

# NAG Library Function Document

## nag\_real\_band\_lin\_solve (f04bbc)

### 1 Purpose

nag\_real\_band\_lin\_solve (f04bbc) computes the solution to a real system of linear equations  $AX = B$ , where  $A$  is an  $n$  by  $n$  band matrix, with  $k_l$  subdiagonals and  $k_u$  superdiagonals, and  $X$  and  $B$  are  $n$  by  $r$  matrices. An estimate of the condition number of  $A$  and an error bound for the computed solution are also returned.

### 2 Specification

```
#include <nag.h>
#include <nagf04.h>

void nag_real_band_lin_solve (Nag_OrderType order, Integer n, Integer kl,
    Integer ku, Integer nrhs, double ab[], Integer pdab, Integer ipiv[],
    double b[], Integer pdb, double *rcond, double *errbnd, NagError *fail)
```

### 3 Description

The  $LU$  decomposition with partial pivoting and row interchanges is used to factor  $A$  as  $A = PLU$ , where  $P$  is a permutation matrix,  $L$  is the product of permutation matrices and unit lower triangular matrices with  $k_l$  subdiagonals, and  $U$  is upper triangular with  $(k_l + k_u)$  superdiagonals. The factored form of  $A$  is then used to solve the system of equations  $AX = B$ .

### 4 References

Anderson E, Bai Z, Bischof C, Blackford S, Demmel J, Dongarra J J, Du Croz J J, Greenbaum A, Hammarling S, McKenney A and Sorensen D (1999) *LAPACK Users' Guide* (3rd Edition) SIAM, Philadelphia <http://www.netlib.org/lapack/lug>

Higham N J (2002) *Accuracy and Stability of Numerical Algorithms* (2nd Edition) SIAM, Philadelphia

### 5 Arguments

- 1: **order** – Nag\_OrderType *Input*  
*On entry:* the **order** argument specifies the two-dimensional storage scheme being used, i.e., row-major ordering or column-major ordering. C language defined storage is specified by **order** = Nag\_RowMajor. See Section 2.3.1.3 in How to Use the NAG Library and its Documentation for a more detailed explanation of the use of this argument.  
*Constraint:* **order** = Nag\_RowMajor or Nag\_ColMajor.
- 2: **n** – Integer *Input*  
*On entry:* the number of linear equations  $n$ , i.e., the order of the matrix  $A$ .  
*Constraint:* **n**  $\geq$  0.
- 3: **kl** – Integer *Input*  
*On entry:* the number of subdiagonals  $k_l$ , within the band of  $A$ .  
*Constraint:* **kl**  $\geq$  0.

