HADES
(Haskins Analysis Display and Experiment System)

Philip Rubin, Ph.D.
Vice President for Technical Resources
Research Staff
email: rubin@haskins.yale.edu

and

Anders Löfqvist, Ph.D.
Research Staff
email: lofquist@haskins.yale.edu

Haskins Laboratories, 270 Crown St.
New Haven, CT 06511

www: http://www.haskins.yale.edu/

and

Yale University School of Medicine
Department of Surgery (Otolaryngology)

I. INTRODUCTION

HADES (Haskins Analysis Display and Experiment System) refers to a family of computer programs that has been developed at Haskins Laboratories to provide for the display and analysis of multiple channel physiological, speech, and other sampled data in an experimental context. *HADES* has become the main system for signal display and analysis at Haskins and is also being used at a number of academic research sites around the world (examples include Alfonso et al, 1993; Remez et al, 1994; Vatikiotis-Bateson et al, 1993, Vatikiotis-Bateson & Kelso, 1993, and Wada et al, in press). In general, *HADES* is used in two ways. The principal use of the system is for the display and analysis of physiological signals. These signals can be acquired from a variety of sources, including the optoelectronic position measurement systems, the EMMA magnetometer hardware, and other transduction devices. The second main use of *HADES* is for automated editing, labelling, and analysis of speech signals. This paper provides an overview of the *HADES* system, including a brief history of its development, with the main intent of describing the features that are unique to this custom-developed signal processing system. Descriptions and figures are provided to show the main features of the system along with details about some of its more novel aspects. *HADES* incorporates a procedural programming language (*SPIEL*). A considerable portion of this paper will describe this language and will include selected detailed programming examples.

Three main functions lie at the heart of the *HADES* system: **display, manipulation** and **analysis** of sampled data. Signal vectors are separated from display tools to allow for multiple views of the same data set. Data sets of up to 64 channels, supporting mixed sampling rates, can be handled. A variety of display and analysis tools are available to the user. Some of these tools are fairly general for the types of signals being used. Examples of standard displays include simple time waveform plots, spectrograms, spectral cross-sections, etc. For analysis, we provide standard Discrete Fourier Transform (DFT) and Linear Predictive Coding (LPC) analyses. Other tools are more specific to the research environment at Haskins Laboratories and have been (or are being) developed in the context of these needs. In particular, the evolution of *HADES* has been strongly influenced by the use of an electromagnetic midsagittal articulometer (EMMA) for acquiring information about speech production (Perkell, Cohen, Svirsky, Matthies, Garabieta, and Jackson, 1992; Gracco and Nye, 1993). We have found, however, that most of the tools and primitives that we have developed are of use to researchers outside of Haskins Laboratories. Less standard displays and analyses include phase and lissajous plots, TIFF displays, animation of vocal tract articulator markers, centroid calculations, event marking, etc.

The most significant feature of *HADES* is the incorporation of a procedural language (known as *SPIEL*, Signal Processing Interactive Editing Language). *SPIEL* permits the creation and customization of specialized analysis procedures that can be stored as text files, edited, etc., and are similar to functions and subroutines in programming languages like *C* and *Fortran*. *SPIEL* procedures are either interpreted from command-line entry or from text stored in ASCII command files. Signals (which are vectors of time-varying numerical values) are treated as primitives and can be manipulated (added, multiplied, etc.) as if they were numerical variables. All of the program's options are also available to the language as variables, and most operations of the programs can be specified as commands. This procedural language lets users automate routine operations, such as labelling and removing stretches of silence, and permits simple processing/analysis, within individual signals and across sets of separate signals.

The *HADES* system was designed to run on VAX computers, using the VMS operating system. The program is written in *C*, however some of the signal processing routines, particularly those based on the IEEE package of digital signal processing routines (IEEE, 1979), were written in *Fortran*. The development of *HADES* on a VAX platform combines historical

configuration requirements at Haskins Laboratories (described below) along with the need for an analysis package that would run on engineering workstations. In a limited form (text only), the program will run on any terminal connected to a VAX and can also be accessed via *Ethernet* from microcomputer terminals that support either Tektronix 4010/4014 graphics or *X Windows/Motif* emulation. Audio input and output is done using networked Gradient DeskLab sound systems, which can be accessed from most of our VAX workstations.

A variety of flavors of *HADES* exist. These are related, again, to the historical development of the system at Haskins Laboratories along with changing workstation graphical user interface (GUI) standards. At present, *HADES* exists in two main flavors: *HADES*, which runs on VAX VMS workstations that support *UIS* graphics (Rubin, et al, 1991); and *XHADES*, which runs on VAX VMS workstations that support *X Windows* graphics. A third version of *HADES*, called *MHADES*, is presently under development. *MHADES* is designed for full compatibility with the *DECwindows Motif* user interface. Finally, *AHADES* is in the planning stages. *AHADES* is a version of *MHADES* that will run on Digital's newer Alpha (DEC AXP) platform. In general, we will refer to all members or the *HADES* family of programs by the generic *HADES* name.

II. HISTORY

A detailed description of the history of the development of the *HADES* is provided in Rubin (1995). The exact character of the *HADES* system has been shaped by several major influences. In brief, the main factors have been (a) the desire to modernize and consolidate a variety of existing signal-related programs at Haskins Laboratories; (b) the need to provide a custom software facility for handling the large data sets generated in experiments using the EMMA system at Haskins; and (c) the change to engineering workstations that used raster graphics for display and provided tools for developing sophisticated graphical user interfaces.

During the 1970s a large set of signal processing programs was developed at Haskins Laboratories. These programs were written for a Digital PDP-11/45 and then a VAX 11/780. One of the most important of these was *WENDY* (Szubowicz, 1982), a waveform editing program that included a primitive procedural language for performing iterative operations and defining macros to repeat complex or frequently used operations. *WENDY* ran on a single CPU that supported a number of Tektronix 4010/4014 compatible storage display terminals. Shortly after the development of *WENDY*, a program called *SPA* (SPectral Analysis) was designed to provide DFT-based spectral analysis based on the IEEE package of signal processing subroutines (IEEE, 1979). *SPA* was intended to supplement *ILS* (Interactive Laboratory System), a commercial package of LPC-based analysis and filtering routines from Signal Technology Incorporated. A wide variety of other related programs were being used at Haskins at this point in time including programs for supporting sampled data files such as *AFM* (Arithmetic File Manipulation), *CPC* (viewing PCM data), *INPUT* (converting analog signals to digital form), and *OUTPUT* (digital to analog). The *PSP* (Physiological Signal Processing), *ACT*, and *ACE* programs were developed to display and analyze physiological time domain data.

Shortly after we began using one of our first engineering workstation (a VAXstation II/GPX), in 1986, development began on a prototype for a new display/analysis system. Several major design considerations were at the heart this project, including:

- the development of a graphical user interface for ease of use (including multiple display windows, menus, dialog boxes, etc.)

- a command window for entering text commands and/or command strings

- multiple waveforms in multi-panel windows, for manipulation of multi-channel data (e.g. physiological measurement, dichotic speech)
- the consolidation of a variety of signal-processing functions from our other programs
- a rich set of signal-processing primitives, tailored to our particular needs
- specialized display primitives
- the implementation of a procedural programming language within the program.

Although microcomputer-based systems existed (see, for example, Jamieson, et al, 1989), internal considerations dictated a VAXstation-based system. In particular this decision was influenced by the existence of a wide variety of other custom-developed VAX software that were using, and could not easily rewrite or replace. Our design decisions were also influenced by some of the other workstation-based systems developed during this period. Examples include *Spire* (Cyphers, 1985; Zue et al, 1986), *MITSYN* (Henke, 1987), and *ESPIRIT* (Gayvert, Biles, Rhody, and Hillenbrand, 1989). The result of this initial prototyping process was a program called *SPEED* (Maverick & Rubin, 1988). *SPEED* was a signal processing display and editing program that was implemented on a VAXstation II/GPX equipped with Data Translation D/A and A/D boards, attached to the Q-Bus, for signal input and output.

SPEED was conceived as a prototype and was never intended to be a large-scale system. Our next step was the beginning of the development of an environment that included an extensible programming language with flexible signal processing primitives, and was also fully integrated with other Haskins software tools. The Haskins Analysis Display and Experiment System (*HADES*) provided a vehicle for standardizing and consolidating many of the signal processing tools (e.g. *SPA*, *PSP*, *ACT*, *ACE*, *AFM*, etc.) that had been developed at the Laboratories over the years. At this point in time, the *HADES* design was also heavily influenced by our acquisition of an electromagnetic midsagittal articulometer (EMMA) system (Perkell et al, 1992).

Löfqvist, Gracco and Nye (1993) have pointed out that processing two-dimensional movement signals like those obtained from a magnetometer system often requires the handling and storing of a large amount of data. They note:

> "In a typical experiment, x and y position signals are obtained from which velocity and acceleration may be derived. In some systems, a correction index is also recorded for each receiver coil, providing information on the operation of the tilt correction algorithm. If data from nine receivers have been recorded together with the audio signal during the production of many utterances with several repetitions of each, the number of data files tends to grow very quickly. Software is required for opening and displaying multiple signal files, marking events such as the peaks, valleys and zero crossings in signals, and making measurements of the labeled signals. In addition to displaying position or velocity over time, it is also very useful to display x-y position plots of signals so that articulatory movement trajectories can be observed. Furthermore, it is helpful to have routines for filtering, differentiating, and averaging of signals and to derive new representations of the data using functions of the position information. Since many of the processing routines will be used repetitively on tokens and utterances, it saves time to automate these routines as much as possible. At Haskins, we have developed a software package, Haskins Analysis Display and Experiment System (HADES), that incorporates most of these features … "

Based on the design and potential use of the EMMA system, it was determined that the development of *HADES* would require a system that flexibly handled large numbers of independent channels of data. This resulted in certain fundamental constructs in *HADES*, including the *signal* primitive (a vector of numerical data, usually representing time-varying information, which can be manipulated internally as if it were a variable in a programming language), string manipulation routines for creating filenames, facilities for outputting data to both binary and ASCII files, customized display primitives, analysis tools customized to our own particular experimental requirements, and an integrated language that would support the rapid creation of procedures specific to our particular needs. The rest of this paper provides an overview of *HADES*, along with detailed programming examples using the procedural language.

III. *HADES* FEATURES

III.A. *HADES* User Interface

III.A.1. The *HADES* Desktop

HADES can be used for a variety of purposes. The program is usually used in two main ways. In the first approach, the user displays signals and does interactive manipulation, measurement, and/or analysis. The approach is usually best accomplished using the graphical user interface in *HADES*. A second main use of the program is to analyze larger data sets. These are generally handled more easily using procedures created in *HADES* and run from the command line interface.

Figure 1 shows the way the screen looks when the program starts. This desktop combines a *graphical user interface* with a command window that provides a *command line interface*. At the top of the desktop is the *HADES* menu bar. This menu bar lets you select from a subset of the *HADES* commands, using the mouse. The window that is in the middle of the desktop is known as the **command window.** This window is a standard *DECwindows / Motif* terminal window, used for text entry and output. In *HADES* this command window is used for command input, variable setting, and for getting printouts from the program.

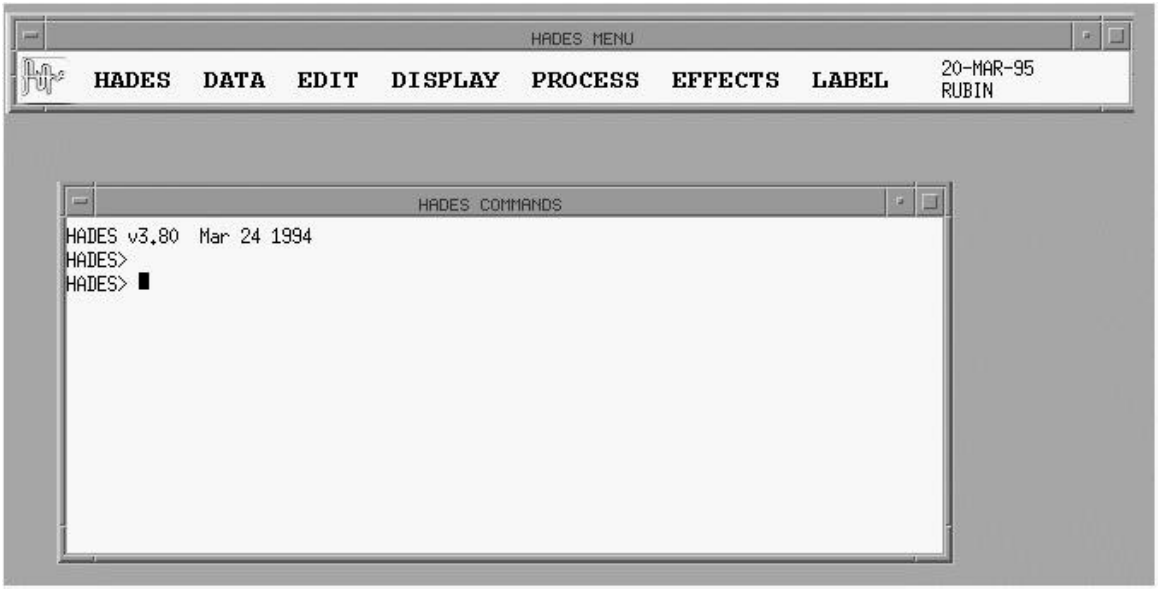

Figure 1: *HADES* GUI, showing menu bar and command window

Command line input consists of any valid *HADES* statement, which can be a command, or a line of text that can interpreted by the program, such as A=7. Details about *HADES* commands are provided elsewhere in this document and a listing of selected commands can be found in Appendix II. From the Command Window, variables can be set, including numbers and strings. In addition, flag variables can be set to selected constants. A listing of *HADES* functions is provided in Appendix III. Shown below is a short transcript of a *HADES* command line session in which a sampled data file (COW.PCM) is opened, smoothed, and saved with a new name (SCOW.PCM). Note that the *HADES* command line syntax is fairly straightforward.

(**Note**: In the following example, text shown in bold has been printed on the screen by the program.)

```
HADES> open cow
reading file MIKE$DUB0:[RUBIN.HADES]COW.PCM;1
signal COW created
HADES> smooth cow
HADES> save cow as scow
  COW SAVED AS SCOW.PCM
HADES>
```

III.A.2. The Menu Bar

A major feature of the Graphical User Interface is the **menu bar** and its associated submenus (referred to as *menus*). These menus provide quick access to many of the program's commands as well as providing a summary of the program's functions. The *HADES* menu bar contains seven menus: HADES, DATA, EDIT, DISPLAY, PROCESS, EFFECTS, and LABEL. These menus are used to control different aspects of the program. The data menu, for example, is used to get data into and out of the program as well as providing tools that help to view data and other program entities. The menu bar is shown in Figure 2, below. At the right side of the menu bar, a small graphic provides information about the date, time, and current user. *HADES* makes use of a graphics device known as *hierarchical menus*. With this approach, menu bar column selections can bring up additional submenus. A detailed Figure, showing all of the *HADES* menu commands is provided in Appendix I.

Figure 2: *HADES* Menu Bar

III.A.3. Dialog boxes

A standard component of most programs that include a graphical user interface is the *dialog box.* Dialog boxes provide a quick method for specifying command and program options, and for entering text and numerical information. This is often crucial for less experienced users of programs, particularly if the program has a wide range of possible choices. The dialog box can serve as self-documentation for a program by displaying the relevant variables, flags, and other potential selections. In addition, dialog boxes help to organize options into functional groups and provide constraints that help to minimize user error. *HADES* makes use of dialog boxes in a number of different areas. The Menu Bar includes commands, such as SPECTRAL ANALYSIS, or FILTER, that result in a dialog box being presented. Most of the display windows in *HADES* (described below) include a **Toolbox icon** that results in a dialog box being displayed. An example of the first type of dialog box is shown in Figure 3. This is the **Analysis Parameters Dialog Box** used for customizing the spectral analysis parameters. The boxes on the top row are known as buttons. Clicking on any one of these will choose a set of analysis parameters (WINDOW TYPE, WINDOW SIZE and WINDOW SEPARATION) with one quick operation. The WINDOW TYPE box shows another type of button — this is a pop-up menu button: a list of different options for WINDOW TYPE will be shown with selection being done by clicking and dragging. The WINDOW SEPARATION box allows for direct entry by typing a value into the box. Alternatively, clicking on the right and left arrows will step the value up or down. The three buttons at the bottom of the box are more straightforward. Clicking on the CANCEL button will exit the dialog, and return you to the state you were in prior to making changes to the values in the dialog box. Clicking on ACCEPT will change the specified variables, but take no further action. Clicking on the EXECUTE will change the specified variables and then analyze the appropriate signal. Dialog boxes similar to this one are used throughout *HADES*. This example describes only a portion of the types of data entry that are used in the program.

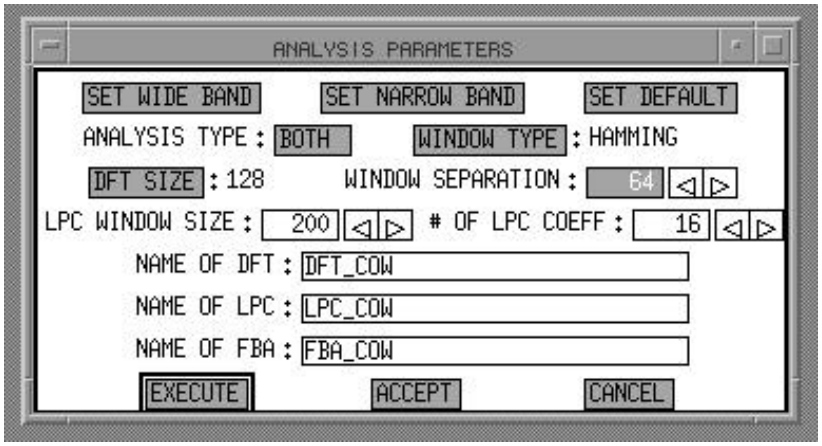

Figure 3: Analysis Parameters Dialog Box

Toolbox dialog boxes work in the same manner as dialog boxes invoked from the Menu Bar. However, a Toolbox dialog box is accessed by pressing on a graphical icon within a particular display window. The toolbox dialog box controls variables and options related to that particular window type. An example is provided in Figure 4, the **Panel Display Toolbox**. This dialog box controls many of the options that are used for customizing displays of waveforms or other time-based signals. Examples include line width, line pattern, and line color. Immediate feedback based upon changing this flags is provided in the graphical display at the top of the Toolbox. A variety of other options can be controlled in this dialog box, including display labelling and scaling.

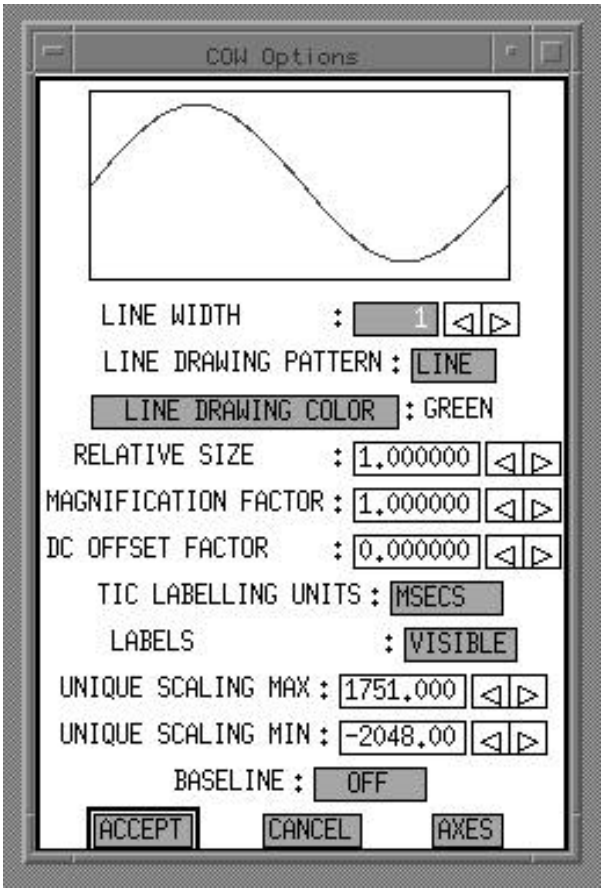

Figure 4: Panel Toolbox Dialog Box

III.A.4. Windows

Windows are an essential part of the *HADES* graphical user interface. A window is a graphical device for presenting data on the screen. In general, windows can be moved around, resized, temporarily shrunk to icon form (iconized), and closed. Figure 5 shows a window known as the Display Window. This window is described in greater detail below. At this point, a number of the important elements will be mentioned because they occur in many of the different windows found in *HADES*.

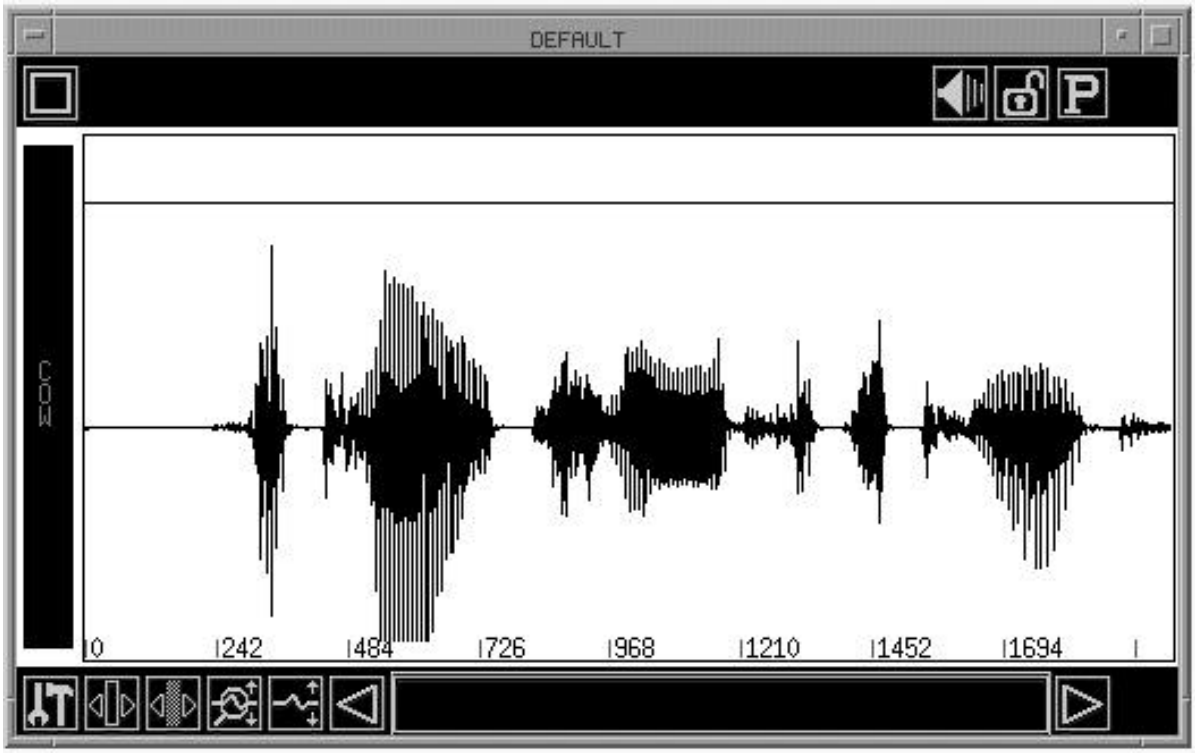

Figure 5: The Display Window

The present version of *HADES*, *XHADES*, was written to run under Digital's *DECwindows Motif* environment, which is based on the *X Window* System, designed at the Massachusetts Institute of Technology, and the Open Software Foundation's *Motif* standard. *HADES* windows take advantage of certain elements of the *DECwindows Motif* environment, including the *window title bar* at the top of the window that shows the name of the window. The window title bar also includes a *maximize button* at the top right, which is a toggle that lets you enlarge a window to its maximum size or return it to its normal size, and, to its left, a *minimize button* that lets you shrink the window to an icon — a small graphic representation of the window. Windows can be moved by clicking and dragging on the window title bar. Windows can be resized using the resize border that surrounds the individual windows.

