

# NAG Library Function Document

## nag\_dwt\_2d (c09eac)

### 1 Purpose

nag\_dwt\_2d (c09eac) computes the two-dimensional discrete wavelet transform (DWT) at a single level. The initialization function nag\_wfilt\_2d (c09abc) must be called first to set up the DWT options.

### 2 Specification

```
#include <nag.h>
#include <nagc09.h>

void nag_dwt_2d (Integer m, Integer n, const double a[], Integer lda,
                double ca[], Integer ldca, double ch[], Integer ldch, double cv[],
                Integer ldcv, double cd[], Integer ldcd, Integer icomm[],
                NagError *fail)
```

### 3 Description

nag\_dwt\_2d (c09eac) computes the two-dimensional DWT of a given input data array, considered as a matrix  $A$ , at a single level. For a chosen wavelet filter pair, the output coefficients are obtained by applying convolution and downsampling by two to the input,  $A$ , first over columns and then to the result over rows. The matrix of approximation (or smooth) coefficients,  $C_a$ , is produced by the low pass filter over columns and rows; the matrix of horizontal coefficients,  $C_h$ , is produced by the high pass filter over columns and the low pass filter over rows; the matrix of vertical coefficients,  $C_v$ , is produced by the low pass filter over columns and the high pass filter over rows; and the matrix of diagonal coefficients,  $C_d$ , is produced by the high pass filter over columns and rows. To reduce distortion effects at the ends of the data array, several end extension methods are commonly used. Those provided are: periodic or circular convolution end extension, half-point symmetric end extension, whole-point symmetric end extension and zero end extension. The total number,  $n_{ct}$ , of coefficients computed for  $C_a$ ,  $C_h$ ,  $C_v$ , and  $C_d$  together and the number of columns of each coefficients matrix,  $n_{cn}$ , are returned by the initialization function nag\_wfilt\_2d (c09abc). These values can be used to calculate the number of rows of each coefficients matrix,  $n_{cm}$ , using the formula  $n_{cm} = n_{ct}/(4n_{cn})$ .

### 4 References

Daubechies I (1992) *Ten Lectures on Wavelets* SIAM, Philadelphia

### 5 Arguments

- 1: **m** – Integer *Input*  
*On entry:* number of rows,  $m$ , of data matrix  $A$ .  
*Constraint:* this must be the same as the value **m** passed to the initialization function nag\_wfilt\_2d (c09abc).
- 2: **n** – Integer *Input*  
*On entry:* number of columns,  $n$ , of data matrix  $A$ .  
*Constraint:* this must be the same as the value **n** passed to the initialization function nag\_wfilt\_2d (c09abc).

