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Spectroscopic Binary Solver

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Abstract

Spectroscopic Binary Solver is a Microsoft Visual Basic® software application used to determine the orbital parameters of a binary star system based on observed radial velocities. SBS is an interactive process facilitated by the use of real-time graphical controls and data presentation, as opposed to a computer solution that simply produces a numerical output. This paper describes the software functions, and is accompanied by an installer and example data for various case studies.

1 Introduction

Spectroscopic Binary Solver (hereafter referred to as SBS) is a Microsoft Visual Basic® software application used to determine the orbital parameters of a binary star system based on observed radial velocities. SBS is an interactive process facilitated by the use of real-time graphical controls and data presentation, as opposed to a computer solution that simply produces a numerical output. SBS begins by reading in a text file containing observed radial velocities of either one or both stars (single-line or double-line data sets) of a binary system and ultimately estimates the spectroscopic orbital parameters relevant to Eq. 1 (Lehmann-Filhés 1894).

$$V_{\mathrm{rad}} = K\left[\cos\left(\nu+\omega\right)+e\cos\left(\omega\right)\right]+\gamma \qquad (1)$$

where

V_{rad} = observed radial velocity
K = semi-amplitude
e = eccentricity
ω = longitude of periastron
ν = true anomaly
γ = systemic velocity

2 Starting SBS

SBS.exe is launched by the usual clicking of the mouse on the appropriate Windows® Start menu item or desktop icon. The user is presented with an initial view similar to that shown in Fig. 1 (less the plotted data). The user executes the primary functions via a column of command buttons located in the upper right quadrant. SBS sessions typically involve a progression through the Read File, Period, Solve and Error Est. command buttons. The upper left quadrant of the application windows contains slider bars which enable to user to modify the orbital parameters so as to manually fit a calculated phase-velocity curve to the observation data. Various check boxes to the right of the slider bars allow the user to assume fixed parameter values, to assume the special case of circular orbits, or to allow the systemic velocities (gamma velocities) to vary independently for unusual double-line data sets. Adjacent to the check boxes are the text boxes that display the current value of each orbital parameter. A vertical root mean square (RMS) goodness-of-fit progress bar is located to the upper right.

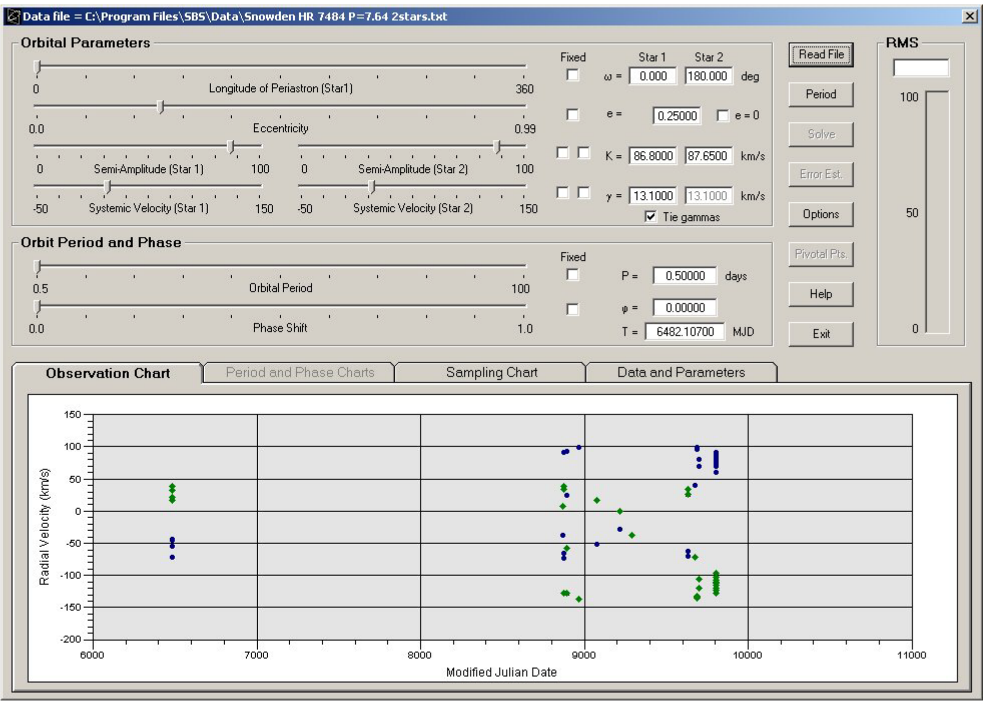

Figure 1: Charted double-line observation data.

