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# DECON: FUNCTIONAL SPECIFICATIONS FOR COMPUTATION OF RELATIVE RECEIVER FUNCTIONS



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This document contains the functional specifications for a program to compute relative receiver functions by a deconvolution method. The program structure is discussed; and individual subroutines are named and their function is specified. Though not a working program, these functional specifications determine the orientation, flow and interaction of the software in detail which is exceeded only by the code itself.

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ABSTRACT

This document contains the functional specifications for a program to compute relative receiver functions by a deconvolution method. The program structure is discussed; and individual subroutines are named and their function is specified. Though not a working program, these functional specifications determine the orientation, flow and interaction of the software in detail which is exceeded only by the code itself.

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## INTRODUCTION

The object of this program package is to produce a set of relative receiver functions (RRF) for a given array of stations. Each RRF models all near receiver contributions to observed seismic waveforms; including crustal reverberations, acoustic impedance amplification effects, laterally refracted arrivals and variations in anelastic attenuation. Clearly the RRF's must be functions of back azimuth and incidence angle, and must be recomputed for each source region under consideration.

This program package generates convolution filters intended for use in synthetic seismogram or other foreward modeling applications. The two major steps involved in the computation are Trace Deconvolution and Minimum Entropy Deconvolution (MED), and both steps are specifically designed to produce filters which may be applied in a convolution sense. In the trace deconvolution step, a reference station must be chosen with spectral character most like a deconvolution filter (no zeros), while the rest of the stations in the array must appear more like convolution filters (bandlimited). Processing by MED adds additional tapers at the high frequency end of the bandpass, and generates RRF's with all of the proper characteristics of convolution filters.

## PROGRAM STRUCTURE

The computation of relative receiver functions is implemented as two separate program packages: DECON and FMED. DECON performs the trace deconvolution and outputs an average spectral ratio for each station pair (secondary/ reference). FMED uses the trace deconvolutions to estimate relative receiver functions. The theory behind the software is given by Hart et al, (1979) and Lundquist et al, (1980 a,b).

DECON requires a set of trace pairs, and the accumulation and preparation of the trace pairs are often the most time consuming portions of receiver function estimation. The trace pairs for different secondary stations in the array need not be the same, but the reference station must be common for each array. Each trace is Fourier transformed; a ratio of secondary to reference trace is taken and the ratios are averaged in log amplitude sense. To avoid division by zero, the ratio is taken only over a specified frequency range; so bandwidth is an important consideration in developing receiver functions. Other assumptions on the trace deconvolution process depend upon the type of array used, and are discussed in Lundquist et al., (1980 a).

FMED estimates relative receiver functions from the spectral ratios by finding common spectral content in the set of spectral ratios for an array and ascribing that to the reference station. This is done by means of a simplicity criterion (Wiggins, 1978) implemented in the frequency domain (Lundquist et al, 1980 a). The method is an interative technique to maximize simplicity as a function of a specific norm. Convergence to a maximum is a function of reference station, weight functions applied and the quality of the trace deconvolutions. The maximum found is not necessarily unique, but is often useful. One filter is estimated and applied to the entire array of trace deconvolutions, so the receiver functions estimated are still relative in that they cannot predict absolute amplitudes.

DECON CALLLING SEQUENCE

```
DECON
     DECINS
          LINOG1
          HAGINL
     DATIN
          INTERP
     VNORM
     TAP
     PLOT
     COOLB
     CDATA
     DATIN
          INTERP
     VNORM
     TAP
     PLOT
     COOLB
     CDATA
     CMPR
     FPEAK
          CONJ
          COOLB
     COR1
     PLOT
     FLNFLD
     COOLB
     PLOT
```

FMED CALLING SEQUENCE

```
FMED
     COOLB
     GBANDP
     COOLB
     TTAPER
     COOLB
     PLOT
     COOLB
     PREMED
          COOLB
          COOLB
          CAUS
               COOLB
               COOLB
          FMDOUT
     PLOT

PLTMED
     PLOT
```