- 3: **a**[**lda** × **n**] – const double *Input*  
**Note:** the  $(i, j)$ th element of the matrix  $A$  is stored in **a**[( $j - 1$ ) × **lda** +  $i - 1$ ].  
*On entry:* the  $m$  by  $n$  data matrix  $A$ .
- 4: **lda** – Integer *Input*  
*On entry:* the stride separating matrix row elements in the array **a**.  
**Constraint:** **lda** ≥ **m**.
- 5: **ca**[*dim*] – double *Output*  
**Note:** the dimension, *dim*, of the array **ca** must be at least **ldca** ×  $n_{cn}$  where  $n_{cn}$  is the argument **nwcn** returned by function nag\_wfilt\_2d (c09abc).  
The  $(i, j)$ th element of the matrix is stored in **ca**[( $j - 1$ ) × **ldca** +  $i - 1$ ].  
*On exit:* contains the  $n_{cm}$  by  $n_{cn}$  matrix of approximation coefficients,  $C_a$ .
- 6: **ldca** – Integer *Input*  
*On entry:* the stride separating matrix row elements in the array **ca**.  
**Constraint:** **ldca** ≥  $n_{cm}$  where  $n_{cm} = n_{ct}/(4n_{cn})$  and  $n_{cn}$ ,  $n_{ct}$  are returned by the initialization function nag\_wfilt\_2d (c09abc).
- 7: **ch**[*dim*] – double *Output*  
**Note:** the dimension, *dim*, of the array **ch** must be at least **ldch** ×  $n_{cn}$  where  $n_{cn}$  is the argument **nwcn** returned by function nag\_wfilt\_2d (c09abc).  
The  $(i, j)$ th element of the matrix is stored in **ch**[( $j - 1$ ) × **ldch** +  $i - 1$ ].  
*On exit:* contains the  $n_{cm}$  by  $n_{cn}$  matrix of horizontal coefficients,  $C_h$ .
- 8: **ldch** – Integer *Input*  
*On entry:* the stride separating matrix row elements in the array **ch**.  
**Constraint:** **ldch** ≥  $n_{cm}$  where  $n_{cm} = n_{ct}/(4n_{cn})$  and  $n_{cn}$ ,  $n_{ct}$  are returned by the initialization function nag\_wfilt\_2d (c09abc).
- 9: **cv**[*dim*] – double *Output*  
**Note:** the dimension, *dim*, of the array **cv** must be at least **ldcv** ×  $n_{cn}$  where  $n_{cn}$  is the argument **nwcn** returned by function nag\_wfilt\_2d (c09abc).  
The  $(i, j)$ th element of the matrix is stored in **cv**[( $j - 1$ ) × **ldcv** +  $i - 1$ ].  
*On exit:* contains the  $n_{cm}$  by  $n_{cn}$  matrix of vertical coefficients,  $C_v$ .
- 10: **ldcv** – Integer *Input*  
*On entry:* the stride separating matrix row elements in the array **cv**.  
**Constraint:** **ldcv** ≥  $n_{cm}$  where  $n_{cm} = n_{ct}/(4n_{cn})$  and  $n_{cn}$ ,  $n_{ct}$  are returned by the initialization function nag\_wfilt\_2d (c09abc).
- 11: **cd**[*dim*] – double *Output*  
**Note:** the dimension, *dim*, of the array **cd** must be at least **ldcd** ×  $n_{cn}$  where  $n_{cn}$  is the argument **nwcn** returned by function nag\_wfilt\_2d (c09abc).  
The  $(i, j)$ th element of the matrix is stored in **cd**[( $j - 1$ ) × **ldcd** +  $i - 1$ ].  
*On exit:* contains the  $n_{cm}$  by  $n_{cn}$  matrix of diagonal coefficients,  $C_d$ .

- 12: **ldcd** – Integer *Input*  
*On entry:* the stride separating matrix row elements in the array **cd**.  
*Constraint:* **ldcd**  $\geq n_{cm}$  where  $n_{cm} = n_{ct}/(4n_{cn})$  and  $n_{cn}$ ,  $n_{ct}$  are returned by the initialization function nag\_wfilt\_2d (c09abc).
- 13: **icomm**[180] – Integer *Communication Array*  
*On entry:* contains details of the discrete wavelet transform and the problem dimension as setup in the call to the initialization function nag\_wfilt\_2d (c09abc).
- 14: **fail** – NagError \* *Input/Output*  
 The NAG error argument (see Section 2.7 in How to Use the NAG Library and its Documentation).

## 6 Error Indicators and Warnings

### NE\_ALLOC\_FAIL

Dynamic memory allocation failed.  
 See Section 2.3.1.2 in How to Use the NAG Library and its Documentation for further information.

### NE\_BAD\_PARAM

On entry, argument  $\langle value \rangle$  had an illegal value.

### NE\_INITIALIZATION

Either the initialization function has not been called first or **icomm** has been corrupted.  
 Either the initialization function was called with **wtrans** = Nag\_MultiLevel or **icomm** has been corrupted.

### NE\_INT

On entry, **ldca** =  $\langle value \rangle$ .  
 Constraint: **ldca**  $\geq \langle value \rangle$ , the number of wavelet coefficients in the first dimension.  
 On entry, **ldcd** =  $\langle value \rangle$ .  
 Constraint: **ldcd**  $\geq \langle value \rangle$ , the number of wavelet coefficients in the first dimension.  
 On entry, **ldch** =  $\langle value \rangle$ .  
 Constraint: **ldch**  $\geq \langle value \rangle$ , the number of wavelet coefficients in the first dimension.  
 On entry, **ldcv** =  $\langle value \rangle$ .  
 Constraint: **ldcv**  $\geq \langle value \rangle$ , the number of wavelet coefficients in the first dimension.  
 On entry, **m** =  $\langle value \rangle$ .  
 Constraint: **m** =  $\langle value \rangle$ , the value of **m** on initialization (see nag\_wfilt\_2d (c09abc)).  
 On entry, **n** =  $\langle value \rangle$ .  
 Constraint: **n** =  $\langle value \rangle$ , the value of **n** on initialization (see nag\_wfilt\_2d (c09abc)).