- 4: **ku** – Integer *Input*  
*On entry:* the number of superdiagonals  $k_u$ , within the band of  $A$ .  
*Constraint:*  $\mathbf{ku} \geq 0$ .
- 5: **nrhs** – Integer *Input*  
*On entry:* the number of right-hand sides  $r$ , i.e., the number of columns of the matrix  $B$ .  
*Constraint:*  $\mathbf{nrhs} \geq 0$ .
- 6: **ab**[*dim*] – double *Input/Output*  
**Note:** the dimension, *dim*, of the array **ab** must be at least  $\max(1, \mathbf{pdab} \times \mathbf{n})$ .  
*On entry:* the  $n$  by  $n$  matrix  $A$ .  
This is stored as a notional two-dimensional array with row elements or column elements stored contiguously. The storage of elements  $A_{ij}$ , for row  $i = 1, \dots, n$  and column  $j = \max(1, i - k_l), \dots, \min(n, i + k_u)$ , depends on the **order** argument as follows:  
if **order** = Nag\_ColMajor,  $A_{ij}$  is stored as  $\mathbf{ab}[(j - 1) \times \mathbf{pdab} + \mathbf{kl} + \mathbf{ku} + i - j]$ ;  
if **order** = Nag\_RowMajor,  $A_{ij}$  is stored as  $\mathbf{ab}[(i - 1) \times \mathbf{pdab} + \mathbf{kl} + j - i]$ .  
See Section 9 for further details.  
*On exit:* **ab** is overwritten by details of the factorization.  
The elements,  $u_{ij}$ , of the upper triangular band factor  $U$  with  $k_l + k_u$  super-diagonals, and the multipliers,  $l_{ij}$ , used to form the lower triangular factor  $L$  are stored. The elements  $u_{ij}$ , for  $i = 1, \dots, n$  and  $j = i, \dots, \min(n, i + k_l + k_u)$ , and  $l_{ij}$ , for  $i = 1, \dots, n$  and  $j = \max(1, i - k_l), \dots, i$ , are stored where  $A_{ij}$  is stored on entry.
- 7: **pdab** – Integer *Input*  
*On entry:* the stride separating row or column elements (depending on the value of **order**) of the matrix  $A$  in the array **ab**.  
*Constraint:*  $\mathbf{pdab} \geq 2 \times \mathbf{kl} + \mathbf{ku} + 1$ .
- 8: **ipiv**[**n**] – Integer *Output*  
*On exit:* if **fail.code** = NE\_NOERROR, the pivot indices that define the permutation matrix  $P$ ; at the  $i$ th step row  $i$  of the matrix was interchanged with row **ipiv**[ $i - 1$ ]. **ipiv**[ $i - 1$ ] =  $i$  indicates a row interchange was not required.
- 9: **b**[*dim*] – double *Input/Output*  
**Note:** the dimension, *dim*, of the array **b** must be at least  
 $\max(1, \mathbf{pdb} \times \mathbf{nrhs})$  when **order** = Nag\_ColMajor;  
 $\max(1, \mathbf{n} \times \mathbf{pdb})$  when **order** = Nag\_RowMajor.  
The ( $i, j$ )th element of the matrix  $B$  is stored in  
 $\mathbf{b}[(j - 1) \times \mathbf{pdb} + i - 1]$  when **order** = Nag\_ColMajor;  
 $\mathbf{b}[(i - 1) \times \mathbf{pdb} + j - 1]$  when **order** = Nag\_RowMajor.  
*On entry:* the  $n$  by  $r$  matrix of right-hand sides  $B$ .  
*On exit:* if **fail.code** = NE\_NOERROR or NE\_RCOND, the  $n$  by  $r$  solution matrix  $X$ .
- 10: **pdb** – Integer *Input*  
*On entry:* the stride separating row or column elements (depending on the value of **order**) in the array **b**.

Constraints:

if **order** = Nag\_ColMajor, **pdb**  $\geq \max(1, \mathbf{n})$ ;  
 if **order** = Nag\_RowMajor, **pdb**  $\geq \max(1, \mathbf{nrhs})$ .

11: **rcond** – double \*

Output

On exit: if no constraints are violated, an estimate of the reciprocal of the condition number of the matrix  $A$ , computed as  $\mathbf{rcond} = 1 / (\|A\|_1 \|A^{-1}\|_1)$ .

12: **errbnd** – double \*

Output

On exit: if **fail.code** = NE\_NOERROR or NE\_RCOND, an estimate of the forward error bound for a computed solution  $\hat{x}$ , such that  $\|\hat{x} - x\|_1 / \|x\|_1 \leq \mathbf{errbnd}$ , where  $\hat{x}$  is a column of the computed solution returned in the array **b** and  $x$  is the corresponding column of the exact solution  $X$ . If **rcond** is less than *machine precision*, then **errbnd** is returned as unity.

13: **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.

The Integer allocatable memory required is  $\mathbf{n}$ , and the double allocatable memory required is  $3 \times \mathbf{n}$ . In this case the factorization and the solution  $X$  have been computed, but **rcond** and **errbnd** have not been computed.

See Section 3.2.1.2 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\_INT

On entry, **kl** =  $\langle value \rangle$ .

Constraint: **kl**  $\geq 0$ .

On entry, **ku** =  $\langle value \rangle$ .

Constraint: **ku**  $\geq 0$ .

On entry, **n** =  $\langle value \rangle$ .

Constraint: **n**  $\geq 0$ .

On entry, **nrhs** =  $\langle value \rangle$ .

Constraint: **nrhs**  $\geq 0$ .

On entry, **pdab** =  $\langle value \rangle$ .

Constraint: **pdab**  $> 0$ .

On entry, **pdb** =  $\langle value \rangle$ .

Constraint: **pdb**  $> 0$ .

### NE\_INT\_2

On entry, **pdb** =  $\langle value \rangle$  and **n** =  $\langle value \rangle$ .

Constraint: **pdb**  $\geq \max(1, \mathbf{n})$ .

On entry, **pdb** =  $\langle value \rangle$  and **nrhs** =  $\langle value \rangle$ .

Constraint: **pdb**  $\geq \max(1, \mathbf{nrhs})$ .