The lower portion of the application window contains four tabbed panes containing the observation chart, period and phase charts, sampling chart, observation data list and parameter summary. The observation chart is a simple chart of the raw observation data values. The sampling chart presents a periodogram of the sampling intervals. The period and phase charts provide for real-time visual feedback to the user during the orbit solution process. The fourth tabbed pane contains a list of the observation data and display of the final parameter summary report. The parameter summary is also automatically saved as the text file *report.txt* in the SBS application directory.

3 Reading in the data

The user begins the analysis by clicking on the *Read File* button to select a PC-format data text file containing up to 1000 radial velocity observations per star. Each line of data must consist of an observation time (in decimal days) and a measured radial velocity (in km/s or m/s) separated by either spaces or tabs. The data file may include a velocity error estimate after the velocity value (without the '±' symbol) for plotting purposes only. SBS will indicate any provided velocity error with error bars on the observation and phase charts, however, the lack of user-supplied error estimates will not affect the final solution as SBS fits the data to the orbit model with even weighting. SBS assumes that the random errors associated with observation times are insignificant for all practical purposes. For the case of double-line systems (both stars observed) the data must be separated into two blocks. The second data block must be preceded by a line consisting of the label *STAR2*. A *STAR1* label is optional for the first data block. Data text lines that begin with an apostrophe (') or an asterisk (*) will be ignored as comments. Blank lines are ignored. Including a line consisting of the label m/s will change the velocity units from km/s to m/s for that data set only.

The observed radial velocities are plotted against time of observation on the observation chart as shown in Fig. 1. Double-line data sets are differentiated by the shape and color of the plotted points. The observation chart also displays a cyclic phase curve overlay per the current orbital parameters (after the initial orbital period determination) if the data spans fewer than 50 period cycles. Example data sets gleaned from the literature from previously published radial velocity studies by Cesco & Struve (1946), Franklin (1952), Marcy *et al.* (1997), Popper (1989), Rauw & Vreux (1999), and Snowden & Koch(1969) are included with the SBS software in the *data* subdirectory. The user may view these example data files with a text editor in order to clarify the data file format requirements.

The user may elect to exclude data from orbit analysis by clicking on individual data points with either mouse button. The will cause the plotted symbol to change from solid to unfilled and the listing in the data list to be labeled as being excluded. The user may click again to include the data point. Data may also be excluded/included by double-clicking on the appropriate row in the data list. The user is cautioned to exercise good judgment when excluding any data. It must be understood that the phase chart cannot be used to identify outliers unless the true orbital period has been selected. Likewise, if the exclusion of a small portion of the data points results in a significantly different solution then one must conclude that the data set is of poor quality and the results suspect.

4 Period search

The first and most critical analytical step is to determine the correct orbital period using any of the three period determination algorithms provided by SBS: the normalized periodogram method (Lomb 1976, Scargle 1982), the string length minimization method (Dworetsky 1983) and the phase dispersion minimization method (Marraco & Muzzio 1980). The minimum valid trial period must be at least twice as large as the smallest observation interval, and the maximum trial period should be no larger than the total time span of all observations (Hilditch 2001). These theoretical extents often extend beyond what can be reliably searched in a single scan, and so default period search extents are used to initially limit the theoretical period search range to a more practical range. The period chart plots a series of trial search periods against a calculated discriminant factor which indicates the best fit orbit period with either a minimum or a maximum depending on the period search algorithm. The period chart indicates the current period value as well as any user-selected period alias effects as solid (actual period) and dashed (alias periods) vertical bars as shown in Fig. 2. The user may qualitatively evaluate the selected period value by visually inspecting the dispersion of the plotted observation data on the phase chart.