Certain standard elements of *HADES* are not part of the *Motif* environment. For example, *HADES* does not use the *Motif* window menu button at the upper left, instead the *close box* under it is used for closing *HADES* windows. At the bottom left is the *toolbox icon*. Clicking on the toolbox icon brings up a dialog box that is specific to the particular window being used. As mentioned above, the toolbox dialog box for a window is used to specify options for that display (see Figure 4). The various other icons in the Display Window, which are specific to the *HADES* environment, are described in a later section.

III.A.5. Picon: The Programmable Icon

The **Picon** (Programmable Icon) provides a quick method for letting users access and run custom written procedures. These procedures, written in *SPIEL* the programming language of *HADES*, are used for analysis, display, labelling, and measurement. Section IV, below, provides the details of the *SPIEL* programming language and annotated programming examples. Figure 6 shows an example of a Picon window. This window includes a list of *SPIEL* procedures. These procedures can be run simply by clicking on the procedure name. Commands exist for creating and editing these Picon lists. The Picon feature of *HADES* has proven to be important in speeding up the often tedious chore of interactive data measurement.

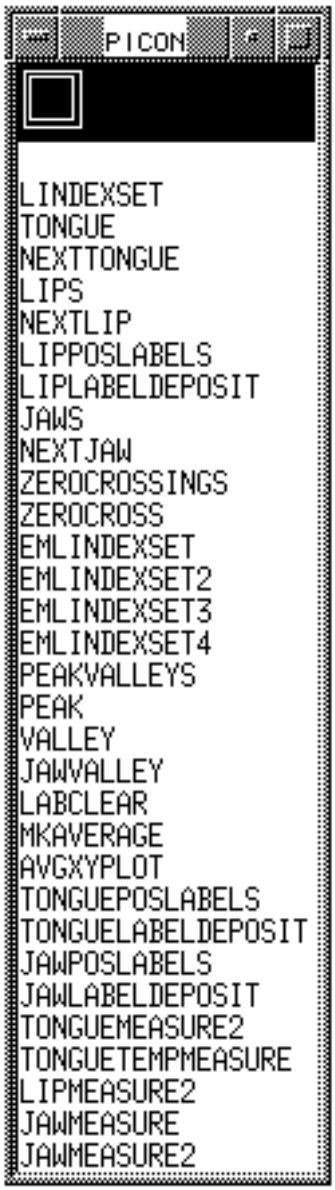

Figure 6: Picon: The Programmable Icon

III.B. *HADES* Displays

Fundamental to the *HADES* environment is a rich set of graphical tools used to represent, and allow the manipulation of, a variety of different data types. The focus of these tools is on sampled data time-based signals, but also includes displays for spectral information and gray-scale images. This section provides an overview of the *HADES* display tools.

III.B.1. The Display Window

HADES is designed to display and analyze sampled data or other time-varying information. This data can be from a number of sources, including speech signals, physiological records, synthesized information, analysis results, etc. Individual numerical vectors are represented as **signals**, which are primitives in the *HADES* system and can be directly manipulated. The fundamental *HADES* display type is the **Display Window**, which provides a graphical interface for representing and manipulating signals. The Display Window is the most frequently used display type in *HADES*. Time-based data, including both sampled data and spectral analysis data, can be displayed. In addition, multiple signals can be displayed as separate panels or overlayed in a single panel. Figure 7 provides an overview of the elements that comprise the Display Window.

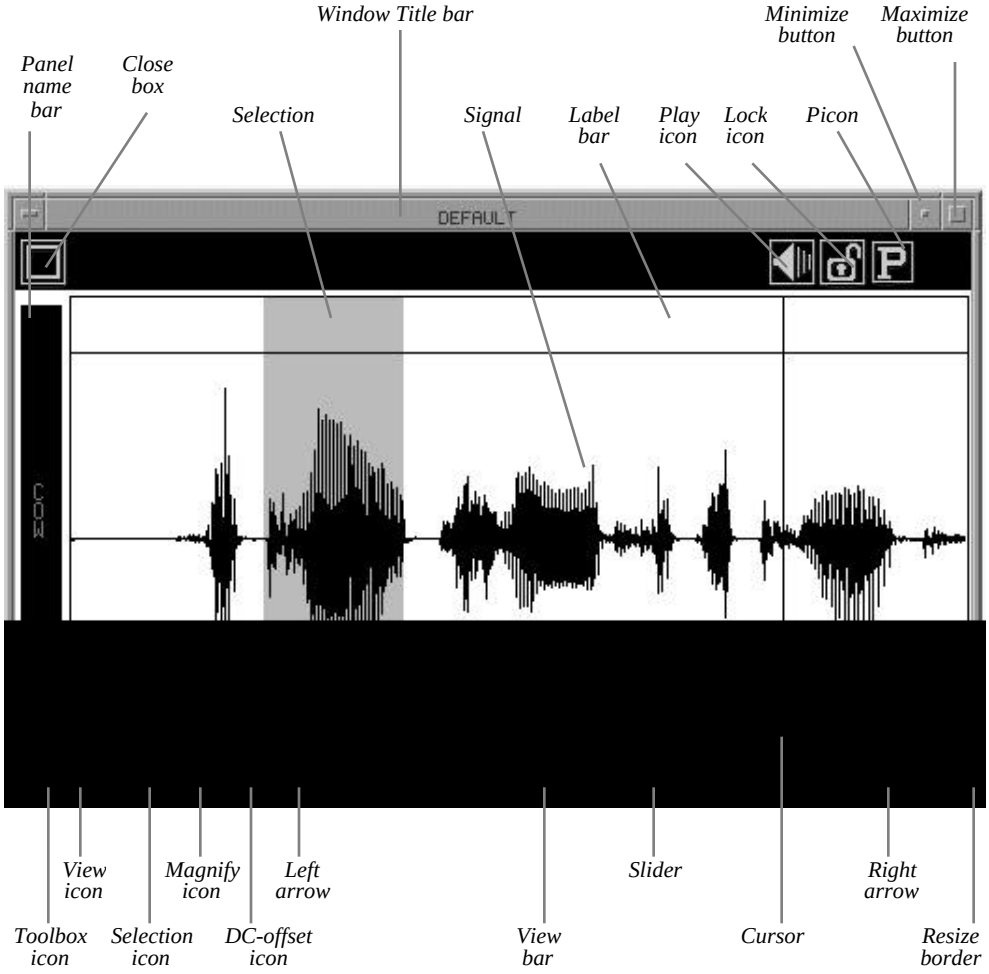

Figure 7: *HADES* Display Window

Because the Display Window is used so frequently, a lot of design effort has gone into making sure that this window allows easy access to those functions that are most needed by users. One important feature of the display interface is the **selection**. A portion of the signal can be graphically selected by the user using the mouse to click and drag over a portion of the display. The selection can be seen as the highlighted portion of the signal in Figure 7, above. The size of the selection can be re-adjusted in a number of ways, including by directly using the mouse to control the position of the left and right edges of the highlighted portion. Icons in the Display Window interface and commands in the *HADES* procedural language can be used to separately control and manipulate the selection. A vertical cursor (which provides a time reference marker) can be placed in the window using the mouse. In addition, labels (named time markers) can be placed using the mouse. Labels are discussed in detail in section III.C.1. Display windows that have multiple signals have additional controls for **panels**. These are described below in section III.B.3.

In addition to the standard *HADES* window icons (Iconize Icon, Close box, Toolbox icon, Resize icon), the Display Window includes icons specific to this window type. Examples include the Play icon, which is used to provide audio output of selected signals; the DC-Offset icon, which raises or lowers the DC offset of a signal; the Magnify icon, which grows or shrinks (vertically) the displayed portion of the signal. Icons are accessed by moving the pointer over them using the mouse and clicking the button. Several of the icons can be controlled by multiple buttons on the VAX 3-button mouse or multiple clicking using other mice when using a software *X Windows* emulator (such as the single-button Macintosh mouse). An example would be the Selection icon. On the VAX, pressing the left button decreases the selection size, pressing the right button increases the selection size, while pressing the middle button sets the selection to the size of the entire window (zooms it). In addition to special purpose icons, the Display Window includes other graphical interface elements such as the horizontal scroll bar at the bottom of the window which is used for controlling the view of both the entire signal and of a selection. A number of elements comprise the horizontal scroll bar, including left and right arrows, a View bar, and a Slider.

Displaying waveforms in *HADES* serves as an example of the flexibility of program's interface. A variety of options are available to the user. In general, *HADES* commands can be graphically selected from the menu (in this case selecting TEMPORAL from the DISPLAY menu, which results in a list of open signals that the user can select from). Keyboard shortcuts are available — in this case, `Ctrl-D` which displays the most recently opened signal. Alternatively, command line entry can be used to enter the appropriate command, using the required syntax for that command. For example, the syntax for the DISPLAY command is:

```
DISPLAY sig1 [sig2 sig3 ...] [ IN windowname]
```

where `sig1, sig2, sig3`, etc., are names of signals to be displayed, and `windowname` is the optional name of the window to display the signal(s) in. In general, the DISPLAY command displays signals in a default window (called `DEFAULT`). However, *HADES* supports multiple named display windows. Thus, multiple signals can either be displayed as panels within a single window, or as multiple separate windows, or some combination of both.

III.B.2. The Display Control Panel

When the DISPLAY command is used to display a signal, an additional window is opened at the bottom of the screen. This window is known as the **Control Panel** as shown in Figure 8. The Control Panel provides information about the *active signal* and lets the user set selected values and flags.

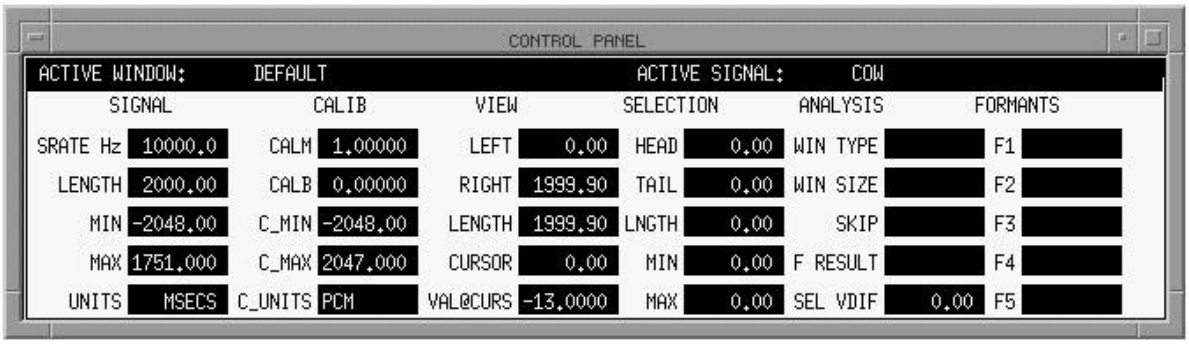

Figure 8: The Control Panel

The Control Panel is divided into six columns. The first column, called SIGNAL, provides information about the active signal. The second column, called CALIB, provides information about the calibration values for the active signal. Calibration usually come from the header of the file that the signal was read from: this is called the *file header*. Each signal carries its calibration information, along with other information, around with it in what is called its *signal header*. The third column, called VIEW, provides information about the portion of the active signal that can be seen in its panel. The fourth column, called SELECTION, provides information about the highlighted selection. The fifth column, called ANALYSIS, provides information about analysis parameters plus some miscellaneous information. The sixth column, called FORMANTS, lists peak-picked formant center-frequency values (F1 through F5) obtained using LPC analysis.

III.B.3. Spectral displays

A spectrogram can be created in a number of ways. In the figure shown below, a sampled data signal, COW, has been displayed in a Display Window. The menu bar command **PROCESS**:SPECTRAL ANALYSIS was then used to perform a DFT spectral analysis of the sampled data signal. Selecting this command from the menu bar also resulted in a spectrogram being displayed, as an additional panel, in the same Display Window that the signal used for analysis is in. Another method of displaying a spectrogram is to read a DFT signal from a file, or create one using the methods described above, and then display it using the DISPLAY command or the **DISPLAY**:TEMPORAL menu selection, which invokes a *signal picker* (a graphical list of signal names) to select the signals that will be displayed.

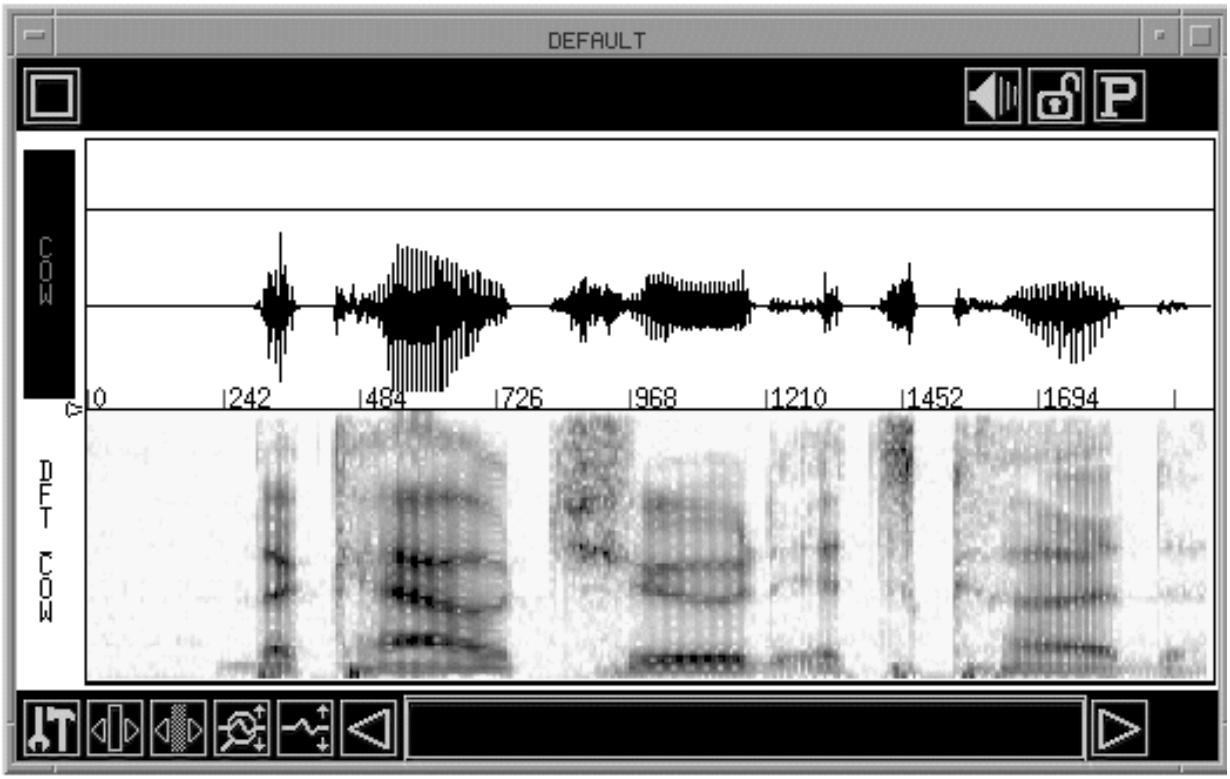

Figure 9: Display Window with waveform and spectrogram

Formants may be traced by hand on a spectrogram plot by selecting the TRACE box on the panel toolbox (clicking with two buttons on the vertical namebar at the left side of the signal). This brings up the Spectral Trace Setup Dialog Box which lets you select from one to five formants. While in *trace mode* you select a formant number and a color. Clicking and dragging the mouse on the spectrogram marks the plot in the appropriate color for the selected formant. Redrawing with the same formant in the same time range will erase the earlier trace and mark a new one. Once formant values have been retrieved, they can be saved to an ASCII data file. This file can be used for a variety purposes including driving a formant-based speech synthesizer. This technique is also now often used to derive formant center-frequency values used to create sinewave synthesis replications of spoken utterances (Rubin, 1980; Remez et al, 1981, 1994).

A spectral **cross-section** plot (shown in Figure 10, below) is generated whenever there is a mouse click on a temporal spectrographic display. Multiple cross-section windows can be created, with each window representing a frame marked by the cursor location on the temporal display. Once the cross-section has been drawn, the frame may be changed by clicking (and holding) on either of the arrows drawn under the plot, or by clicking on a new location in the temporal display. Clicking on the cross-section plot area will retrieve the frequency and magnitude at the location of the click (this information can optionally be automatically recorded to an ASCII journal file.)

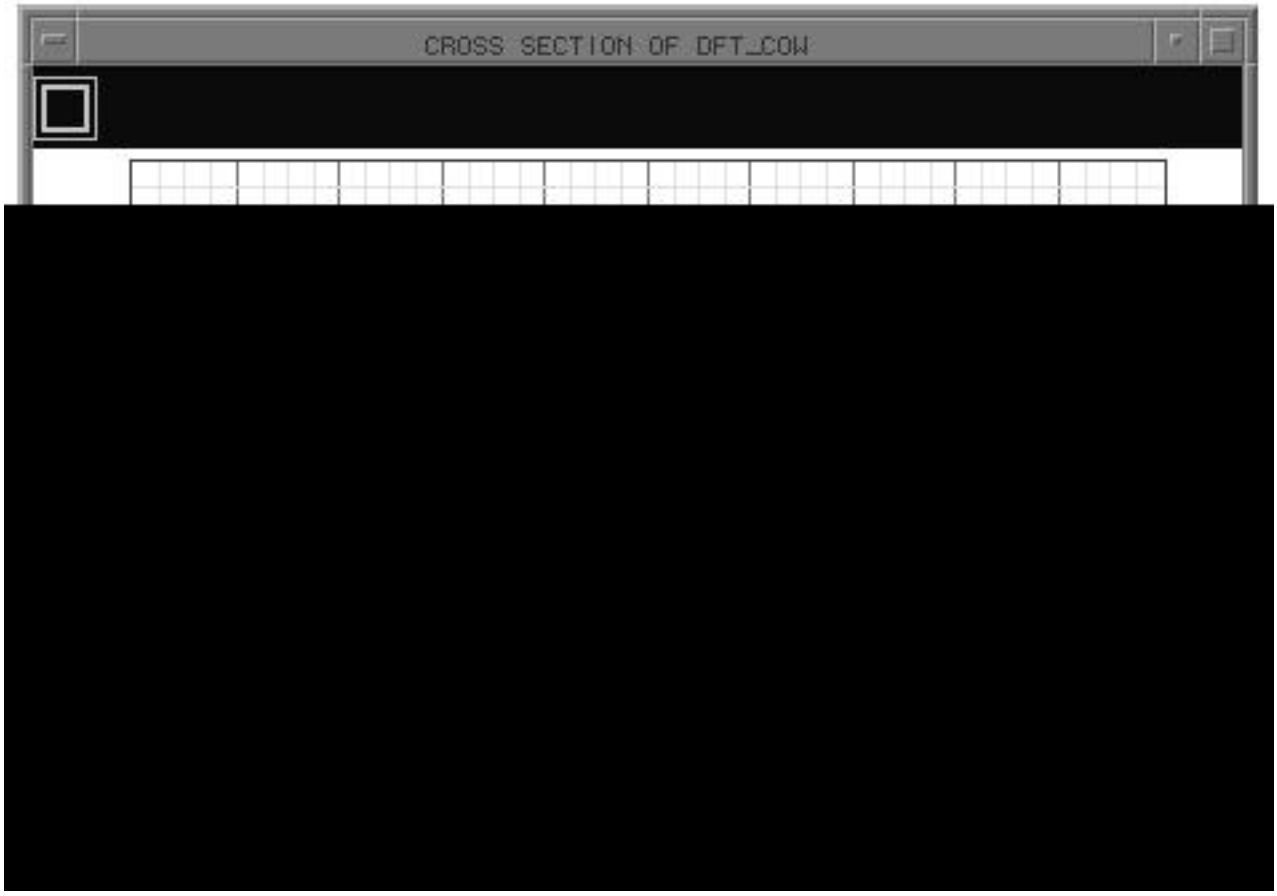

Figure 10: Spectral cross-section

A waterfall display (3D spectrogram) may be generated for any DFT signal which has been opened or created. A small waterfall display is shown below.

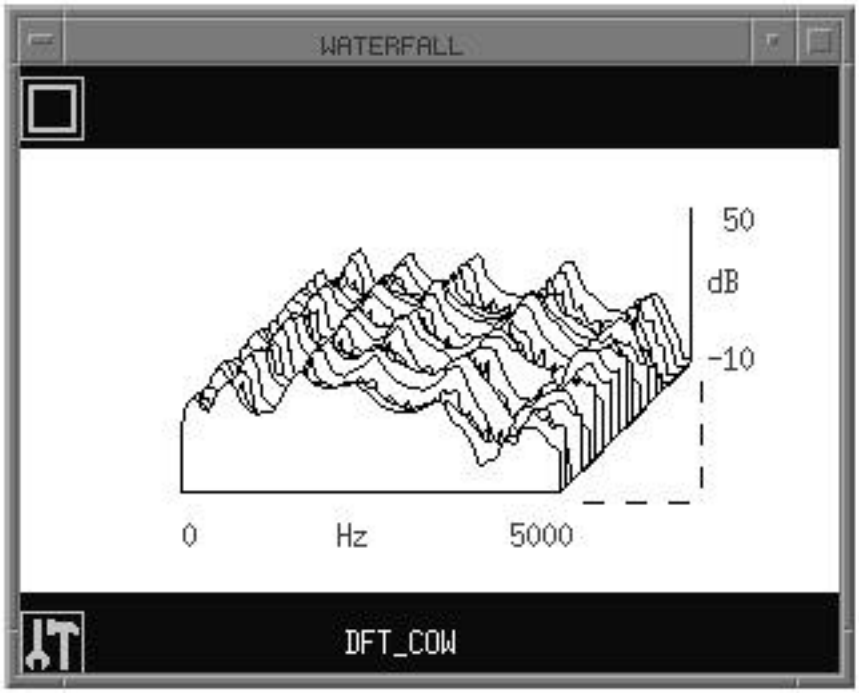

Figure 11: 3D Waterfall spectral display

III.B.4. Multiple Panel displays

Multiple signals can be displayed in a single window. This can be done using the **DISPLAY**:TEMPORAL menu bar selection, which brings up the **signal picker,** letting you select several signals to be displayed at the same time. Another method is to use the DISPLAY command, which has the following command format:

DISPLAY *sig1 sig2 ... sign* IN *windowname*

The figure below shows a Display Window with multiple signals. This particular display has four signals. Each signal is displayed in a separate *panel*. The name of each signal is shown at the left of the signal in the *panel name bar*. The four signals are: R1T1AUDIO, R1T1ULY, R1T1LLY, and R1T1PRES. The top signal is a speech waveform, the bottom three signals are physiological data. The user can move between panels by clicking on the name of the signal to the left of its display (making that signal the *active signal*) and can graphically control the relative height of any individual panel using the arrow at the bottom left of each signal panel. A large number of *flags* are available within *HADES* for controlling details of the graphical appearance of the Display Window. In the case of the Multiple Panel display, the most important ones are used for determining whether the individual panels are stacked, as in Figure 12, or overlayed, as in Figure 13, and whether or not panel separators appear (they appear in Figure 12).

