SAC2000: Signal Processing and Analysis Tools for Seismologists and Engineers

Peter Goldstein, Doug Dodge, and Mike Firpo, Lee Minner
Lawrence Livermore National Laboratory

Abstract

SAC2000 or SAC, as many users refer to it, is a primary signal processing and analysis tool for a large portion of the international seismological research and engineering communities including academic, government, and business institutions. SAC has extensive, well-documented, well-tested, and well-maintained data processing and analysis capabilities, a macro programming language which allows users to develop new analysis techniques and customized processing programs, and the ability to do both batch and interactive processing. SAC's Strengths also include the ability to process a diverse range of data types. Its extensive usage (> 400 institutions worldwide) has made it much easier for researchers to develop collaborative research projects. SAC is relatively easy to use and is available on a variety of hardware platforms. Part of its popularity is due to its user oriented development philosophy, which has led to consistent, backward compatible development, guided by users input and needs.

We present a brief overview of the fundamental features of SAC2000 and discuss some recent enhancements that make it a much more powerful tool for seismic analysis. These new features range from I/O enhancements to significant new processing capabilities and include a number of features that significantly increase user efficiency and productivity. Documentation is also a strength of SAC with detailed manuals available through SAC's help facility and the world wide web at http://www.llnl.gov/sac. Future plans for SAC involve selected upgrades and re-engineering with object oriented development techniques to provide more flexible and efficient tools for the analysis of large databases or distributed data sets.

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Introduction

SAC2000 or SAC, as many users refer to it, has long been a primary signal processing and analysis tool for a large portion of the international seismological research and engineering communities including academic, government, and business institutions. SAC has attained this popularity for a variety of reasons. Foremost, are its extensive, well-documented, well-tested, and well-maintained data processing and analysis capabilities, its macro programming language which allows users to develop new analysis techniques and customized processing programs, and its ability to do both batch and interactive processing. SAC's Strengths also include its ability to process a diverse range of data types and its extensive usage (> 400 institutions worldwide) which has made it much easier for researchers to develop collaborative research projects. SAC is relatively easy to use and is available on a variety of hardware platforms. Much of its popularity is probably due to its user oriented development philosophy, which has led to consistent, backward compatible development, guided by users input and needs.

Development of SAC2000 began in 1993 as a follow-on to the development of the original Seismic Analysis Code (SAC) (Tull, 1987; Tapley and Tull, 1992). Motivation for this development included the recognition that existing tools could not handle the anticipated amount of readily available seismic data, the desire to improve processing and analysis capabilities by taking advantage of state of the art seismological and computational techniques, and the need to improve upon the efficiency, memory utilization, and portability of the existing tools (Goldstein and Minner, 1995; Goldstein *et al.,* 1998). To accomplish these goals the original 100,000+ line SAC code was translated from FORTRAN to C and significant additions, modification, and improvements have been made to address development needs. The original FORTRAN code is included as part of the handbook distribution. Primary support for this development has been through the Department of Energy and Lawrence Livermore National Laboratory's treaty monitoring program with significant collaboration with the seismic research community. A primary development goals for SAC2000 has been to meet the seismic signal processing and analysis needs of the DOE treaty monitoring R&D teams and the rest of the treaty monitoring R&D community.

SAC2000 is currently available on a variety of hardware platforms using the Unix or Linux operating systems. These include Sun Solaris, PC and MAC Linux, Compaq/Dec Alpha, IBM RS6000, and SGI. Access to SAC2000 can be obtained by contacting Peter Goldstein via email at (peterg@llnl.gov).

Overview

SAC2000's extensive signal processing capabilities include: data inspection, signal correction, and quality control, unary and binary data operations, travel-time analysis, spectral analysis including high-resolution spectral estimation, spectrograms and binary sonograms, and array and three-component analysis (Figure 1). These capabilities have proved useful for solving a number of geophysical problems including, estimation and analysis of strong ground motions, earthquake, explosion, volcanic source studies, seismic discrimination and identification studies, magnitude estimation, travel-time analysis, studies of wave propagation phenomena such as path and site effects, and investigations of Earth structure. It has also proved useful for analysis of other geophysical data such as measurements of electromagnetic or hydro-acoustic phenomena. Table 1 summarizes some of SAC's processing capabilities. More detailed descriptions of SAC's capabilities can be found in the introduction and tutorial sections of the help and web pages.

Table 1. Typical processing capabilities available with SAC.