**NE\_INT\_3**

On entry, **pdab** =  $\langle value \rangle$ , **kl** =  $\langle value \rangle$  and **ku** =  $\langle value \rangle$ .  
 Constraint: **pdab**  $\geq 2 \times \mathbf{kl} + \mathbf{ku} + 1$ .

**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 3.6.6 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 3.6.5 in How to Use the NAG Library and its Documentation for further information.

**NE\_RCOND**

A solution has been computed, but **rcond** is less than *machine precision* so that the matrix  $A$  is numerically singular.

**NE\_SINGULAR**

Diagonal element  $\langle value \rangle$  of the upper triangular factor is zero. The factorization has been completed, but the solution could not be computed.

**7 Accuracy**

The computed solution for a single right-hand side,  $\hat{x}$ , satisfies an equation of the form

$$(A + E)\hat{x} = b,$$

where

$$\|E\|_1 = O(\epsilon)\|A\|_1$$

and  $\epsilon$  is the *machine precision*. An approximate error bound for the computed solution is given by

$$\frac{\|\hat{x} - x\|_1}{\|x\|_1} \leq \kappa(A) \frac{\|E\|_1}{\|A\|_1},$$

where  $\kappa(A) = \|A^{-1}\|_1 \|A\|_1$ , the condition number of  $A$  with respect to the solution of the linear equations. `nag_real_band_lin_solve` (f04bbc) uses the approximation  $\|E\|_1 = \epsilon \|A\|_1$  to estimate **errbnd**. See Section 4.4 of Anderson *et al.* (1999) for further details.

**8 Parallelism and Performance**

`nag_real_band_lin_solve` (f04bbc) is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

`nag_real_band_lin_solve` (f04bbc) makes calls to BLAS and/or LAPACK routines, which may be threaded within the vendor library used by this implementation. Consult the documentation for the vendor library for further information.

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**

The band storage scheme for the array **ab** stored in `Nag_ColMajor` is illustrated by the following example, when  $n = 5$ ,  $k_l = 2$ , and  $k_u = 1$ . Storage of the band matrix  $A$  in the array **ab**:

Band matrix $A$	Band storage in array $\mathbf{ab}$	
	order = Nag_ColMajor	order = Nag_RowMajor
$a_{11}$ $a_{12}$	* * * + +	* * $a_{11}$ $a_{12}$ + +
$a_{21}$ $a_{22}$ $a_{23}$	* * + + +	* $a_{21}$ $a_{22}$ $a_{23}$ + +
$a_{31}$ $a_{32}$ $a_{33}$ $a_{34}$	* $a_{12}$ $a_{23}$ $a_{34}$ $a_{45}$	$a_{31}$ $a_{32}$ $a_{33}$ $a_{34}$ + *
$a_{42}$ $a_{43}$ $a_{44}$ $a_{45}$	$a_{11}$ $a_{22}$ $a_{33}$ $a_{44}$ $a_{55}$	$a_{42}$ $a_{43}$ $a_{44}$ $a_{45}$ * *
$a_{53}$ $a_{54}$ $a_{55}$	$a_{21}$ $a_{32}$ $a_{43}$ $a_{54}$ *	$a_{53}$ $a_{54}$ $a_{55}$ * * *
	$a_{31}$ $a_{42}$ $a_{53}$ * *	

Array elements marked \* need not be set and are not referenced by the function. Array elements marked + need not be set, but are defined on exit from the function and contain the elements  $u_{13}$ ,  $u_{14}$ ,  $u_{24}$ ,  $u_{25}$  and  $u_{35}$ . In this example when **order** = Nag\_ColMajor the first referenced element of **ab** is **ab**[3] =  $a_{11}$ ; while for **order** = Nag\_RowMajor the first referenced element is **ab**[2] =  $a_{11}$ .

In general, elements  $a_{ij}$  are stored as follows:

if **order** = Nag\_ColMajor,  $a_{ij}$  are stored in **ab**[( $j - 1$ )  $\times$  **pdab** + **kl** + **ku** +  $i - j$ ]

if **order** = Nag\_RowMajor,  $a_{ij}$  are stored in **ab**[( $i - 1$ )  $\times$  **pdab** + **kl** +  $j - i$ ]

where  $\max(1, i - \mathbf{kl}) \leq j \leq \min(\mathbf{n}, i + \mathbf{ku})$ .

