**VERSION 1.7 OF MATSEIS AND THE GNEM R&E REGIONAL SEISMIC ANALYSIS TOOLS**

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ABSTRACT

To improve the nuclear event monitoring capability of the U.S., the NNSA Ground-based Nuclear Explosion Monitoring Research & Engineering (GNEM R&E) program has been developing a collection of products known as the Knowledge Base (KB).  Though much of the focus for the KB has been on the development of calibration data, we have also developed numerous software tools for various purposes. The Matlab-based MatSeis package and the associated suite of regional seismic analysis tools were developed to aid in the testing and evaluation of some Knowledge Base products for which existing applications were either not available or ill-suited.   This presentation will provide brief overviews of MatSeis and each of the tools, emphasizing features added in the last year.

MatSeis was begun in 1996 and is now a fairly mature product.  It is a highly flexible seismic analysis package that provides interfaces to read data from either flatfiles or an Oracle database.  All of the standard seismic analysis tasks are supported (e.g. filtering, 3 component rotation, phase picking, event location, magnitude calculation), as well as a variety of array processing algorithms (beaming, FK, coherency analysis, vespagrams).  The simplicity of Matlab coding and the tremendous number of available functions make MatSeis/Matlab an ideal environment for developing new monitoring research tools (see the regional seismic analysis tools below).  New MatSeis features include: addition of *evid* information to events in MatSeis, options to screen picks by author, input and output of *origerr* information, improved performance in reading flatfiles, improved speed in FK calculations, and significant improvements to Measure Tool (filtering, multiple phase display), Free Plot (filtering, phase display and alignment), Mag Tool (maximum likelihood options), and Infra Tool (improved calculation speed, display of an F statistic stream).

Work on the regional seismic analysis tools (CodaMag, EventID, PhaseMatch, and Dendro) began in 1999 and the tools vary in their level of maturity.  All rely on MatSeis to provide necessary data (waveforms, arrivals, origins, and travel time curves).  CodaMag Tool implements magnitude calculation by scaling to fit the envelope shape of the coda for a selected phase type (Mayeda, 1993; Mayeda and Walter, 1996).  New tool features include: calculation of a yield estimate based on the source spectrum, display of a filtered version of the seismogram based on the selected band, and the output of codamag data records for processed events.  EventID Tool implements event discrimination using phase ratios of regional arrivals (Hartse et al., 1997; Walter et al., 1999).  New features include: bandpass filtering of displayed waveforms, screening of reference events based on SNR, multivariate discriminants, use of *libcgi* to access correction surfaces, and the output of discrim_data records for processed events.  PhaseMatch Tool implements match filtering to isolate surface waves (Herrin and Goforth, 1977).  New features include: display of the signal's observed dispersion and an option to use a station-based dispersion surface.  Dendro Tool implements agglomerative hierarchical clustering using dendrograms to identify similar events based on waveform correlation (Everitt, 1993).  New features include: modifications to include arrival information within the tool, and the capability to automatically add/re-pick arrivals based on the picked arrivals for similar events.

**OBJECTIVE**

MatSeis was originally developed to support signal-processing research for the GNEM R&E program at Sandia Labs. The initial goal was simple: to develop a graphical user interface (GUI) to help a user bring data from an Oracle database into Matlab. Once the data was in Matlab, researchers could then run various scripts and/or functions to test algorithms. This goal was quickly accomplished thanks to the tremendous range of existing Matlab functionality, but Sandia chose to extend development because it became apparent that the package had potential to be much more useful than had been expected. Within a year we had developed a simple, interactive seismic analysis package built around 4 basic data types: waveforms, arrivals, origins, and travel time curves. However, because the bulk of Sandia's development work went towards signal processing, early versions of MatSeis had an odd look and feel: the package had an extensive set of signal processing capabilities (e.g. filtering, rotation, beaming, FK, coherency, vespagrams), while at the same time it lacked many of the more common seismic analysis utilities (e.g. a locator, magnitude calculations, a quick and easy phase picker) because these were not needed for Sandia's research efforts at that time.

The second MatSeis development phase began when Sandia began to use the package as a base upon which to develop specialized regional seismic analysis tools. Over the past few decades, many studies have suggested ways to improve regional monitoring, yet relatively few of the ideas presented have found their way into operational software. The reason is that those who actually monitor have limited time and resources to put towards evaluating these ideas, and so generally only the most sure-fire get implemented. What is needed is a prototyping environment in which promising analysis techniques can be implemented and evaluated quickly and with relatively little effort. Sandia recognized that MatSeis/Matlab offered just such an environment, and taking advantage of this we began to build a set of prototypes for various regional analysis tasks, focusing first on the techniques and data sets generated by the research of our colleagues at Lawrence Livermore National Lab (LLNL) and Los Alamos National Lab (LANL). Currently the tools support phase match filtering, regional magnitude calculations, discrimination, and event clustering using waveform correlation.

An unplanned but welcome side effect of the development of these tools has been the improvement of MatSeis itself. To properly use the tools, it is necessary to add new picks, re-time picks, re-locate events, etc. Thus, Sandia was forced to fill in many of missing basic seismic analysis utilities, and to improve many of the existing ones. The result is that MatSeis is now a significantly more complete, more robust package.

