CRUST – Climatic Research Unit Standardisation Program Documentation

1. Background

Standardisation of tree-ring measurements can be a complicated process and users of this program should have background knowledge of the different methods that can be selected and the reasons and potential limitations that are associated with that selection. For general background we recommend Fritts (1976), Cook and Kairiukstis (1990) and information available from http://web.utk.edu/~grissino/index.htm. Further background of Regional Chronology Standardisation (RCS) is in Melvin (2004) and Briffa and Melvin (2011). The primary reference to the CRUST program is the Part 1 paper (Melvin and Briffa 2013a) with further details given in Part 2 (Melvin and Briffa 2013b *in preparation*).

The CRUST program is designed to enable a user to standardise tree-ring measurements using different implementations of RCS, particularly the "signal-free" variant (SF RCS). The more traditional "curve-fitting" standardisation methods are also incorporated as options. The CRUST program has a graphical interface, accessed via a mouse controlled menu system which allows the user to experiment with various options. There is a "batch" processing option where the user creates a file containing file names and parameters and invokes the program to process these creating output files containing chronologies. Currently the program is compiled using GFORTRAN open source compiler and DISLIN graphics on Linux (or Windows). It will compile and run on MacOS but implementing this is as yet incomplete. The program was inspired by ARSTAN (Cook 1985) and much of the "non-RCS" code is based on that in ARSTAN.

2. Using the program

The program reads and writes ASCII text files. Input files must conform to one of a number of fixed formats. These files can be created and amended using simple editors such as GEDIT (or Wordpad). Many options create a general report of progress which is saved as a report to file "zzz.prn".

The program reads several files which need to be available in the directory from which the program is run. The measurement data file list "ars.fil" must be present and must

contain a list (at least one) of the names of measurement data files (in Tucson, Heidelberg or compact formats). The maximum file name length is 60 characters, including directory names. Note that file names in Linux are case sensitive while in Windows they are not. Help messages (accessed by clicking the right mouse button at appropriate places) are contained in the "help.prn" file. The help file consists of a sequence of messages (sorted by menu number) with a header line consisting of a 2 digit menu number, a 4 digit button box number, a 4 digit message number, and a 4 digit count of the number of 80-character lines of text following the header. Default detrend parameters are read in from "RCSdefault.fil" and used for processing the first measurement-data file. The user can reset and save the default parameters or can directly edit the parameter file.

2.1 Running CRUST

Double click on "CRUST" (or "CRUST.exe"). The program should start by opening an initial menu screen with various messages and button boxes to click. If the program fails to run using the mouse, try running the program using the "TERMINAL" (or "DOS") mode which will preserve error messages (if any) sent by the operating system and might indicate the problem.

2.2 Status at the top left a status box will indicate what the program is doing/waiting for with options "Click Mouse", "Input Integer", "Input Real", "Input name" or "Running". When inputting an integer or real number numeric characters (or minus or decimal point) are required while an input name requires 3 or more characters. Input is terminated by entering the return character (or by the program when the character limit is reached). If you make an error (or the program thinks you entered an invalid name or a number outside the allowable range) the program will ignore your entry. If you enter an incorrect value, press return and try again; keys, such as backspace, will not work during character/number entry.

2.3 Mouse the x-y address of the mouse when clicked (left or right) controls which action has been selected. Mouse button clicks outside valid boxes may be ignored. The right mouse is used solely for help messages and selecting a button box or (in some cases clicking above an on-screen message) will cause an appropriate help message to be displayed. Left mouse clicks outside the button boxes are ignored. Selecting (by left mouse click) a button box will trigger the appropriate action e.g. select a sub-menu,

toggle the selected parameter to another value, or save data. Help messages (held in "help.prn") are currently written only in English but could easily be translated into another language.

3 Menu system

3.1 Start menu

3.1.1 File List Filename the default list of raw data files is expected to be held in the file "ars.fil". This button can be used to enter the name of an alternative file list e.g. "fred.fil". File lists can be created, using an editor or similar procedure (outside CRUST).

3.1.2 Current Data File displays the name of the currently selected raw data file (from the file list). Click on this button to use the select menu to pick an alternative raw data file and click exit to return.

3.1.3 Curve-fit detrend selects a menu of options to perform curve-fitting detrending.

3.1.4 RCS detrend selects the RCS detrending menu.

3.1.5 Reports/Figures menu selects a menu that can be used to produce various reports or figures.

3.1.6 Various other menus Some other menus to run processing specific to published or planned papers may be present.

3.1.7 Journal On/Off if the journal is "on" some of the intermediate data from detrending procedures is appended to the file "journal.prn" e.g. the number of signal-free iterations.