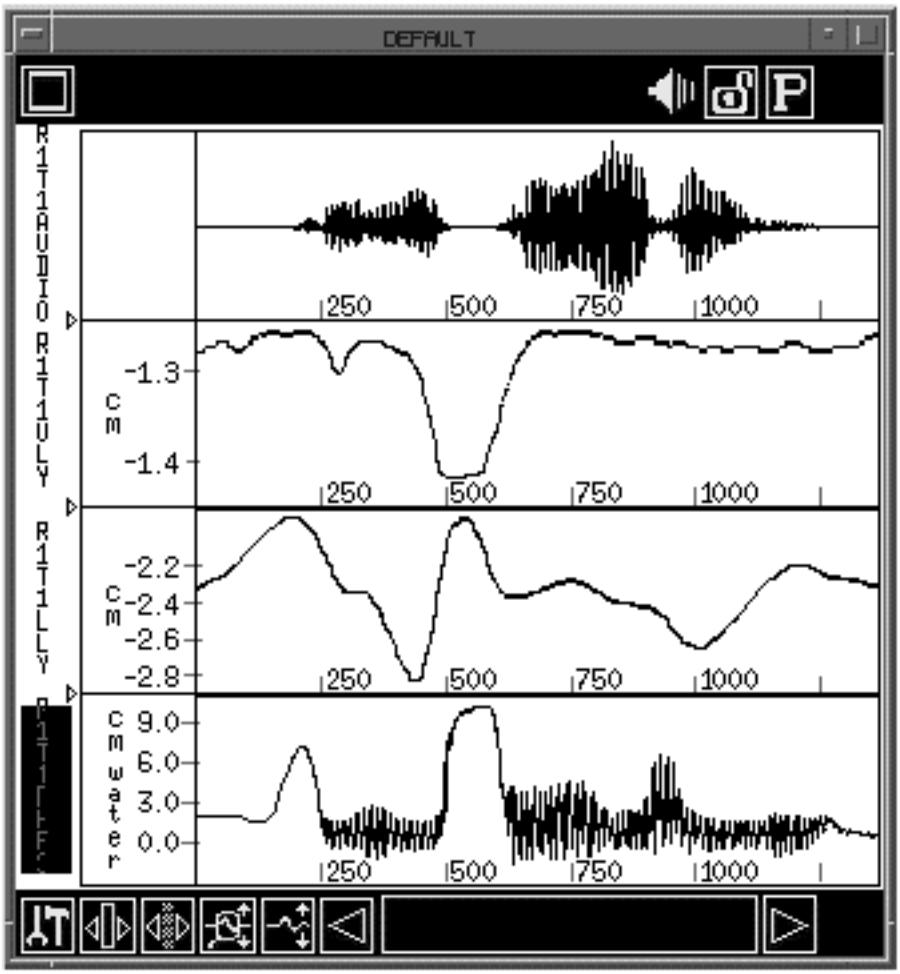

Figure 12: Multi-panel Display Window

Panels are often overlayed for direct comparison of signals. The figure below shows a Display Window with multiple signals that are overlayed and scaled to a common scale. This display has three signals: U102T1ULY (the y position from a marker placed on the upper lip of a subject), U102T1LLY (the y position from a marker placed on the lower lip of a subject), and U102T1JAWY (the y position from a marker placed on the jaw of a subject). Note that the line width is varied for the different signals and that there is no panel separator. The flags that are used to customize this display can be accessed directly using the Panel Dialog Box (by clicking on the Toolbox icon at the bottom left of the window), or by setting values using the *HADES* procedural language.

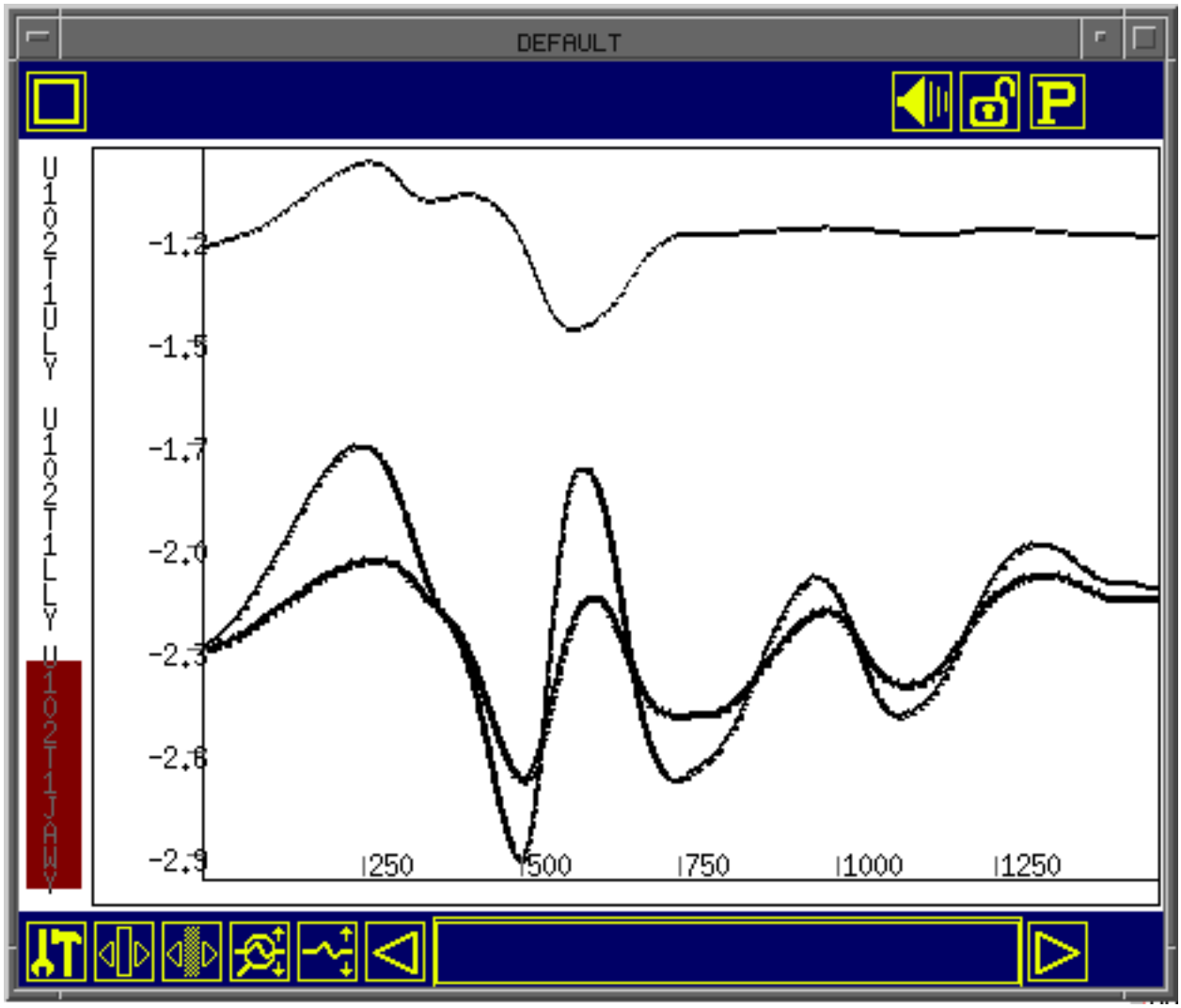

Figure 13: Multi-panel display window — overlayed

III.B.5. Lissajous display

The Lissajous display creates a cross-plot of two waveform signals. The Lissajous plots one signal on the horizontal (x) axis versus a second signal on the vertical (y) axis. Each signal is scaled to its physical range before plotting (no adjustment is made for different sampling rates). This display type is particularly useful for observing the movement of points in a Cartesian reference frame, as with microbeam pellets, magnetometer receivers, etc. To get a better sense of how such points move in time, the plotting speed can be slowed down using a delay variable that controls tenths of seconds to pause between displaying data points. As with waveforms, Lissajous plots can be overlayed, and the color of individual plots can be varied, providing for cross-signal comparison. The combination of the delay feature and individual size and colors for overlayed traces provides for limited animation of the x-y positions of points, such as the midsagittal trajectories of EMMA receivers.

Figure 14 provides an example of a Lissajous display. This figure represents a midsagittal view of the results of data captured during a magnetometer run in which a number of receivers have been placed on the speech articulators. The receiver trajectories (their x-y positions over time) are plotted, resulting in the set of small, tight curves. In this figure, a number of plots have been overlayed and a grid feature has been turned on for reference. The slowly varying curve at the top represents the hard palate.

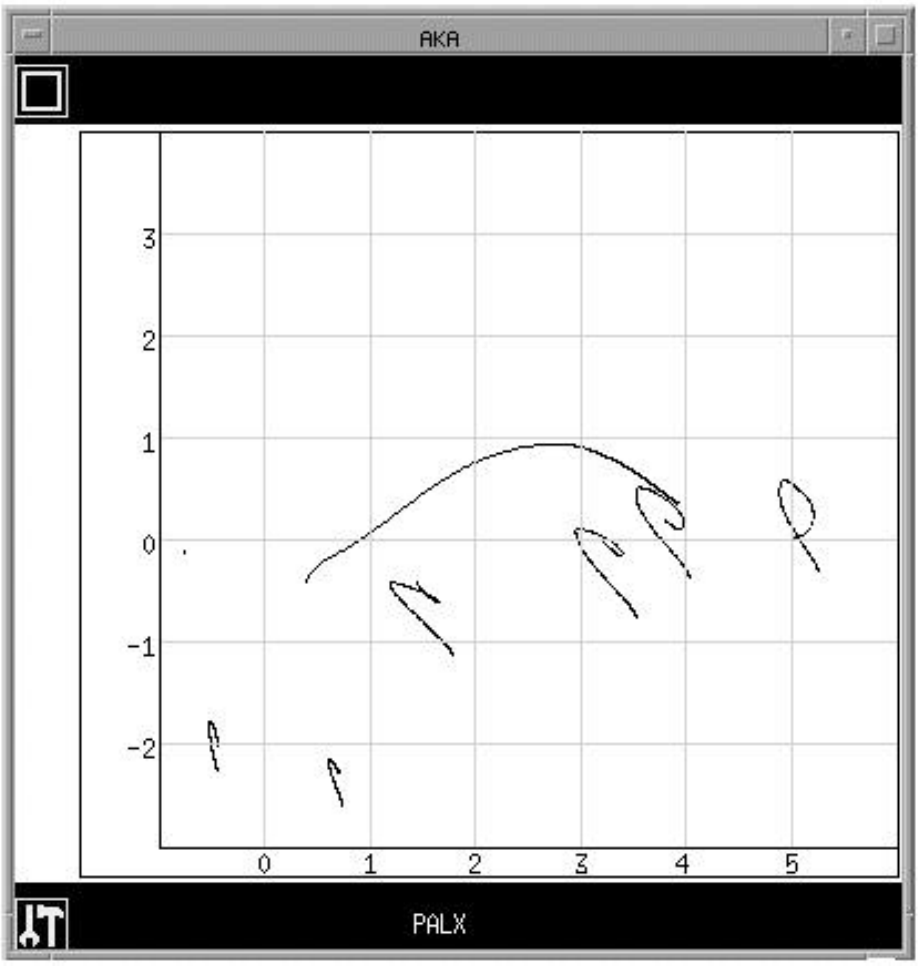

Figure 14: Lissajous display

III.B.6. Phase display

The Phase display creates a difference, or phase, plot of a single waveform signal. The sample values are plotted along the x-axis, against the difference (from the previous sample) on the y-axis. This is useful for providing information about position versus velocity. The signal is scaled to its physical range before plotting. As with the Lissajous plot, the drawing speed can be slowed down using a delay variable. Also, Phase plots can be overlayed, and the color of individual plots can be varied, providing for cross-plot comparison. Figure 15 provides an example of a Phase display.

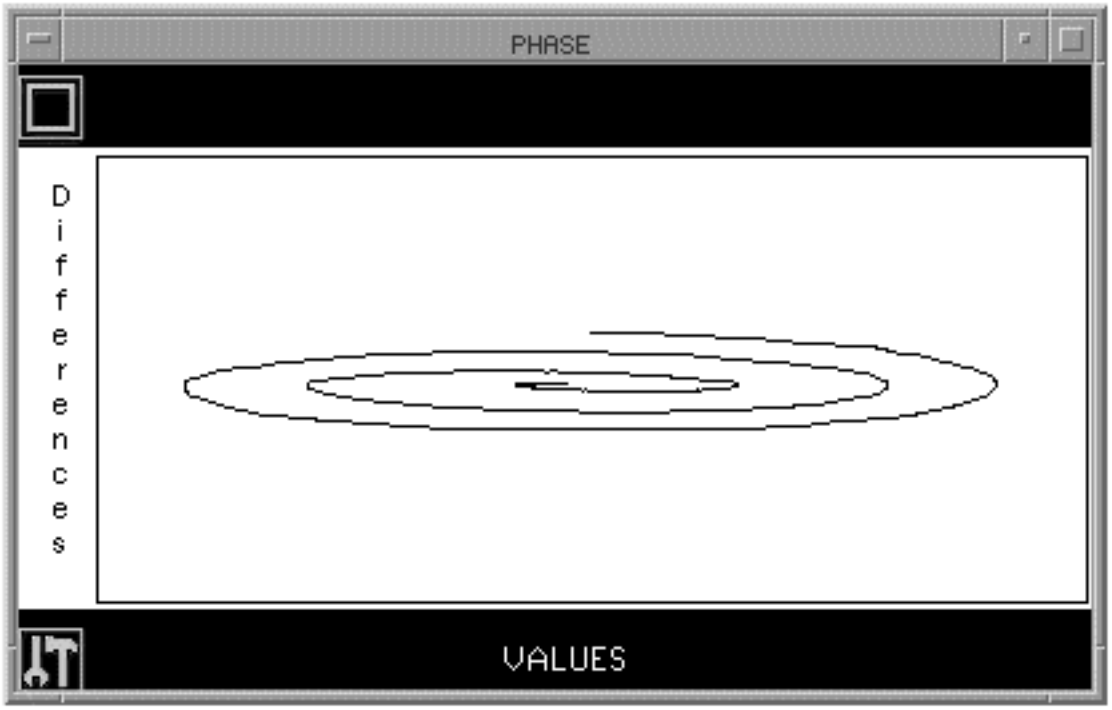

Figure 15: Phase display

III.B.7. TIFF Display

HADES can display graphics files that are in TIFF (Tagged Image File Format) format (Davenport and Vellon, 1987) and capture portions of the screen as TIFF files. Using this public domain format for digital images allows free interchange between Macintosh, PC-compatible, and VAXstation-based programs.

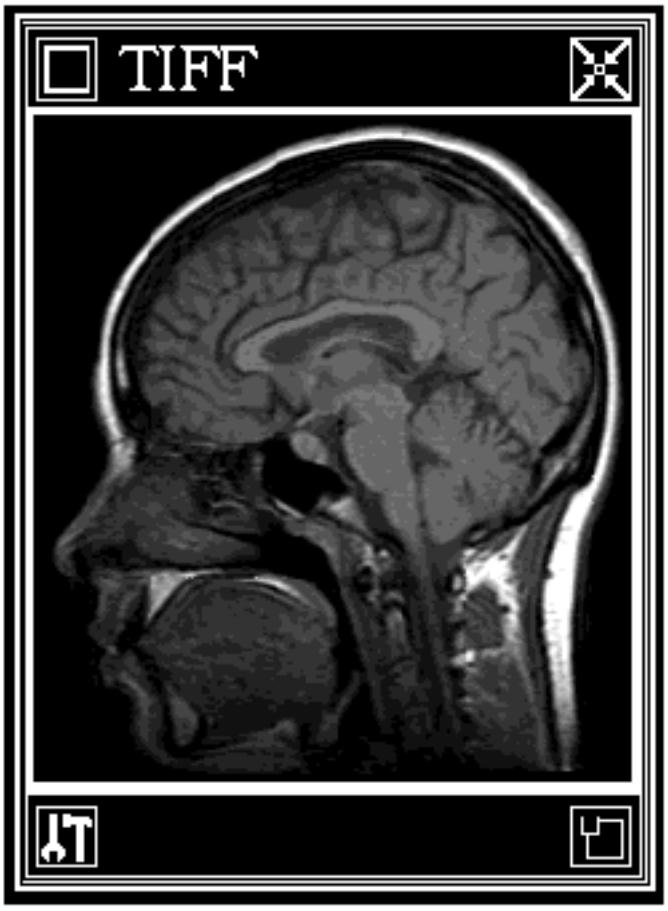

Figure 16: TIFF display of MRI of vocal tract

III.C. Signal measurement

The major use of *HADES* is the measurement, processing, and analysis of signals. These can be accomplished using the graphical interface, the command line interface, or by creating custom procedures in the *HADES* procedural language (*SPIEL*). This section focuses on signal labelling. Section III.D provides an overview of some of the analysis and processing tools. Information about *SPIEL* including detailed examples can be found in Section IV and Appendix VI.

III.C.1. Labelling signals

Labels represent a way of marking exact locations or a range of values in signals and sampled data files. In this approach a label consists of a name and a set of fields. Each field consists of a field name and an integer, decimal, or string value. Labels may also have comments. Labels can be represented graphically by a time marker being drawn on the signal. This marker includes a vertical line that corresponds to the central time value for the label and a horizontal bar that specifies the label's temporal range (see Figure 17).

Labels are stored in ASCII text files and are usually given a name related to the sampled data file or signal they are associated with. For example, if you have a sampled data file named COW.PCM, then the default label file will be called COW.LAB. However, label files can optionally have any name and can be associated with any signal or file. Each label must have a name field that contains the name of the label, and a central time field whose value represents its location in the signal. All other fields are optional. Below we have defined the label fields that are presently supported in *HADES.*

Field	Example	Description
CHANNEL	CHANNEL=COW	Signal that label came from
TIME	TIME=1119.4	Center time in msec.
LRANGE	LRANGE=300.326	Distance of left edge of selection from center time in msec.
RRANGE	RRANGE=235.483	Distance of right edge of selection from center time in msec.
SAMPLE	SAMPLE=11195	Sample number of center time
AMPLITUDE	AMPLITUDE=75	Value of sample at center time
ATTRIBUTE	ATTRIBUTE=0	Controls line drawing type, where: 0 = solid line 1 = dashed line

Labels can either be set from *SPIEL*, or by working interactively with the data shown in a Display Window. In this latter approach, labels are placed in a number of ways. One way is to choose a location in the signal, using the mouse to move the pointer to the appropriate place, and then press the right mouse button. This will bring up a dialog box that provides for the specification of the label name, an alias, times for left and right ranges, and an attributes and comment field. Another method is to choose a location for the cursor, using the mouse,

and pressing the middle button to place the cursor in the signal. Pressing `Ctrl-L` or choosing **LABEL**:SET LABEL from the menu bar will bring up the *Label Dialog Box*. An additional way of marking a label is to use the mouse to select a portion of the signal by clicking and dragging, and then using one of the methods just described to bring up the Label Dialog Box. Labels can also be generated by the Event Marking routines in *HADES* (see section III.C.2, below) or can be created using *SPIEL* procedures. In addition, *HADES* functions are available for retrieving label times and/or name strings. These values can then be used in *SPIEL* procedures to automate processing. Detailed examples of this approach are provided in section IV.

An example of a signal that has been labelled is shown in the figure below. This Display Window has two panels. The top panel, called `OLD`, contains the waveform for the sentence "The cow chewed its cud" prior to labelling. The bottom panel, called `COW`, shows the results of manually labelling a section of speech. Each word was first selected, a label was set near the middle of the selection, and the label was given a name.

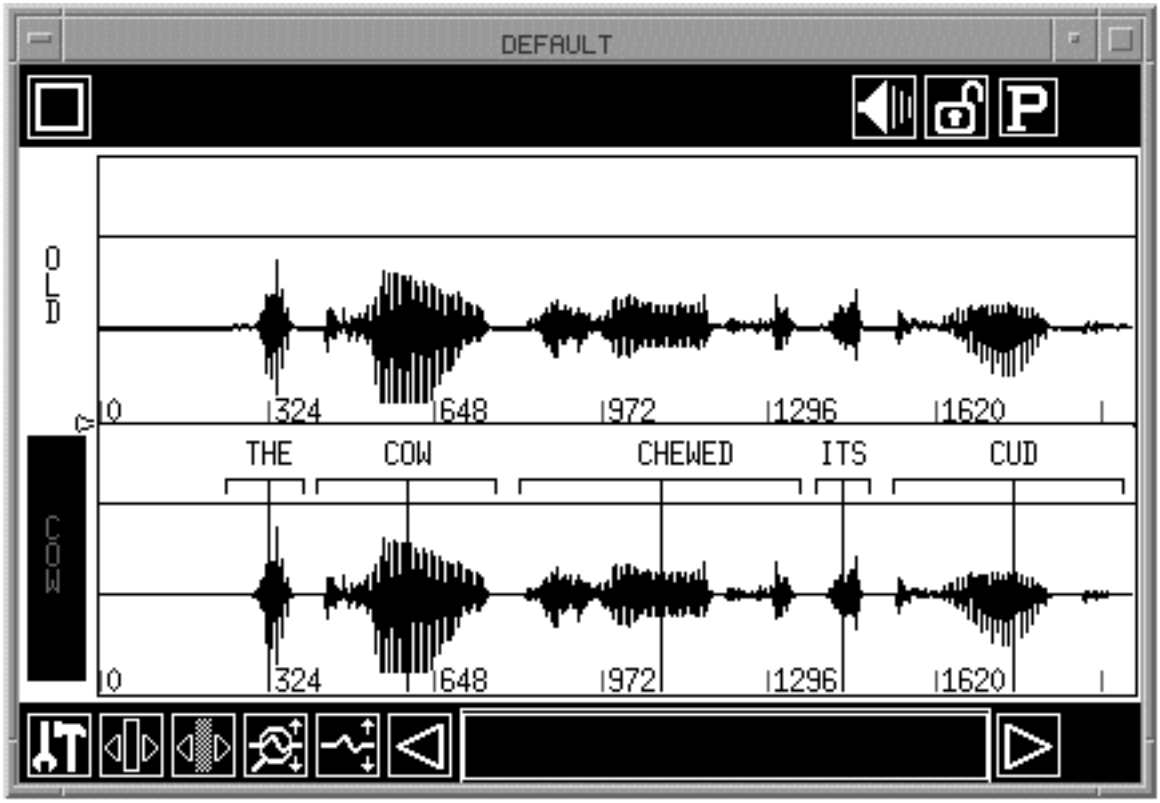

Figure 17: Display Window showing a labelled signal

Listing the labels for this signal would show the following information:

```
LABELS ATTACHED TO SIGNAL COW:

THE:    TIME =  313.977  SAMPLE =  3141   LRANGE =  75.082   RRANGE= 75.082  AMP = 101
COW:    TIME =  607.478  SAMPLE =  6076   LRANGE = 177.466   RRANGE=150.163  AMP =  75
CHEWED: TIME = 1119.4    SAMPLE = 11195   LRANGE = 300.326   RRANGE=235.483  AMP = 578
ITS:    TIME = 1443.61   SAMPLE = 14437   LRANGE =  54.605   RRANGE= 40.954  AMP =-219
CUD:    TIME = 1771.24   SAMPLE = 17713   LRANGE = 235.483   RRANGE=228.657  AMP =  82
```

Figure 18 provides an example of a physiological signal in which labels have been individually placed by hand and given mnemonic label names, where V1 indicates valley-1, and P1 indicates peak-1, etc.

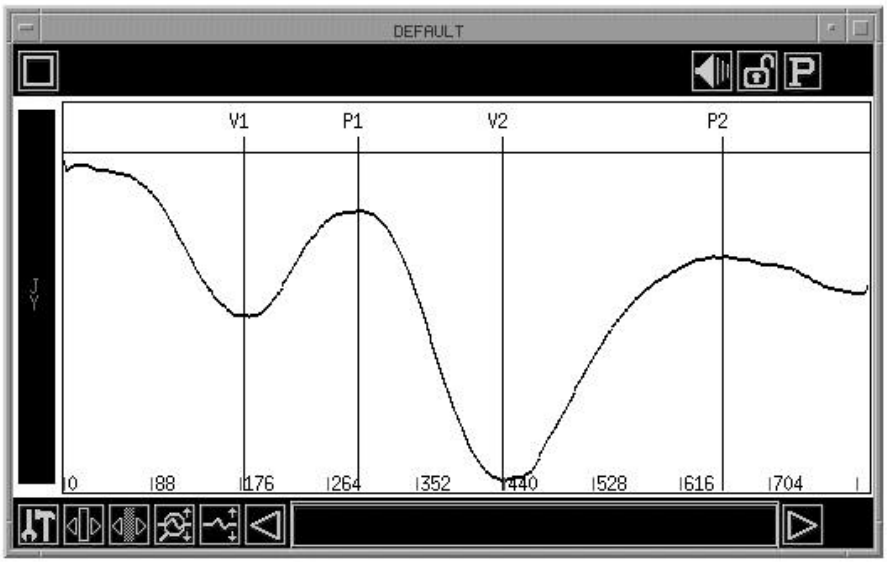

Figure 18: A hand-labelled signal

The next example, in the figure below, shows the same signal marked with labels that were placed by hand but were given names automatically using the AUTOLABEL command, with _LABELID=A, and _LABELINDEX=5. To use autolabelling, select the AUTOLABEL command (**LABEL**:AUTOLABEL). A dialog box will request information about the LABELID, which is a prefix that starts each label name, and the LABELINDEX, which is the number to start labelling at. Clicking the right mouse button places a label and increments the LABELINDEX, automatically creating label names (e.g. A5, A6, A7, A8).