**RESEARCH ACCOMPLISHED**

The following sections describe MatSeis, and the four regional seismic analysis tools. The important new features for Version 1.7 are highlighted for each.

**MatSeis**

The main MatSeis graphical window is a standard time vs. epicentral distance plot that can display waveforms, arrivals, origins, and travel time curves (Figure 1). The user can interact with this display by clicking directly on the displayed objects, by using the buttons along the bottom, by using the menus along the top, or by typing commands at the Matlab prompt. MatSeis is predominantly written as Matlab m-file functions, which are organized in a set of directories according to the general purpose of each. However, the package also includes a set of compiled C functions linked to the m-files via the Matlab cmex utility. Typically the C functions are introduced where performance of an m-file is too slow (e.g. FK calculations).
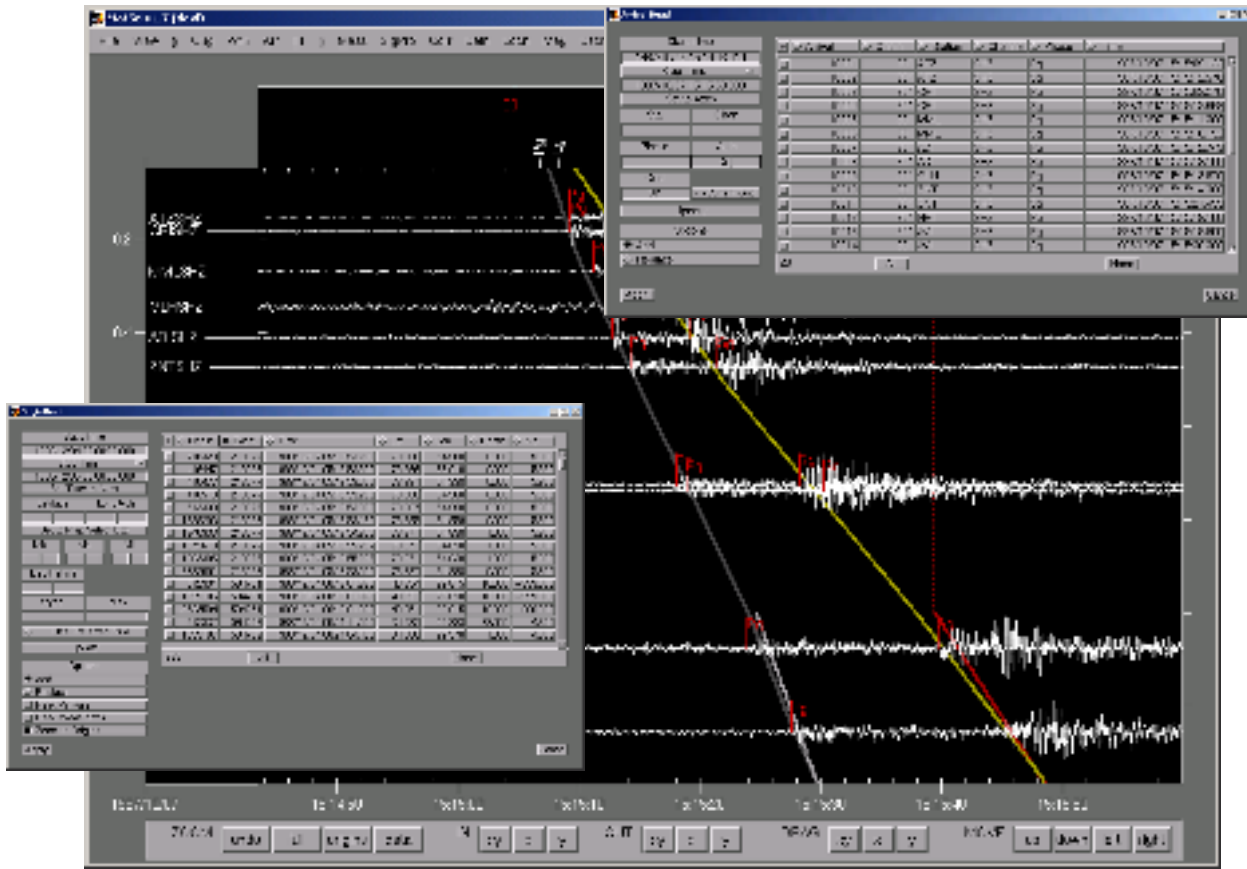
**Figure 1. The main MatSeis display is a standard time vs. epicentral distance waveform profile. This figure shows all 4 data objects: waveforms, arrivals, origins, and travel time curves. Also shown are the re-designed popups to read in arrivals (upper right) and origins (lower left).**

**Data IO**

MatSeis can read CSS3.0 format data from either an Oracle database, or flatfiles. Output is restricted to flatfiles only. The number of tables used by MatSeis has steadily expanded and now includes: *affiliation, amplitude, arrival, assoc, event, instrument, nextid, netmag, network, origerr, origin, remark, sensor, site, sitechan, stamag, wfdisc,* and *wftag*. In Version 1.7, flatfile data reads have been greatly sped up, making it practical to work with larger data sets than has been the case in the past. In order to allow the user to better control the data read into MatSeis, Version 1.7 has an extensive set of filters for both origins (*lat, lon, magnitude, etype, auth*) and arrivals (*sta, chan, phase, auth, orid*). In the origin read popup, *evid* is now displayed, which makes it more convenient to work with multiple origins for the same event.