3.1.8 Quit leaves the program losing any generated data that has not been saved.

3.2 Curve-fitting detrend menu

3.2.1 Data File displays the name of the currently selected raw data file (from the file list). Click on this button to use the select menu to pick an alternative raw data file and click exit to return.

3.2.2 Current Tree displays the currently selected core/tree name. Click on this button to use the select menu to pick an alternative tree and click exit to return. The list from which selection is made is sequenced using the selected sorting method (see Sort Trees) and it may be necessary to page back or forward in the list.

3.2.3 **Previous** selects the previous tree (if there is one) using the selected sorted sequence.

3.2.4 **Next** selects the next tree (if there is one) using the selected sorted sequence.

3.2.5 **Sort Trees** displays the currently selected sort key for trees and selecting this option allows you to step through the allowable sorting options (i.e. by growth rate, tree name, pith year, last year, not sorted, tree age and tree final diameter).

3.2.6 **Ignore First** ignores the first few rings (number can be selected) of each core/tree in creating chronology. Uses pith offset estimates, if available, to assess ring age. Note some subsequent processes may fail if any tree is left with insufficient rings. Will only ignore up to a maximum of half of the rings in any tree.

3.2.7 **Quit** leaves detrending losing any generated data that has not been saved.

3.2.8 **Calc CRN** causes the chronology to be recalculated using the currently selected parameter values and overwriting the previously created chronology. This option should be selected after the chronology options have been changed. Highlighted in red when options have changed and chronology has not been recalculated.

3.2.9 **Save Data** invokes a sub-menu allowing various data produced in the calculation of the current chronology to be saved.

3.2.10 **Save Plot** saves the current figure as a postscript file "detrend.eps".

3.2.11 **Transform** selects either "No Transform", "Adaptive power" or "Basal Area". The adaptive power is that provided by the program ARSTAN (i.e. the code taken from ARSTAN, transform option 4). Selecting power transform will set Index Creation option to "Residuals". De-selecting power transform will set index creation option to "Ratios". Basal Area Increment is calculated presuming measurements are ring width and the tree is concentric prior and ideally requires pith offset estimates to be available.

3.2.12 **Pith Offset** selects either "PO on" or "PO off" to or ignore pith offset estimates (presuming they are available). Only relevant if using basal area increment, ignore first few rings, or some curve fitting e.g. Hugershoff curves.

3.2.13 **Index Creation** selects either "Ratios" or "Residuals" to create tree index series. Using ratios roughly corrects the problem of sample variance being proportional to the local mean for TRW and is consistent with the signal-free method. The use

of residuals generally requires some form of variance correction i.e. power transform. To use ratios with power transform, select the power transform option first (sets differences by default) and then select ratios.

3.2.14 Mean Chronology selects "Arithmetic" or "Robust" method of averaging to create chronologies. The robust mean procedure was taken from ARSTAN. Using robust mean can be an improvement where sample counts are between 10 and 20.

3.2.15 Signal-Free selects to use the Signal-Free method or not with an option to select the maximum number of iterations. Signal free method will remove the common signal from individual measurement series prior to fitting curves or creating RCS curves. This option is designed to allow convenient comparison of the effects of using the signal-free method. Its use with curve-fitting methods is recommended.

3.2.16 STD Chron provides options to generate "STD", "ARS" and "RES" chronologies as specified in ARSTAN. Implements a simplified form of the autoregressive options available in ARSTAN. The unadjusted (STD) option is default and recommended but the user can also select to produce the "ARS" or "RES" chronologies. The processing involved is applied to tree indices after all other processes (e.g. iterative signal-free methods) are completed.

3.2.17 Ratios CRN the default is "Ratios CRN". There is an experimental option "Normal CRN" to convert the values of tree indices so that they have a normal distribution prior to averaging to produce a chronology. This corrects the problem of tree-indices which are generated as fractional deviations having a skewed distribution (especially for RCS).

3.2.18 Variance stabilisation selects either "Var.Stab Off" or "Var.Stab On". The chronology variance stabilisation is based on the RBAR method (Osborn 1997, Dendrochronologia 15, 89-99). We recommend that variance stabilisation is used where core numbers are low. Note that RBAR used should be based on mean inter-tree correlations and generally works well when measurements series are "mean-tree" but this is not suitable for sparcely replicated parts of the chronology (<5 trees) and individual trees have multiple cores.

3.2.19 No detrend (idt=0) uses the measurement data without fitting a detrending curve thus creating a chronology of the mean of raw measurement data over time.

3.2.20 Exp/Any Line (idt=1) fits a modified negative exponential, or a straight line with any slope.

3.2.21 Exp/Neg Line (idt=2) fits a modified negative exponential, or a straight line with negative slope, or a horizontal line.