Capability	Operation
File I/O	Extensive read and write capabilities with a variety of formats including: SAC, CSS3.0, GSE2.0, PC SUDS, SEGY, and ASCII text
Spectral analysis	Flexible/customizable filtering, spectral estimation, spectrograms, auto and cross correlation, Wiener filtering, Hilbert transforms, phase unwrapping, filter design
Binary operations	File addition, subtraction, multiplication, rectification, trace rotation
Signal correction	Instrument response removal and convolution, glitch removal, interpolation, smoothing
Event analysis	Automated and interactive picking, particle motion analysis, phase identification, Map making through an interface to GMT
Array analysis	Frequency-wavenumber analysis, record section plotting with travel time overlays
Modeling	Trace overlaying, travel time calculations, source function generation, and convolution
Macro capabilities	Interactive development of macros and batch processing scripts, compatibility with MATLAB,

Recent Developments

Over the last few years, our focus has been on enhancing SAC's ability to process large data sets and combine and utilize data and results from a variety of tools and data sources. We have also incorporated a number of processing and analysis tools such as more powerful TRANSFER, TRAVELTIME, and 3-component processing capabilities and an interface to MATLAB. A few selected features are described below and summaries of some of these new capabilities are given in Table 2 through 6.

Table 2. Recent additions to SAC's processing and analysis capabilities. Additional details are also available in the HELP facility built into SAC.

TRANSFER FROM EVALRESP	Utilizes Tom McSweeney's evalresp library to correct for instrument response
TRANSFER FROM FAP	Utilizes a frequency/amplitude/phase (FAP) file to correct for instrument response
TRANSFER FROM DBASE	Finds an evalresp, fap, or polezero file from an Oracle database

	to correct for instrument response
TRAVELTIME TAUP	Reads traveltime curves produced by TauP (Crotwell et. al. 1998)
TRAVELTIME PICKS	Stores arrival information in T0 - T9 headers
WHITEN	Applies a linear filter to the input signal to "whiten" or "flatten" the signal's spectrum
FILTERDESIGN FILE	Saves the responses from FILTERDESIGN to a set of SAC files for analysis
GMTMAP/MAP	Mapping display using Generic Mapping Tool
3C	MATLAB based three component analysis tool
MAT	A general interface between MATLAB and SAC

TRANSFER

SAC's TRANSFER command has long been used to remove instrument responses from waveform data. Three new options make it a much more flexible and powerful tool for working with modern waveform data.

The EVALRESP option enables the user to apply transfer functions extracted from SEED data volumes using the evresp code (Version 3.2.11) by Thomas J. McSweeney. The RESP files can be in the current directory or can be specified by full path and name. By default, the EVALRESP option uses the STATION-CHANNEL-NETWORK-DATE-TIME information in the SAC headers to identify the correct RESP file and extract the proper transfer function from that file. However, it is possible to override this default and use any RESP file by specifying additional options to TRANSFER.

The FAP option uses instrument response information from a frequency-amplitude-phase (FAP) file in the standard format used at the Center for Monitoring Research (pIDC). FAP files have five columns: frequency, amplitude, phase, amplitude error, and phase error.

The DBASE option searches an Oracle™ database for the applicable instrument response file, which can be of type EVALRESP, POLEZERO, or FAP. The file found is used in the calculations of the TRANSFER command. Note: In order to use the DBASE option, the user must have access to an Oracle™ database with links to the applicable files, the database must be formatted as described in the HELP TRANSFER documentation, and the user must have the Oracle™ version of SAC2000.

TRAVELTIME

Traveltime modeling capabilities were introduced into SAC a few years ago and have been undergoing sporadic development since that time. The main features of this command allow a user to compute traveltimes for a large variety of phases, for the source receiver configurations of the data in memory, plot these traveltime with the data, overlay traveltime curves on the data, and store the traveltimes in the waveform headers. The most recent developments take advantage of new one-dimensional traveltime modeling capabilities developed by Crotwell et al., (1999) and allow a user to generate traveltime curves for arbitrary spherically symetric earth models. It is also possible to read traveltime curves from a text file and overlay them on the data.

MATLAB Three-Component Data Analysis Tool

Although SAC has had particle motion analysis capabilities for some time, this feature has been limited to the simultaneous analysis of two components and produced limited quantitative results. We have developed a new, MATLAB-based tool for interactive and batch mode analysis of 3-component seismic data. This tool will improve a user's ability to detect and identify seismic phases, especially secondary phases. It has also helped us process data and identify problems with data such as incorrect sensor orientation information.

This tool has a number of capabilities including: graphical data selection and filter design, automatic back-azimuth and incidence angle estimation, interactive, graphical, three-component particle motion analysis, and maximum-likelihood probability estimates of selected wavetypes (Christoffersson et al., 1988).

Figure 2 displays a selected example of the interactive version of this three-component data analysis tool. Interactive data/window selection, phase picking and signal rotations are done in the main window. Popup windows are used to: filter the data (no windows shown), interactively analyze particle motions (Particle motion module), and compute maximum-likelihood probabilities for selected wavetypes (ML-polarization analysis module).

I/O

SAC I/O capabilities have been enhanced significantly by significantly expanding and improving the underlying data structure and data management module. SAC now has two parallel internal data buffers: the original buffer which houses the data in traditional SAC format, and a second buffer which stores the data in CSS 3.0 tables. As needed, SAC2000 can seamlessly move the data between the two buffers, allowing fully compliant CSS 3.0 reading and writing capability. This new data management module also allows users to access data in a CSS 3.0 schema Oracle™ database and a number of other relational and non-relational data formats (see Table 3).