### NE\_INT\_2

On entry, **lda** =  $\langle value \rangle$  and **m** =  $\langle value \rangle$ .  
 Constraint: **lda**  $\geq m$ .

### NE\_INTERNAL\_ERROR

An internal error has occurred in this function. Check the function call and any array sizes. If the call is correct then please contact NAG for assistance.

An unexpected error has been triggered by this function. Please contact NAG.  
See Section 2.7.6 in How to Use the NAG Library and its Documentation for further information.

## NE\_NO\_LICENCE

Your licence key may have expired or may not have been installed correctly.  
See Section 2.7.5 in How to Use the NAG Library and its Documentation for further information.

## 7 Accuracy

The accuracy of the wavelet transform depends only on the floating-point operations used in the convolution and downsampling and should thus be close to *machine precision*.

## 8 Parallelism and Performance

nag\_dwt\_2d (c09eac) is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

Please consult the x06 Chapter Introduction for information on how to control and interrogate the OpenMP environment used within this function. Please also consult the Users' Note for your implementation for any additional implementation-specific information.

## 9 Further Comments

None.

## 10 Example

This example computes the two-dimensional discrete wavelet decomposition for a  $6 \times 6$  input matrix using the Daubechies wavelet, **wavnam** = Nag\_Daubechies4, with half point symmetric end extension.

### 10.1 Program Text

```

/* nag_dwt_2d (c09eac) Example Program.
 *
 * NAGPRODCODE Version.
 *
 * Copyright 2016 Numerical Algorithms Group.
 *
 * Mark 26, 2016.
 */

#include <string.h>
#include <nag.h>
#include <nag_stdlib.h>
#include <nagc09.h>
#include <nagx04.h>

int main(void)
{
    /* Scalars */
    Integer exit_status = 0;
    Integer i, j, m, n, nf, nwcm, nwc, nwct, nwl, pda, pdb, pdc;
    /* Arrays */
    char mode[24], wavnam[20], title[50];
    double *a = 0, *b = 0, *ca = 0, *cd = 0, *ch = 0, *cv = 0;
    Integer icomm[(180)];
    /* NAG types */
    Nag_Wavelet wavnamenum;
    Nag_WaveletMode modenum;
    Nag_MatrixType matrix = Nag_GeneralMatrix;
    Nag_OrderType order = Nag_ColMajor;
    Nag_DiagType diag = Nag_NonUnitDiag;
    NagError fail;

```

```

INIT_FAIL(fail);

printf("nag_dwt_2d (c09eac) Example Program Results\n\n");

/* Skip heading in data file and read problem parameters */
#ifdef _WIN32
scanf_s("%*[\n] %" NAG_IFMT "%" NAG_IFMT "%*[\n]", &m, &n);
#else
scanf("%*[\n] %" NAG_IFMT "%" NAG_IFMT "%*[\n]", &m, &n);
#endif
pda = m;
pdb = m;
#ifdef _WIN32
scanf_s("%19s%23s*[\n]\n", wavnam, (unsigned)_countof(wavnam), mode,
        (unsigned)_countof(mode));
#else
scanf("%19s%23s*[\n]\n", wavnam, mode);
#endif
if (!(a = NAG_ALLOC((pda) * (n), double)) ||
    !(b = NAG_ALLOC((pdb) * (n), double)))
{
    printf("Allocation failure\n");
    exit_status = -1;
    goto END;
}
printf(" Parameters read from file :: \n");
printf(" DWT :: Wavelet : %s\n", wavnam);
printf("      End mode: %s\n", mode);
fflush(stdout);

/*
 * nag_enum_name_to_value (x04nac).
 * Converts NAG enum member name to value
 */
wavnamenum = (Nag_Wavelet) nag_enum_name_to_value(wavnam);
modenum = (Nag_WaveletMode) nag_enum_name_to_value(mode);

/* Read data array */
#define A(I, J) a[(J-1)*pda + I-1]
for (i = 1; i <= m; i++)
#ifdef _WIN32
for (j = 1; j <= n; j++)
scanf_s("%lf", &A(i, j));
#else
for (j = 1; j <= n; j++)
scanf("%lf", &A(i, j));
#endif
#ifdef _WIN32
scanf_s("%*[\n] ");
#else
scanf("%*[\n] ");
#endif

printf("\n");
fflush(stdout);
nag_gen_real_mat_print_comp(order, matrix, diag, m, n, a, pda, "%8.4f",
        "Input Data      A :", Nag_NoLabels, 0,
        Nag_NoLabels, 0, 80, 0, 0, &fail);
if (fail.code != NE_NOERROR) {
    printf("Error from nag_gen_real_mat_print_comp (x04cbc).\n%s\n",
        fail.message);
    exit_status = 1;
    goto END;
}
printf("\n");

/* nag_wfilt_2d (c09abc).
 * Two-dimensional wavelet filter initialization
 */
nag_wfilt_2d(wavnamenum, Nag_SingleLevel, modenum, m, n, &nwl, &nf, &nwct,