Program DECON

This is the main program controlling data input and computation and output of spectral ratio trace deconvolutions. After reading in preliminary parameters, the spectral ratios are computed and averaged in a major loop on event number. Finally, the result is output to diskfile and plot.

| | | | |
|---|---|---|---|
| Calls: | DECINS | - | Computes spectral ratio of secondary station instrument response to that of reference station. |
| | DATIN | - | Inputs and reinterpolates one seismogram. |
| | VNORM | - | Computes the transparency norm of the input seismogram. |
| | TAP | - | Applies cosine tapers to front and back of seismic trace. |
| | COOLB | - | Utility Fast Fourier Transform routine. |
| | CDATA | - | Finds effective bandwidth of seismogram spectrum. |
| | CMPR | - | Computes the RMS difference between amplitude spectra of current spectral ratio and previous one. |
| | FPEAK | - | Filters spectral ratio with Bartlett filter and applies a time shift. Returns time domain signal. |
| | COR1 | - | Correlation routine to find time shift required to maximize fit between two time domain sequences. |
| | FLNFLD | - | Fills out-of-band spectral components with zero and folds about Nyquist to complete spectrum. |

| | | |
|---|---|---|
| Reads: | T0, T0S | - Seismometer free periods for reference and secondary stations, respectively. If T0, T0S less than zero, then TG, TGS (below) will be instrument response number in a file of instrument responses. |
| | TG, TGS | - Periods of galvanometers unless T0, T0S less than zero. |
| | S, SS | - Coupling between T0 and TG. |
| | H0, H0S | - Damping constants of seismometers. |
| | HG, HGS | - Damping constants of galvonometers. |
| | XLIN, XLINS | - Inductances. |
| | TDECON | - Length of DECON trace in time domain stack. Frequency domain average of spectral ratio is independent of TDECON. |
| | DT | - Sample interval |
| | NCOS | - Length of cosine taper in samples. |
| | SCALE | - Plot scale factor. |
| | F1, F4 | - Frequency band for spectral ratio and frequency domain averaging. |
| | F2, F3 | - Frequency band for time domain stack. F1<F2<F3<F4. |
| | ISDAC | - Appropriate to SGI data input types, only. |
| | ISP | - Specifies output plot requests. |
| | ITAPDT | - Length of linear taper of the ends of data traces. Rarely other than unity. |
| | ICMPS | - Flags request for comparison between current spectral ratio and a previous run. Rarely used. |
| | START | - Time of window start of reference trace. |
| | TSTP | - Stop time for reference trace window. |

| | | | |
|---|---|---|---|
| | POL | - | Polarity flag. POL equal to zero causes input trace to be inverted. |
| | START1 | - | Window start time for secondary station. |
| | TSTP1 | - | Window stop time for secondary station. |

(NOTE: Four lines of input are read in loop on event number. These are the reference station window parameters, the reference station file name (read by DATIN), the secondary station window parameters and the secondary station file name. This input format continues until START is less than -999.)

| | | | |
|---|---|---|---|
| | TSHFT | - | Time of circular shift of frequency domain averaged traced deconvolution |
| | TZ | - | First TZ seconds of trace deconvolution set to zero. |
| | TCOS | - | Next TCOS seconds smoothed with cosine taper. |
| | IFLAG | - | Defines convolution option.<br>$<0$ apply trapezoidal filter<br>$=0$ apply instrument response<br>$>0$ apply Bartlett filter.<br><br>Though options are offered, program is nearly always run with Bartlett filter option. |
| | TWD | - | Triangle width in seconds for definition of the Bartlett filter. |
| Outputs: | DECFFT | - | Final frequency domain averaged trace deconvolution after time shift and tapers applied. This is input file for program FMED. |

Subroutine DECINS (INST, RS, ARGS, IF1, IF4, DT)

Does deconvolution of instrument responses to permit equalization of instruments during trace deconvolution. The response functions are either computed or interpolated, depending upon request.