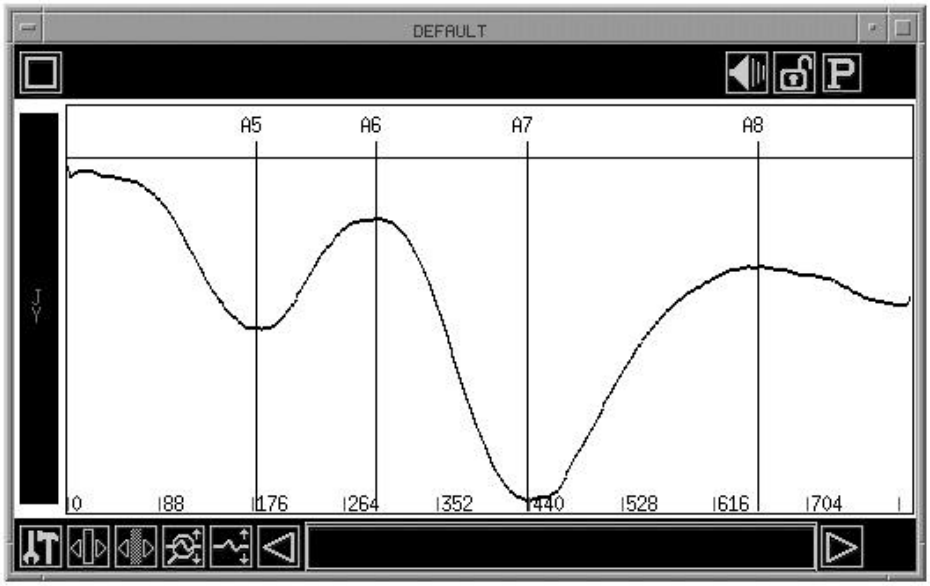

Figure 19: A signal labelled by means of autolabelling

III.C.2. Event marking

Event marking in *HADES* may be used to label significant events in signals. These events include:

- peaks
- valleys
- plateaus
- onsets
- offsets
- segments
- zero crossings

Each event type (e.g. peak, zero crossing) has its own definition and often has associated variables (such as noise criteria) used to tune the event location. A variety of marking choices and label options are available within the event marking package, including a number of flags and string variables. These can be seen in the Event Marking Dialog Box. In addition to finding significant events in signals, through the use of these flags and variables event marking also provides for an orderly labelling and numbering of these events. String variables are used to create names. This supports the generation of user procedures for automatically dealing with events in large data sets.

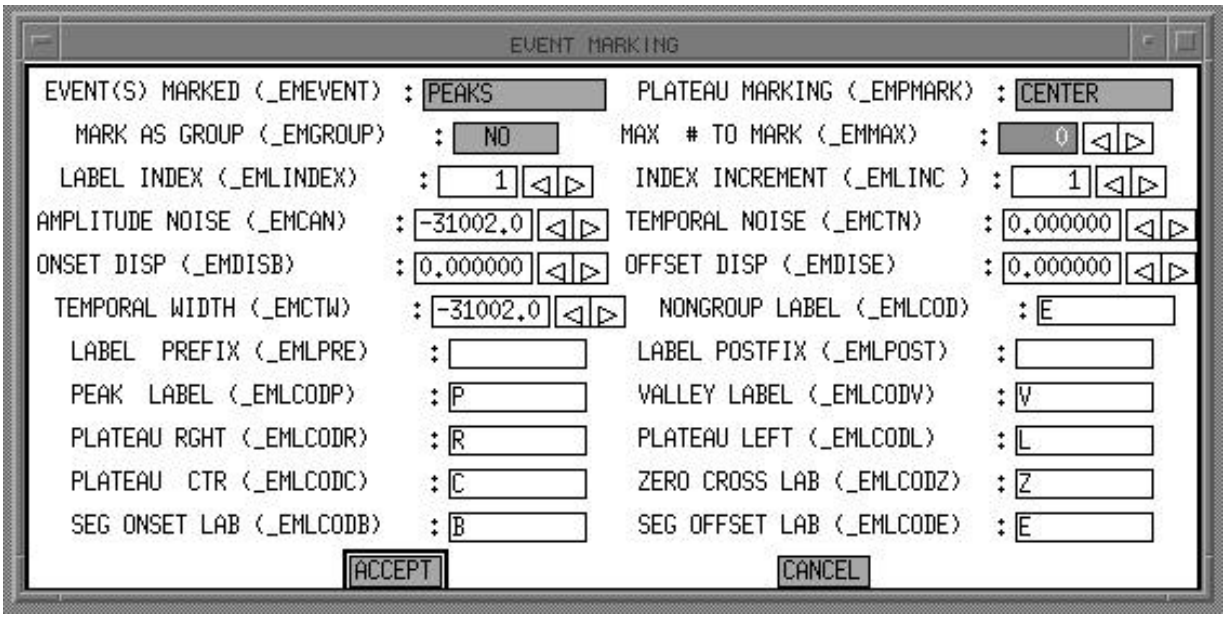

Figure 20: Event Marking dialog box

III.D. Signal processing and analysis

III.D.1 Waveform editing and manipulation

HADES can be used, interactively, to graphically edit and manipulate signals. As an example, this is often done with audio waveforms. The user can CUT, COPY, PASTE, SILENCE, TRIM, portions of the waveform. *Effects*, such as AMPLIFY, FADEIN, FADEOUT, INVERT, RECTIFY, REVERSE, etc., can be used to provide quick global waveform manipulations. Audio feedback is available for evaluating the results of these changes. This use of the program is similar to what is now commonly available in desktop sound manipulation programs, such as the *SoundEdit* series on the Macintosh and also replaces the functionality of the previous waveform manipulation workhorse at Haskins, a program named *WENDY* (Szubowicz, 1982) used heavily during the 1970s and 1980s. Although the use of *HADES* in this way seems very similar to the desktop computer programs, they are many differences. The most important is the accessible and powerful integrated procedural language, *SPIEL*, which permits custom user-developed procedures that can automate repetitive signal manipulation in large data sets. *SPIEL* will be discussed in greater detail in section IV.

III.D.2 Signal processing

A variety of different processing tools are available in *HADES*. These tools can be accessed in a variety of ways, including through the menus, the command language, user functions, and *SPIEL*. The signal processing tools include:

- Amplification — modifies the energy of the signal or signal portion
- Averaging — creates an averaged signal from a set of signals
- DCadd — adds a DC constant to all signal values
- Demean — the mean of a signal is calculated and then subtracted from all signal values
- Integration — calculate the definite integral
- Rectification — performs in-place full or half wave rectification
- RMS — calculates the RMS (root mean square) energy using the following algorithm:

```
RMS = 20*log10(sqrt(sum1/npts));
```

where `sum1` is the running sum of `x*x` (where `x` is an individual data point), and `npts` is the number of points in the vector

- Smoothing — replaces the signal with a smoothed version using odd-number filters: triangular, rectangular, Hamming, or Hanning

- Filtering — creates FIR low-pass and high-pass filters.

Figure 22 shows the Filter Parameters Dialog Box. High- and low-pass FIR filters can be created within *HADES* using *SPIEL* or through this dialog box. Optionally, filters designed by other programs (such as *MATLAB*) can be imported into *HADES*. The filters are implemented with or without automatic phase correction. The Filter Parameters Dialog Box shows the state of the current default filter (the one most recently created or imported) and also lets the user set filter creation parameters. These include the cutoff frequency, the number of points in the filter, the filter type (high-pass or low-pass), and the window type (Hamming, Hamming, triangular, or rectangular). Filter created in *HADES* can be exported for use with external applications.

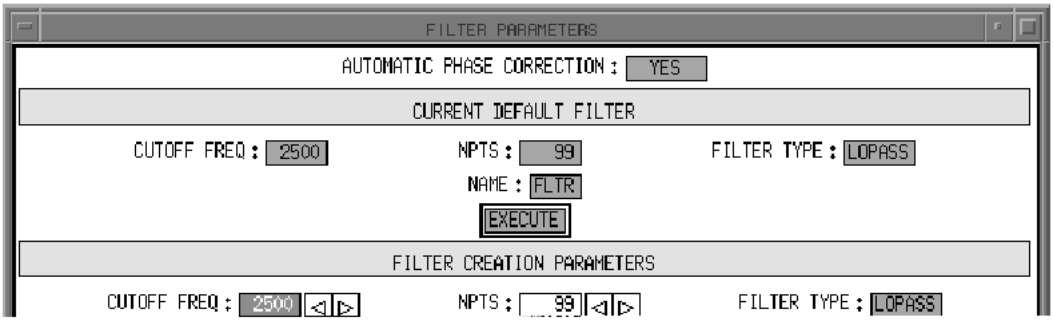

Figure 21: Filter Parameters dialog box

The source reference for several of the processing algorithms is Strum and Kirk (1989).

III.D.3 Spectral analysis

HADES provides for spectral analysis using the Discrete Fourier Transform (DFT) and Linear Predictive Coding (LPC). These techniques are standard approaches for speech and signal analysis, thus, we will not go into detail about them here. Instead we will focus on how signal analysis is implemented in *HADES* and details specific to the *HADES* environment. A variety of sources provide additional information on speech analysis. Among others, we refer the reader to Atal, 1985; Fallside, 1985; Fallside & Woods, 1985; Markel & Gray, 1976; O'Shaughnessy, 1988, 1995; Rabiner & Schafer, 1979; and Witten, 1982) .

Within *HADES*, a number of spectral displays are available, as shown above in section III.B.3, including gray-scale spectrograms, LPC and FBA time-based pseudo-spectrograms, spectral cross-sections, and 3D spectral waterfalls. Additional spectral calculations include the centroid measure.

Spectral analysis of a signal, based on the Discrete Fourier Transform, can be performed by *HADES*, creating a DFT signal which can be displayed or saved. Alternatively, pre-analyzed DFT data can be read in from files saved by *HADES*. Three global flag variables are used to control the DFT spectral analysis. The first, _DFTWINT, specifies the type of window used in the analysis. The size of the analysis window is set by _DFTWINS. The amount (number of points) that the analysis is shifted over for each frame is specified by _DFTSKIP. LPC analysis creates a signal with the same use and privileges as DFT analysis, and also creates an associated FBA signal. The FBA signal was designed by the first author for use in a variety of programs at Haskins Laboratories during the 1980s. An FBA file is an ASCII file that contains the formant, bandwidth, and amplitude values from an LPC analysis file created with the *ILS* program, along with other selected information. The creation of this file provided a means for capturing this data and using it without having to remain within the *ILS* framework. DFT, LPC, and FBA signals can be displayed simultaneously in a window, along with a waveform or waveforms. This is useful for direct comparison of the different analysis techniques. Figure 21 shows such a window, with a waveform, and DFT, raw LPC (smoothed), and FBA (peak-picked formant center frequencies) displays.

Spectrograms are generated by DFT analysis of the sampled data files using the IEEE package of signal processing routines (IEEE, 1979). Our particular implementation is based on an earlier Haskins program called *SPA*, written by Richard McGowan and Philip Rubin. As usual, analysis can be procedure-, command-, or menu-driven. When using the menu command, a dialog box guides the user through the selection of analysis options such as source data file, analysis type, window type and size, starting and ending portions of the waveform to analyze. Once a spectrogram has been calculated and displayed, the user can interact with this spectral display. For example, a spectral cross-section can be generated whenever there is a mouse click on the spectrogram display. Spectral cross-sections show frequency-magnitude information for a single frame. A full spectral analysis of a single frame can quickly be obtained by placing a cursor in a waveform and using the SNAPSHOT command or menu selection.

An additional spectral measure is the **centroid,** which is a weighted average of magnitudes that is used to define the center of mass over a frequency range. This option may be selected from the tools menu on the cross-section plot, or used as a typed command without going through the graphical display. If done graphically, the frequency range can be selected with the mouse. The code used to generate the centroid is shown in Appendix V. The inclusion of support for calculating centroids in the *HADES* program provides a good example of how this program has been customized to the particular needs of the Haskins research community. This particular analysis was one that was frequently requested by users and was of sufficient importance to be included as a *HADES* primitive. Other less frequently

used analyses are often developed in *SPIEL*. If *SPIEL* is not appropriate for or designed for the task, data can be exported in a form that can be used in a wide variety of other programs (usually tab-delimited ASCII files). *HADES* is regularly used in conjunction with external programs including custom-developed Haskins software, *BMDP* on the VAX, *Matlab* on a number of hardware platforms (Macintosh, PC, SGI, SUN, VAX, etc.), and a variety of microcomputer-based statistics, spreadsheet, and display programs.

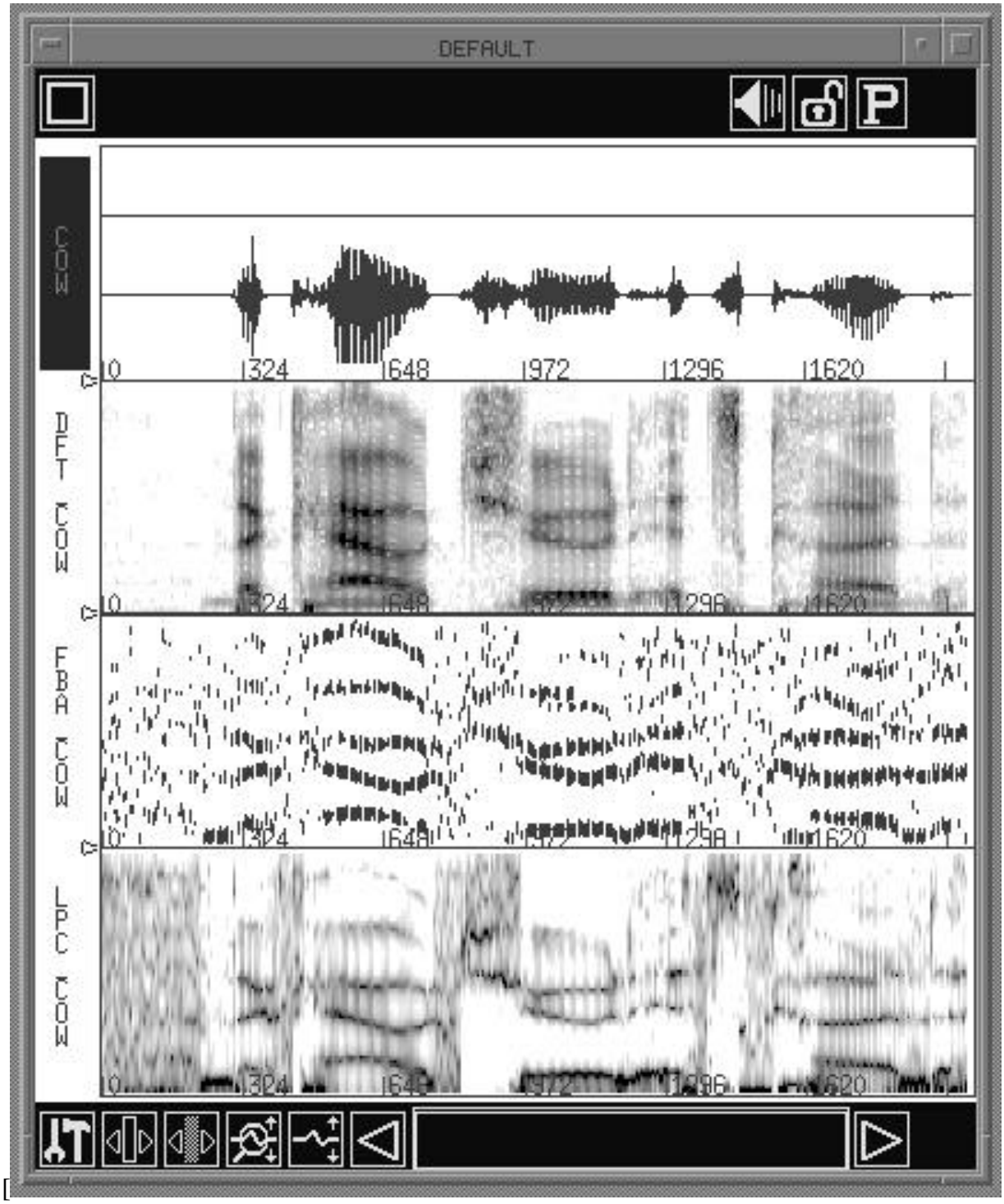

Figure 22: DFT, LPC, and FBA display

III.D.4 Temporal analysis

Several frame-based temporal analyses are available in *HADES*, including fundamental frequency (F0) analysis, energy analysis, and zero-crossing count. Temporal analysis of a signal results in a new signal being generated. This new signal contains a value for each frame, with a sampling rate adjusted according to the frame size. If temporal analysis is selected via the menu, an additional panel is added to the active display window containing a display of the resulting analysis vector. Details about the different analysis types are provided below.

Temporal analysis parameters can be set from within *SPIEL* or by using the Temporal Analysis Parameters Dialog Box, shown below. This dialog box lets users select the type of analysis, the analysis frame size, signal names, and a variety of other parameters related to the analysis. Frame size is always specified in samples (flag: _FRAME). The default depends upon the sampling rate of the signal. All calculations are performed with unscaled signal values, regardless of header scaling.

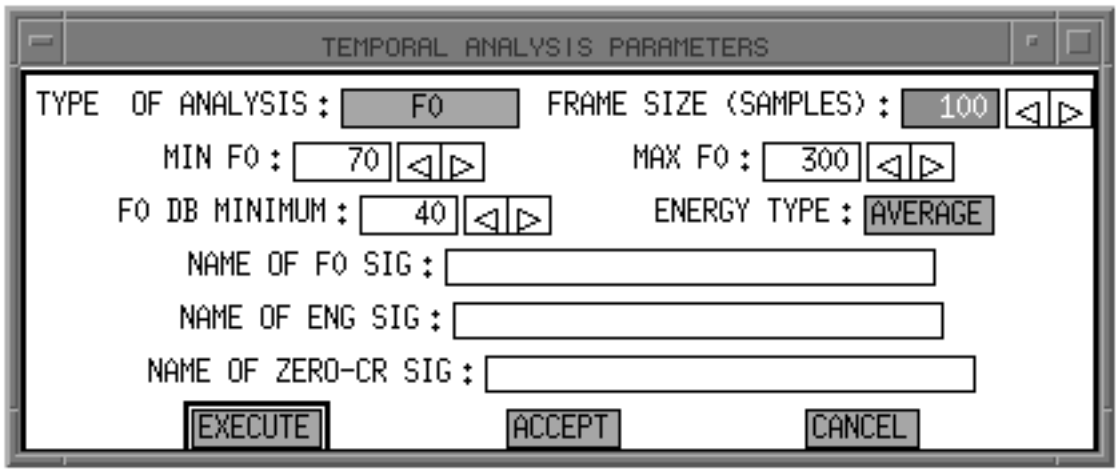

Figure 23: The Temporal Analysis Parameters Dialog Box

F0 analysis

Fundamental frequency (F0) is estimated using a standard autocorrelation method to find the pitch period (see, e.g., Rabiner and Schafer, 1978, or Witten, 1982). The particular algorithm used is based upon code written by Seiichi Tenpaku (1992) for the ATR Laboratories *SpeechTools* system. Three parameters are used:

_F0MIN	minimum expected F0 value
_F0MAX	maximum expected F0 value
_F0DBMIN	dB level required for F0

Users who require a more sophisticated fundamental frequency analysis are directed towards external programs, such as Eric Keller's *Signalyze* program on the Macintosh (Keller, 1992), or the *SoundScope* program from GW Instruments (GW Instruments, 1992). Other approaches for pitch analysis in *HADES* include hand measurement, which is fairly

simple within *HADES* with a small amount of data, and yields the most accurate results; or automatic peak picking using the *HADES* **event marking** options (see section III.C.2).

Energy analysis

Three types of energy measure are available, selected with the _ENERGY flag:

DB	compute 10*log10(average ss)
AVERAGE	compute average sum of squares over the frame (default)
PEAK	find the peak square over the frame, and normalize to max volts squared, yielding range 0 to 100.

Zero-crossing analysis

A signal vector is created based upon a count of zero-crossings within a pre-defined temporal window. The zero crossing count can be displayed as a temporal signal. Zero-crossings are a special class of event mentioned about in the Event Marking section (III.C.2). For temporal analysis, the zero-crossing count is defined as:

```
(# of crossings over midscale within frame)/(sizeof frame)
```

III.E. Special Features in *HADES*

III.E.1. Journaling

HADES provides a means for saving the results of certain measurements and including user-created comments in an ASCII file. This file is known as the **journal file**. The process of writing information to this file is called *journaling*. The user can either open a journal file of their own choosing or they can use the default file. The default journal file is opened and enabled for writing when a `JOURNAL OPEN` command is given. Journal files are opened in append mode, and the program writes the date and time in the journal file upon opening. *HADES* will automatically write centroid calculations and cross-section cursor values to the journal file when it is enabled. The *SPIEL* procedure in section IV.B.4 provides an example of how the journal file can be used. In this example, a variety of information is written to the journal file including tongue receiver positions and displacement, velocity, duration of movements, and coding variables for an Analysis of Variance.

III.E.2. Data scaling and calibration

Issues of data scaling and calibration within *HADES* are of importance in terms of the display, measurement, and comparison of signals. Whether or not signals are scaled is determined by the header of the sampled data file (the PCM header). Usually speech is unscaled, and physical data is scaled. Unscaled data always defaults to a range of -2048 to 2047. Data in files is stored as short integers in the range 0 to 4095; for scaled data, the header contains calibration constants which determine the actual range.

Plot scaling options

When data is being plotted, a large number of options are available for controlling how the actual display looks. This is useful when different signal types are mixed and they need to be viewed together and compared against each other. The options include the following.

AUTO	Scale to the max/min of the panel signal, as specified by its header information.
POOLED	Scale to the smallest min/largest max of all the signals in the window, based on their header information.
FIXED	Scale to the min/max specified by the window toolbox
UNIQUE	Scale to the min/max specified by the panel toolbox
RANGE	Scale to a fixed amplitude range (in window toolbox) with a midpoint determined by the min/max of the panel.

The scaling mode for a window is set initially to the default specified in the flag `__WINSCALE`. This is set to `__FIXED` at startup, and may be reset by the user: e.g., `__WINSCALE = __AUTO`. For a given window, the scaling mode may be changed with the toolbox.

Signal scaling

Signal values are stored as unsigned integers in the range 0 to 4095. The signals are scaled (or not) according to the values `calm` and `calb` in the signal header. Before operations, stored values are converted to floating point:

```
(stored_value - 2048)*calm + calb
```

Rescaling after operations

Unscaled signals are never scaled as a result of a *HADES* operation. By default, scaled data is automatically rescaled after applying functions, pasting, and math operations, except for the extract function and for pasting into an empty window, in which cases the created signal inherits the scaling of its parent. Scaled data is not rescaled after effects.

A user flag has been provided to override the default:

`_RESCALE = _NONE (or _OFF)`	no rescaling: data is clipped.
`_RESCALE = _ALL  (or _ON)`	always rescale.
`_RESCALE = _DEFAULT`	use the default described above.

RESCALING COMMANDS:

`RESCALE signal min max`	flags the header as scaled data, and computes calibration constants (header values cal_m and cal_b) which generate min and max from stored values 0 and 4095.
`UNSCALE signal`	flags the header as unscaled data, and removes stored scaling parameters from the header.

III.E.3. Signal Lists

In *HADES*, a set of signals can be organized as a single entity (primitive) that certain commands can directly operate on. This primitive is called a **signal-list**. A signal-list is essentially a string vector in which each element is the name of a signal. There are several ways to create a signal-list. A signal-list can by created from the menu bar, using the SLIST command (**DATA**:SLIST). Selecting this command will put the **signal picker** up on the screen. The signal picker can then be used to select the desired signals that will go in the signal-list and also lets you name the signal-list.