**Arrival Picking and Amplitude Measurement**

Arrivals can be added, deleted, renamed, and retimed in the main MatSeis display, but it is a cumbersome process and impractical when editing more than a few arrivals. The recommended method is to use an auxiliary utility called Measure Tool (Figure 2) that can be launched from the main display. Measure Tool is designed to help analysts quickly and efficiently pick arrivals and measure amplitudes for an event. The theoretical arrival times for the TT curves in MatSeis, are shown for reference. Version 1.7 includes a set of controls to filter the waveforms, and the filtering can be toggled on or off. Once an arrival has been picked, the user can choose from a set of amplitude measurements (e.g. Peak-Peak, Zero-Peak, RMS), and the measurement is automatically made after the user sets the window. A toggle allows the user to choose whether or not to correct the measurements for instrument response.
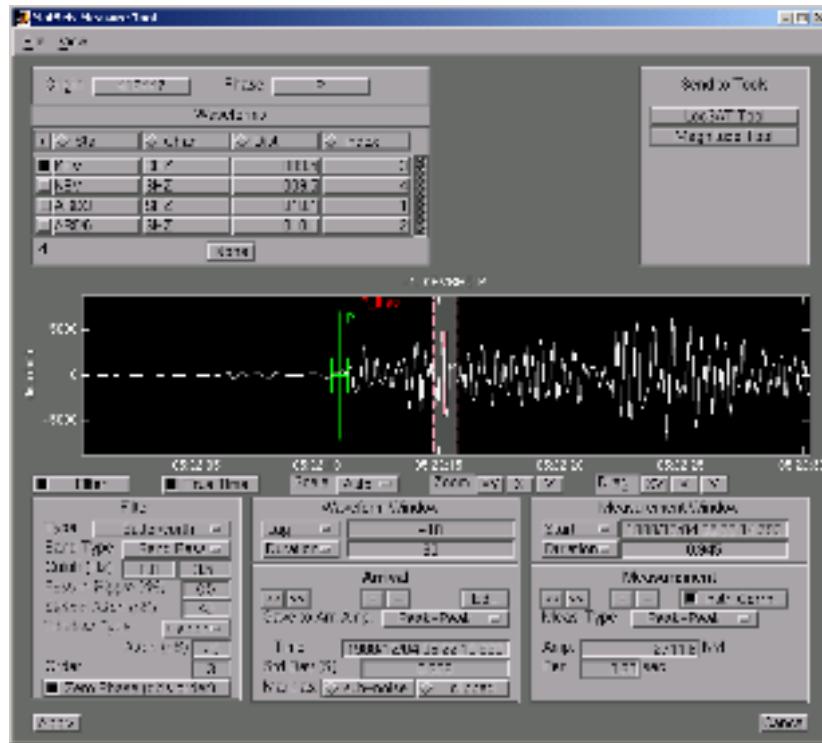
**Figure 2. Measure Tool has been designed specifically to allow the analyst to quickly pick, retime, and measure amplitudes for arrivals.**

**Magnitude**

Magnitudes can be calculated in MatSeis using either of two tools. The Magnitude Tool (Figure 3) offers a variety of standard amplitude-based magnitude formulas for local, regional, and teleseismic data. The user can screen the data used by phase, period, and distance.
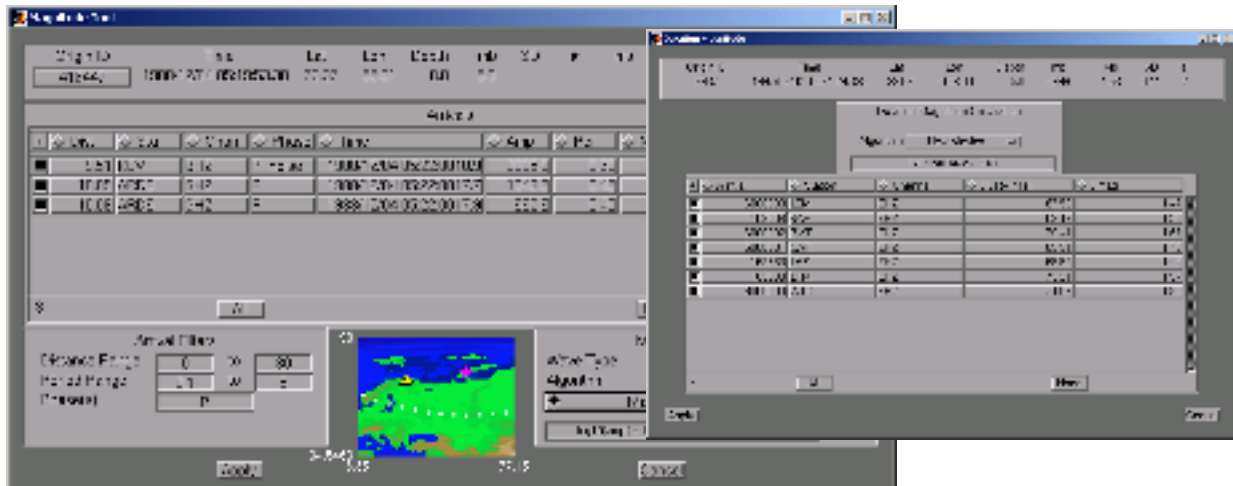