| | | | |
|---|---|---|---|
| Called by: | DECON | | |
| Calls: | LINOG1 | - | Linear or logarithmic interpolation routine. Used when response function read from a data file. |
| | HAGINL | - | Computes instrument response using instrument constants read by DECON. |
| Input: | RS, ARGS | - | dummy work space |
| | IF1, IF4 | - | frequency limits for ratio of instrument responses |
| | DT | - | sample interval. Used with MAXX (in parameter statement) to define DF, the frequency sample interval. |
| Output: | INST | - | the spectral ratio of secondary instrument to reference instrument |

Subroutine LINOG1(N, X, Y, XZ, Y1, I)

Linear interpolator, but assumes X scale is logarithmic on input. Y scale may be linear or logarithmic.

| | | | | |
|---|---|---|---|---|
| Called by: | | DECINS | | |
| Calls | : | none | | |
| Input | : | N | - | index of last point in X array |
| | | X | - | input abscissa array (frequency) |
| | | Y | - | input ordinate array (amplitude or phase response) |
| | | XZ | - | desired abscissa point |
| | | I | - | index of last X value used in previous call Minimizes search for X values bracketing X2. |
| Output | : | Y1 | - | interpolated ordinate value |

Subroutine HAGINL (F, PT, PG, S, HP, HG, XL, R, ARG)

Computes instrument response using Hagiwara formula.

| | | | | |
|---|---|---|---|---|
| Called by: | DECINS | | | |
| Calls | : | None | | |
| Input | : | F | - | frequency at which response desired |
| | | PT | - | seismometer period |
| | | PG | - | galvanometer period |
| | | S | - | coupling between PT and PG |
| | | HP | - | damping of galvanometer |
| | | XL | - | inductance |
| Output | : | R | - | amplitude response at frequency F |
| | | ARG | - | phase response |

Subroutine DATIN (X1, DT, START, NP, IFLG)

Inputs one seismogram, reinterpolates if necessary and subtracts mean. This routine is highly machine and user dependent, and may be redefined for each new format or data type used.

| | | | |
|---|---|---|---|
| Called by: | DECON | | |
| Calls : | system routines for file manipulation and direct disk reads. | | |
| | INTERP | - | linear interpolator |
| Input : | DT | - | sample interval |
| | START | - | window start time in seconds |
| | NP | - | number of points in desired output array |
| | IFLG | - | Pertinent only to SGI PRIME data files. Set = 0 |
| Reads : | seismogram and descriptive information. Exact details are machine and user dependent. | | |
| Output : | X1 | - | desired seismogram |

Subroutine INTERP (X, Y, KK1, X1, DEL, KK2, XOUT)

Linear interpolation subroutine.

| | | | | |
|---|---|---|---|---|
| Called by: | | DATIN | | |
| Calls | : | none | | |
| Input | : | X | - | array of abscissa values |
| | | Y | - | array of ordinate values |
| | | KK1 | - | length of X and Y arrays in samples |
| | | X1 | - | start time of desired output array in seconds |
| | | DEL | - | sample interval of desired output array |
| | | KK2 | - | number of points in desired output array |
| Output | : | XOUT | - | interpolated output starting at time START and sampled at time interval DT |

Subroutine VNORM (X, V, NP)

Computes the transparency norm defined by:

$$V = \frac{\Sigma X^4}{(\Sigma X^2)^2}$$

| | | | | |
|---|---|---|---|---|
| Called by: | | DECON | | |
| Calls | : | none | | |
| Input | : | X | - | time domain array |
| | | NP | - | length of X in samples |
| Output | : | V | - | transparency norm |

Subroutine TAP (X, ISTP, NCOS, ITAPDT)

Applies cosine tapers to front and back of a time domain array and linear tapers to the back of the array.