3.2.22 Sloping Line (idt=3) fits a straight line with any slope.

3.2.23 Neg Slope Line (idt=4) fits a straight line with a negative slope or a horizontal line.

3.2.24 Horiz Line (idt=5) fits a horizontal straight line, the mean of each series.

3.2.25 Hugershoff (idt=6) fits a Hugershoff curve, or a modified negative exponential, or a line with negative slope, or a horizontal line.

3.2.26 General Exp (idt=7) fits a general exponential curve, or a line with negative slope, or a horizontal line.

3.2.27 Spline 50% Var fits a smoothing spline with 50% amplitude reduction at the selected frequency. Specified as a positive value (idt is between 10 and 9999).

3.2.28 Spline 50% N fits a smoothing spline with 50% amplitude reduction set at a selected percentage of the series length. The percentage is specified as a negative number (idt lies between -3 and -999).

3.3 RCS Detrend Menu

3.3.1 Data File displays the name of the currently selected raw data file (from the file list). Click on this button to use the select menu to pick an alternative raw data file and click exit to return.

3.3.2 Sort Trees displays the currently selected sort key for trees and selecting this option allows you to step through the allowable sorting options (i.e. by growth rate, tree name, pith year, last year, not sorted, tree age and tree final diameter).

3.3.3 Ignore First ignores the first few rings (number can be selected) of each core/tree in creating chronology. Uses pith offset estimates, if available, to assess ring age. Note some subsequent processes may fail if any tree is left with insufficient rings. Will only ignore up to a maximum of half of the rings in any tree.

3.3.4 Quit leaves detrending losing any generated data that has not been saved.

3.3.5 Calc CRN causes the chronology to be recalculated using the currently selected parameter values and overwriting the previously created chronology. This option

should be selected after the chronology options have been changed. Highlighted in red when options have changed and chronology has not been recalculated.

3.3.6 **Save Data** invokes a sub-menu allowing various data produced in the calculation of the current chronology to be saved.

3.3.7 **Save Plot** saves the current figure as a postscript file "detrend.eps".

3.3.8 **Display Options** invokes a menu that allows the user to select various characteristics of the currently displayed figure (e.g. which lines to display, line types, line thickness or colours).

3.3.9 **Save Parameters** saves the currently selected parameter values and plot options to the RCS default file "RCSdefault.fil". These parameters will be used when the program is started (it is recommended that a backup copy of this file is retained).

3.3.10 **Select RCS menu** experimental - calls a menu allowing manual allocation of trees to RCS curves**.**

3.3.11 **RCS Tree menu** invokes a menu allowing examination of the RCS curve and the index values for series of measurements from individual trees**.**

3.3.12 **Transform** select either "No Transform", "Adaptive power" or "Basal Area". The adaptive power is that provided by the program ARSTAN (i.e. the code taken from ARSTAN, transform option 4). Selecting power transform will set Index Creation option to "Residuals". De-selecting power transform will set index creation option to "Ratios". Basal Area Increment is calculated presuming measurements are ring width and the tree is concentric prior and ideally requires pith offset estimates to be available.

3.3.13 **Pith Offset** selects either "PO on" or "PO off" to or ignore pith offset estimates (presuming they are available). Relevant if using basal area increment and ignore first few rings. We recommend that PO should always be used with RCS.

3.3.14 **Index Creation** selects either "Ratios" or "Residuals" to create tree index series. Using ratios roughly corrects the problem of sample variance being proportional to the local mean for TRW and is consistent with the signal-free method. The use of residuals generally requires some form of variance correction i.e. power transform. To use ratios with power transform, select the power transform option first (sets differences by default) and then select ratios.

3.3.15 Mean Chronology selects "Arithmetic" or "Robust" method of averaging to create chronologies. The robust mean procedure was taken from ARSTAN. Using robust mean can be an improvement where sample counts are between 10 and 20.

3.3.16 Signal-Free selects to use the Signal-Free method or not with an option to select the maximum number of iterations. Signal free method will remove the common signal from individual measurement series prior to fitting curves or creating RCS curves. This option is designed to allow convenient comparison of the effects of using the signal-free method. It is recommended to always use this option with RCS, especially when using multiple RCS curves or chronologies built solely from living trees.

3.3.17 STD Chron provides options to generate "STD", "ARS" and "RES" chronologies as specified in ARSTAN. Implements a simplified form of the autoregressive options available in ARSTAN. The unadjusted (STD) option is default and recommended but the user can also select to produce the "ARS" or "RES" chronologies. The processing involved is applied to tree indices after all other processes (e.g. iterative signal-free methods) are completed.