**Figure 3. The Magnitude Tool (left) and Duration Mag Tool (right) allow the user to select the type of magnitude formula , and provides a clickable list to control which station measurements are used for the network magnitude.**

Individual measurements can be turned on or off by clicking on their rows in a table, and a small map shows the positions of the stations relative to the source location. A new feature in Version 1.7 is an option to calculate a maximum likelihood magnitude, if some of the arrivals have been designated as sub-noise or clipped (Blandford & Shumway, 1993; Ringdal, 1976).

The Duration Magnitude Tool has a similar look and feel, but calculates magnitude base on duration of signal above noise, as picked by an analyst. The tool includes a default formula for New Mexico, and can be easily modified to include calibrated formulas for any number of other regions.

**Infra Sound Analysis**

MatSeis-1.7 includes Infra Tool, a tool for analysis of infrasound array data. This tool uses cross-correlations of the array channels to derive azimuth and velocity for incoming signals. The calculation is made for a short user-defined moving window, so the result is a stream of azimuth, velocity, correlation, and fstat. The tool displays these streams, along with the filtered data channels (Figure 4). The user can change the filter parameters and/or the moving window parameters (length, %overlap), and re-calculate the streams.
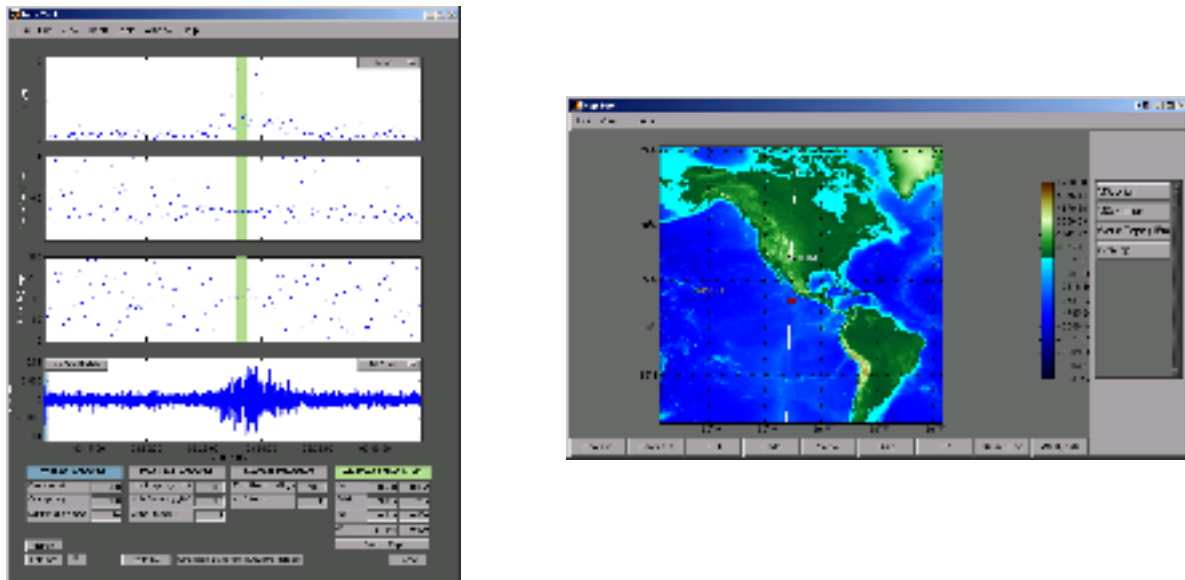


**Figure 4. The Infra Tool helps the user derive great circle path information from infrasound array data (left). Great circles can be plotted using the Map Tool (right).**

Once the streams have been calculated, the user can set an analysis window to measure average values and standard deviations for each of the calculated streams. The average azimuth value can then be sent to the map and plotted as a great circle. Using data from two or more infrasound arrays, events can be located by crossing the great circles.

**Regional Seismic Analysis Tools**

**Phase Match Tool**

PhaseMatch Tool is a waveform analysis interface launched from MatSeis that allows the user to calculate the predicted surface wave dispersion for a given source to receiver path by ray tracing through a model, and then use the model dispersion to generate and apply a matched filter (Herrin and Goforth, 1977). The tool (Figure 5) allows the user to view the observed waveform, the model dispersion, the predicted waveform, the cross-correlation of the predicted and observed waveforms, and the match-filtered waveform. The user can control the frequency range of the model dispersion used, as well as the time limit of the portion of the cross-correlated waveform from which the match-filtered waveform is taken. Once a satisfactory filtering has been achieved, the user can send either the

observed waveform or the filtered waveform to Measure Tool to measure surface wave amplitudes, which can then be used to determine event magnitude.