| | | | |
|---|---|---|---|
| Called by: | DECON | | |
| Calls : | None | | |
| Input : | X | - | array to be tapered |
| | ISTP | - | length of X in samples |
| | NCOS | - | length of cosine tapers |
| | ITAPDT | - | length of linear taper |
| Output: | X | - | tapered version |

Subroutine (PLOT)

System dependent time domain plot routine.

| | | | | |
|---|---|---|---|---|
| Called by: | | Various | | |
| Calls | : | System plot routines | | |
| Input | : | X | - | array to be plotted |
| | | DT | - | sample interval |
| | | N | - | length of X in samples |
| | | SCALE | - | scale value such as number of mm/sec. |

Output : hard copy plot

Subroutine COOLB (NN, XX, SIGNI)

Utility subroutine for computation of Fast Fourier Transforms.

| | | | | |
|---|---|---|---|---|
| Called by: | | Various | | |
| Calls | : | None | | |
| Input | : | XX | - | complex array to be transformed |
| | | NN | - | power of 2 describing length of XX |
| | | SIGNI | - | Forward transform done when SIGNI = -1.0; inverse transform done when SIGNI = 1.0. |
| Output | : | XX | - | transformed version |

Subroutine CDATA (C, IF1, IF4, WTL, XMAX)

Searches amplitude spectrum for maximum value of spectrum and for frequencies at which spectrum has decayed to the water level relative to the maximum.

| | | | | |
|---|---|---|---|---|
| Called by: | | DECON | | |
| Calls | : | None | | |
| Input | : | C | - | complex spectrum to be evaluated |
| | | IF1 | - | index of minimum frequency to be tested |
| | | IF4 | - | index of maximum frequency to be tested |
| | | WTL | - | water level |
| Output | : | IF1 | - | either as input or index of frequency at which water level is reached on low frequency side of maximum value. |
| | | IF4 | - | either as input or index of frequency at which water level is reached on high frequency side of maximum value. |
| | | XMAX | - | maximum spectral amplitude |

Subroutine CMPR (IF1, IF4)

Compares amplitudes of two spectra input in common and outputs RMS difference between the two to a printer file.

| | | |
|---|---|---|
| Called by: | DECON | |
| Calls : | None | |
| Input : | IF1, IF4 - | frequency limits for comparison |
| Output : | None | |

Subroutine FPEAK (PEAK, IF1, IF4, DT, SHFT)

Applies a Bartlett filter to a spectrum input in common, applies a time shift, inverse transforms and returns time domain array.

| | | | | |
|---|---|---|---|---|
| Called by: | | DECON | | |
| Calls | : | CONJ | - | folds complex spectrum about the Nyquist frequency |
| | | COOLB | - | utility Fast Fourier Transform routine |
| Input | : | IF1, IF4 | - | frequency limits |
| | | DT | - | sample interval |
| | | SHFT | - | desired time shift in seconds |
| Output | : | PEAK | - | filtered array |

Subroutine CONJ (C, LX1)

Folds complex spectrum about Nyquist frequency to obtain complete frequency domain representation.

| | | | | |
|---|---|---|---|---|
| Called by: | | FPEAK | | |
| Calls | : | None | | |
| Input | : | C | - | complex spectrum defined from D.C. to the Nyquist frequency |
| | | LX1 | - | index of the Nyquist frequency |
| Output | : | C | - | complete spectrum |

Subroutine COR1 (PEAK, PEAK1, JSHFT, NPTS, IMAX)

Routine to estimate the shift required to maximize fit between two time domain arrays.

| | | | |
|---|---|---|---|
| Called by: | DECON | | |
| Calls : | None | | |
| Input : | PEAK, PEAK1, | - | the time domain arrays to be compared |
| | JSHFT | - | maximum shift |
| | NPTS | - | number of points to compare |
| Output : | IMAX | - | shift value at maximum correlation |

Subroutine FLNFLD (C, IF1, IF4)

Routine to fill out-of-band components of a bandlimited spectrum with zeros, then fold about Nyquist frequency.