The total number of floating-point operations required to solve the equations  $AX = B$  depends upon the pivoting required, but if  $n \gg k_l + k_u$  then it is approximately bounded by  $O(nk_l(k_l + k_u))$  for the factorization and  $O(n(2k_l + k_u)r)$  for the solution following the factorization. The condition number estimation typically requires between four and five solves and never more than eleven solves, following the factorization.

In practice the condition number estimator is very reliable, but it can underestimate the true condition number; see Section 15.3 of Higham (2002) for further details.

The complex analogue of nag\_real\_band\_lin\_solve (f04bbc) is nag\_complex\_band\_lin\_solve (f04cbc).

## 10 Example

This example solves the equations

$$AX = B,$$

where  $A$  is the band matrix

$$A = \begin{pmatrix} -0.23 & 2.54 & -3.66 & 0 \\ -6.98 & 2.46 & -2.73 & -2.13 \\ 0 & 2.56 & 2.46 & 4.07 \\ 0 & 0 & -4.78 & -3.82 \end{pmatrix} \quad \text{and} \quad B = \begin{pmatrix} 4.42 & -36.01 \\ 27.13 & -31.67 \\ -6.14 & -1.16 \\ 10.50 & -25.82 \end{pmatrix}.$$

An estimate of the condition number of  $A$  and an approximate error bound for the computed solutions are also printed.

### 10.1 Program Text

```

/* nag_real_band_lin_solve (f04bbc) Example Program.
 *
 * NAGPRODCODE Version.
 *
 * Copyright 2016 Numerical Algorithms Group.
 *
 * Mark 26, 2016.
 */

#include <stdio.h>
#include <nag.h>
#include <nag_stdlib.h>

```

```

#include <nagf04.h>
#include <nagx04.h>

int main(void)
{
    /* Scalars */
    double errbnd, rcond;
    Integer exit_status, i, j, kl, ku, n, nrhs, pdab, pdb;

    /* Arrays */
    double *ab = 0, *b = 0;
    Integer *ipiv = 0;

    /* Nag Types */
    NagError fail;
    Nag_OrderType order;

#ifdef NAG_COLUMN_MAJOR
#define AB(I, J) ab[(J-1)*pdab + kl + ku + I - J]
#define B(I, J) b[(J-1)*pdb + I - 1]
    order = Nag_ColMajor;
#else
#define AB(I, J) ab[(I-1)*pdab + kl + J - I]
#define B(I, J) b[(I-1)*pdb + J - 1]
    order = Nag_RowMajor;
#endif

    exit_status = 0;
    INIT_FAIL(fail);

    printf("nag_real_band_lin_solve (f04bbc) Example Program Results\n\n");

    /* Skip heading in data file */
#ifdef _WIN32
    scanf_s("%*[\n] ");
#else
    scanf("%*[\n] ");
#endif

#ifdef _WIN32
    scanf_s("%" NAG_IFMT "%" NAG_IFMT "%" NAG_IFMT "%" NAG_IFMT "%*[\n] ",
            &n, &kl, &ku, &nrhs);
#else
    scanf("%" NAG_IFMT "%" NAG_IFMT "%" NAG_IFMT "%" NAG_IFMT "%*[\n] ",
            &n, &kl, &ku, &nrhs);
#endif

    if (n >= 0 && kl >= 0 && ku >= 0 && nrhs >= 0) {
        /* Allocate memory */
        if (!(ab = NAG_ALLOC((2 * kl + ku + 1) * n, double)) ||
            !(b = NAG_ALLOC(n * nrhs, double)) || !(ipiv = NAG_ALLOC(n, Integer)))
        {
            printf("Allocation failure\n");
            exit_status = -1;
            goto END;
        }
        pdab = 2 * kl + ku + 1;
#ifdef NAG_COLUMN_MAJOR
        pdb = n;
#else
        pdb = nrhs;
#endif
    }
    else {
        printf("%s\n", "One or more of nmax, kl, ku or nrhs is" " too small");
        exit_status = 1;
        return exit_status;
    }
    /* Read A and B from data file */
    for (i = 1; i <= n; ++i) {
        for (j = MAX(i - kl, 1); j <= MIN(i + ku, n); ++j) {