One syntax for creating a signal-list via the Command Window is:

listname = list

where	*listname*	is the name of the signal-list that is created
	list	is a list of signal names

Example:

Assuming that the following signals have already been opened:

```
COW, ARTHUR, S1, S2
```

A signal-list called *mylist* can be created by typing:

```
mylist=cow arthur s1 s2
```

Another way to create a signal-list from the Command Window, or from a Procedure, is to define a signal-list string vector. This can be done with the SLIST command.

The command format for the SLIST command is:

SLIST *listname*[*index*] *string*

where	*listname*	is the name of the signal-list being created or added to
	index	is an integer indicating the position for the entry of the *string* in the signal-list (i.e. for the first entry, *index*=1, for the second entry, *index*=2, etc.).
	string	is the string or variable to insert as this item in the list

A single-element signal-list can be defined by:

SLIST *list_name*[1] = *value*

Example:

In this example we set-up the same signal-list as in the previous example.
Once again it is assumed that the following signals have already been opened :

```
COW, ARTHUR, S1, S2
```

A signal-list called *mylist* can be created by typing the following:

```
SLIST mylist[1]="cow"
SLIST mylist[2]="arthur"
SLIST mylist[3]="s1"
SLIST mylist[4]="s2"
```

Although this appears to be more cumbersome than the method used in the previous example, this form is easier to use if a signal-list is being created in a procedure using a loop.

Examples of the use of signal lists can be found in section IV.

III.E.4. Flags

The wide range of options available in *HADES* presents a daunting design challenge: how to provide the greatest flexibility to the user in terms of getting at the power of these options, while preserving simplicity of use. To accomplish this goal, *HADES* embodies a variety of approaches. Most options are available to users as choices within topic-oriented dialog boxes (see section III.A.3). Examples include the options that can be set for signal processing and analysis (see, above, Figure 21, The Filter Parameters dialog box. and Figure 23, The Temporal Analysis Parameters dialog box), and the complex set of options available for event marking (see Figure 20, the Event Marking dialog box). More general parameters can be set in the Flags Dialog Box, as shown below in Figure 24.

Optional parameters in *HADES* are referred to as FLAGS. In addition to setting these flags from dialog boxes, they can be directly set at the command line:

e. g. : `_UNITS=_SECONDS,` which sets the fundamental *HADES* time unit to seconds.

A large number of pre-defined CONSTANTS (such as `ON, OFF, MSEC, SEC,` etc.) are available. The values that these flags can take are all available as global variables to the procedural language, *SPIEL*. A partial listing of *HADES* flag variables and constants can be found in Appendix IV. Examples of the use of flags and constants in *SPIEL* procedures are provided in section IV, below.

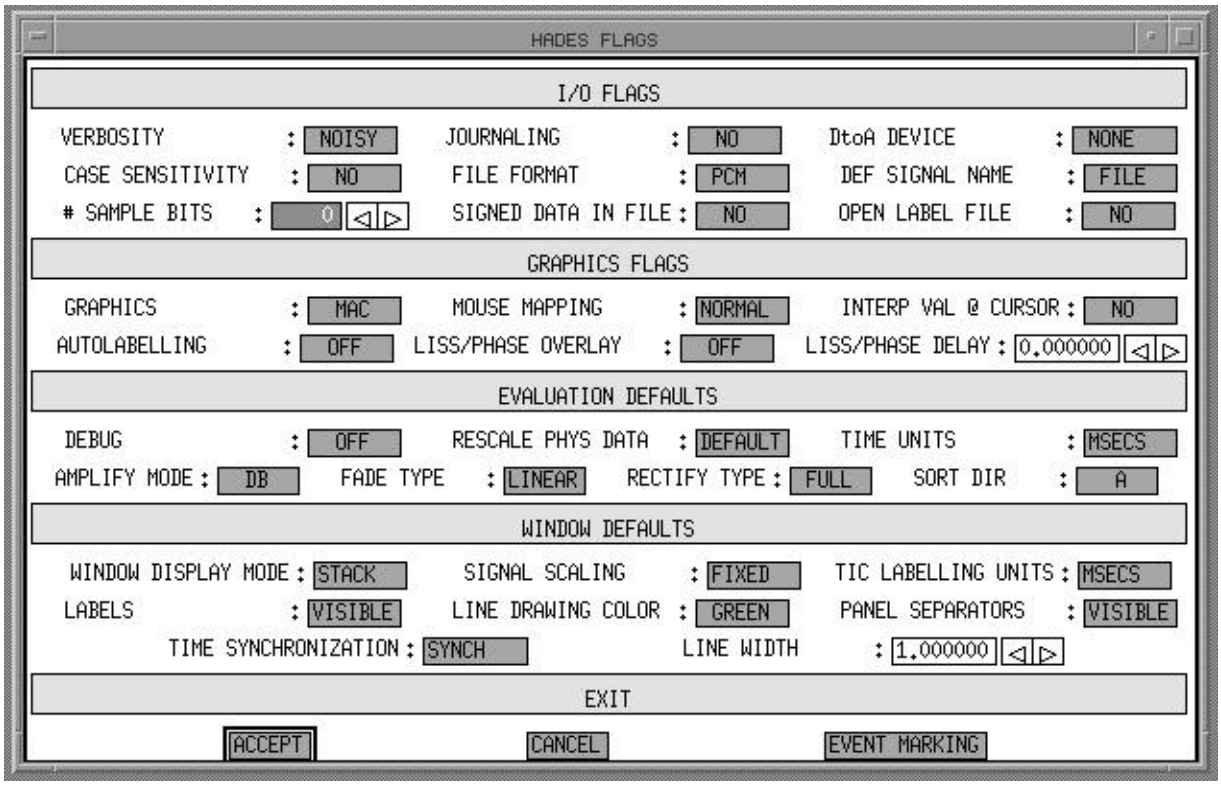

Figure 24: The Flags Dialog Box

III.E.5. Attributes

Attributes are a special category of flags. They refer to sets of flags with a functional organization. Additional *HADES* commands are often used to manipulate these attributes. At present *HADES* includes a number of different attributes sets:

- Signal attributes provide information about signal primitives
- Panel attributes control options for Display Window Panels
- Window attributes control selected Display Window options

Details follow regarding these attributes sets, including relevant flags and additional attributes-related commands. Attributes, like other flags, can be treated as variables and, thus, can be manipulated in a variety of ways.

III.E.5.a. Signal Attributes

Signal attributes are used to keep track of information about signals that have been opened in *HADES*. Signals are vectors of time-varying data and a fundamental *HADES* data type or primitive. Examples of selected signal attributes flags include:

```
_SIGNAME      name stored in header
_SIGRATE      samples/second
_SIGNBITS     # of sampling bits
_SIGCALM      calibration scale factor
_SIGCALB      calibration offset factor
_SIGCALU      calibration units
```

```
_SIGDFTHEAD   DFT head in msec
_SIGDFTTAIL   DFT tail in msec
_SIGDFTWS     size of the DFT window
_SIGDFTWT     type of analysis window
_SIGDFTWSK    skip size (time resolution)
_SIGDFTLPC    name of the associated LPC or DFT signal
_SIGDFTFBA    name of the associated FBA signal
```

These values always refer to the current *active* signal, and are reloaded every time a new active signal is selected. A dialog box, under the DATA menu, displays the current values, allowing resetting of the relevant attributes. The dialog box also permits the selection of other signals for attribute display, with an option for resetting the active signal.

HADES includes several special purpose commands related to signal attributes. These commands are:

```
LIST SIGATT signalname       lists the attributes of the named signal

JOURNAL SIGATT signalname    journals the attributes of the named signal

CSIGATT sig1 sig2            copies the attributes from sig1 to sig2

SIGATT sig attribute value   sets the attribute value for named signal
```

III.E.5.b. Window Attributes

Window attributes are used to control selected Display Window options. The basic window attributes command is:

```
WINDOW attribute [=] value
```

which will change window attributes after the window has been drawn.

Window attributes include:

SYNCH	sets time synchronization of the window
MAX	sets the upper limit for fixed data scaling
MIN	set lower limit for fixed scaling
RANGE	sets the range for fixed-range scaling
MODE	sets _OVERLAY or _STACK mode
SCALE	sets the data scaling options

III.E.5.c. Panel Attributes

Temporal displays can have more than one signal displayed in a window. In general, each signal is displayed in a separate **panel**, unless the overlay option has been selected. A wide variety of options is available for controlling the appearance of panels and the data within panels. The basic panel attribute command is:

```
PANEL # attribute [=] value
```

This command operates on a default **panel list** (*plist*), which is a *HADES* data structure that specifies a list of panel names. The panel list is basically a vector of strings. If no panel lists

have been specifically created (see PLIST and CREATE commands, described below), the default panel list will be the panel list in the active window. Otherwise, the default panel list will be the one named in the global variable _PLIST .

A panel number (#) identifies which panel in the list is affected by the command. Panels are counted from 1, starting at the top of the display.

The list of panel attributes is long and includes the following :

```
SIGNAL              name of the signal
LINECOLOR           line color for the signal
LINEWIDTH           line width
LINESTYLE           line drawing style (solid, dotted, etc.)
LEFT                left edge of view in default UNITS
RIGHT               right edge of view
MAGNIFY             magnification factor
DC                  dc offset amount
UNITS               MSEC, SECONDS, SAMPLES
BASELINE            visibility
LABS                visibility
MAX                 max value for UNIQUE scaling mode
MIN                 min value for UNIQUE scaling mode
SIZE                size relative to other panels (default 1)
```

```
Additional flags that control the display appearance include:
      _X_TIK            _Y_TIK
      _X_TIKMINOR       _Y_TIKMINOR
      _X_NUM            _Y_NUM
      _X_NUMDEC         _Y_NUMDEC
      _X_TEXT           _Y_TEXT
      _X_TEXTVIS        _Y_TEXTVIS
      _X_GRID           _Y_GRID
      _X_GRIDINC        _Y_GRIDINC
      _X_GRIDLINE       _Y_GRIDLINE
      _X_GRAY           _Y_GRAY
      _X_GRAYMINOR      _Y_GRAYMINOR
      _X_ZERO           _Y_ZERO
      _X_LEFT           _Y_TOP
      _X_RIGHT          _Y_BOT
      _Y_TIKRIGHT
```

Once all the desired attributes have been set, the changes may be displayed (if the active *plist* is already in a window) by using the UPDATE command.

Other commands that relate to panels include the following:

```
PANEL ADD signalname    add a signal to the active  plist

PANEL # DELETE          delete specified panel #

PANEL COPY source_panel# dest_panel#
                        copy the attributes of one panel to
                           another panel

PLIST siglist AS plistname
                        create a panel list with the given name.

CREATE WINDOW [windowname] [USING plistname]
                        create and display a window containing
                             the named plist.
```

```
CREATE PLIST [plistname] [FROM windowname]
                          create a plist from a window

UPDATE                    redraw all windows containing active plist
```

III.E.5.d. Axis Settings

Window and panel attributes are often used to customize the display's appearance. An additional set of flags can also be used to provide precise control over the axis labelling. As usual, these flags can be set from the command line, from *SPIEL* procedures, or from the Axis Settings Dialog Box, shown in Figure 25.

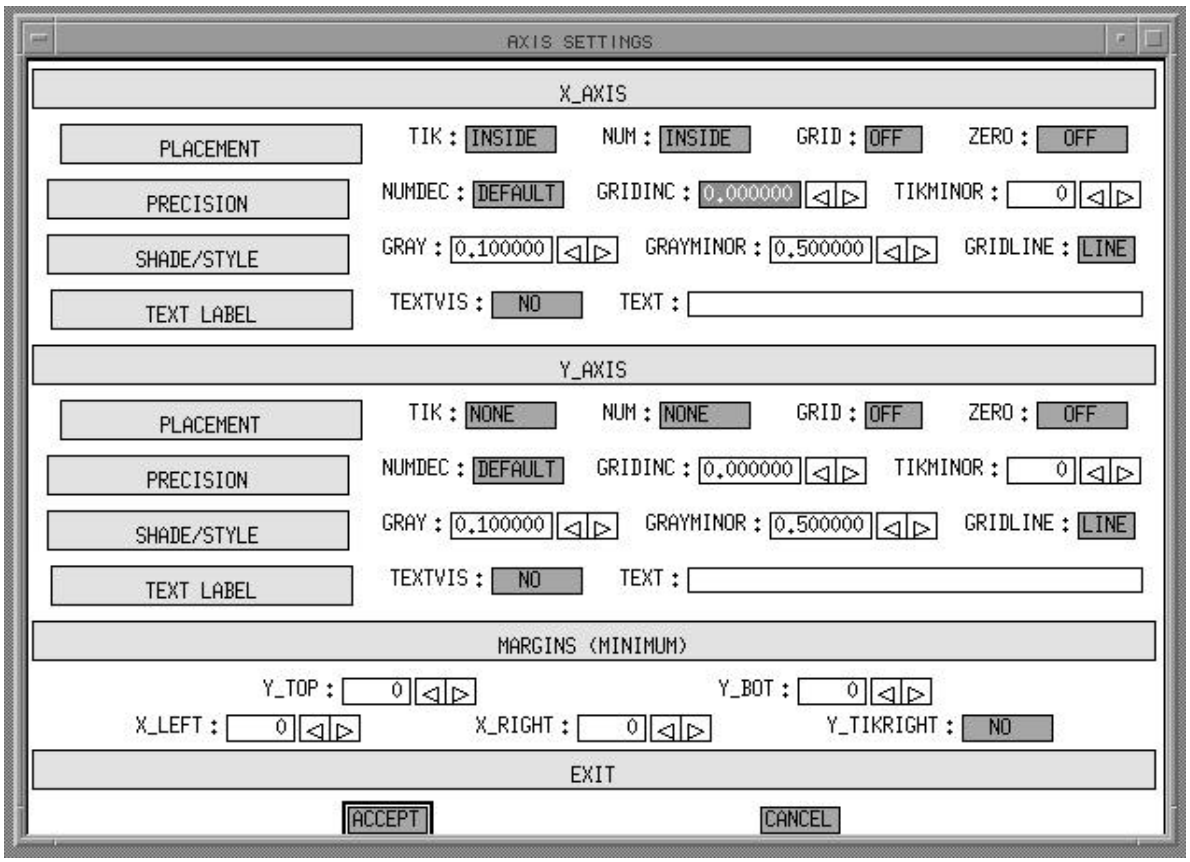

Figure 25: The Axis Settings Dialog Box

III.E.6. Importing and Exporting Data

HADES supports a variety of alternate file formats for inputting and outputting data. The native file format for sampled data (or other time-varying) signals at Haskins Laboratories has been in use for over twenty years and is called the PCM format (Whalen et al, 1990). *HADES* also supports several additional sampled data formats, including ILS, STM, and ASCII. The default file format may be set from the Flags Dialog Box.

ILS format refers to sampled data created by standard *ILS*, a commercial signal processing system developed by STI. (Haskins implementation of the ILS systems has modified it to deal with PCM format). *ILS* analysis files are not supported. The STM format was developed at the Indiana University Psychology Department Speech Lab. Non-integral sampling rates are supported only by PCM format. STM format supports only 10,000 Hz and 20,000 Hz sampling rates.

HADES handles data with amplitude resolutions other than 12 sample bits in the analog to digital conversion. Values from 1 to 16 are allowed. A global variable, _NBITS, determines this resolution. Bit resolution is stored as part of the signal header, thereby supporting different resolutions for different signals. The default, _NBITS =0, checks the file header for bit information, setting the number of bits for the signal (the signal *nbits*) to 12 if none is found. If _NBITS is set to a nonzero value, the signal *nbits* will be set to _NBITS **regardless of header specification**. Sample values are assumed to be stored in the range 0 to 2**(_NBITS)-1. Amplitudes are calculated with an offset of 2**(_NBITS-1), after which physical scaling, if any, is applied.

The main interchange format in *HADES* is in the form of ASCII files. In addition to sampled data, data can be exported from *HADES* as a journal file, which records selected measurements and saves them in an ASCII file (see section III.E.1). Label files (see section III.C.1) are also saved in ASCII format. However, the most powerful use of ASCII export involves creating *SPIEL* procedures to format and save the results of *HADES* analyses and measurements. Detailed examples of such procedures are provided in section IV, below. This technique makes *HADES* compatible with a wide variety of workstation and desktop computer programs for statistics, data manipulation, and data plotting.

IV. *SPIEL*

While most of the commands and functions in *HADES* can be executed from the menus or the keyboard, significant amounts of time and effort can be saved by creating *procedures* that are used to help automate the repetitive processing of signals. To accomplish this, *HADES* incorporates a procedural language called *SPIEL* (Signal Processing Interactive Editing Language) that allows the user to create customized routines used for the processing of the data from experiments.

IV.A. The *SPIEL* language

SPIEL is the procedurally-oriented programming language that is an intrinsic part of *HADES*. Procedures can be created that take advantage of most of the structures of *HADES*, including commands, command-line entry of values, variables, and data structures. In addition, there are facilities of *HADES* that are specific to *SPIEL*, such as conditionals and looping structures. A listing of *HADES* commands can be found in Appendix II and functions in Appendix III.

IV.A.1 Mathematical, logical, and comparison primitives

MATHEMATICAL OPERATORS

+	addition
-	subtraction
*	multiplication
/	division
^	exponentiation

MATHEMATICAL FUNCTIONS

ABS	absolute value
COS	cosine
MAX	maximum of a scalar
MIN	minimum of a scalar
SIN	sine
SQR	square
SQRT	square root
TAN	tangent

LOGICAL OPERATORS

NOT	NOT
OR	OR
AND	AND

COMPARISON OPERATORS

==	equal to
<	less than
<=	less than or equal to
>	greater than
>=	greater than or equal to
<>	not equal to

RESERVED CHARACTERS

( )	demarcation of PROCEDURE arguments; mathematical grouping
[ ]	indexing of signal and vector elements

IV.A.2. Control structures

SPIEL provides control structures for conditional branching and conditional looping. The first, the IF — END IF structure, executes a statement or set of statements if a particular condition is met. Conditions may be built using comparative operators. The general form of the IF structure is:

```
IF (condition)
     statement
     .
     .
END IF
```

The second control structure, the WHILE — END WHILE, executes a statement or set of statements while a particular condition is true. Conditions may be built using comparative operators. WHILE structures are useful for creating loops. The general form of the WHILE structure is:

```
WHILE (condition)
     statement
     .
     .
END WHILE
```

The FOR — END FOR loops through a series of statements, incrementing an index, and checking to see if this index is within the range specified by the user. The general form of the FOR structure is:

```
FOR index = val1 TO val2 { STEP val3 }
     statement
     .
     .
END FOR
```

IV.A.3. Miscellaneous

Keyboard input in procedures is provided by the GET command. Its format is:

```
GET "prompt" varlist
```

The text of the *prompt* is printed and the user enters the variables of the *varlist.*

The FSLIST command creates a signal list by reading an ASCII file containing the names of signals. It has the form:

```
FSLIST filename listname
```

The *filename* is the name of the ASCII file containing the list of signal names and the *listname* is the name that will be given to the signal list.

IV.B. *SPIEL* examples

The following sections provide examples of procedures written in *SPIEL*. These are based on a set of routines that has been developed to process two-dimensional movement signals recorded using an electromagnetic transduction technique. As a background to the presentation of the *SPIEL* routines, a brief description of the characteristics of the movement signals will be provided first.

IV.B.1. Signals and signal naming conventions

Movement signals were recorded using a three-coil transmitter system described by Perkell, et al., (1992). Further details about the experimental procedures can be found in Löfqvist and Gracco (1994), and Löfqvist, Gracco, and Nye (1993). Receivers were placed on the upper and lower lips, the lower incisors, and at four positions on the tongue. For the sake of convenience, the tongue receivers will be referred to by their locations as tongue tip (tt), tongue blade (tbl), tongue body (tb), and tongue root (tr), although we acknowledge that the boundaries between these parts of the tongue are imprecise, and the receiver referred to as "tongue root" actually has a higher and more forward position than is customary for that location. In addition, receivers placed on the bridge of the nose and on the upper incisors were used for correction of head movements. All data were subsequently corrected for head movements, and then rotated and translated to bring the occlusal plane into coincidence with the x axis. The linguistic material consisted of VCV sequences with all possible combinations of the vowels /i, a, u/ and the stop consonants /p, t, k, b, d, g/. The sequences were placed in the carrier phrase "Say ... again" with sentence stress occurring on the second vowel of the VCV sequence. Ten tokens of each sequence were recorded at self-selected speaking rates and intensity levels. The articulatory movement signals (induced voltages from the receiver coils) were sampled at 625 Hz after low-pass filtering at 200 Hz. The speech signal was pre-emphasized, low-pass filtered at 9.5 kHz and sampled at 20 kHz. The resolution for all signals was 12 bits. After voltage-to-distance conversion, the movement signals were low-pass filtered using a 25-point triangular window with a 3 dB cutoff at 18 Hz. To obtain instantaneous velocity, the first derivative of the position signals was calculated using a 3-point central difference algorithm. The velocity signals were smoothed using the same triangular window.

The files containing the individual signals are identified by utterance number, token number and signal name; the file extension is .PCM. Thus, the file U3T5TBY.PCM contains the vertical tongue body receiver signal for token 5 of utterance 1, while U45T8TTVX.PCM contains the horizontal velocity of the tongue tip receiver for token 8 of utterance 45. Figure 14 shows a plot of receiver trajectories for the sequence /aka/. The subject is facing to the left. A tracing of the hard palate is also shown.

IV.B.2. Creating tangential velocity signals

One particular problem in analyzing two-dimensional movements is locating the proper points in time for making measurements. In the analysis of one-dimensional movements, these points are usually identified by zero crossings in the first derivative of the position signal, i.e., velocity. For two-dimensional movements, marking zero crossings separately in the horizontal and vertical velocity signals usually results in those points occurring at different times. The preferable solution is to use tangential velocity, defined as $\upsilon = \sqrt{(\dot{x}^2 + \dot{y}^2)}$, where $\dot{x}$ is horizontal velocity and $\dot{y}$ is vertical velocity, for locating measurement points, since it is based on both the horizontal and vertical components of the movement (cf. Löfqvist, Gracco & Nye, 1993). The following procedure reads in velocity signal files for all tongue receivers of the specified tokens for a specified utterance and creates the corresponding tangential velocity signals. These signals are then saved into files with the proper file names.

Before this procedure is executed, three steps have been taken.
The two signal lists `mylist` and `tonguetanlist` have been created from two ASCII files as follows:

```
fslist siglist.txt mylist
fslist tanvel.txt tonguetanlist
```

The list `mylist` contains names of signals and is reprinted here, since it will be used in all the following procedures.

SIGLIST.TXT

```
1     audio         audio signal
2     ulx           upper lip horizontal position
3     ulvx          upper lip horizontal velocity
4     uly           upper lip vertical position
5     ulvy          upper lip vertical velocity
6     llx           lower lip horizontal position
7     llvx          lower lip horizontal velocity
8     lly           lower lip vertical position
9     llvy          lower lip vertical velocity
10    jawx          jaw horizontal position
11    jawvx         jaw horizontal velocity
12    jawy          jaw vertical position
13    jawvy         jaw vertical velocity
14    ttx           tongue tip horizontal position
15    ttvx          tongue tip horizontal velocity
16    tty           tongue tip vertical position
17    ttvy          tongue tip vertical velocity
18    tblx          tongue blade horizontal position
19    tblvx         tongue blade horizontal velocity
20    tbly          tongue blade vertical position
21    tblvy         tongue blade vertical velocity
```

```
22    tbx          tongue body horizontal position
23    tbvx         tongue body horizontal velocity
24    tby          tongue body vertical position
25    tbvy         tongue body vertical velocity
26    trx          tongue root horizontal position
27    trvx         tongue root horizontal velocity
28    try          tongue root vertical position
29    trvy         tongue root vertical velocity
30    ttvtan       tongue tip tangential velocity
31    ttcurv       tongue tip curvature
32    tblvtan      tongue blade tangential velocity
33    tblcurv      tongue blade curvature
34    tbvtan       tongue body tangential velocity
35    tbcurv       tongue body curvature
36    trvtan       tongue root tangential velocity
37    trcurv       tongue root curvature
38    ulvtan       upper lip tangential velocity
39    llvtan       lower lip tangential velocity
40    jawvtan      jaw tangential velocity
```

In order the create a pathname to locate files, the first part of a VAX VMS disk directory name has been created:

```
dirprefix=TU$1:[LOFQUIST.MAGAL.U
```

Once the procedure has been created, its name will be placed in the *HADES* Picon window which can be configured to contain a clickable list of procedure names. Prior to running the procedure described below, the Picon has to be cleared and set to the tear-off mode, so that it will appear as a tear-off menu:

```
picon clear
_piconwin=_tearoff
```

In the procedure listed below, everything on a line after the character “!” is ignored. The comments on the right of each line have been added here to help in interpreting the statements.