3.3.18 Ratios CRN the default is "Ratios CRN". There is an experimental option "Normal CRN" to convert the values of tree indices so that they have a normal distribution prior to averaging to produce a chronology. This corrects the problem of tree-indices which are generated as fractional deviations having a skewed distribution (especially for RCS).

3.3.19 Variance stabilisation selects either "Var.Stab Off" or "Var.Stab On". The chronology variance stabilisation is based on the RBAR method (Osborn 1997, Dendrochronologia 15, 89-99). We recommend that variance stabilisation is used where core numbers are low. Note that RBAR used should be based on mean inter-tree correlations and generally works well when measurements series are "mean-tree" but this is not suitable for sparcely replicated parts of the chronology (<5 trees) and individual trees have multiple cores.

3.3.20 Smoothing RCS Curve options for smoothing the RCS curve can be selected from: a spline with age dependent smoothing; an unsmoothed RCS curve; a modified negative exponential; a fitted straight line; a Hugershoff curve; a spline

with selected stiffness of 'n' years; or a spline with stiffness n% of series length. The first option is strongly recommended, while the other options are included for historical experimentation. The age dependent smoothing option uses a stiffness of 10-years plus ring age, is only fitted where sample counts >3, the RCS curve is not allowed to rise in its final third (except for BAI or trees > 1500-years old), and where otherwise incomplete the RCS curve is completed by linear extension.

3.3.21 Multiple RCS toggle to use either a single RCS curve or multiple RCS curves or selected RCS curves if RCS curves have been created using the "Select RCS menu". The number of curves can be set within limits: 40 trees per RCS curve with a maximum of 11 RCS curves.

3.3.22 RCS Type toggle to use either an "age-based", or a "diameter-based", or an "age and diameter based curves. The default and standard is to use age based RCS curves. Experimental options to use diameter based RCS curves or the average of age and diameter based curves are included see Melvin 2004.

3.3.23 Mean Adjust if the option to use multiple RCS curves is selected, the user can choose between tree-index series with "default values", or "mean signal". Default values of tree indices have mean of 1.0 for each RCS curve. The "single mean" option rescales the mean values of each series of tree indices to the mean value that would have resulted from using one-curve RCS.

3.3.24 Mean Chronology if multiple RCS curves is selected, then a number of options are available for averaging the multiple (i.e. sub) chronologies to form a single chronology. The default is to create a chronology as the arithmetic (or robust) mean of all tree indices. Alternative options allow the use of the arithmetic mean of sub-chronologies or the mean of sub-chronologies after each has been rescaled to have a mean to 1.0.

3.4 **Figures Menu**

Exact specifications of the processing options used in this menu can be seen in the fortran code "rfigs.f90".

3.4.1 Plot-3 runs the detrending program and creates chronologies (output file crns.crn) in Tucson index format for the list of measurement files and the parameter options

specified (input file crns.fil). Detrending options selected in the input file are used to generate the output chronologies.

3.4.2 **Plot-4 c**reates mean-tree raw data files from list of files "mean.fil" with "M" appended to the output file name. Program presumes that all cores in an input file have names of the same length, cores of each tree have the same name up to the last digit, and that the last digit (a, b, c or 1, 2 or 3) thus represents cores of the same tree. Where these cores overlap in time they are averaged together producing a tree with "M" as the last digit of the name otherwise cores are copied from input to output with their name unchanged. Report "mean.prn" is produced with lines showing each "M" core created, the inter core correlation for the cores used, and cores carried across unchanged.

3.4.3 **Plot-5 c**reates file "rawstats.prn" from list of files "ars.fil" reporting core count, start year, end year, length, mean tree to CRN correlation, and mean inter-sample correlation (RBAR if mean tree) for each raw data file listed.

3.4.4 **Plot-6 c**reates "missing.prn" report for the list of files in "ars.fil" reporting all missing rings (-ve ring measurement) and rings with measurement value of zero.

3.4.5 **Plot-7** where measurement data files have missing values (-ve ring measurements) the program will infill these values for the purpose of fitting curves. This option saves the currently selected measurement data file with missing values replaced by the "in-filled" values; output file "***.mis" for Tucson format or "***.hei" for heidelburg format. The program averages measurements by chronology year and by ring age. For a tree with missing rings the relative growth rate (sum of measurements of tree/sum of RCS curve values) for the common period. Missing rings in years with other trees present are replaced by the mean of the other values scaled by the relative growth rate. In years with no other trees, the missing values are replaced by the RCS curve value scaled by the relative growth rate.

3.4.6 **Plot-9 s**aves indices of individual trees from the selected file in CRN format in file "trees.crn".