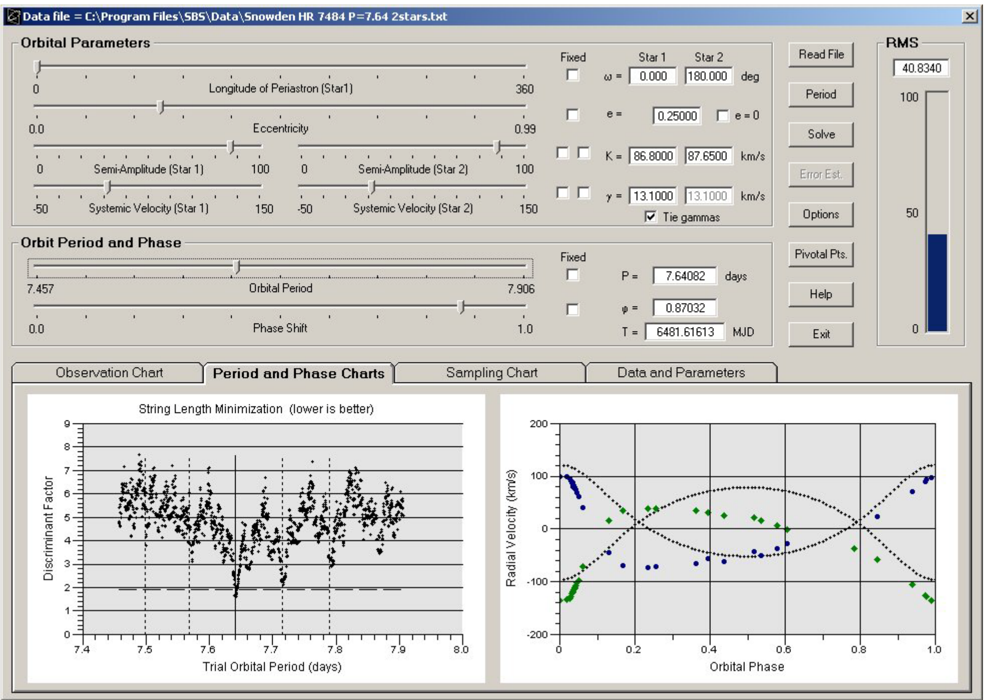

Figure 2: Identifying the orbital period.

SBS uses between 1,000 and 4,000 trial period steps when searching for the orbital period. A logarithmic stepping scheme is utilized to scale the step sizes period value such that smaller steps are used at the lower end of the period search. The user is advised not to search over more than two orders of magnitude in a single scan as the true period may not be indicated if it falls within a large trial interval. As an example, it is generally better to begin with a period search from 1 to 100 days rather than from 0.01 to 100 days as the latter range will increase the trial step sizes for the larger period values. SBS will automatically select the most likely period search value as the current period value and indicate the selected period with a vertical bar on the period chart.

The initial period search will probably not identify the true period either because the trial period steps were too coarse or because the actual period was outside of the period search range. To improve trial period resolution one must narrow the search extents by clicking either mouse button first on the desired low and then again on the desired high period search value anywhere on the period chart. Double-click with either mouse button on the period chart to restore the default period search extents. The period search extents may also be set in the Options dialog window. The user may vary the period manually by moving the period slider. The period slider action will be smoother and less chaotic when a narrow period range is plotted on the period chart. A good estimate of an orbital period is shown below Fig. 2. Note that the remaining orbital parameters in Fig. 2 have yet to be determined.

The user should be aware of period aliases and harmonics. Aliases are an artifact of repeated intervals in the observation data and can fool the user into accepting a false solution as an alias can appear to be legitimate solutions in the phase chart. Harmonics can appear as higher order period solutions on the period chart but rarely cause a problem as harmonics are readily identifiable in the phase chart. The sampling chart is a periodogram of the data sampling rate, rather than the velocity values, which allows the user to understand and identify potential period alias effects associated with sampling intervals. Common unintentional observation sampling intervals are one sidereal day, one lunar month and one year. The user may modify the sampling chart time axis as with period chart in order to search for potential alias effects. Figure 3 indicates a possible alias effect associated with a sampling interval of about 800 days. This sampling interval can be seen between some of the data groups in the observation chart of Fig. 1. The vertical dashed lines in the period chart of Fig. 2, which were calculated based on the current period and an 800 day alias effect, clearly indicate the false alias minima.

The pivotal points routine is an optional analysis tool which identifies data points that unduly effect the result of the period search. Such pivotal points should be examined (via temporary exclusion) to ensure that they are not driving the model toward an erroneous solution. The pivotal points routine operates by removing and replacing one data point at a time and then recalculating the best period using the normalized periodogram method. The normalized periodogram method is used because it is quick and the results tend to be affected to a greater extent by outliers than the dispersion methods. The absolute change in best fit period is calculated per excluded data point and then presented to the user in a sorted list. The user may then elect to discard data points with significantly large period effects and run

