-3 : NEIGH(2)=POLY-1
1040 NEIGH(3)=POLY+2 : IF POLY MOD ARW=0 THEN NEIGH(3)=POLY
1050 RETURN
1060 REM

```

```

100 REM MUSIC GENERATING PROGRAM (COMPPROB.BAS)
110 REM PREPARED FOR STEVE GLAVIN BY STEVE PRASHKER
120 REM (C) STEVE PRASHKER 1985
130 REM
140 REM THIS PROGRAM AUTOMATICALLY CREATES A PATH AND GENERATES NOTES BASED
150 REM ON THE POLYGON PROBABILITY VALUES.
160 REM
170 REM INITIALIZE THINGS
180 REM
190 DIM FREQ(500), DURA(500), MODU(500), PROBU(500), NEIGH(3)
200 PRINT CHR$(12):
210 PRINT "MUSIC GENERATING PROGRAM" : PRINT
220 INPUT "Enter processed filename = "; F$
230 INPUT "Enter drive = "; D$
240 F$=D$+"."+F$
250 OPEN "R":#1,F$,20:FIELD #1,20 AS Q$
260 GET #1 : NP=CUS(LEFT$(Q$,4))
270 GET #1,8 : REM DUMMY READ to skip to right place
280 PRINT NP
290 ARW=2*SQR(NP)
300 FOR I=1 TO NP
310 GET #1
320 FREQ(I)=CUS(MID$(Q$,5,4))
330 DURA(I)=CUS(MID$(Q$,9,4))
340 MODU(I)=CUS(MID$(Q$,13,4))
350 PROBU(I)=CUS(MID$(Q$,17,4))
360 NEXT I
370 REM
380 REM SET UP START PARAMETERS
390 REM
400 INPUT "Enter start polygon # = "; POLY
410 INPUT "Enter # of notes to play = "; NOTES
420 INPUT "Enter modrate = "; MODRATE
430 RANDOMIZE
440 REM
450 REM PLAY MUSIC
460 REM
470 FOR I=1 TO NOTES
480 PRINT "POLY=";POLY
490 REM MODULATE MUSIC NOTE
500 MINFREQ=FREQ(POLY)-MODU(POLY)/2
510 FOR J=.1 TO DURA(POLY) STEP MODRATE
520 MODU=RUN(3)*MODU(POLY)
530 FQ=MINFREQ+MODU
540 SOUND FQ,MODRATE
550 NEXT J
560 GOSUB 610 : REM GET NEIGHBOR
570 GOSUB 920
580 NEXT I
590 END
600 REM
610 REM NEIGHBOURS RULES
620 REM
630 REM ARW IS ARRAY WIDTH DEFINED AS 2*((NP)^(.5))
640 REM
650 PS=POLY MOD 4 : REM 0-RIGHT; 2-LEFT; 1-TOP; 3-BOTTOM
660 ON PS+1 GOTO 680,700,760,820
670 REM
680 REM TOP
690 REM
700 NEIGH(1)=POLY+1 : NEIGH(2)=POLY+3
710 NEIGH(3)=POLY-ARW+2 : IF NEIGH(3)<0 THEN NEIGH(3)=POLY
720 GOTO 900

```

```

730 REM
740 REM LEFT
750 REM
760 NEIGH(1)=POLY+1 : NEIGH(2)=POLY-1
770 NEIGH(3)=POLY-2 : IF POLY MOD ARW=2 THEN NEIGH(3)=POLY
780 GOTO 900
790 REM
800 REM BOTTOM
810 REM
820 NEIGH(1)=POLY+1 : NEIGH(2)=POLY-1
830 NEIGH(3)=POLY+ARW-2 : IF NEIGH(3)>NP THEN NEIGH(3)=POLY
840 GOTO 900
850 REM
860 REM RIGHT
870 REM
880 NEIGH(1)=POLY-3 : NEIGH(2)=POLY+1
890 NEIGH(3)=POLY+2 : IF POLY MOD ARW=0 THEN NEIGH(3)=POLY
900 RETURN
910 REM
920 REM
930 REM CHOOSE NEIGHBOUR WITH HIGHEST PROBABILITY
940 REM
950 MN=0 : REM SET MAX VALUE
960 FOR H=1 TO 3
970 MX=PROB(NEIGH(H))
980 IF PREVP<NEIGH(H) THEN 1000
990 IF MX>MN THEN MN=MX : Q0=H
1000 NEXT H
1010 PREVP=POLY
1020 POLY=NEIGH(Q0)
1030 RETURN
1040 REM

```

END

21.06.88

FIN