New features for the Version 1.7 include an option to display the signal's observed dispersion, and an option to use a station-based dispersion surface.
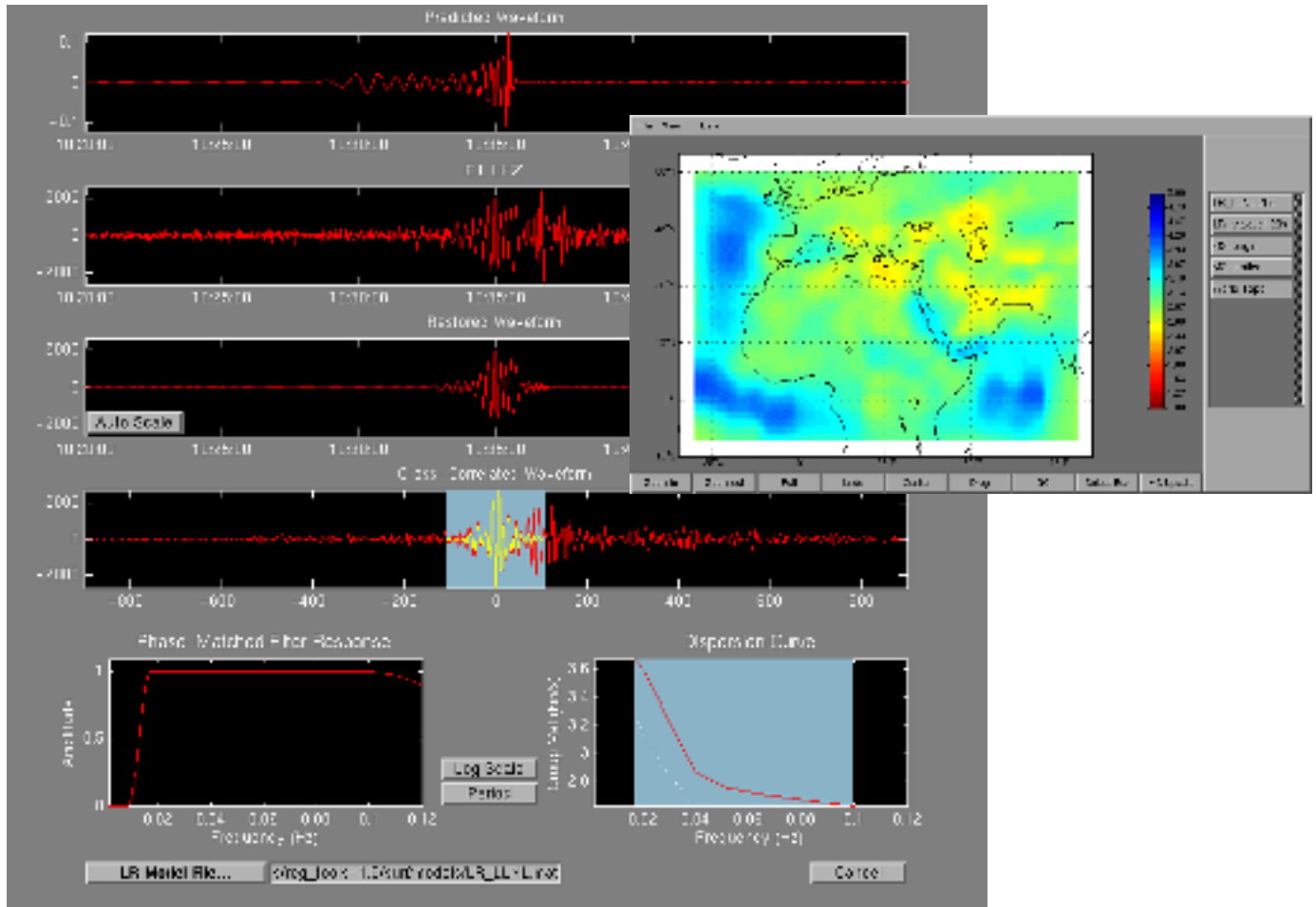


**Figure 5. Phase Match Tool allows the user to use the information from a dispersion model (upper right) to design a phase-match filter to isolate surface waves.**

**Coda Magnitude Tool**

CodaMag Tool is a waveform analysis interface launched from MatSeis that allows the user to calculate magnitudes and source spectra for an event of interest by fitting empirical decay functions to narrow-band coda envelopes of a given phase (currently Lg). The technique was developed by Mayeda and has been described in detail in several papers (Mayeda, 1993; Mayeda and Walter, 1996; Mayeda, et al., 1999). The tool consists of two displays. The main one shows the calculated moment spectrum and the derived magnitudes. The second display shows how the spectrum was derived. The user can adjust the Lg arrival window, examine the fit between the observed and synthetic envelopes, and control which frequency bands are used for the magnitude calculations. The various required parameters (frequency bands, groups velocity windows, decay curves, etc.) are read from parameter files unique to each station.