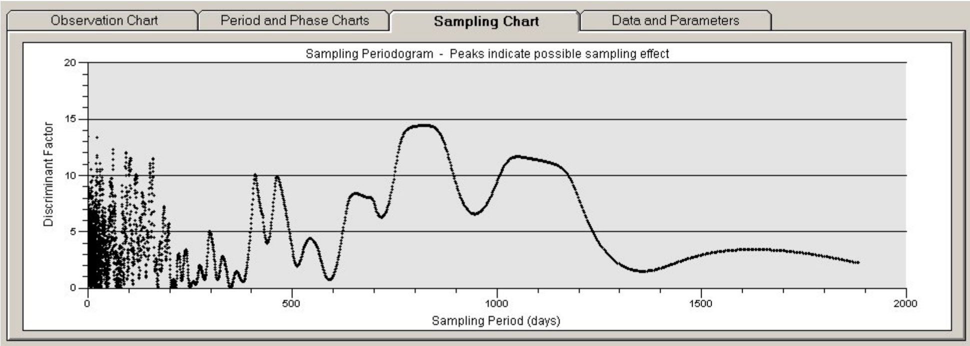

Figure 3: Observation sampling periodogram.

a new period search. The pivotal point routine works best when zoomed in to a narrow period search range so as to maximize resolution in the period searches and also to minimize the number of trial periods to be searched and thus speed up the computations. It should be made clear that a pivotal point may or may not be a statistical outlier; it may have a strong effect simply due to the sampling history. Actual outliers are easily identified by inspecting the phase chart after the correct period has been determined.

5 Determination of the orbital parameters

Once the orbital period has been determined the user then proceeds on to determine the remaining orbital parameters. The GUI slider, checkbox, and textbox controls allow the user to interactively converge upon the orbital solution. This is done primarily by adjusting the various parameter value sliders and observing the effect on the calculated phase curve fit. Such slider movements will result in a real time update of the phase chart as well as the overall goodness-of-fit root mean square (RMS) progress bar. Use the *Options* dialog to change the extents of systemic velocity, semi-amplitude and period if necessary to either expand the range or increase the resolution (using a smaller range) of the parameter sliders. Any orbital period adjustments subsequent to the period determination should be very small and the period slider range narrow enough to clearly resolve the period search maximum or minimum. The period can be automatically reset to the best period search result by clicking on the *Period* command button. The phase chart plots the observed radial velocity data (large symbols) as well as a fitted curve (small dots) against orbit phase per the current orbital parameter values. The fitted curve is always plotted with periastron at zero phase.

Moving the upper *Orbit Parameters* sliders will alter the fitted phase curve in the phase chart. Conversely, moving the lower *Orbit Period and Phase* sliders will replot the observed velocity data in the phase chart. The use of a phase shift GUI control rather than a time of periastron control avoids complications in the user interface which have to do with the dependency of time of periastron on orbital period and/or assumed circular orbits. The displayed time of periastron value will only be correct when the observation data and calculated fitted phase curve converge.

The user may directly set a parameter value by typing the value into the text boxes followed by either pressing the *Enter* key on the keyboard or clicking on the appropriate *Fixed* check box. Values typed directly into the text boxes may be beyond the current range of the associated slider control as long as the new parameter values are valid. The sliders will automatically rescale to accommodate new parameter values. Period and semi-amplitude values must be positive, longitude of periastron must be between 0 and 360 degrees, phase must be between 0 and 1, and eccentricity must be between 0.0 and 0.99. The user may not directly edit the time of periastron value as this is calculated from the orbital period and phase values.

A vertical root mean square (RMS) goodness-of-fit bar is located to the upper right of the application window along with a displayed numerical value calculated as shown in Eq. 2.

$$RMS = \sqrt{\frac{\sum (V_{\text{obs}} - V_{\text{calc}})^2}{(N-1)}} \tag{2}$$

The best fit is achieved when the calculated RMS value is minimized. The progress bar will rescale in real time as the orbital parameters are fitted to the observation data. One convergence strategy is to simply watch the goodness-of-fit RMS bar while manipulating each slider control in turn. A few iterations will often produce a reasonably good fit to the observed radial velocity data.

The user may assume a circular orbit by selecting the $e = 0$ check box. In the case of an assumed circular orbit the eccentricity and longitude of periastron are fixed at zero and the respective sliders disabled. A fictitious periastron is set to coincide with the maximum velocity value at zero phase as is often the convention for a circular orbit. The remaining orbital parameters for an assumed circular orbit are then determined as for a noncircular orbit.