```

```

#ifdef _WIN32
    scanf_s("%lf", &AB(i, j));
#else
    scanf("%lf", &AB(i, j));
#endif
    }
}
#ifdef _WIN32
    scanf_s("%*[\n] ");
#else
    scanf("%*[\n] ");
#endif

    for (i = 1; i <= n; ++i) {
        for (j = 1; j <= nrhs; ++j) {
#ifdef _WIN32
            scanf_s("%lf", &B(i, j));
#else
            scanf("%lf", &B(i, j));
#endif
        }
    }
#ifdef _WIN32
    scanf_s("%*[\n] ");
#else
    scanf("%*[\n] ");
#endif

/* Solve the equations AX = B for X */
/* nag_real_band_lin_solve (f04bbc).
 * Computes the solution and error-bound to a real banded
 * system of linear equations
 */
nag_real_band_lin_solve(order, n, kl, ku, nrhs, ab, pdab, ipiv, b,
                        pdb, &rcond, &errbnd, &fail);
if (fail.code == NE_NOERROR) {
    /* Print solution, estimate of condition number and approximate */
    /* error bound */

    /* nag_gen_real_mat_print (x04cac).
     * Print real general matrix (easy-to-use)
     */
    fflush(stdout);
    nag_gen_real_mat_print(order, Nag_GeneralMatrix, Nag_NonUnitDiag,
                          n, nrhs, b, pdb, "Solution", 0, &fail);
    if (fail.code != NE_NOERROR) {
        printf("Error from nag_gen_real_mat_print (x04cac).\n%s\n",
              fail.message);
        exit_status = 1;
        goto END;
    }

    printf("\n%s\n%6s%10.1e\n\n",
          "Estimate of condition number", "", 1.0 / rcond);

    printf("%s\n%6s%10.1e\n\n",
          "Estimate of error bound for computed solutions", "", errbnd);
}
else if (fail.code == NE_RCOND) {
    /* Matrix A is numerically singular. Print estimate of */
    /* reciprocal of condition number and solution */
    printf("\n");
    printf("%s\n%6s%10.1e\n\n",
          "Estimate of reciprocal of condition number", "", rcond);
    /* nag_gen_real_mat_print (x04cac), see above. */
    fflush(stdout);
    nag_gen_real_mat_print(order, Nag_GeneralMatrix, Nag_NonUnitDiag,
                          n, nrhs, b, pdb, "Solution", 0, &fail);
    if (fail.code != NE_NOERROR) {
        printf("Error from nag_gen_real_mat_print (x04cac).\n%s\n",
              fail.message);
    }
}

```

```

        exit_status = 1;
        goto END;
    }
}
else if (fail.code == NE_SINGULAR) {
    /* The upper triangular matrix U is exactly singular.  Print */
    /* details of factorization */
    printf("\n");
    /* nag_band_real_mat_print (x04cec).
    * Print real packed banded matrix (easy-to-use)
    */
    fflush(stdout);
    nag_band_real_mat_print(order, n, n, kl, kl + ku, ab, pdab,
        "Details of factorization", 0, &fail);
    if (fail.code != NE_NOERROR) {
        printf("Error from nag_band_real_mat_print (x04cec).\n%s\n",
            fail.message);
        exit_status = 1;
        goto END;
    }

    /* Print pivot indices */
    printf("\n%s\n", "Pivot indices");
    for (i = 1; i <= n; ++i) {
        printf("%11" NAG_IFMT "%s", ipiv[i - 1],
            i % 7 == 0 || i == n ? "\n" : " ");
    }
    printf("\n");
}
else {
    printf("Error from nag_real_band_lin_solve (f04bbc).\n%s\n",
        fail.message);
    exit_status = 1;
    goto END;
}

END:
    NAG_FREE(ab);
    NAG_FREE(b);
    NAG_FREE(ipiv);

    return exit_status;
}

```

## 10.2 Program Data

nag\_real\_band\_lin\_solve (f04bbc) Example Program Data

```

    4      1      2      2      :Values of N, KL, KU and NRHS

-0.23   2.54  -3.66
-6.98   2.46  -2.73  -2.13
         2.56   2.46   4.07
         -4.78  -3.82 :End of matrix A

    4.42 -36.01
    27.13 -31.67
    -6.14  -1.16
    10.50 -25.82           :End of matrix B

```

## 10.3 Program Results

nag\_real\_band\_lin\_solve (f04bbc) Example Program Results

```

Solution
          1          2
1      -2.0000      1.0000
2       3.0000     -4.0000
3       1.0000      7.0000
4      -4.0000     -2.0000

```



Estimate of condition number  
5.6e+01

Estimate of error bound for computed solutions  
6.3e-15

---