Important new features in Version 1.7 include a yield estimate based on the source spectrum, an option to display filtered seismograms in addition to the Hilbert envelopes, and the capability to write out data records to capture results.
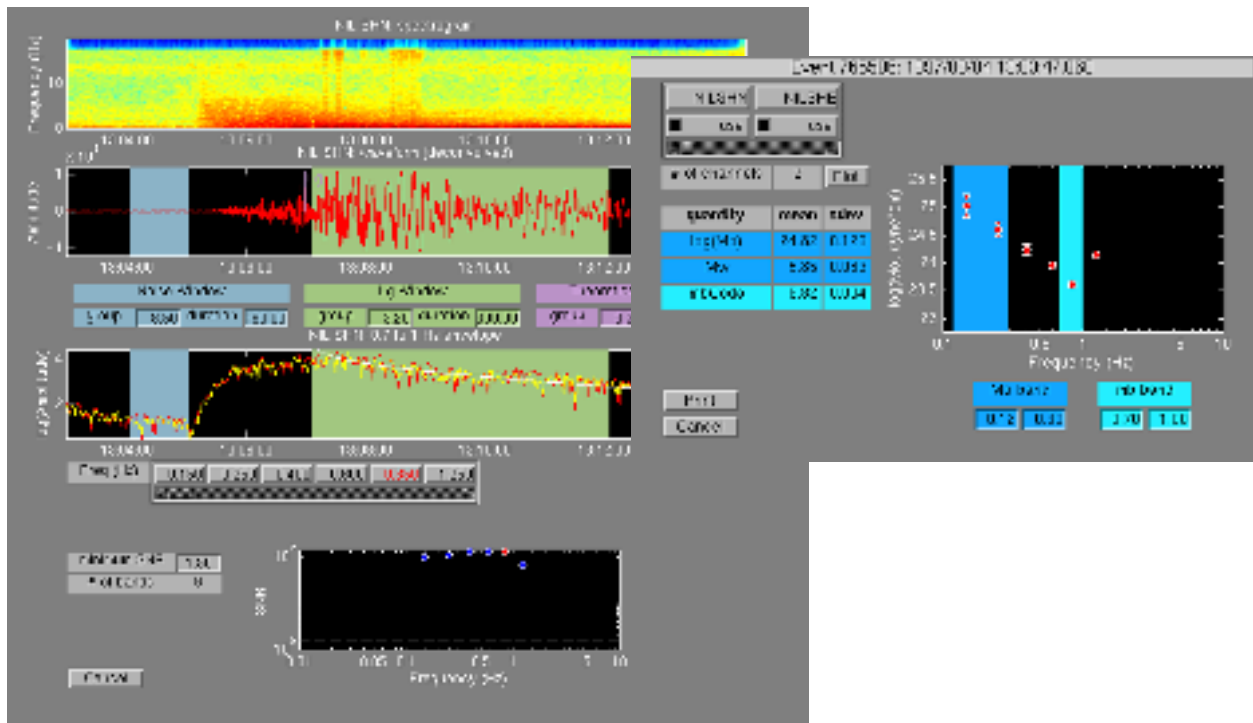
**Figure 6. The Coda Mag Tool implements the methodology developed by Mayeda. Coda envelopes are fit for a series of narrow frequency bands (left), and the scaling factors are then used to derive a moment spectrum, from which various magnitudes can be taken (right).**

**Event Identification Tool**

EventID Tool is a waveform analysis interface launched from MatSeis that allows the user to identify an event of interest (i.e. explosion or earthquake) using spectral ratios of standard regional arrivals (see Hartse et al., 1997; Walter et al., 1999). The tool (Figure 7) consists of three displays. The main display plots the phase ratio for the current event against a backdrop of the same ratio for archived events that have already been identified. The user can choose different phases and/or frequency bands to ratio to try to improve the separation of the earthquake and explosion populations, and the display will immediately update. A second display shows the user a plot of an "MDACogram" (i.e. the MDAC corrected measurements at all of the phase/frequency combinations) for the current event along with all of the archived events. This can be useful in deciding which ratio will yield the best separation. If there are questions about the amplitude measurements themselves, a third display can be brought up, and the user can easily examine group velocity windows for the phases and change them if necessary. If they are changed, the measurements will automatically be re-made and the ratios updated in the main display.