```

```

        &nwcn, icomm, &fail);
if (fail.code != NE_NOERROR) {
    printf("Error from nag_wfilt_2d (c09abc).\n%s\n", fail.message);
    exit_status = 2;
    goto END;
}
nwcm = nwct / (4 * nwc);
if (!(ca = NAG_ALLOC((nwcm) * (nwc), double)) ||
    !(cd = NAG_ALLOC((nwcm) * (nwc), double)) ||
    !(cv = NAG_ALLOC((nwcm) * (nwc), double)) ||
    !(ch = NAG_ALLOC((nwcm) * (nwc), double))
    )
{
    printf("Allocation failure\n");
    exit_status = -1;
    goto END;
}

pdc = nwcm;
/* nag_dwt_2d (c09eac).
 * Two-dimensional discrete wavelet transform
 */
nag_dwt_2d(m, n, a, pda, ca, pdc, ch, pdc, cv, pdc, cd, pdc, icomm, &fail);
if (fail.code != NE_NOERROR) {
    printf("Error from nag_dwt_2d (c09eac).\n%s\n", fail.message);
    exit_status = 1;
    goto END;
}
fflush(stdout);

/* Print decomposition */
#ifdef _WIN32
    strcpy_s(title, (unsigned)_countof(title),
             "Approximation coefficients  CA :");
#else
    strcpy(title, "Approximation coefficients  CA :");
#endif
nag_gen_real_mat_print_comp(order, matrix, diag, nwcm, nwc, ca, pdc,
                            "%8.4f",
                            title, Nag_NoLabels, 0, Nag_NoLabels, 0, 80, 0,
                            0, &fail);

printf("\n");
fflush(stdout);
#ifdef _WIN32
    strcpy_s(title, (unsigned)_countof(title),
             "Diagonal coefficients      CD :");
#else
    strcpy(title, "Diagonal coefficients      CD :");
#endif
nag_gen_real_mat_print_comp(order, matrix, diag, nwcm, nwc, cd, pdc,
                            "%8.4f",
                            title, Nag_NoLabels, 0, Nag_NoLabels, 0, 80, 0,
                            0, &fail);

printf("\n");
fflush(stdout);
#ifdef _WIN32
    strcpy_s(title, (unsigned)_countof(title),
             "Horizontal coefficients     CH :");
#else
    strcpy(title, "Horizontal coefficients     CH :");
#endif
nag_gen_real_mat_print_comp(order, matrix, diag, nwcm, nwc, ch, pdc,
                            "%8.4f",
                            title, Nag_NoLabels, 0, Nag_NoLabels, 0, 80, 0,
                            0, &fail);

printf("\n");
fflush(stdout);
#ifdef _WIN32
    strcpy_s(title, (unsigned)_countof(title),
             "Vertical coefficients        CV :");
#else

```

```

    strcpy(title, "Vertical coefficients          CV :");
#endif
    nag_gen_real_mat_print_comp(order, matrix, diag, nwcm, nwc, cv, pdc,
                               "%8.4f",
                               title, Nag_NoLabels, 0, Nag_NoLabels, 0, 80, 0,
                               0, &fail);

    printf("\n");

    /* nag_idwt_2d (c09eac).
     * Two-dimensional inverse discrete wavelet transform
     */
    nag_idwt_2d(m, n, ca, pdc, ch, pdc, cv, pdc, cd, pdc, b, pdb, icomm, &fail);
    if (fail.code != NE_NOERROR) {
        printf("Error from nag_idwt_2d (c09eac).\n%s\n", fail.message);
        exit_status = 3;
        goto END;
    }
    fflush(stdout);

    /* Print reconstruction */
#ifdef _WIN32
    strcpy_s(title, (unsigned)_countof(title),
            "Reconstruction          B :");
#else
    strcpy(title, "Reconstruction          B :");
#endif
    nag_gen_real_mat_print_comp(order, matrix, diag, m, n, b, pdb, "%8.4f",
                               title,
                               Nag_NoLabels, 0, Nag_NoLabels, 0, 80, 0, 0,
                               &fail);
END:
    NAG_FREE(a);
    NAG_FREE(b);
    NAG_FREE(ca);
    NAG_FREE(cd);
    NAG_FREE(ch);
    NAG_FREE(cv);
    return exit_status;
}