For the case of a double-line system where radial velocities are measured for both stars of a binary system one needs to solve for additional orbital parameters. Though two stars are designated as *STAR1* and *STAR2* by the user in the data set, SBS does not make any formal distinction between primary and secondary stars. The longitude of periastron of the second star, ω_2, is automatically maintained at exactly 180 degrees out of phase with the longitude of periastron of the first star, ω_1. The semi-amplitudes K_1 and K_2, on the other hand, do vary independently from each other. The systemic velocities, or gamma velocities, are normally the same for both stars but may be allowed to vary independently by unselecting the *Tie gammas* check box. This is sometimes necessary due to circumstances such as mass transfer and stellar winds which can offset radial velocity observations for one of the two stars of a given system. Selecting the *Tie gammas* check box forces the systemic velocities values and slider positions to remain synchronized. An example of a double-line parameter fit is shown in Fig. 4.

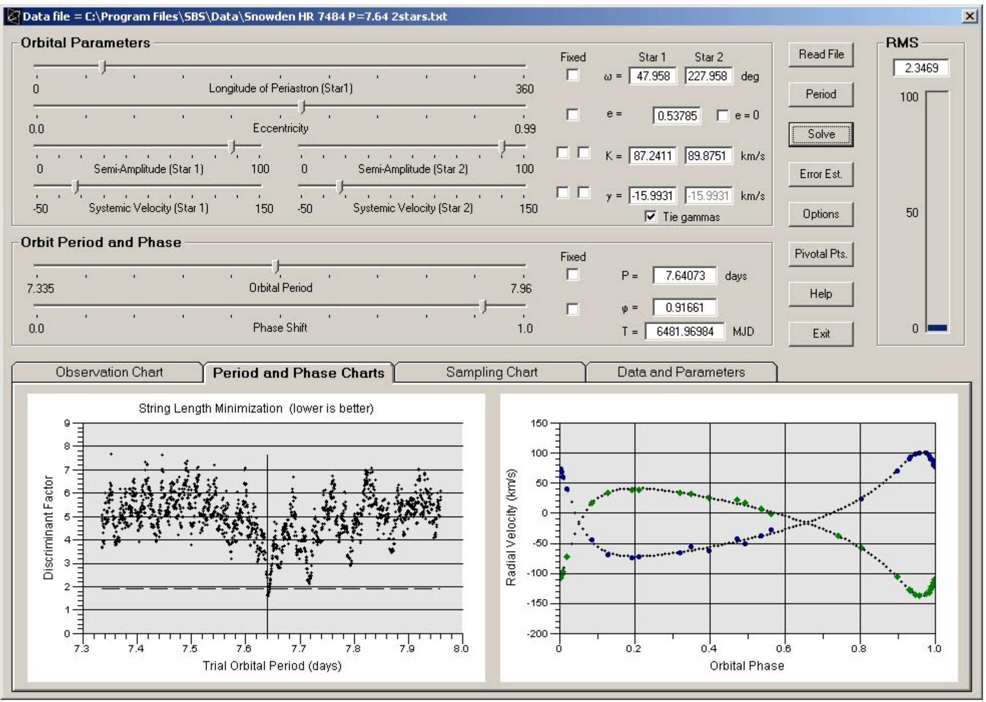

Figure 4: Orbital parameters fitted to the observation data.

6 Downhill Simplex solver

Clicking on the *Solve* button instructs SBS to automatically solve for the orbital parameters via the Downhill Simplex method. The Downhill Simplex, developed by Nelder & Mead (1965), is a purely numerical minimization algorithm that searches for the minimum of a function without requiring any knowledge of parameter space gradients. The simplex calculates a minimization function and numerically crawls through the parameter space searching for a global minimum. Unlike some of the gradient-based algorithms, the Downhill Simplex is stable and will not diverge to a solution that is worse than the initial parameter set. A disadvantage of the Downhill Simplex is that it generally requires a large number of iterations. For the case of SBS the function to be minimized is the calculated phase chart goodness-of-fit RMS value displayed in the upper right corner of the application window. The solver will automatically terminate after 2,000 iterations, which is usually sufficient to drive reasonable initial parameter values to a good orbit solution.

The period must be close to the true value in order for the automatic solver to work. It is also best if eccentricity is not set to an extreme value prior to initiating the Downhill Simplex solver (unless the orbit is circular). On occasion the solver will either get stuck in a local minimum or be trapped by a physical boundary (usually eccentricity limits), in which case the user needs to restart the solver for a different set of initial parameter values. The user may elect to restrain the solver to fixed parameter values by selecting the appropriate check boxes located to the right of the sliders.