3.4.7 **Plot-10** converts chronologies from Tuscon format to column format. Reads the chronologies in "crns.crn" and saves the index values and sample counts from these chronologies in column format in file "column.prn".

3.4.8 **Plot-13** this option allows a search for duplicated measurement data. All cores in all files of "ars.fil" are sorted: firstly by their first year and secondly by their last year and a report "core_years.prn" is produced. Where core name, first year, last year or the sum of measurements are the same as those from the previous tree they are left blank in the report.

3.4.9 **Plot-14** this option is used to look for duplicated measurement data. All cores in all files of "ars.fil" are sorted firstly by their core name, secondly by their first year and thirdly by lasy year and a report "core_years.prn" is produced. Where core name, first year, last year or the sum of measurements are the same as those from the previous tree they are left blank in the report.

3.4.10 **Plot-15 & 16** create plots of trees by first year (15) or last year (16) showing tree distribution over time. Uses the file currently selected from "ars.fil". If pith estimates (.pth file with same name as raw file and in same directory) are available plots will also show the pith offset estimates in blue.

3.4.11 **Plot-18** produces a report, "core_pith.prn", to assist in the creation of "***.pth" file for the currently selected data. Presumes there are multiple cores for each tree. Reports the core name, the pith year (default is year before the first ring), the radius of missing pith or pith offset, first ring year and last ring year, pith estimate, missing radius estimate, and the radius of the first 50 rings. The pith offset is based on examining the piece of wood. The pith estimate is the sum of the first few rings i.e. the estimated number of pith years. The missing radius for cores that start later than the earliest ring of the tree is the sum of the missing measurements of the oldest core. The sum of the first 50 rings of the earliest core is also given.

3.4.12 **Plot-20 r**eads files in "RCS.fil" and creates an Arstan compatible (column format) pith file "***.Apth".

3.4.13 **Plot-22 c**ombines site files to creates one raw data file (and .pth file) using all the trees in all the files in "are.fil".

3.4.14 Plot 26 calculates the adjusted EPS for selected chronology using two-curve SF RCS creating a figure and an EPS report. Uses the Rbar segment length specified in the RCS default file.

3.4.15 Plot 27 calculates the adjusted EPS for selected chronology using one-curve SF RCS creating a figure and an EPS report. Uses the Rbar segment length specified in the RCS default file.

3.4.16 Plot29 creates an "adjusted" MXD data file and associated report – as per the descriptions in Melvin et al. 2012 and Briffa et al. 2013.

3.4.17 Plot30 creates an "adjusted" TRW data file and associated report – as per the descriptions in Melvin et al. 2012 and Briffa et al. 2013.

3.4.18 Plot 32 calculates bootstrap error limits for the selected data using CRU method (creates 1000 chronologies using random selection (with replacement) of the available cores/trees) and calculates the +/- 2.5% limits for each year.

3.5 RCS Tree menu

3.5.1 Current Tree displays the currently selected tree name. Selecting this option allows the selection of another tree from the names listed (sequence depends on the current selected sorting method).

3.5.2 Previous selects the previous tree using the currently selected sorted sequence.

3.5.3 Next selects the next tree using the currently selected sorted sequence.

3.5.4 Sort Trees displays the currently selected sort key for trees. Selecting this option allows the user to step through the allowable sorting options.

3.5.5 Save Plot saves the current figure as a postscript file "detrend.eps".

3.5.6 Display Options invokes a menu that allows the user to select various lines, line types, or colours to be displayed.

3.5.7 **Exit** leaves the RCS tree menu.

3.6 **Selected RCS curves menu** (experimental)

The object of this section of the program is to allow the user to create pre-selected multiple RCS curves by manually selecting which trees are used to create each RCS curve, which RCS curves are used to detrend each tree, and to save (and later to use) these curves, along with the parameters values used when they were created. An additional option "Selected RCS" was added to the existing menu option "Single RCS"

or “Multiple RCS”. The “Selected RCS” option can only be used if the appropriate RCS curves for the currently selected measurement data file have already been created and saved as “***.src” files. The currently loaded trees must match the .src file tree list. The parameters used when creating and saving RCS curves will limit options for chronology creation and the user is not allowed to change the following parameters while this option is selected: transform on/off (itn); RCS curve smoothing option (idt); ratios/differences because of need to change power transform (ind); signal-free on/off (sfo); use of pith offset (poo); type of RCS curve (age related, basal area etc) (trc); or the number of RCS curves to use (srcno). The remaining options for chronology creation do not alter the generation of RCS curves and can be set appropriately whilst in the “Selected RCS” option of the main menu. These include: arithmetic/robust mean (krb); variance stabilisation on/off (isb); ring transform on/off (gtr); and mean of chronologies (gtr) options.