| | | | | |
|---|---|---|---|---|
| Called by: | | Various | | |
| Calls | : | None | | |
| Input | : | C | - | complex spectrum to be completed |
| | | IF1, IF4 | - | indices of bandlimit frequencies |
| Output | : | C | - | complete spectrum |

Program FMED

This is the main program controlling input of trace deconvolutions (from DECON) and computation of relative receiver functions. The program reads in DECFFT files for each secondary station, initializes a corresponding array for the reference station, and then attempts to maximize the simplicity, or minimize the entropy, of the set of trace deconvolutions by maximizing the varimax norm. Effectively this determines common spectral character in the array of DECON transfer functions, and puts that spectral content into the reference station receiver function. Since one filter is determined and applied to all input traces, the resulting receiver functions are still relative in that any spectral content common to all seismograms will still be missing. In particular, absolute amplitude is not predicted by these filters.

| | | | | |
|---|---|---|---|---|
| Calls | : | COOLB | - | utility Fast Fourier Transform routine |
| | | GBANDP | - | Gaussian bandpass routine |
| | | TTAPER | - | applies several time domain tapers |
| | | PLOT | - | system dependent plot routine |
| | | PREMED | - | performs the iterative computation and application of the minimum entropy deconvolution filter. |
| Reads | : | NSTA | - | number of stations in the array. Includes reference station. |
| | | LSG | - | number of points output for each station at each iteration |
| | | NITER | - | number of iterations |
| | | DT | - | sample interval |
| | | IFP | - | initialize filter array as a spike at sample IFP |

| | | |
|---|---|---|
| ITP | - | initialize reference station trace as spike at ITP. Reference trace will be filtered by the same bandpass used on other traces. That is, the reference trace is initialized as the bandpass impulse response centered at sample ITP. |
| IREF | - | index of the station to be used as the reference for this FMED run. If same as DECON reference, then IREF=NSTA. Otherwise, all traces multiplied by the inverse of trace IREF, effectively changing reference station. |
| TCOS | - | time of beginning of cosine taper of end of traces |
| TZ | - | cosine taper ends and zero trace begins at time TZ |
| TEXP | - | generate causal time domain signal by zeroing trace up to arrival time. TTAPER searces backward from TEXP to a zero crossing and smoothly zeros all earlier points. |
| IWTOPT | - | option number for definition of weight function |
| WTL | - | percent maximum spectral amplitude for prewhitening |
| F1, F2, F3, F4, | - | frequencies for bandpass filter |
| ISP | - | specifies stations for which spectra will be plotted<br>GT.0 plot both input and final output<br>EQ.0 no plots<br>LT.0 plot final output only |
| ISOUT | - | NE.0 time domain receiver functions output to diskfiles |
| W | - | weight functions. Must read, even though a different weight option is used. |

| | | |
|---|---|---|
| Input File names | : | Usually DECFFT files from DECON. |
| SCALE | - | Gain factor (Z = Z/scale). May include, if required, correction for geometric attenuation. |
| Output file names | : | Used for plot labels even if ISOUT = 0. |

Outputs: Plots of spectra, if requested. All other output is done by PREMED.

Subroutine GBANDP (X, KF1, KF2, KF3, KF4)

Applies a simple Gaussian bandpass filter to the input complex array.

| | | | | |
|---|---|---|---|---|
| Called by: | | FMED | | |
| Calls | : | None | | |
| Input | : | X | - | array to be filtered. Length defined by parameter statement to be consistent with FMED. |
| | | KF1, KF2 | - | indices of frequencies with zero amplitude and unit relative amplitude, respectively, or the low frequency end of the bandpass |
| | | KF3, KF4 | - | indices of frequencies with unit relative amplitudes and zero amplitude, respectively, on the high frequency end of the bandpass |
| Outputs | : | X | - | filtered version |

Subroutine TTAPER (Z, TCOS, TZ, TEXP, DT)