Table 3. Recent Additions to SAC’s I/O Capabilities.

READCSS/WRITECSS	Complete CSS 3.0 compliance; reads and writes both CSS 3.0 flat files, and a CSS 3.0 binary formats
READDB	Access CSS 3.0 data from an Oracle database
READGSE/WRITEGSE	GSE 2.0 I/O
READSUDS	Reads PC SUDS with automatic byte conversion
READ SEGY	Reads IRIS/PASSCAL version of SEGY files
READ ALPHA	Reads SAC formatted Alpha files (replaces CONVERT)
READTABLE	This is the old READALPHA command, renamed to avoid confusion with READ ALPHA

ADDED CONVENIENCE

A number of recent enhancements have been made to improve user efficiency and productivity. Examples include a SORT command for sorting traces based on header variables such as distance or magnitude, a command called CUTIM which cuts data in memory instead of requiring the user to specify a cut window before reading the data, a DELETECHANNEL command which allows user to eliminate selected channels from data in memory, and a history command for reviewing recently executed commands. A summary of these and additional commands is given in Tables 4.

Table 4. Recent ease-of-use enhancements.

SORT	Sort files based on header values
CUTIM	Cut files in memory, can make multiple cuts
PRINTHLP	Prints the specified HELP file
PRINT option	An option to most plotting command, sends plot to printer
PRINT command	Prints the most recent SGF file
SGF OVERWRITE	Allows SGF files to over-write previous SGF files
DELETECHANNEL	Removes specified files from memory
FILENUMBER	Tags most plots with file numbers, for use with DELETECHANNEL
PICKAUTHOR	Specifies preferred authors when reading picks from CSS data
PICKPHASE	Specifies preferred phases when reading picks from CSS data
MERGE	MERGE can now merge overlapping files
HISTORY	View prior SAC commands. Reissue commands with ! or !! (as in UNIX)
maximum file number	SAC can now hold 1000 files in memory

Three new commands (Table 5) called ROLLBACK, RECALLTRACE, and COMMIT enhance user efficiency by allowing the user to undo changes to data (ROLLBACK), save selected header variables that have been modified during processing with the unprocessed waveform (RECALLTRACE) and constrain future ROLLBACK commands to return to the current state of the data (COMMIT).

Table 5. Process Management Commands

COMMIT	Protect changes from being undone with ROLLBACK or REACALLTRACE
ROLLBACK	Undo changes since last COMMIT
RECALLTRACE	Commit the header, rollback the waveform

INCORPORATING YOUR OWN CODE

Table 6 summarizes features which allow the user to incorporate code into SAC, or to read and write SAC data files from his/her own code. Detailed descriptions of how to use these features are available in the EXTERNAL_INTERFACE, LOAD, INPUT_OUTPUT, BLACKBOARD, and APPENDIX help and web pages.

Table 6. Software Interface Enhancements

command interface	Allows users to write commands in C or FORTRAN and add them to SAC
sacio.a	A library with SAC's I/O routines callable from stand-alone FORTRAN or C programs

Future Work

Future plans for SAC include continued maintenance and selected upgrades while simultaneous collaborations with the seismic community are undertaken to re-engineer SAC as an object oriented program with an interface that will give programmers direct access to SAC's methods. The programming interface will allow SAC to be used as a "seismological compute engine" from within other programs. Users will be able to develop analysis systems within SAC using its macro processing capabilities, and then implement "production" versions of the systems through the programming interface. The goal of such a re-engineering is to provide more flexible and efficient tools for the analysis of large databases or distributed data sets.

Examples of selected upgrades include incorporation of a Coda magnitude command, incorporation of the high resolution spectral estimation subprocess commands with the main body of the code, enhancements to our interface to the GMT mapping tools (Wessel and Smith, 1991), and new array analysis capabilities. When feasible we will also continue work to make SAC more compatible with other data formats (currently supported formats include, CSS3.0, GSE2.0, PC suds, SEGY, and ASCII text) and tools such as MATLAB (www.mathworks.com) and the TauP toolkit (Crotwell et al., 1999).

Conclusions

SAC2000 is a fundamental signal processing and analysis tool for much of the seismological community. Its extensive signal processing and analysis capabilities allow researchers to address a variety of problems in number of fields including earthquake engineering volcano seismology, test ban monitoring R&D and earth structure studies. Recent and future developments in SAC will attempt to address the challenges presented by significant increases in the amount of available data, the opportunity or need to access and use databases or distributed data sets, and the potential for more efficient development of seismic analysis tools through the use of state-of-the-art software development tools and collaborations on the development of new software and re-engineering reuse of existing software. We welcome feedback on the existing version of SAC and proposed developments.

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