An additional menu “Select RCS” has been created to allow the creation and saving of multiple RCS curves. This menu can only be selected if “Multiple RCS” is already selected. Prior to the selection of this menu the main standardisation options should be selected and these will be used in the creation of RCS curves.

3.6.1 **Load SRCS** this option will load saved parameter values, RCS curves, and tree allocations.

3.6.2 **Save SRCS** this option will save the currently selected parameter values, RCS curves, and tree allocations. It will overwrite any existing “***.src” files. The user must manually copy, rename and save any existing files that may need to be kept prior to using save RCS.

3.6.3 **Sort** this option only changes the sequence in which trees are displayed which is useful if sample names are used to classify tree types (e.g. modern, sub-fossil etc).

3.6.4 **Calc CRN** this will create a new set of RCS curves and will recalculate a new chronology, using the currently selected allocation of trees to RCS curves and parameter settings. Should be used prior to saving and after every few changes.

There is one RCS curve selections for each RCS curve, numbered 1-n and the curve selected for use on the currently displayed tree will be highlighted. Visual comparison of raw measures and RCS curve allows estimation of the goodness of fit. Selecting another RCS curve will allocate the currently displayed tree to the selected RCS curve, changing the display. Next and previous can be used to examine other trees.

Selecting the currently named tree will produce a list of trees, with currently selected RCS curve number. Selecting a tree will allocate the currently selected RCS curve to that tree. Selecting an RCS curve will change the current selection of RCS curve. Page forward and backward are also available where tree counts are sufficient.

4 Detrend Structure

The process of standardising consists of a sequence of procedures, some of which may be repeated iteratively to implement the signal-free process.

4.1 **Read Data**

The raw measurement data, consisting of measurement series for each tree, is read and stored (x). Missing values (negative measurement value) set a logical to false (xok) and missing values are infilled (see Figures Menu, Plot 7). For each tree the name (A8) is stored along with first year (fy), last year (ly) and number of years (yr). The year the pith grew (pth) and the radius of missing wood to the pith (pthr) are read in if available with defaults of the year before the first measurement year and 1mm of pith if pith offset estimates are not available.

4.2 **Modify data**

Transformed measurements (tx) by default are copied from measurements (x). Option are available to convert ring-width measurements to Basal Area Increments (BAI) which presumes circular stems, using pith offset estimates if available or data can be “Power Transformed” using option 4 of ARSTAN (Cook 1985). If power transform is used then indices should be created using differences. The modified data can be saved.

4.2 **Allocate trees** (RCS only)

This consists of creating tree counts by year (xnum), chronology logicals (cok) for years with valid measurements, and chronology first year (xfy), last year (xly) and length (xyr). If using RCS the ring-age values of tree counts by age (mcnt), RCS curve logicals (mok)

for ages with valid measurements, and RCS curve first age (sfy), last age (sly) are created. If using multiple RCS these values are created for the multiple chronologies and multiple RCS curves as well values as for the overall single chronology and RCS curve. For multiple RCS the trees (sorted by the selected method) are allocated to the chosen number of RCS curves as equally as possible.

4.3 **Signal-Free**

If signal-free methods are not used the procedures in 4 are processed once only, otherwise the processes in 4 are repeated iteratively until an endpoint is reached: either reaching the selected number of iterations or when values cease to change.

4.4.1 **Signal-free values**

For the first iteration, signal-free measurements (fx) are set to the transformed measurements (tx) while in each subsequent iteration fx is set to tx divided by the current chronology (xcrn).

4.4.2 **Detrending curves**

Detrending curves (cx) are created using various curve fitting options, or by creating an RCS curve (or multiple RCS curves). RCS curve value can be age based, diameter based, the average of both, or Basal Area depending on selected options. RCS curves and fitted curves are based on the use of signal-free measurements if the signal-free option is selected.

4.4.3 **Tree indices**

Tree indices (dx) are created using ratios (dx = tx/cx) or as differences (dx = tx-cx). When differences are used the range of index values for each tree is set to the range that would occur were ratios used (as per ARSTAN). Ratios are recommend here because they are compatible with the multiplicative model of tree growth (Melvin 2004).

4.4.4 **Modify tree indices**

If using multiple RCS, the values of tree indices can be re-scaled to have the same mean as they would have using one RCS curve (mean single option).

4.4.5 **Create Chronologies**

Tree indices are averaged in to a chronology (or multiple chronologies if selected) using either arithmetic mean or robust mean (as ARSTAN robust option).

4.4 Mean of chronologies - Where multiple chronologies are created then they can be averaged together using the mean of all trees (default), the mean of all chronologies, the mean of chronologies after each has mean set to 1.0, the BFM of chronologies i.e. means set to match over common period before averaging, or count-weighted BFM of chronologies.