Note that in the following procedures, which will be explained in some detail, large portions of the code are dedicated to the manipulation of strings to create directory and file names.

```
!*******************************************************************************
!      Procedure MKTAN is used to create tangential velocity signals for tongue
!      receivers. It prompts for the first and last utterance to be processed.

define procedure mktan                                  ! define a new procedure
  _smoothsiz=25                                         ! set smoothing window to 25 points
  get "Enter number of utterance to process:" utt       ! prompt for utterance
  get "Enter first and last token to process:" stoken etoken     ! prompt for tokens
  dirsuffix=num2str(utt)+"]"                        ! create second part of directory name
  dirname=dirprefix+dirsuffix                       ! create full directory name
  _directory=dirname                                ! set directory flag
  type "Directory is:" _directory                   ! report directory name
  prefix="U"+num2str(utt)+"T"                       ! create first part of signal name
  ! loop for tokens
  for j=stoken to etoken                            ! initialize loop for tokens
    reportname=prefix+num2str(j)                    ! create name to report status
    type "Working on:" reportname                   ! report status
    k=1                                             ! initialize pointer for extracting
                                                    !  name from signal list
    ! loop for receivers
    for i=15 to 29 step 4                           ! initialize loop for tongue
                                                    !   receivers/signals
      xsuffix=sliststr(mylist,i)                    ! extract second part of horizontal
                                                    !   velocity signal name from signal list
      m=i+2                                         ! pointer into signal list for
                                                    !   vertical velocity signal name
      ysuffix=sliststr(mylist,m)                    ! extract second part of  vertical
                                                    !   velocity signal name from signal list
      xtempname=prefix+num2str(j)+xsuffix           ! create name of horizontal velocity signal
      ytempname=prefix+num2str(j)+ysuffix           ! create name of  vertical velocity signal
      open xtempname                                ! open horizontal velocity signal
      open ytempname                                ! open vertical velocity signal
      xsig=xtempname                                ! create copy of horizontal signal
      ysig=ytempname                                ! create copy of vertical signal
      tempsig=sqrt((xsig*xsig)+(ysig*ysig))         ! create tangential velocity signal
      smooth tempsig                                ! smooth tangential velocity signal
      taninfix=sliststr(tonguetanlist,k)            ! extract middle part of new signal
                                                    !   name from signal list
      newtsigname=prefix+num2str(j)+taninfix+"VTAN"       ! create new signal name
      save tempsig as newtsigname                   ! save the created signal
      close *                                       ! close all open signals
      k=k+1                                         ! increment pointer for extracting name
                                                    !   from signal list
    end for                                         ! end of loop for tongue receivers/signals
    ! end loop for receivers
  end for                                           ! end of loop for tokens
  ! end loop for tokens
end                                                 ! end of procedure
picon mktan                                         ! map procedure to Picon
!
!*******************************************************************************
```

After setting the flag for the size of the window used for smoothing signals to 25 (`_smoothsiz=25`), the procedure prompts for utterance number and tokens.

The name of the directory where the signal files are located is created using string manipulation. Although such manipulations can be avoided by having the program prompt the user for the necessary information, automating them will in many instances save time, in particular when making measurements where the procedures can be left running without user intervention. Manipulating strings to form names of signals and files may require that a number be turned into a string using the function `num2str()`. This is so because the name of files to be opened and processed usually contain utterance and token numbers that can be incremented in

branching and looping structures for flow control. In the case shown here, the number `utt` is first converted into a string using the function `num2str(utt)`, and concatenated with the string `]`, so that `dirsuffix` is set to e.g. 10]. Next, the full name of the directory is formed by concatenating the variables `dirprefix` and `dirsuffix (TU$1:[LOFQUIST.MAGAL.U10])`. The flag for the directory is set `(_directory=dirname)` and the name of the directory is typed (`type dirname`).

The first part of the signal name is formed by string manipulation `(prefix="U"+num2str(utt)+"T")`, e.g. U10T, and a loop for the tokens is initialized using a FOR — END FOR statement `(for j=stoken to etoken)`. The current utterance and token number are typed and a counter is initialized that will be used to extract names from the signal list `mylist (k=1)`. Another loop is initialized that will open and process the tongue receiver velocity signals for the specified tokens `(i=15 to 29 step 4)`. The second part of the names for the horizontal and vertical velocity signals are extracted from the signal list using the function `sliststr() (xsuffix=sliststr(mylist,i) and ysuffix=sliststr(mylist,m))`. The full signal names for the two velocity signals are strung together as `xtempname` and `ytempname`, and the signal files are opened. Copies of these two signals are made and used to create the tangential velocity signal `(tempsig)`. A useful and powerful feature of *HADES* is the possibility to use signals in mathematical expressions like the one used hereto create the tangential velocity signal `tempsig=sqrt((xsig*xsig)+(ysig*ysig))`. The newly created signal is smoothed. The middle part of the name of the new signal is extracted from a signal list `(taninfix=sliststr(tonguetanlist,k)`, and the full name is created by concatenation and `tempsig` is saved with the proper name. All open signals are closed, the counter `k` is incremented and the loop is repeated for the next receiver. When all the signals for a token have been processed, the token loop is incremented and the tangential velocity signals for the next token are created until all the tokens have been processed. The procedure is mapped to the Picon.

IV.B.3 Opening and displaying signals and saving labels into files

The processing of movement signals involves opening and displaying the signals, marking (labelling) events such as zero crossings, peaks, and valleys in selected signals, and saving the labels into files. The labels will later be used for making measurements of the recorded movements. The following set of procedures is used to label tangential velocity signals of tongue receivers. The following procedures are used:

`tansignals`	sets up a loop for opening and displaying tangential velocity signals for a set of tokens of an utterance.
`tandisplay`	displays the audio signal and the tangential velocity signals.
`displayparameters2`	sets window and panel attributes of the display window.
`tanlabeldeposit`	saves the labels in the tangential velocity signals into files.
`nexttan`	checks for the last token and displays the next token.

Before these procedures are executed, a few steps have been taken. The two signal lists `ulist` and `mylist` have been created from two ASCII files. The list `ulist` contains the names of the VCV utterances and is used to name the window in which the signals are displayed to assist the user in mapping between utterance number and utterance name.

```
fslist ulist.txt ulist
fslist siglist.txt mylist
```

The first part of a disk directory name has been created:

```
dirprefix=TU$1:[LOFQUIST.MAGAL.U
```

The Picon has been cleared and set to the tear-off mode, so that the Picon appears as a tear-off menu:

```
       picon clear
       _piconwin=_tearoff

! ********************************************************************************************
!      Procedure TANSIGNALS is used to set up a loop for opening and displaying
!      tangential velocity signals. It prompts for utterance number and tokens.
!      A call is made to the procedure TANDISPLAY to create and window and display
!      the signals.
! ********************************************************************************************

define procedure tansignals                                        ! define a new procedure
  get "Enter number of utterance to open and display:" utt         !prompt for utterance
  get "Enter first and last token to display:" stoken etoken       ! prompt for tokens
  dirsuffix=num2str(utt)+"]"                          ! create second part of directory name
  dirname=dirprefix+dirsuffix                         ! create directory name
  _directory=dirname                                  ! set directory flag
  type "Directory is:" _directory                     ! report directory name
  ! loop for audio signals
  for j=stoken to etoken                              ! initialize loop for opening audio
                                                      !   signal of all tokens
    fname="U"+num2str(sutt)+"T"+num2str(j)+"AUDIO"          ! create name of audio signal
    open fname                                        ! open audio signal
  end for                                             ! end of loop for opening audio signals
  ! end loop for audio signals
  token=stoken                                        ! initialize token counter
  ! loop for tokens
  while (token <= etoken)                             ! initialize loop for tokens
    prefix="U"+num2str(utt)+"T"+num2str(token)        ! create first part of signal name
    ! loop for signals
    for i=30 to 36 step 2                             ! initialize loop for receivers/signals
      suffix=sliststr(mylist,i)                       ! extract second part of signal name
                                                      !   from signal list
      fname=prefix+suffix                             ! create name of signal
      open fname                                      ! open the signal
    end for                                           ! end of loop for receivers/signals
    ! end loop for signals
    token=token+1                                     ! increment the token counter
  end while                                           ! end of loop for tokens
  ! end loop for tokens
  token=stoken                                        ! reset the token counter
  tandisplay                                          ! call procedure to display signals
  token=token+1                                       ! increment token counter
end                                                   ! end of procedure
picon tansignals                                      ! map procedure to the Picon
!
! ********************************************************************************************
```

The procedure prompts for utterance number and tokens. The name of the directory where the signal files are located is created using string manipulation. The flag for the directory is set (`_directory=dirname`) and the name of the directory is typed (`type dirname`).

A loop is initialized for opening the audio signals of all the specified tokens using a FOR — END FOR statement (`for j=stoken to etoken`). The name of the audio signal is strung together (`fname="U"+num2str(sutt)+"T"+num2str(j)+"AUDIO"`) and the signal is opened.

When all the audio signals have been opened, the token counter is reset to the first token (`token=stoken`).A loop to open the tangential velocity signals of the tongue receivers for the specified tokens is initialized using a WHILE — END WHILE statement (`while (token <= etoken)`). The first part of the signal name is strung together (`prefix="U"+num2str(utt)+"T"+num2str(token)`). A FOR — END FOR statement is used to

initialize another loop that will open the tangential velocity signals (`for i=30 to 36 step 2`). The second part of the signal name is extracted from the signal list `mylist` (`suffix=sliststr(mylist,i)`), the complete name is formed (`fname=prefix+suffix`), and the signal is opened (`open fname`). The token counter is incremented (`token=token+1`) and the statemenes in the loop are repeated until all the signals have been opened. When the signals are opened, the token counter is reset, and a call is made to the procedure TANDISPLAY to create a window and display the signals. Finally, the token counter is incremented.

```
! ********************************************************************************
!      Procedure TANDISPLAY creates a signal list of the signals to display.
!      This list is used to create a panel list. Window attributes are defined,
!      and a window is created using the panel list.
! ********************************************************************************

define procedure tandisplay                ! define a new procedure
  delete variable tandisplist              ! delete copy of signal list
  uttname=sliststr(ulist,utt)              ! extract name of utterance from signal list
                                           ! create name of window for displaying signals
  tanwindow=uttname+"U"+num2str(utt)+"T"+num2str(token)+"_tangential_velocity"
  prefix="U"+num2str(utt)+"T"+num2str(token)      ! create first part of signal name
  audiosigname=prefix+"AUDIO"                     ! create name of audio signal
  slist tandisplist[1] audiosigname               ! add name of audio signal to list
  j=2                                             ! initialize pointer into signal list
  ! loop for signals
  for k=30 to 36 step 2                           ! initialize loop for signals
    suffix=sliststr(mylist,k)                     ! extract second part of
                                                  !   signal name from list
    tempname=prefix+suffix                        ! create full name of signal
    slist tandisplist[j] tempname                 ! add name of signal to list
    j=j+1                                         ! increment pointer into signal list
  end for                                         ! end of loop for signals
  ! end loop for signals
  plist tandisplist as tandisplistp               ! create panel list using signal list
  displayparameters2                              ! call procedure to define
                                                  !   window attributes
  _winllx=470                                     ! define horizontal position for window
  _winlly=225                                     ! define vertical position for window
  create window tanwindow using tandisplistp      ! create window using panel list
end                                               ! end of procedure
!
! ********************************************************************************
```

First, the old version of the signal list `tandisplist` is deleted. The name of the utterance is extracted from the list `ulist` (`uttname=sliststr(ulist,utt)`). The name of the window for displaying the signals (e.g. AKA-U3T5_ TANGENTIAL-VELOCITY) is created by string manipulation.

The name of the audio signal is created and added as the first element to the signal list `tandisplist` (`slist tandisplist[1] audiosigname`). A pointer into the signal list `tandisplist` is set to 2 (`j=2`). A loop for adding signal names to the list `tandisplist` is initialized using a FOR — END FOR statement (`for k=30 to 36 step 2`). The second part of the signal name to be added to the list is formed, then the complete name (`tempname`), and the name is added as the next element to the list (`slist tandisplist[j] tempname`). The pointer (`j`) is incremented and the next signal name is added to the list. When all the signals have been added to the list, the panel list `tandisplistp` is created from the signal list `tandisplist` (`plist tandisplist as tandisplistp`). A call is made to the procedure `displayparameters2` to set up window and panel attributes (see below). The position of the window on the screen is specified (`_winllx=470`) and (`_winlly=225`), and the window is

created with the proper name using the panel list `tandisplistp (create window tanwindow using tandisplistp)`.

```
! ********************************************************************************************
!      Procedure DISPLAYPARAMETERS2 sets up display parameters for time plots.
! ********************************************************************************************

define procedure displayparameters2        ! define a new procedure
  _x_grid=_off                             ! turn off horizontal grid in all panels
  _x_gridinc=100                           ! set horizontal tick spacing to 100 ms
  _x_tik=_inside                           ! place horizontal tick marks inside panel
  _x_num=_outside                          ! place horizontal tick labels outside panel
  _x_numdec=0                              ! set number of decimals in horizontal tick
                                           ! labels to 0
  _y_grid=_off                             ! turn off vertical grid in all panels
  _y_tik=_outside                          ! place vertical tick marks outside panel
  _y_num=_outside                          ! place vertical tick marks outside panel
  _y_numdec=1                              ! set number of decimals in horizontal tick
                                           ! labels to 1
  _linecolor=_black                        ! set line color for signals to black
  _winhigh=800                             ! define height of display window on screen
  _winwide=600                             ! define height of display window on screen
end                                        ! end of procedure
!
! ********************************************************************************************
```

Figure 26 shows a window that has been created using the procedure TANDISPLAY. The utterance is “Say aka again”. The signal at the top is the audio signal. The tangential velocity signals are from receivers placed on the tongue tip, the tongue blade, the tongue body, and the tongue root.

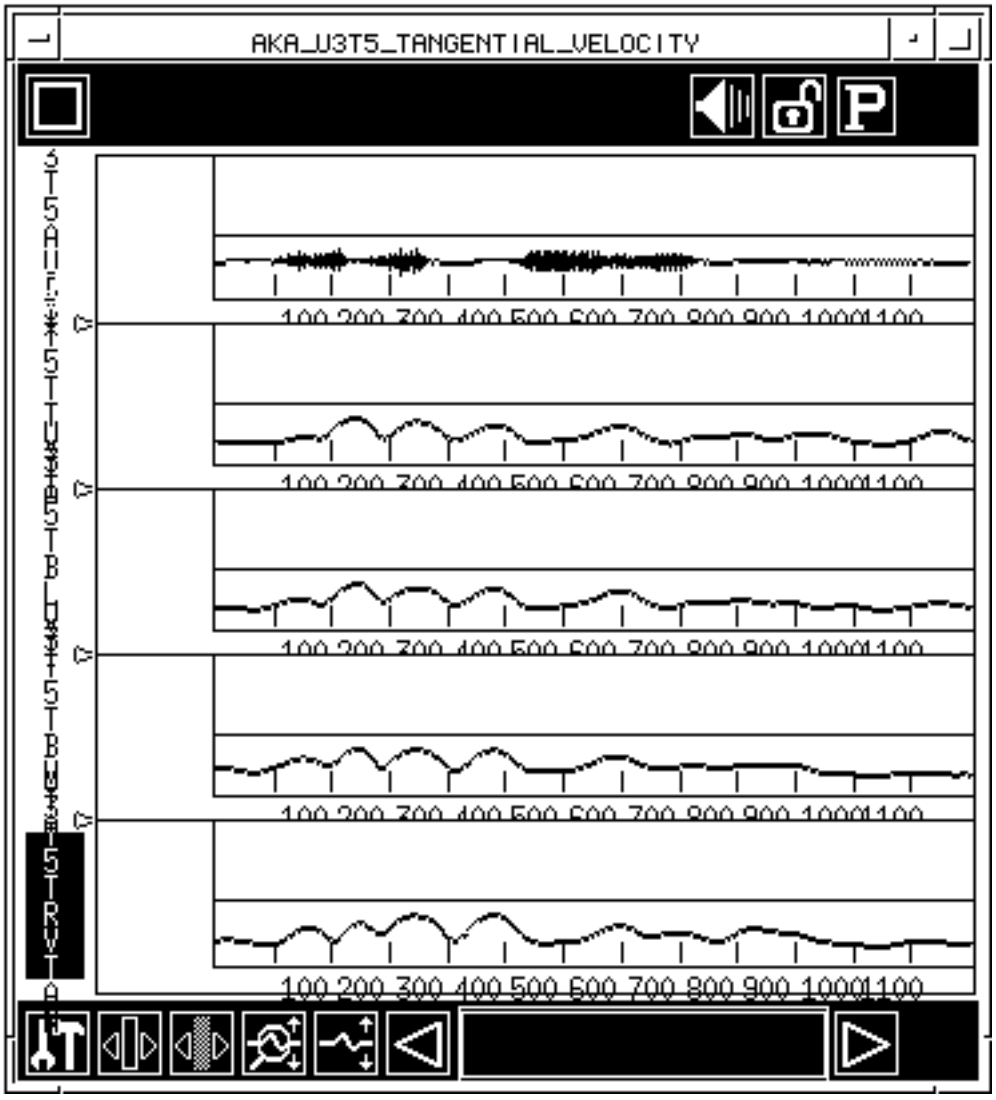

Figure 26: Example of a window created using the procedure TANDISPLAY. The signals are from top to bottom, audio, tangential velocity of tongue tip, tongue blade, tongue body, and tongue root.

Peaks and valleys in the tangential velocity signals are labeled using the event marking routines of *HADES*. An example of signals with such labels is shown in Figure 27, below. The labels have been placed at three minima of tangential velocity, V1, V2, V3, and at two peaks of tangential velocity, P1, P2. The three labels at the valleys occur during the diphthong in “say” (V1), the first vowel in “aka” (V2), and during the stop closure for the velar stop consonant /k/ in “aka” (V3). The two labels at the peaks occur during the movement from the diphthong in “say” to the first vowel in “aka” (P1), and from the first vowel in “aka” to the velar stop consonant /k/ in “aka” (P2). The placement of these labels has been made to examine movement characteristics in VCV sequences as a function of the identity of the first and second vowels and the middle consonant (see Löfqvist and Gracco (1994) for further details).

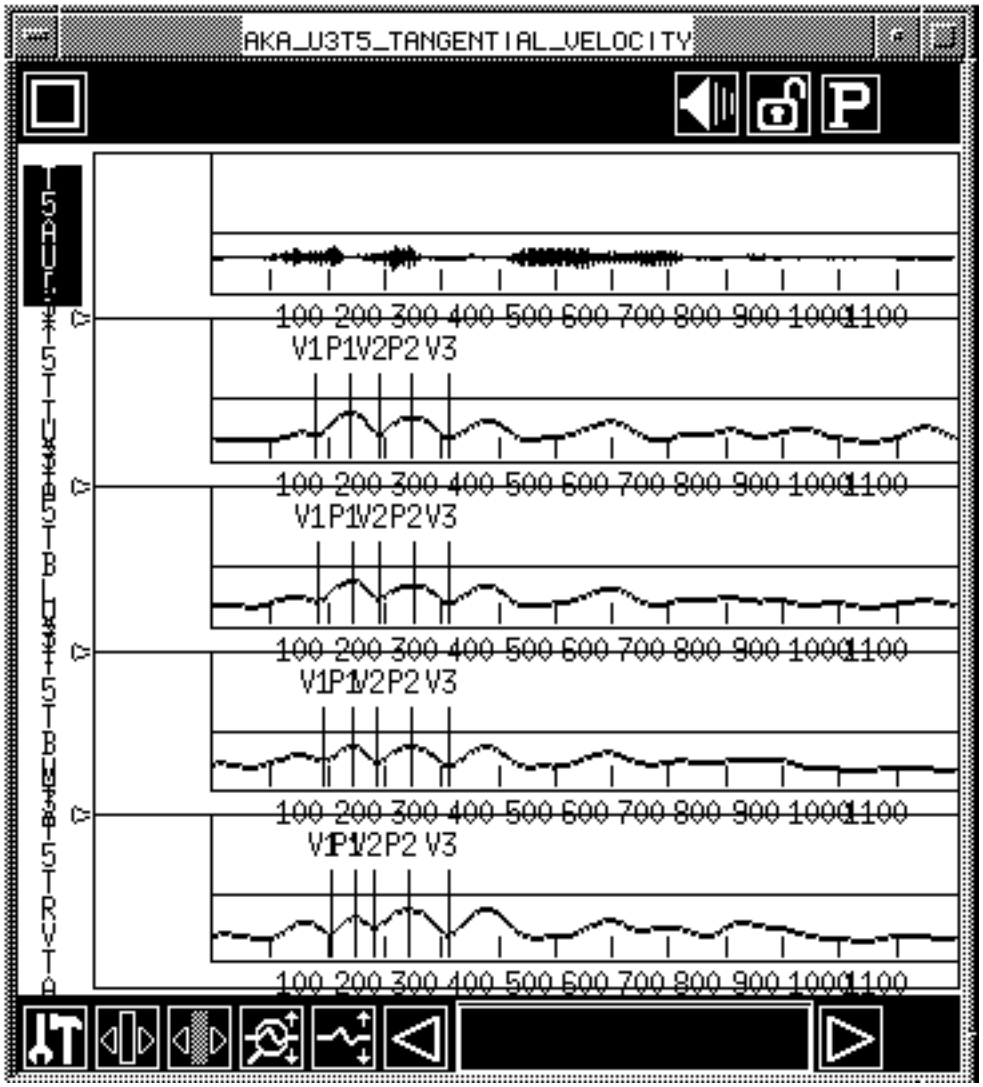

Figure 27: The same display as in Figure 26 with labels in the tangential velocity signals.

The labels are saved into files using the procedure TANLABELDEPOSIT.

```
! ********************************************************************************************
!      Procedure TANLABELDEPOSIT saves labels in tangential velocity tongue
!      receiver signals into files with name of the signal and the extension .LAB.
! ********************************************************************************************

define procedure tanlabeldeposit                    ! define a new procedure
  ! loop for signals
  for l=2 to 5                                      ! initialize loop for signals
    tanactsigname=sliststr(tandisplist,l)           ! extract the name of a signal
                                                    !   from list
    _active=tanactsigname                           ! set the active signal
    lt=lablocs(tanactsigname)                       ! create vector of label positions in
                                                    !   the active signal
    mx=len(lt)                                      ! get length of this vector
    if (mx <> 5)                                    ! check the length of the vector
      type “Error in labels for:” tanactsigname     ! if length of vector <> 5,
                                                    !   report error
      return                                        !   exit procedure
```

```
    end if                                          ! end of vector check
    lname=tanactsigname+".LAB"                      ! create name of label file
    label save lname                                ! save labels into file
  end for                                           ! end of loop for signals
  ! end loop for signals
  type "Labels saved into files for" prefix         ! report progress
end                                                 ! end of procedure
picon tanlabeldeposit                               ! map procedure to Picon
!
! ********************************************************************************
```

A loop for saving the signals is initialized using a FOR — END FOR statement (`for l= 2 to 5`). The counter (`l`) goes from 2 to 5 because labels will only be found in the 4 signals representing tangential velocity, while none occurs in the audio signal (which is the first signal in the list). The name of the signal is extracted from the signal list as `tanactsigname` (`tanactsigname=sliststr(tandisplist,l)`) and set to the active signal. To verify the number of labels in the active signal, a vector is first created of the labels in the signal (`lt=lablocs(tanactsigname)`). The length of this vector is set into a variable (`mx=len(lt)`). The length of the vector is examined and if it is not equal to 5 (`if (mx <> 5)`), an error message is typed, and the procedure exits. If the number of labels is correct, the name of the file for saving the labels is created (`lname=tanactsigname+".LAB"`) and the labels are saved into the file (`label save lname`). The loop is repeated until all the labels have been saved and a progress report is typed.