Routine applies several time domain tapers to a complex time domain array. (1) Zeros all imaginary parts. (2) Applies cosine taper from time TCOS to TZ at end of trace. (3) Zeros all amplitude for times greater than TZ. (4) Applies an exponential taper to front of trace from zero crossing before TEXP to first sample.

| | | | | |
|---|---|---|---|---|
| Called by: | | FMED | | |
| Calls | : | None | | |
| Input | : | Z | - | complex time domain array to be filtered |
| | | TCOS | - | time to start cosine taper |
| | | TZ | - | time to end cosine taper and begin zero fill |
| | | TEXP | - | Routine searches back in time from TEXP to find a zero crossing. Trace amplitudes before the zero crossing are smoothed exponentially. Primary use is for causal truncations. Rarely used in practice. |
| | | DT | - | sample interval |
| Output | : | Z | - | tapered version |

Subroutine PREMED (IREF)

Routine to compute filter which maximizes the verimax norm in the frequency domain. The theory and a discussion of this application are given by Wiggins (1978) and Lundquist et al., (1980 a,b). The filter is initialized in FMED as a delayed delta function. The filter is applied in this routine to each DECON spectral ratio and the varimax norm is computed. The filter is then reestimated based upon the norm and reapplied to the data. The process is done for a specified number of iterations.

Note that the convergence of the technique is not guaranteed. It is not sufficient to declare a minimum change in the norm and let the program iterate until that threshold is found. Personal attention is required to maintain adequate control of the process.

| | | | | |
|---|---|---|---|---|
| Called by: | | FMED | | |
| Calls | : | COOLB | - | utility Fast Fourier Transform routine |
| | | CAUS | - | applies causal tapers to the filter |
| | | FMDOUT | - | outputs relative receiver functions and descriptive information to diskfile |
| Input | : | IREF | - | trace number used for reference trace |

All flags and parameters read by FMED are made available to PREMED in common blocks.

Output : Relative Receiver Functions are output to diskfiles, if requested, at the last iteration.

A disk file is generated with the output from each it iteration. This will be used for input to PLTMED for plotter output.

A separate diskfile is generated which allows monitoring of the varimax norms.

Subroutine CAUS (F, NN)

Routine tapers the FMED filter. Filter is transformed to time domain; all samples before first zero crossing are set to zero; all samples in the second half of the array are set to zero, and the array is transformed back to frequency.

| | | | | |
|---|---|---|---|---|
| Called by: | | PREMED | | |
| Calls | : | COOLB | - | utility Fast Fourier Transform routine |
| Input | : | F | - | FMED filter in complex frequency domain |
| | | NN | - | power of 2 defining length of F |
| Output | : | F | - | tapered version |

Subroutine FMDOUT (II, NOUT))

Routine to output a relative receiver function and its descriptive information to a diskfile.

| | | | | |
|---|---|---|---|---|
| Called by: | | PREMED | | |
| Calls | : | System dependent file open and close routines. | | |
| Input | : | II | - | station number for current RRF output |
| | | NOUT | - | number of points to output |
| | | All flags and parameters read by FMED are made available to FMDOUT in common blocks, including name of output files. | | |
| Output | : | Diskfiles containing NOUT points of relative receiver function for station II, along with descriptive information. | | |

Program PLTMED

This program plots the results of FMED. The results for each station at each iteration were written to file MEDPR by PREMED, so the user may plot some or all of the output. In normal usage, the analyst would first examine file FMEDFR which contains the varimax norms for each station and each iteration. Convergence and instablility are indicated by those norms, and the amount of plotting can be tailored to the amount of change in the waveform as determined by change in the norms.

| | | | | |
|---|---|---|---|---|
| Calls | : | System plot routines | | |
| Reads | : | IPITER | - | Flag determining which iterations to plot. |
| | | IPSTA | - | Flag determining which stations to plot. Output will be generated only when both IPITER and IPSTA are nonzero. |
| | | MEDPR | - | disk file containing output of FMED for each station at each iteration. The input data is present as iteration zero. |
| Output | : | Hard copy plots. | | |

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