4.4 AR Model -The final chronology can be left as STD or AR modelled (as per ARSTAN) to produce ARS or RES version of the chronology. (Options ARS and RES may not be compatible with all other options).

4.5 Normal Distribution - Tree indices can be converted to have a normal distribution prior to averaging into a chronology.

4.6 Stabilise Variance - The variance of the final chronology can be stabilised using the Rbar count weighted method of Osborn (1997).

4.7 Save chronology - Chronology can be saved in Tuscon or column format

5 Background (or batch processing) Standardisation

After the heading line, the batch processing standardisation file "crns.fil" needs to contain pairs of lines; the first containing the name of the data file to be used (60 characters) followed by an optional file-name subscript (3 characters) and the second containing the word "PAR" followed by 15 four-digit numbers and 4 six-digit numbers containing the parameter values to be used during the standardisation.

Sample entries in the "crns.crn" file

```
    IDT ITN RDT IND KRB ISB SFO POO SRC TRC GTR TST BFC IDB JRB SRCNO SFONO RDTNO
../../raw/finnmrg.raw                                          NEG
PAR   2   1   1   1   1   1   2   1   1   1   1   4   1   1   1     2    20    60
../../raw/finnmrg.raw                                          RCS
PAR  -2   1   1   1   1   1   2   1   1   1   1   4   1   1   1     2    20    60
```

The procedure produces the output file "crns.crn" which will contain the chronologies in Tucson format. A summary description of the parameter selections will appear in the 3 line heading for each chronology. The batch procedure can be invoked from the "Figures Menu", item 3 "Create CRNS".

1 **IDT** – Parameter selects the detrending method from:
   - -2 RCS method
   - 0 No Detrend
   - 1 Modified Negative Exponential or Any line
   - 2 Modified Negative Exponential or Negative line
   - 3 Any Slope line

4 Negative Slope Line
5 Horizontal Line or mean
6 Hugershoff Curve
7 General Exponetial
=> 10 Spline with 50% variance cut of "n"
=< -10 Spline with 50% variance cut of "-n% of tree age"

2 **ITN** - Transform options are (1) "No Transform", (2) "Adaptive power" or (3) "Basal Area". The adaptive power transform is that of program ARSTAN (program code copied from ARSTAN, transform option 4) and should normally be used with IND set to "Residuals". A further option is to convert ring width to basal area increment (BAI) prior to processing. This presumes the original measurement series are ring widths and sensibly requires pith offset estimates to be available.

3 **RDT** – RCS curve smoothing options are (1) age dependant spline, (2) an unsmoothed RCS curve, (3) a modified negative exponential, (4) a fitted straight line, (5) a Hugershoff curve, (6) a spline with selected stiffness 'n' years, or (7) a spline with n% of series length stiffness. Option 1 is the only one that is recommended although the other options have been used in the past. See Melvin et al. 2007 for discussion of options.

4 **IND** - Use "Ratios" or "Residuals" to create tree index series. Using ratios (dividing measurements by expected growth) roughly corrects the problem of variance being proportional to the local mean for TRW and the use of residuals (subtracting expected growth from measurements) generally requires some form of variance correction i.e. power transform.

(Menu only - to use ratios with power transform, select the power transform option first (sets differences by default) and then select ratios.

5 **KRB** – The method of averaging series of tree indices to create a chronology can be either by (1) arithmetic mean or (2) robust mean (procedure copied from ARSTAN). Robust mean can be an improvement where sample count is between 10 and 30.

6 **ISB** - Option of (1) not using, (2) using variance stabilisation or (3) experimental option of high-frequency only variance stabilisation. Variance stabilisation based on the RBAR (Osborn et al. 1997). Note that RBAR should be based on mean inter-tree correlations and works OK if measurements series are mean-tree but is not suitable for sparcely replicated parts of the chronology (<5 trees) when individual trees have multiple cores.

7 **SFO** – The Signal-Free method can be (1) used or (2) not used. Is recommended to always use this option with RCS, especially when using multiple RCS curves

or chronologies built solely from living trees. See Melvin and Briffa 2008 (for curve fitting) and 2013 (for RCS).

8 **POO –** The user can (1) use or (2) not use ignore pith offset estimates (presuming they are available). We recommend always using pith offset estimates if they are available.

9 **SRC** - The options are (1) single RCS, (2) multiple RCS curves, or experimental option (3) select RCS curves which allows the use of pre-specified (and saved) RCS curves (see Annex). Multiple RCS limited to 40 trees per RCS curve and a maximum of 11 RCS curves. Need to choose number of RCS curves. The recommended method of sorting is growth rate but other options can be set using TST parameter.