Version 1.7 has several important new features including the ability to apply MDAC2 corrections (Walter and Taylor, 2002) to the spectral measurements, as well as kriged corrections from Ground Truth events, the option to use multi-variate discriminants, the capability to screen the reference events shown, based on signal-to-noise ratio, and the capability to write out data records for processed events.
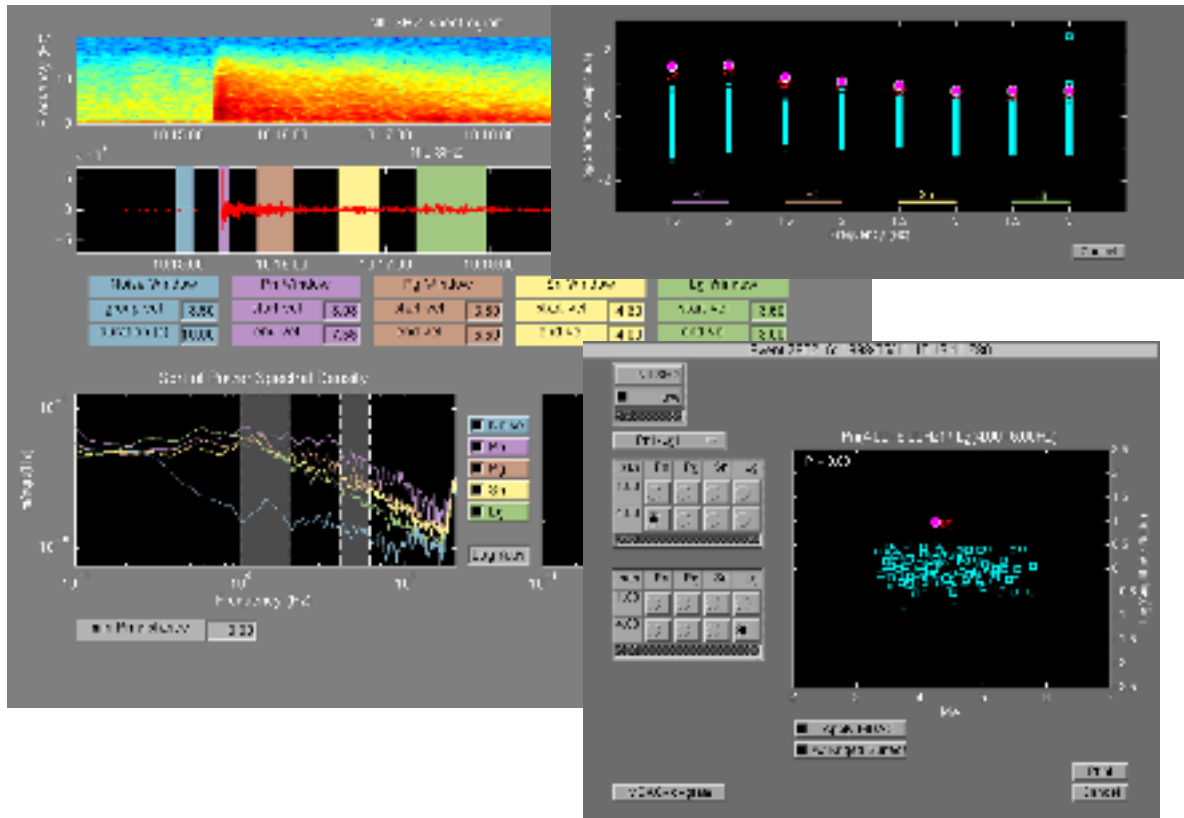
**Figure 7. The EventID Tool helps the user discriminate explosions from earthquakes using standard phase-ratio methods. The user can view the overall results (lower right) or an "MDACogram" (upper right), or examine and change how the measurements for each phase were made (left).**

**Dendrogram Tool**

The DendroTool provides a tool to perform waveform correlation-based cluster analysis techniques on seismic data. The purpose of Dendro Tool is quite simple: to allow a user to quickly and efficiently determine whether a waveform of interest matches any in the available archives. By arranging the correlations in a hierarchical dendrogram, rather than just determining the most similar waveform, the user gets a much more complete picture of how the current event fits with the archived events. For example, in regions with repeated mining explosions, the mines are often easily identified as distinct clusters, and new mining events can be readily identified as such by association with those clusters.

Dendro Tool consists of many interfaces to help the user assess the effectiveness of the clustering and to use the clusters to identify the events. The main display shows the dendrogram, along with a set of metrics that can be used to determine the correlation level to use to identify the families of events. Once a level has been chosen, the families are assigned separate, distinct colors to make them easier to see. Parameters controlling filtering and windowing of the waveforms, the method used to build the dendrogram, etc. can be set using another display, and the dendrogram will then be updated. The color-coded waveforms for any or all of the families in the dendrogram display can be sent to the MatSeis utility Free Plot for viewing to assess the validity of the families. The color-coded locations of the events in any or all of the families can be sent to the MatSeis Map Tool to see how the families agree with the locations. Within the Dendro Tool, origin times for any or all of the families can be used to generate color-coded histograms by year, month, day of year, day of week, or hour of day.

Dendro Tool can form dendrograms based on a single-phase window for a single station, or the user can choose to use multiple windows and/or multiple stations. The method of combining the multiple correlations (minimum, maximum, mean, median) is user controlled.