```

## 10.2 Program Data

```

nag_dwt_2d (c09eac) Example Program Data
6
Nag_Daubechies4 Nag_HalfPointSymmetric          : m,n
: wavnam, mode
8.0000  7.0000  3.0000  3.0000  1.0000  1.0000
4.0000  6.0000  1.0000  5.0000  2.0000  9.0000
8.0000  1.0000  4.0000  9.0000  3.0000  7.0000
9.0000  3.0000  8.0000  2.0000  4.0000  3.0000
1.0000  3.0000  7.0000  1.0000  5.0000  2.0000
4.0000  3.0000  7.0000  7.0000  6.0000  1.0000 :a

```

## 10.3 Program Results

```
nag_dwt_2d (c09eac) Example Program Results
```

```
Parameters read from file ::
```

```
DWT :: Wavelet : Nag_Daubechies4
      End mode: Nag_HalfPointSymmetric
```

```
Input Data      A :
8.0000  7.0000  3.0000  3.0000  1.0000  1.0000
4.0000  6.0000  1.0000  5.0000  2.0000  9.0000
8.0000  1.0000  4.0000  9.0000  3.0000  7.0000
9.0000  3.0000  8.0000  2.0000  4.0000  3.0000
1.0000  3.0000  7.0000  1.0000  5.0000  2.0000
4.0000  3.0000  7.0000  7.0000  6.0000  1.0000
```

```
Approximation coefficients CA :
6.3591 10.3477 8.0995 10.3210 8.7587 3.5783
```

11.5754	6.3762	12.1704	7.4521	8.6977	14.8535
2.0630	8.4499	15.4726	12.1764	3.8920	2.7112
10.2143	6.2445	13.8571	8.1060	7.7701	13.2127
6.3353	8.7805	10.2727	10.0472	6.8614	7.5814
11.7141	11.1018	5.2923	8.1272	14.5540	2.5729

Diagonal coefficients			CD :		
0.4777	1.0230	-0.3147	0.0625	0.0831	-1.3316
1.0689	1.5671	-2.1422	0.5565	1.7593	-2.8097
-0.9555	-1.9276	0.9195	-0.2228	-0.5125	2.6989
0.2899	0.4453	-0.5695	0.1541	0.4749	-0.7946
0.4944	1.4145	0.3488	-0.1187	-0.6212	-1.5177
-1.3753	-2.5224	1.7581	-0.4316	-1.1835	3.7547

Horizontal coefficients			CH :		
0.4100	-0.1827	1.5354	0.0784	0.8101	-1.3594
2.3496	-0.9422	2.3780	-1.0540	2.7743	-2.2648
-1.2690	0.0152	-6.9338	-1.7435	-1.6917	1.2388
0.6317	-0.0969	2.3300	0.4637	0.6365	-0.1162
-0.2343	0.3923	5.5457	2.1818	0.2103	-0.8573
-1.8880	0.8142	-4.8552	0.0736	-2.7395	3.3590

Vertical coefficients			CV :		
1.5365	5.9678	3.4309	-1.0585	-5.0275	-4.8492
0.6779	-0.0294	-5.3274	1.6483	4.8689	-1.8383
-1.1065	-2.8791	0.1535	0.0982	0.8417	2.8923
-0.1359	-2.6633	-5.8549	1.8440	6.2403	0.5697
1.4244	5.2140	1.6410	-0.4669	-3.2369	-4.5757
1.0288	2.2521	0.0574	-0.1359	-0.5170	-2.6854

Reconstruction			B :		
8.0000	7.0000	3.0000	3.0000	1.0000	1.0000
4.0000	6.0000	1.0000	5.0000	2.0000	9.0000
8.0000	1.0000	4.0000	9.0000	3.0000	7.0000
9.0000	3.0000	8.0000	2.0000	4.0000	3.0000
1.0000	3.0000	7.0000	1.0000	5.0000	2.0000
4.0000	3.0000	7.0000	7.0000	6.0000	1.0000

---