7 Parameter errors

Clicking on the *Error Est.* button will generate a parameter summary report as shown as Fig. 5. Errors for the primary parameters (ω, e, K, γ, P, ϕ) are estimated by deviating each parameter in turn and solving the model for a given deviated parameter such that chi squared is increased by one. The estimation of errors is only meaningful after SBS has converged to an orbit parameter solution as the error estimation routine does not attempt to improve the parameter fit. A base chi squared value representing the nominal parameter fit , shown in Eq. 3, is adjusted by assuming a single representative value for all velocity standard deviations σ_i such that the chi squared value equals N-1 (Press *et al.* 1992).

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{V_{i,\mathrm{obs}} - V_{i,\mathrm{calc}}}{\sigma_i} \right)^2 \tag{3}$$

The required parameter deviation is initially unknown and so trial and error is employed in an attempt to increase the chi squared value by 0.5 to 5, and then a parabola fit is used to estimate the chi squared plus one deviation. This is done separately for plus and minus deviations. Parameter errors are indicated as zero for fixed parameters and also when SBS failed to calculate a meaningful chi squared deviation. One possible reason for an error estimate failure is the case where the solution was not fully converged prior to estimating parameter errors. Error estimate failures can also be attributed to the ambiguities associated with near-circular orbits, in which case it is suggested that the user assume a circular orbit. A single plus/minus error is propagated for the derived values (T, $a \sin(i)$, $f(m)$). Phase ϕ is not shown in the parameter summary.

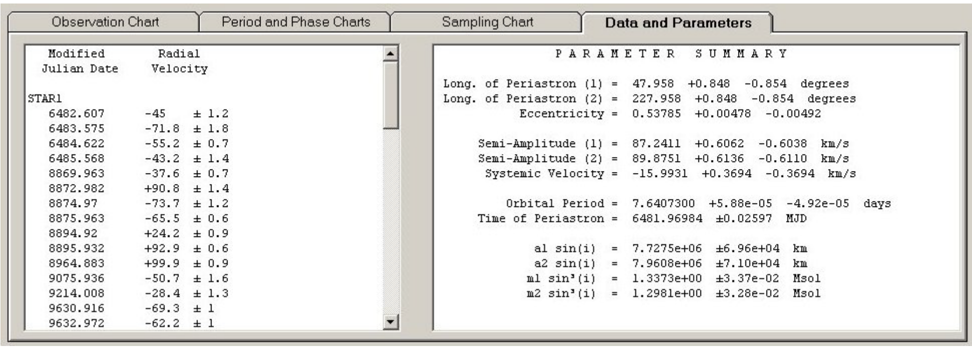

Figure 5: Parameter summary for a double-line data set.

8 Options dialog

The *Options* dialog window allows the user to specify the period search extents, select the desired period search algorithm, specify the number of bins and smoothing for the phase dispersion minimization period search method. The user may also specify the sampling chart, systemic velocity and semi-amplitude extents and specify the velocity units. Finally, the user may select alias effects to be indicated on the period chart. These options may be used for the current session only by clicking on the *Apply* button or used and saved for subsequent SBS sessions by clicking on the *Save* button. These saved options are written to a text file in the SBS application directory and will become the default values for the next SBS session, except that km/s will always be the default units of velocity. SBS will use programmed default option values if the options text file is not present. The *Options* dialog window is shown as Fig. 6.

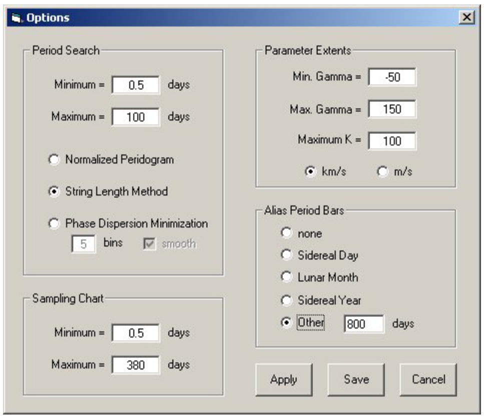

Figure 6: SBS user options.

The initial period search will range from the greater of either twice the minimum sampling interval or the default period search minimum, extending to the lesser of either the total data time span or the default period search maximum. The *Options* button remains inactive until SBS reads in the data file due to the dependency of the period search extents on the observation data. After reading in the data file, the user is able alter the period search extents through the *Options* dialog. The programmed default period search extents are somewhat arbitrarily programmed as 1 to 100 days, however, the user may redefine the default period search extents for subsequent SBS sessions by clicking on the *Save* button in the *Options* dialog window.

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