The procedure NEXTTAN is used to display and label the signals of the next token.

```
! ********************************************************************************
!      Procedure NEXTTAN checks for last token, deletes the active window,
!      displays the signals for the next token and increments the token counter.

define procedure nexttan                    ! define a new procedure
  if (token > etoken)                       ! check for the last token
    type "All done!"                        !   report the last token
    return                                  !   exit procedure
  end if                                    ! end of check
  delete window tanwindow                   ! delete window
  tandisplay                                ! call procedure to display signals
  token=token+1                             ! increment the token counter
end                                         ! end of procedure
picon nexttan                               ! map procedure to Picon
! ********************************************************************************
```

First, the token is checked to see if it is the last one (`if (token > etoken)`). If it is the last token, the message "`All done!`" is typed and the procedure stops. If the token is not the last one, the window is deleted, a call is made to the procedure TANDISPLAY to create and display the signals for the next token, and the token counter is incremented.

IV.B.4. Making measurements of signals

After the movement signals have been labeled, the labels are used for making measurements. The following procedure uses labels placed in the tangential velocity signal to measure tongue receiver positions and displacement, velocity, and duration of movements. The measurements are sent to a *journal file*. In addition to the measurements, coding variables for an Analysis of Variance are also sent to the journal file. The following measurements are made for each token and tongue receiver:

1. The vertical and horizontal position at the labels V1, V2, V3 in Figure 27.

2. The Euclidean distance for the two movements whose onset and offset are defined by V1 and V2, and by V2 and V3.
3. The path of the two movements whose onset and offset are defined by V1 and V2, and by V2 and V3.
4. The tangential velocity at the labels P1 and P2.
5. The duration of the two movements whose onset and offset are defined by V1 and V2, and by V2 and V3.

```
! ********************************************************************************************
!      Procedure TANDISPVELEMASURES2 measures x and y positions of tongue receivers
!      at points of minimum tangential velocity for diphthongs in the carrier,
!      first vowel, and middle consonant,
!      Euclidean distance and path of opening movement
!      for first vowel and closing movement for the middle consonant,
!      peak tangential velocity, and duration of the
!      opening and closing movement. Measurements are coded for ANOVA
!      and sent to an output file named UxTANDISPVEL2.DAT.
! ********************************************************************************************

define procedure tandispvelmeasures2              ! define a new procedure
  get "Enter number of utterance to open and measure:" utt       ! prompt for utterance
                                                                 !   number
  get "Enter first and last token to measure:" stoken etoken     ! prompt for
                                                                 !   first and last token
  token=stoken                                    ! initialize the token counter
  fslist siglist.txt mylist                       ! create a signal list
  dirsuffix=num2str(utt)+"]"                      ! create second part of directory name
  dirname=dirprefix+dirsuffix                     ! create the directory name
  _directory=dirname                              ! set the directory flag
  type "Directory is:" _directory                 ! report the directory name
  type "Opening files for utterance" utt          ! report progress
  ! loop for tokens
  while (token <= etoken)                         ! initialize loop for tokens
    prefix="U"+num2str(utt)+"T"+num2str(token)    ! create first part of signal name
    m=30                                          ! initialize pointer
    _labelopen=0                                  ! set flag for no automatic opening
                                                  !   of label files
    ! loop for position signals
    for i=14 to 28 step 2                         ! initialize loop for opening
                                                  !   position signals
      suffix=sliststr(mylist,i)                   ! extract second part of signal file
                                                  !   name from list
      fname=prefix+suffix                         ! create the signal name
      lsuffix=sliststr(mylist,m)                  ! extract second part of label file
                                                  !   name from list
      lname=prefix+lsuffix+".LAB"                 ! create name of the label file
      open fname                                  ! open the signal file
      label open lname                            ! open the label  file
      if (i==16 or i==20 or i==24)                ! check for receiver/signal
        m=m+2                                     ! set pointer
      end if                                      ! end of receiver check
    end for                                       ! end of loop for opening
                                                  !   position signals
    ! end loop for position signals
    _labelopen=1                                  ! set flag for automatic opening
                                                  !   of label files
    ! loop for tangential velocity signals
    for n=30 to 36 step 2                         ! initialize loop for opening
                                                  !   tangential velocity signals
      suffix=sliststr(mylist,n)                   ! extract second part of signal name
                                                  !   from list
      fname=prefix+suffix                         ! create signal name
      open fname                                  ! open signal
    end for                                       ! end of loop for opening tangential
    ! end of loop for tangential velocity         !   velocity signals
```

```
  token=token+1                                 ! increment token counter
end while                                       ! end of loop for tokens
! end loop for tokens
type "Signals opened, proceeding with measurements!"   ! progress report
jname="U"+num2str(utt)+"tandispvel2.dat"        ! create name of journal file
journal open jname                              ! open the journal file
if (utt < 28)                                   ! check for utterance number to
                                                !   determine coding variable for ANOVA
  voice=1                                       ! set value of coding variable
end if                                          ! end of utterance number check
  if (utt >= 28)                                ! check for utterance number to
                                                !   determine coding variable for ANOVA
  voice=2                                       ! set value of coding variable
end if                                          ! end of utterance number check
if (utt==1 or utt==6 or utt==7 or utt==13 or utt==28
  or utt==33 or utt==34 or utt==40)              ! check for utterance number to
                                                !   determine coding variable for ANOVA
  vowel=1                                       ! set value of coding variable
end if                                          ! end of utterance number check
if (utt==3 or utt==4 or utt==8 or utt==15 or utt==30
  or utt==31 or utt==35 or utt==42)              ! check for utterance number to
                                                !   determine coding variable for ANOVA
  vowel=2                                       ! set value of coding variable
end if
if (utt==2 or utt==5 or utt==9 or utt==14 or utt==29
  or utt==32 or utt==36 or utt==41)              ! check for utterance number to
                                                !   determine coding variable for ANOVA
  vowel=3                                       ! set value of coding variable
end if                                          ! end of utterance number check
! loop for tokens
for j=stoken to etoken                          ! initialize loop for tokens
  prefix="U"+num2str(utt)+"T"+num2str(j) ! create first part of signal name
  journal voice vowel                           ! send coding variables to journal file
  ! loop for receivers
  for k=14 to 26 step 4                         ! initialize loop for receivers/signals
    xsuffix=sliststr(mylist,k)                  ! extract second part of name of
                                                !   horizontal position signal
    l=k+2                                       ! set pointer for vertical position
                                                !   signal
    ysuffix=sliststr(mylist,l)                  ! extract second part of name of
                                                !   vertical position signal
    xactsigname=prefix+xsuffix                  ! create name of horizontal position
                                                !   signal
    yactsigname=prefix+ysuffix                  ! create name of horizontal position
                                                !   signal
    _units=_samples                             ! set flag for units to samples
    lvx=lablocs(xactsigname)                    ! create vector of label locations
                                                !   in horizontal position signal
    lvy=lablocs(yactsigname)                    ! create vector of label locations
                                                !   in horizontal position signal
    mxx=len(lvx)                                ! get length of vector
    mxy=len(lvy)                                ! get length of vector
    if (mxx <>5 or mxy <> 5)                    ! check lengths of vectors
      type "Error in labels for:" prefix        ! if any vector is not equal to five
      return                                    !   report error and exit
    end if                                      ! end of vector check
    ! loop for position values at minimum tangential velocity, x and y
    for i=1 to 5 step 2                         ! loop for position measurements
      vx1=lvx[i]                                ! point to sample in horizontal
                                                !   position signal
      vy1=lvy[i]                                ! point to sample in vertical
                                                !   position signal
      xvalue=xactsigname[vx1]                   ! get horizontal sample value
      yvalue=yactsigname[vy1]                   ! get vertical   sample value
       journal xvalue                           ! send horizontal value to journal file
       journal yvalue                           ! send vertical   value to journal file
```

```
 end for                                    ! end of loop for position measurements
 ! end of loop for position values
 ! loop for Euclidean distance values
 for i=1 to 3 step 2                        ! initialize loop to measure Euclidean
                                            !   distance
   vx1=lvx[i]                               ! point to sample at horizontal
                                            !   movement onset
   vx2=lvx[i+2]                             ! point to sample at horizontal
                                            !   movement offset
   vy1=lvy[i]                               ! point to sample at vertical
                                            !   movement onset
   vy2=lvy[i+2]                             ! point to sample at vertical
                                            !   movement offset
   xvalue1=xactsigname[vx1]                 ! get sample value at horizontal
                                            !   movement onset
   xvalue2=xactsigname[vx2]                 ! get sample value at horizontal
                                            !   movement offset
   yvalue1=yactsigname[vy1]                 ! get sample value at vertical
                                            !   movement onset
   yvalue2=yactsigname[vy2]                 ! get sample value at vertical
                                            !   movement offset
   tempxvalue=xvalue2-xvalue1               ! compute horizontal movement
                                            !   displacement
   tempyvalue=yvalue2-yvalue1               ! compute vertical movement
                                            !   displacement
   tandisp=sqrt((tempxvalue*tempxvalue)+(tempyvalue*tempyvalue))
                                            ! compute Euclidean distance
   journal tandisp                          ! send Euclidean distance to
                                            !  journal file
 end for                                    ! end of loop for measuring
                                            !   Euclidean distance
! end of Euclidean distance loop
! loop for path length
 for l=1 to 3 step 2                        ! initialize loop for measuring path
   startsamp=lvx[l]                         ! point to sample at movement onset
   endsamp=lvx[l+2]                         ! point to sample at movement offset
   maxsamp=endsamp-1                        ! set counter to last sample-1
   pathlength=0                             ! reset variable for length of path
   i=startsamp                              ! initialize sample counter
   while (i <= maxsamp)                     ! initialize loop for computing
                                            !   length of path
     xvalue1=xactsigname[i]                 ! point to sample in horizontal
                                            !   position signal
     xvalue2=xactsigname[i+1]               ! point to next sample in h.pos.signal
     yvalue1=yactsigname[i]                 ! point to sample in v. pos. signal
     yvalue2=yactsigname[i+1]               ! point to next sample in v. pos. signal
     tempxvalue=xvalue2-xvalue1             ! compute horizontal movement
                                            !   displacement
     tempyvalue=yvalue2-yvalue1             ! compute vertical movement
                                            !   displacement
     tandisp=sqrt((tempxvalue*tempxvalue)+(tempyvalue*tempyvalue))
                                            ! compute Euclidean distance
     pathlength=pathlength+tandisp          ! add value to variable for
                                            !   length of path
     i=i+1                                  ! increment sample counter
   end while                                ! end of loop for computing
                                            !   length of path
   journal pathlength                       ! send length of path to journal file
 end for                                    ! end of loop for computing
                                            !   length of path
 ! end of loop for path length
 if (k==14)                                 ! check number of signal to point to
                                            !   the corresponding tangential
                                            !   velocity signal in signal list
   m=30                                     ! set pointer into signal list
 end if                                     ! end of signal check
```

```
      if (k==18)
        m=32
      end if
      if (k==22)
        m=34
      end if
      if (k==26)
        m=36
      end if
      tanvelsuffix=sliststr(mylist,m)             ! extract second part of name of
                                                  ! tangential velocity signal from list
      tanvelactsigname=prefix+tanvelsuffix        ! create name of tangential vel. signal
      !  loop for peak tangential velocity values
      for i=2 to 4 step 2                         ! initialize loop for measuring
                                                  !   tangential velocity
        lvtan=lablocs(tanvelactsigname)           ! create vector of label locations in
                                                  ! tangential velocity signal
        vtan=lvtan[i]                             ! point to sample at peak tangential vel.
        tanvel=tanvelactsigname[vtan]             ! get sample value at peak tangential vel.
        journal tanvel                            ! send value to journal file
      end for                                     ! end of loop for measuring
      ! end of loop for peak tangential velocity values
      _units=_msec                                ! set flag for units to ms
      lttan=lablocs(tanvelactsigname)             ! create vector of label locations in
                                                  !   tangential velocity signal
      ! loop for movement duration values
      for i=1 to 3 step 2                         ! initialize loop for measuring
                                                  !   movement duration
        time1=lttan[i]                            ! point to label at movement onset
        time2=lttan[i+2]                          ! point to label at movement offset
        tandur=time2-time1                        ! compute movement duration
        journal tandur                            ! send duration to journal file
      end for                                     ! end of loop for measuring mov.duration
      ! end of loop for movement duration values
    end for                                       ! end of loop for receivers/signals
    ! end of loop for receivers
  end for                                         ! end of loop for tokens
  ! end of loop for tokens
  close                                           ! close all open signals
  journal close                                   ! close the journal file
end                                               ! end of procedure
picon tandispvelmeasures2                         ! map procedure to Picon
!
! ************************************************************************************
```

The procedure prompts for the utterance and for the first and last token to measure. The token counter is set to the first token (`token=stoken`). The signal list `mylist` is created from an ASCII file (`fslist siglist.txt mylist`). The directory name is formed and the directory flag is set to the proper directory. A loop for opening the signals for the specified tokens is initialized using a WHILE — END WHILE statement (`while token <= etoken`). The first part of the signal name is created (`prefix="U"+num2str(utt)+"T"+num2str(token)`. A pointer `m` is set to 30; this pointer will be used to extract the name of the corresponding tangential velocity signal from the signal list `mylist`. The flag for automatic opening of label files with signal files is turned off (`_labelopen=0`), because the labels that will be used for measuring the position signals were created in the corresponding tangential velocity signals; the label files thus have to be opened with their proper names.

A loop is initialized to open the position signals using a FOR — END FOR statement (`for i=14 to 28 step 2`). The variable `i` is used to extract part of the signal names from the signal list `mylist` (`suffix=sliststr(mylist,i)`. The name of the signal file is created (`fname=prerix+suffix`). The second part of the name of the label file is extracted from the signal list `mylist` (`lsuffix=sliststr(mylist,m)`). The full name of the label file is created (`lname=prefix+lsuffix+".LAB"`). The signal file and the label file are opened (`open fname`)

(label open lname). The receiver is checked and the pointer m is set to the proper value, i.e. if the next position signal to be opened is from the same receiver, the pointer remains unchanged, otherwise it is incremented. When all the position signals have been opened with the proper label files, the flag for automatic opening of label files with signal files is turned on (_labelopen=1), since the tangential velocity signals will be opened with their own label files. A loop for opening the tangential velocity signals is started using a FOR — END FOR statement (for n=30 to 36 step 2). The second part of the signal name is extracted from the signal list, the complete name is formed, and the signal is opened. The token counter is incremented (token=token+1) and the process is repeated until the signals for all the specified tokens have been opened and a progress report is typed.

The name of a journal file into which the measurements will be saved is formed (jname="U"+num2str(utt)+"tandispvel2.dat") and the journal file is opened (journal open jname). The number of the utterance being measured is evaluated in order to set two coding variables (voice, vowel) that will be used later in an Analysis of Variance.

A loop for measuring the specified tokens is started using a FOR — END FOR statement (for j=stoken to etoken). The first part of the signal name is created and the coding variables are sent to the journal file (journal voice vowel). A loop for receivers is initialized using a FOR — END FOR statement (for k=14 to 26 step 4). The second part of the name of the horizontal position signal is extracted from the signal list (xsuffix=sliststr(mylist,k)) and a pointer (l=k+2) is set to extract the second part of the name of the vertical position signal (ysuffix=sliststr(mylist,l)). The full names of the horizontal and vertical position signals are created. The flag for units is set to samples (_units=_samples) since sample values will be measured. Two vectors of label positions are created for the horizontal (lvx=lablocs(xactsigname)) and vertical (lvy=lablocs(yactsigname) position signals, respectively. The length of the two vectors is calculated (mxx=len(lvx) and (mxy=len(lvy). A check is made to see if the length of any of the two vectors differs from 5 (if (mxx <5> or mxy <> 5)), in which case an error message is typed and the procedure stops.

A loop is started to get the horizontal and vertical positions at the labels V1, V2, and V3 in Figure IV.2, using a FOR — END FOR statement (for i=1 to 5 step 2). A pointer is set to the horizontal and vertical sample (vx1=lvx[i]) (vy1=lvy[i]) and the sample values are obtained (xvalue=xactsigname[vx1]) and (yvalue=yactsigname[lvy1]. The values are sent to the journal file.

A new loop is created to calculate Euclidean distance as a measure of movement displacement using a FOR — END FOR statement (for i=1 to 3 step 2). To make this calculation, the horizontal and vertical receiver positions at movement onset and offset are required. Four pointers are set to the proper values: onset and offset in horizontal position (vx1=lvx[i]) and (vx2=lvx[i=2]) and onset and offset in vertical position (vy1[lvy[i]) and (vy2=lvy[i+2]). The sample values at these points are obtained, and the horizontal and vertical movement displacements are calculated (tempxvalue=xvalue2-xvalue1) and (tempyvalue=yvalue2-yvalue1). Finally, the Euclidean distance is calculated (tandisp=sqr((tempxvalue*tempxvalue)+(temyvalue*tempyvalue)), and this value is sent to the journal file (journal tandisp).

Another loop is started to measure the path traversed by a receiver during a movement by adding the Euclidean distance between successive samples from movement onset to movement offset (for l=1 to 3 step 2). The sample locations at movement onset and offset are obtained (startsamp=lvx[l]) and (endsamp=lvx[l+2]). A counter is set to the last sample minus 1 (maxsamp=endsamp-1). A variable for the length of the path is set to zero (pathlength=0). A sample counter is set to the sample at movement onset (i=startsamp) and a loop is created using a WHILE — END WHILE statement (while (i = maxsamp)). Two pointers are set to the first and second samples in the horizontal position signal

`(xvalue1=xactsigname[i])` and `(xvalue2=xactsigname[i+1])` and two other pointers are set to the corresponding samples in the vertical position signal `(yvalue1=yactsigname[i])` and `(yvalue2=yactsigname[i+1])`. The horizontal and vertical distance between these samples are calculated `(tempxvalue=xvalue2-xvalue1)` and `(tempyvalue=yvalue2-yvalue1)`, and then the Euclidean distance between the samples
`(tandisp=sqr((tempxvalue*tempxvalue)+(temyvalue*tempyvalue))`.
This value is added to the variable `pathlength (pathlength=pathlength+tandisp)`.
The sample counter is incremented `(i=i+1)`, and the procedure repeated until all the samples have been processed.

A check is made of the number of the position signal to set a pointer to the corresponding tangential velocity signal in the signal list `mylist`. The second part of the name of the tangential velocity signal is extracted from the list and then the full name of the signal is created. A loop is initialized to measure the tangential velocity at the labels P1 and P2 in Figure IV.2 `(for i=2 to 4 step 2)`. A vector of label positions in the tangential velocity signal is created `(lvtan=lablocs(tanvelactsigname))`. A pointer is set to the sample at the first label `(lvtan=lvtan[i])`, and the sample value is obtained `(tanvel=tanvelactsigname[vtan])`. This value is sent to the journal file `(journal tanvel)`, and the loop is repeated.

To measure movement duration, the flag for units is set to ms `(_units=_msec)` and a vector of label positions in the tangential velocity signal is created `(lttan=lablocs(tanvelactsigname))`. A loop is created for the measurements `(for i=1 to 3 step 2)`. Two pointers are set to the labels at movement onset and offset, respectively `(time1=lttan[i])` and `(time2=lttan[i+2])`. The duration between movement onset and offset is calculated `(tandur=time2-time1)` and the result is sent to the journal file `(journal tandur)`. When all the measurements for the first receiver have been made, the receiver loop is repeated until all receivers have been processed for the first token. Then, the token loop is incremented and the measurements for that token are made until all tokens have been processed. All open signals are closed `(close *)` and the journal file is closed `(journal close)`.

The journal file with the results of the measurements can later be read by a statistics program to obtain descriptive and inferential analyses of the data.

V. FUTURE DEVELOPMENTS

A third flavor of *HADES*, called *MHADES*, is presently under development. *MHADES* is designed for full compatability with the *DECwindows / Motif* user interface. This will provide for a more intuitive design, because all *HADES* windows will use the same graphical elements (*widgets*) that are used in the parent operating system. In addition, all of the display code is being redesigned to make the program more reliable. A potential future implication in moving to *Motif* is the increased possibility of cross-platform *HADES* development, including the possibility of versions of *HADES* that run on UNIX-based systems, such as the SUN SPARCstation and the Silicon Graphics family of CPUs. These platforms are available at Haskins for testing and development. Unfortunately, a considerable investment of effort would need to be spent removing all system-specific code from *HADES*. In particular, *HADES* makes greate reliance on the VAX T$PARSE library of string parsing code and on a set of specialized, VAX-specific, low-level file input-output routines. At this point, cross-platform development of *HADES* is being evaluated.

Another flavor of *HADES* is in the planning stages. *AHADES* is a version of *MHADES* that will run on Digital's newer Alpha (DEC AXP) platform. *MHADES* is being developed in a manner that will permit easy porting to the Alpha environment. This will let users take advantage of the increased processing power of this RISC-based platform. We expect that *AHADES* would become available within several months of the completion of *MHADES*.

At present, *XHADES* can be run from Macintosh computers attached to our Ethernet network running an *X Windows* emulation program called *eXodus*, from White Pine Software. Most of the graphics in the present paper were created by using the *eXodus* emulator and then capturing the screen displays. We have also tested remote connections to our network, using a the *eXodus eXpress* product via *TCP/IP*. This test has proven successful. *eXodus eXpress* also supports high speed serial/modem connections. The increased throughput of newer inexpensive modems (14,400 and 28,800 baud), and the availability of ISDN and other connectivity solutions, make this approach a promising way for individuals to run *HADES* from their home or university computers.

Another feature that we would like to add to *MHADES* is the enhanced animation of point movement data, particularly to show EMMA receiver trajectories. We presently use the Lissajous display to provide a limited view of such data. A separate program called *MBAT* (MicroBeam Analysis Tool) was developed at Haskins Laboratories by Mark Tiede to provide for such animation. Tiede has moved to the ATR Human Information Laboratories and has developed an enhanced, *Motif* version of *MBAT* called *MAVIS* (Multiple Articulator VISualizer; Tiede, 1994). *MAVIS* is used for viewing synchronized movement data such as that generated by point source tracking methods like the magnetometer or X-ray microbeam systems. It provides simultaneous display of paired time-varying trajectories and their spatial distribution at a temporal offset, which can be incremented automatically for powerful animation effects. The program also supports concurrent display of static backgrounds such as a palate trace. We hope to provide some of this functionality within *MHADES* in the form of new midsagittal point animation window. This window will let the user have control over the animation speed, the size and color of points, and will provide a VCR mode for replaying animations and for easily moving back and forth through them.

VI. CONCLUSION

Desktop computers can now be used as affordable laboratory tools for analyzing speech and physiological signals. Examples include the PC-based *CSRE* system (Jamieson, et al, 1989), and *Signalyze* (Keller, 1992) and *SpeechTools* (GW Instruments, 1992) for the Macintosh. The movement towards *XWindows / Motif* interfaces on engineering workstations provides the user-friendly graphical environment of the desktop computer coupled with the processing power and data throughput of these more powerful processors. A variety of such systems are available, including *Waves* for UNIX-based systems, the new *N!Power* by STI, and the *HADES* family of programs.