The significant new features for Version 1.7 are related to the newly added support for arrivals.  The user can now view the picks along with the waveforms when examining the structure of the dendrograms.  It is now also possible to use Dendro Tool to re-time arrivals based on lags calculated from the waveform cross-correlations.  Once the current event has been added to a dendrogram, the user can then re-time the picks for that event based on the lags with other events in that group.  Once the arrivals have been adjusted, they can then be sent back to MatSeis for other uses (e.g. re-locating the event).
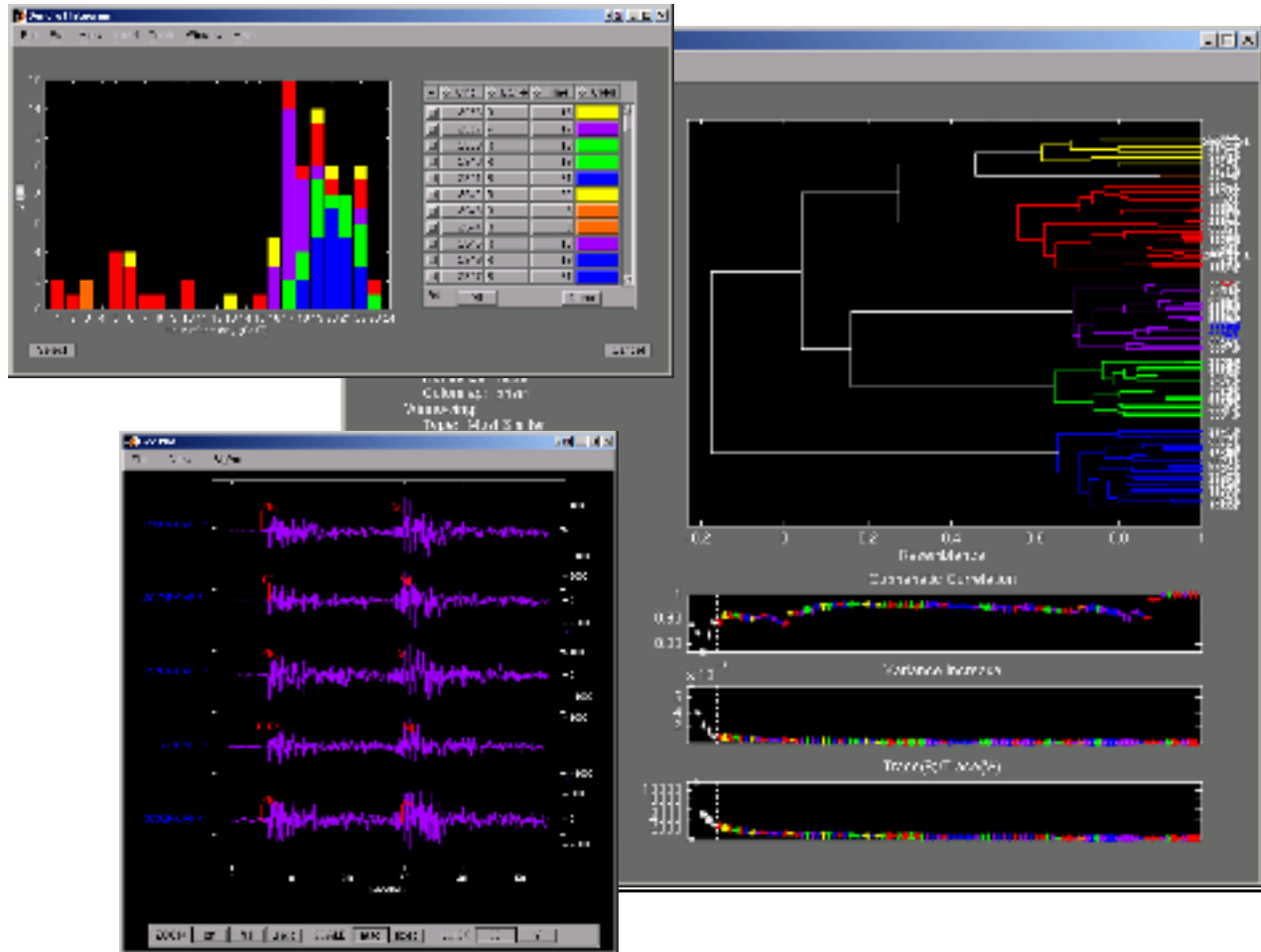


**Figure 8. The Dendrogram Tool employs hierarchical cluster analysis to group similar waveforms.  The main display is a dendrogram (right).  The user can also view the waveforms (lower left) or histograms (upper left) for all or part of the dendrogram.**

<u>**CONCLUSIONS AND RECOMMENDATIONS**</u>

Though started specifically to support signal-processing research in the GNEM program at Sandia Labs, MatSeis has now become an important part of the overall GNEM R&E program.  It provides a much needed bridge between research results and operational monitoring.  The ability of researchers to generate interesting new data sets and ideas continues to overmatch the resources available for testing them in an operational or quasi-operational setting. This is unfortunate both because using some of these products could immediately improve monitoring capabilities, and because feedback on the products could be used to guide further research.

To improve the situation, what is needed is a means to quickly develop realistic prototype software to test products. We believe that MatSeis offers one of the best, if not the best, platforms to do this.  MatSeis handles all of the data I/O with the standard CSS3.0 format, it provides a broad range of basic seismic analysis functions, and perhaps most

importantly, it runs on top of the well-vetted, powerful, flexible, commercial Matlab product. So far, we have used MatSeis as a base to develop a suite of 4 regional seismic analysis tools – Phase Match Tool, Codamag Tool, EventID Tool, and Dendro Tool – which are being used to evaluate some of the analysis methodologies and regional calibration products produced by the GNEM R&E program. We expect to expand the use of MatSeis in the future and develop other prototype tools, where appropriate, to help evaluate promising research products.

The basic MatSeis package is available to all as a data product on the GNEM R&E web site:
http://www.nemre.nn.doe.gov/nemre/

Matlab and the Signal Processing Toolbox are required to run MatSeis. Version 6.1 of Matlab or later is recommended, but the software should run with Matlab versions back as far as 5.3. MatSeis will run on Sun workstations, Windows PC's, and Linux PC's. It should run on other platforms as well, but the C code will need to be re-compiled.

## ACKNOWLEDGEMENTS

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