10 **TRC** –The options are (1) use age based RCS curves, (2) to use diameter based RCS curves or (3) use the average of age and diameter based RCS curves.

11 **GTR** - If multiple RCS curves are selected, then the options (1) use the default values of indices, (2) "ring transform" or (3) single mean. The default leaves index series with means relative to their RCS curves, each with an overall mean of 1.0. With the ring transform the user can specify the ring age (years) or diameter (mm) to use for the ring transformation from multi value to single RCS curve value. The "single mean" option rescales the mean of tree indices to the mean value that would have resulted from using a single RCS curve.

12 **TST** – Trees can be sorted by (1) not sorted, (2) tree age, (3) tree size/diameter, (4) growth rate, (5) tree name, (6) pith year, or (7) last year.

13 **BFC** - If multiple RCS curves are selected, then a number of options are available for averaging the multiple chronologies to form a single chronology. The default is to create a chronology as the arithmetic (or robust) mean of all tree indices. Other options are the arithmetic mean of sub-chronologies and the mean of sub-chronologies with their means set to 1.0.

14 **IDB** - experimental option to change the distribution of tree indices to normal and then these are averaged to create a chronology with "normal" distribution as an alternative to the skewed distribution generated using indices which are fractional deviations.

15 **JRB** – Implements the autoregressive options of ARSTAN. The (1) unadjusted STD option is recommended but the user can select to produce the (2) ARS or (3) RES chronologies. Processes applied to tree indices after all other processes completed.

16 **SRCNO** – Number of RCS curves (range 1 to 11).

17 **SFONO** – Maximum number of signal-free iterations (range 2 to 100).

18 **RDTNO** – Spline detrending of RCS curve (range 5 to 999 or -999 to -5).

6 Error Processing

6.1 There are some differences in the end-of-file markers of character files transferred between Windows, Linux and MAC. End of file errors can arise because of unrecognised end-of-file markers; try opening the file in Gedit (or Wordpad) and saving the file. If the program is run by clicking on the executable then when it fails (program disappears) many of the error messages are lost. These will be visible and retained if the program is run from "Terminal" or the "DOS" prompt.

6.2 The program has set limits (which can only be changed by recompiling) for the maximum length of a chronology, maximum and minimum length of a tree, maximum number of trees, maximum number of rings, maximum number of chronologies, file name sizes etc. Breaching these may produce an error message or program will ignore anything beyond the limit. Most limits are set in first 10 lines of file "detdata.f90" and can be readily changed.

6.3 **Raw-data errors**

If error in reading a raw data file or "???.pth" file message will point to the tree at which the error occurred – if last tree in file could be an end-of-file error. If end-of-file error indicated try deleting any blank lines after the last line of the file, and saving file. Need to check format of raw data removing blank lines, correcting year number sequences, removing duplicate names, and checking for correct end of tree markers (999 or -9999). There are various checks that the years are in sequence and core names are consistent. All trees in a measurement file must have the same end of tree marker as the first tree in that file. If Tucson format is used with a "999" terminator then values of 999 within series of measurements will cause a problem. If Compact format is used then the program presumes that precision = $1/100^{th}$ mm for 3 digit measurements and $1/1000^{th}$ mm for all others. If Heidelberg format is used then the core heading line "Unit=1/1000 mm" or "Unit=1/100 mm" will be recognised and in the absence of these the precision is presumed to be $1/1000^{th}$ mm and each core must have either "DateBegin=" or "DateEnd=" and "Leng=" header lines. (Note that

Heidelberg is case sensitive and output data files from the CRUST program do not preserve unused header information).

7 Data files

7.1 Measurement Files

Examples data files in Tuscon format are:

../data/finnmrg.raw

../data/norwmrg.raw

The program can read Tucson, Compact and Heidelberg format files. If the program can recognise the format it will read the data otherwise it will produce an error message.

7.2 Pith Offset File

Pith offset estimate will be read if they exist otherwise the default that the pith year is the year before the first ring and the missing radius is 1mm. The pith offset file must be in the same directory as the raw data file and have the same name as the raw data except that the extension is ".pth". For the above data files the pith offset files are:

../data/finnmrg.pth

../data/norwmrg.pth

The pith offset file contains one line for each core (or tree) in the raw data file (and may need to finish with a null line). The format of each line is an 11 character core name, 5 character calendar year, and 8 character pith off set estimate. The date is the year the pith grew and must be at least one year prior to the first measured ring of the core. The pith offset measurement is in cm with one decimal place e.g.

Name	Pith Year	Offset(cm)
ra101	1941	0.2
ra102	1938	0.1
ra103	1732	2.0
ra104	1910	1.0

References

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