This paper has concentrated on *HADES*, detailing some of its most important features, including a wide variety of display and analysis tools. The most important feature of *HADES*, however, is its underlying procedural language, *SPIEL*. In part this language is similar to the program based scripting languages in applications such as *Excel* and *Matlab*. An important difference is that the focus of *SPIEL* is much narrower than in these other scripting languages. *SPIEL* has been optimized to handle large data sets of time-varying physiological and audio signals. The emphasis of this system is in providing researchers with sets of primitives and tools, and a language to control them, that makes the job of displaying, manipulating, measuring and analyzing large data sets as simple as possible. The program includes a variety of specialized tools (such as its rich event marking package), but omits many of the sophisticated analyses found in other signal processing packages. The intent of *HADES* was to develop a package that focused on a set of specific approaches, but also integrated smoothly with other programs. The combination of the *SPIEL* procedural language, the ability to label significant events in signals, facilities for journaling data in ASCII files, and simple data import and export, provide this vehicle. *HADES* is rarely used in isolation. As can be seen in the example in the present paper, sophisticated analyses and measurement techniques can provide output to be used by other programs, such as statistical packages, spreadsheets, etc., without concern for the destination platform.

HADES continues to be used at a variety of institutions around the world. Although development of the system has slowed over the past year as the package has stabilized, we hope to continue modernizing it and making it easier to use with the many powerful programs available on both desktop computers and engineering workstations. Also exciting is the beginning of the development of sophisticated procedures in the *SPIEL* language, as seen in the present paper. This ongoing development should prove extremely valuable for both fine-tuning and extending the *HADES* system.

ACKNOWLEDGEMENTS

The *HADES* family of programs and the *SPIEL* procedural language were designed by Philip Rubin — he is the one to blame should you be unhappy with any of the features of the program and its underlying language. The *SPIEL* procedure examples described in section IV of this paper were developed by Anders Löfqvist — contact him if you have any questions about them.

The following individuals, in order, were the main programmers of the *HADES* system — Vance Maverick, Mark Tiede, Marian Pressler, and Simon Levy. Without their tireless efforts and strong opinions about the design and direction of the program, *HADES* would not exist. *HADES* has, in part, developed from earlier programs. A particular influence has been programs and tools developed by Lenny Szubowicz. Significant contributions were derived from the work of Richard McGowan and Douglas Whalen. Members of the Haskins programming staff and technical support staff have contributed in a variety of ways to this project. These individuals are Michael D'Angelo, Vincent Gulisano, William Scully, Donald Hailey and Ed Wiley. The installation and tuning of the EMMA system, along with software for its use at Haskins Laboratories has had a major impact upon the development of *HADES*. Thuse who contributed in this area include Vincent Gracco, Anders Löfqvist , Patrick Nye, Michael D'Angelo, Eric Vatikiotis-Bateson, and Mark Tiede. Louis Goldstein provided design consultation on the *SPEED* prototpe. The design of the formant tracing package was influenced by suggestions from Robert Remez, Jennifer Fellowes and Jennifer Pardo. We are also grateful to the IEEE for the development of their fine package of signal processing subroutines, to Seiichi Tenpaku and the ATR Laboratories for the use of a portion of their *SpeechTools* package, to Eric Keller for his support of the Haskins PCM format in his *Signalyze* program, and to the many users of *HADES* who, over the years, have provided valuable feedback and support. Thanks!

GRANT SUPPORT

The design and development of *HADES* has been supported, in part, by grants and contracts from the National Institutes of Health to Haskins Laboratories including NIH Grant HD-01994, NIH-Grant DC-00121, NIH Grant DC-00043, NIH Grant DC-00044, NIH Grant DC-00825, NIH Grant DC-00865, NIH Contract N01-HD-5-2190, and support from the ATR Laboratories in Kyoto, Japan.

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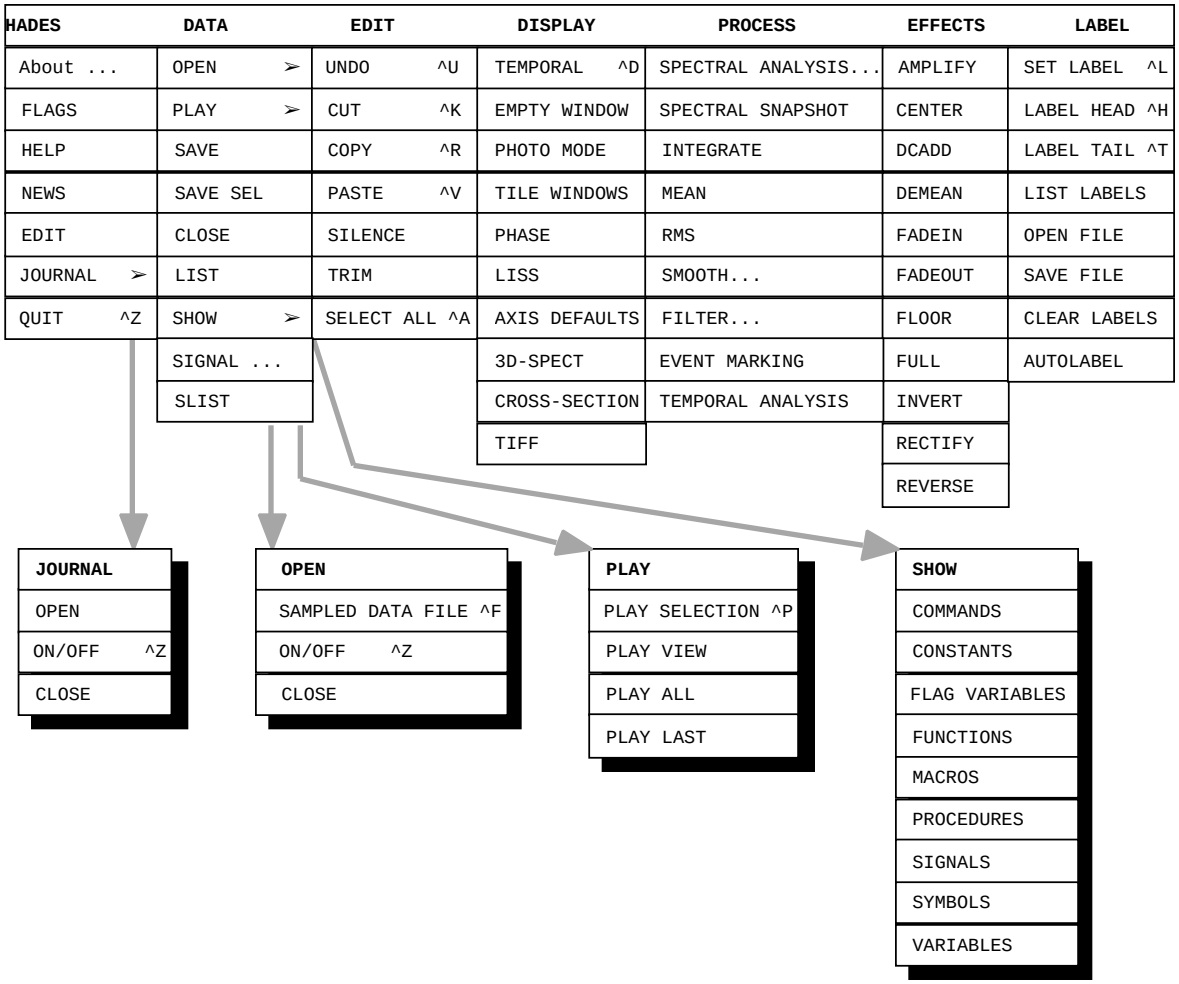
APPENDIX I: *HADES* Menu Bar



APPENDIX II: *HADES* COMMANDS

Command Summary - by Function

Program control

```
CLOSE   - close (delete a list of signals)
DEFINE  - define an entity (vector, signal, macro)
DELETE  - delete an entity
EXIT    - exit HADES
QUIT    - quit (exit from) HADES
RENAME  - rename an entity
RESET   - restore defaults
SHOW    - show (commands, constants, functions, macros, procedures,
                signals, symbols, variables)
SLIST   - defines the next element in a signal-list
TYPE    - evaluate and print expressions on the screen
```

File

```
OPEN    - open PCM file(s)or .DFT file(s) (AS signal(s))
SAVE    - save signal(s) (AS file(s))
SSEL    - save the selection in a file
FSLIST  - creates a signal-list by reading names from a file
```

Signal Editing

```
COPY    - copy the selection
CUT     - cut out (remove) the selection
LABEL   - labelling commands (followed by LIST, CLEAR, or OPEN)
PASTE   - paste previously cut selection at the cursor
RESCALE - rescale signal to specified max and min
SELECT  - specifies the selection range (_HEAD to _TAIL)
SETVAL  - sets signal values by linear interpolation
SILENCE - replace the selection with silence
TRIM    - removes everything except the selection
UNDO    - undo the last edit
UNSCALE - change a scaled signal to unscaled
```

Analysis and signal generation

```
CENTROID- centroid computation from DFT spectral cross-section
DFT     - create a DFT signal from a sampled data signal
GNOISE  - generate a random noise signal
GSINE   - generate a sine wave    signal
```

Effects and Processing

```
AMPLIFY - amplification
CENTER  - centers the signal by adding/subtracting a constant
DCADD   - add/subtract DC to the signal
DEMEAN  - remove the mean from the signal
FADEIN  - ramp the signal up in amplitude
FADEOUT - ramp the signal down in amplitude
FLOOR   - change the signal values to set the minimum to zero
FULL    - change the signal values to fill the full vertical range
INVERT  - flip the signal vertically around midscale
RECTIFY - rectification: full wave and half wave
REVERSE - reverse the signal in time
SMOOTH  - smooth signals
```

Graphics

```
CROSS   - spectral cross-section plot
DCDIS   - changes the displayed DC offset
```

```
DISPLAY - display sampled data or DFT signals in windows
DTIFF   - display a TIFF-format graphics file
LISS    - lissajous cross-plot of two signals
MAGNIFY - magnifies the active panel display
MTIFF   - make a TIFF file from a portion of the screen
PHASE   - phase plot of one signal
PHOTO   - photo mode for displays
REDRAW  - redisplay the active panel
TILE    - tile (visually organize) open windows
WATER   - 3D spectrogram plot
```

Utilities

```
DATE    - put the current date in a string variable
EDIT    - invoke the EDT editor
HELP    - on-screen help
JOURNAL - journal opening, writing or toggling
LIST    - list signals or procedures
MACRO   - macro definition
MEMORY  - shows current status of memory usage
MENU    - menu of commands
NEWS    - news, additions, and other info about HADES
PLAY    - play signal(s)
TIME    - put the current time in a string variable
VAX     - execute VMS command
```

SPIEL

```
FOPEN   - open a text file
FGET    - get input from a text file
FTYPE   - write information to a text file
FCLOSE  - close a text file
GET     - get keyboard input in SPIEL
PROCEDURE - define a SPIEL Procedure
RETURN  - return (exit) from a Procedure
RANK    - rank order a vector
SIG2V   - convert a signal to a vector
SIGNAL  - create an empty signal of specified length
SORT    - sort a signal or vector
V2SIG   - convert a vector to a signal
VECTOR  - create an empty vector of specified size
```

APPENDIX III: *HADES* FUNCTIONS

Function Summary - Alphabetical

ABS(*val*)	absolute value
ACOS(*arg*)	arc cosine (radians)
APPEND(*vec1,vec2*)	append vectors
ASIN(*arg*)	arc sine (radians)
ATAN(*arg*)	arc tangent (radians)
COS(*arg*)	cosine of a radian angle
EXTRACT(*data,start,end*)	extract data stream subsection
FEXIST(*filename*)	checks the existence of a file
INT(*val*)	truncate to integer
INTEGRATE(*signal,start,end*)	definite integral
LABLOC(*signal,label*)	retrieve time location (in _UNITS) of label
LABLOCS(*signal*)	create numeric vector of label times
LABS(*signal*)	create string list of label names
LEN(*signal*)	signal length
LOG(*val*)	natural logarithm
LOG10(*val*)	decimal logarithm
MAX(*arg,start,end*)	max value of numeric entity
MEAN(*arg,start,end*)	mean of a signal or a vector
MIN(*arg,start,end*)	min value of numeric entity
NONV2D(*sig1,sig2,offset*)	performs nonlinear regression of two signals to determine coefficients needed for the voltage-to-distance conversion for the magnetometer system.
NUM2STR(*num*)	convert number to string
OPEN(*file*)	create a signal by reading data from a file
RANDOM({ *seedval* })	returns or seeds a random number
REFRAME(*signal,srate*)	signal sampling rate conversion
RMS(*signal,start,end*)	RMS energy
SAVE(*signal,file*)	save signal to a file
SIN(*arg*)	sine of a radian angle
SLISTSTR(*listname,index*)	extract a symbol from a signal-list
SMOOTH(*signal,wsize*)	smooth a signal
SQRT(*val*)	square root
SRATE(*signal*)	sampling rate of signal
STR2NUM(*string*)	convert string to number
STREXT(*string,start,end*)	extract substring from string
STRLEN(*string*)	string length
STRPOS(*string,substring*)	position of substring in string
TAN(*arg*)	tangent of a radian angle
TYPE(*arg*)	argument type (0=string, 1=numeric, 2=signal)
VELOCITY(*signal*)	replace a signal with its velocity using a central difference function

APPENDIX IV: *HADES* FLAG VARIABLES AND CONSTANTS

Selected Flag Variables and Constants

_ACTIVE	indicates which open signal is the default (*active signal*) for display or analysis, etc.
_AMPMODE	Amplification value specification mode: dB or linear.
_AUTOLABEL	auto-labelling function (off or on)
_CASE	determines whether or not inputs and user-defined symbols are case-sensitive
_CLIP	keeps track of the most recent number of samples clipped by a command or a function.
_CURS	location of the cursor on the waveform plot
_DEBUG	used for keeping track of tokens and program flow in the input evaluation.
_DELAY	slows the plotting speed of LISS or PHASE plots.
_DFTSKIP	The number of points to shift the analysis window to the right after analyzing a frame of data during DFT analysis.
_DFWINS	The number of points in the analysis window for DFT analysis.
_DFTWINT	The type of analysis window to use for DFT spectral analysis. Options are: Hamming, triangular or rectangular windows
_DISPYMAX	Display Y (vertical) maximum.
_DISPYMIN	Display Y (vertical) minimum.
_EOF	End of File flag set when reading ASCII files with the FGET command.
_FADETYPE	FADEIN and FADEOUT ramp type: linear or cosine function.
_FN2SN	controls the default name of signals when opening files.
_FORMAT	specifies the file format for reading and writing sampled data files. Options are: Haskins PCM format; Signal Technologies Inc. ILS format; Indiana STM format; or ASCII (text) format.
_FRESULT	this flag returns the result of certain functions.
_GRAPH	indicates the type of graphics terminal being used Options are: none, UIS, Tektronix, X, or Macintosh.
_HEAD	beginning location of the *selection*, called the *head*
_INTERPOLATE	controls the interpolation of amplitude values at the *cursor* location, and within band interpolation of frequency values on TRACE or CROSS-section clicks.
_JOURNAL	controls journal enabling.
_LABELID	string prefix used for generating label names

_LABELINDEX	numeric suffix used for generating label names
_LABELOPEN	attempt to find and open a label file when using the OPEN command.
_LINECOLOR	default line plotting color.
_LINEWIDTH	default line width.
_LISSOVER	overlay flag for Lissajous Display (LISS)
_LISSXMAX	Lissajous Display X (horizontal) maximum.
_LISSXMIN	Lissajous Display X (horizontal) minimum.
_LISSYMAX	Lissajous Display Y (vertical) maximum.
_LISSYMIN	Lissajous Display Y (vertical) minimum.
_MOUSE	controls mapping of the right and left buttons to SHRINK and GROW
_NBITS	resolution (number of bits)of the analog to digital conversion of a signal.
_PHASEOVER	overlay flag for Phase Display (PHASE).
_PHASEXMAX	Phase Display X (horizontal) maximum.
_PHASEXMIN	Phase Display X (horizontal) minimum.
_PHASEYMAX	Phase Display Y (vertical) maximum.
_PHASEYMIN	Phase Display Y (vertical) minimum.
_RECTYPE	controls the type of rectification done by the RECTIFY command. Options are FULL and HALF.
_RESCALE	controls the rescaling of signals (scaled data only)
_SIGNED	Specifies whether data was stored as signed short integers or unsigned
_SMOOTHSIZ	window size for use with the SMOOTH command.
_SORTD	the sort direction for use with the SORT command.
_SPECHI	high cutoff values for black and white on spectrogram plots.
_SPECLO	low cutoff values for black and white on spectrogram plots.
_SRATE	default sampling rate to use if not specified by the header.
_TAIL	ending location of the *selection*, called the *tail*.
_UNITS	global time units in which _HEAD, _TAIL and _CURS and other time-based measurements are expressed. Options are:_MSEC, _SECONDS , or _SAMPLES
_VERBOSE	controls informational responses to the user, usually regarding command input.
_WATERDX, _WATERDY	default pixel scaling for the waterfall display.
_WINHIGH	default window height.

_WINLABS	labels visible flag.
_WINLLX, _WINLLY	absolute positioning of lower left corner of window (x and y).
_WINMODE	default mode for multi-panel display. Options are: STACK, TRACK or OVERLAY
_WINPSEPS	visibility of panel separators.
_WINRANGE	amplitude range for fixed range scaling mode.
_WINSCALE	scaling mode for signals.
_WINSYNCH	time synchronization of window panels.
_WINTICS	visibilty of ticks.
_WINUNITS	tick labelling units.
_WINWIDE	window width.
_WINXOFF_WINYOFF	increments added to absolute window position (x and y).
_XSECDC	cross-section DC setting.
_XSECFHI	cross-section X-axis frequency high cutoff.
_XSECFLO	cross-section X-axis frequency low cutoff.
_XSECLINE	cross-section plot line style. Options are: LINE, DOT, VLINE, VDOT.
_XSECMAG	cross-section magnitude units for plotting and listing. Options are: DB, LINEAR, POWER.
_XSECSMOOTH	cross-section smoothing
_XSECSMSIZ	cross-section smoothing window size

APPENDIX V: *HADES* CENTROID ROUTINE

```
      SUBROUTINE SPA_CENTX ( Y, LFREQ, UFREQ, BW, CENTX )
C
C       AUTHOR: R. MCGOWAN
C
C
C       PURPOSE: TO FIND THE CENTROID IN THE
C                FREQUENCY DIRECTION FOR A SPECTRUM BETWEEN
C                THE FREQUENCIES LFREQ AND UFREQ.
C:::::::::::::::::::::

        IMPLICIT NONE

        INTEGER  LB
        INTEGER  UB

        INTEGER  J
        INTEGER  I
        INTEGER  LX
        INTEGER  UX

        REAL     Y(1)
        REAL     AREA
        REAL     CENTX
        REAL     LFREQ
        REAL     UFREQ
        REAL     X
        REAL     XX
        REAL     YY
        REAL     LFREQB
        REAL     UFREQB
        REAL     BW
        REAL     BW10
        REAL     XL
        REAL     YL
        REAL     SLOPE
        REAL     H
        REAL     XR

        CENTX = 0.
        AREA = 0.
        LB = INT(LFREQ/BW )
        UB = INT(UFREQ/BW + 1. )
        BW10 = .1 * BW
        LFREQB = LB * BW
        UFREQB = UB * BW

        DO J = LB + 1, UB
          SLOPE = (Y(J+1) - Y(J))/BW
          YL = Y(J)
          XL = (J - 1) * BW
          LX = 0
          UX = 9
          IF ( J .EQ. (LB + 1)) THEN
            XR = (LFREQ - LFREQB)/BW10
            LX = NINT(XR)
          END IF
          IF ( J .EQ. UB ) THEN
            XR = (UFREQB - UFREQ)/BW10
```

```
            UX = 10 - NINT(XR)
          END IF
          DO I = LX, UX
            XX = I * BW10
            X = XL + XX
            H = SLOPE * XX + YL
            AREA = H * BW10 + AREA
            CENTX = X * H * BW10 + CENTX
          END DO
        END DO

        IF ( AREA .EQ. 0. ) THEN
                CENTX = 0.
        ELSE
                CENTX = CENTX/ AREA
        ENDIF

        RETURN
        END
```

==========

APPENDIX VI: A sample *SPIEL* procedure

```
!    Title : pe.com
!    Author: Philip Rubin
!    Date  : April 3, 1995
!
!      The PE procedure opens a PCM file, does an F0 temporal
!      analysis and an ENERGY (in dB) temporal analysis, and then
!      saves the frame #s, f0, and energy values in an ASCII file.
!
!      The PCM filename must be specified without an extension.
!      The output file is the name of the PCM file with the
!      extension "PE." appended.
!      F0 values are limited to range between 0 and pit_max.
!      ENERGY values can range between 0 and energy_max.
!=================================================================

define procedure pe
  _verbose = _none                          ! turn off messages
  pit_max = 999                             ! set a maximum F0 value
  energy_max = 99                           ! set a maximum ENERGY value
  _energy = _db                             ! ENERGY analysis in db
  get "Enter PCM file name (no extension)" pnam
  open pnam                                 ! open the PCM signal
  aname=_signame+".PE"                      ! create the output filename
  f0 pnam wf0                               ! do the F0 temporal analysis
  energy pnam wamp                          ! do the ENERGY      analysis
  nframe=len(wf0)                           ! get # frames in analysis signal
  if ( nframe <1 )
    type "Too few frames !!"                ! exit if error
    return
  end if
  sig2v wf0                                 ! convert working F0     to a vector
  sig2v wamp                                ! convert working ENERGY to a vector
  fopen aname                               ! open an ASCII file
  ftype "frame# f0 (Hz) energy (dB)"
  for i = 1 to nframe                       ! loop for the F0 frames
    wval = wf0[i]                           ! working F0 value
    if (wval<0)
      wval=0                                ! set a low  frequency
    end if
    if (wval>pit_max)                       ! and a high frequency
     wval=pit_max
    end if
    wv2 = wamp[i]                           ! working ENERGY value
    if ( wv2<0 )
      wv2=0                                 ! set a low  energy cutoff
    end if
    if ( wv2 > energy_max )
      wf2=energy_max                        ! set a high energy cutoff
    end if
    ftypef " %.0f %.2f  %.2f",i,wval,wv2  ! write values to ASCII file
  end for                                   ! end the frame loop
  fclose                                    ! close the journal file
  type "File created: " aname
  close pnam                                ! close the PCM signal
end
!=================================================================
```

The following file was created by running the PE procedure on the file KUD.PCM:

frame#	f0 (Hz)	energy (dB)
1	0.00	15.91
2	243.87	43.43
3	0.00	8.61
4	0.00	39.77
5	0.00	39.43
6	0.00	34.70
7	0.00	34.39
8	0.00	33.04
9	0.00	32.22
10	0.00	33.79
11	0.00	38.83
12	0.00	39.43
13	116.23	42.45
14	109.86	43.35
15	105.21	44.37
16	103.07	45.19
17	102.00	44.70
18	99.97	45.64
19	98.01	46.10
20	96.10	47.46
21	95.21	46.55
22	93.42	47.71
23	91.69	47.52
24	91.69	45.46
25	90.09	47.39
26	90.09	47.54
27	87.70	46.86
28	86.16	46.10
29	84.73	44.08
30	188.66	40.03
31	0.00	32.79
32	0.00	25.44

FIGURE CAPTIONS:

Figure 1: *HADES* GUI, showing menu bar and command window

Figure 2: *HADES* Menu Bar

Figure 3: Analysis Parameters Dialog Box

Figure 4: Panel Toolbox Dialog Box

Figure 5: The Display Window

Figure 6: PICON: The Programmable Icon

Figure 7: *HADES* Display Window

Figure 8: The Control Panel

Figure 9: Display Window with waveform and spectrogram

Figure 10: Spectral cross-section

Figure 11: 3D Waterfall spectral display

Figure 12: Multi-panel Display Window

Figure 13: Multi-panel display window — overlayed

Figure 14: Lissajous display

Figure 15: Phase display

Figure 16: TIFF display of MRI of vocal tract

Figure 17: Display Window showing a labelled signal

Figure 18: A hand-labelled signal

Figure 19: A signal labelled by means of autolabelling

Figure 20: Event Marking dialog box

Figure 21: Filter Parameters dialog box

Figure 22: DFT, LPC, and FBA display

Figure 23: The Temporal Analysis Parameters Dialog Box

Figure 24: The Flags Dialog Box

Figure 25: The Axis Settings Dialog Box