

NAG Library Function Document

nag_zporfs (f07fvc)

1 Purpose

nag_zporfs (f07fvc) returns error bounds for the solution of a complex Hermitian positive definite system of linear equations with multiple right-hand sides, $AX = B$. It improves the solution by iterative refinement, in order to reduce the backward error as much as possible.

2 Specification

```
#include <nag.h>
#include <nagf07.h>

void nag_zporfs (Nag_OrderType order, Nag_UploType uplo, Integer n,
                Integer nrhs, const Complex a[], Integer pda, const Complex af[],
                Integer pdaf, const Complex b[], Integer pdb, Complex x[], Integer pdx,
                double ferr[], double berr[], NagError *fail)
```

3 Description

nag_zporfs (f07fvc) returns the backward errors and estimated bounds on the forward errors for the solution of a complex Hermitian positive definite system of linear equations with multiple right-hand sides $AX = B$. The function handles each right-hand side vector (stored as a column of the matrix B) independently, so we describe the function of nag_zporfs (f07fvc) in terms of a single right-hand side b and solution x .

Given a computed solution x , the function computes the *component-wise backward error* β . This is the size of the smallest relative perturbation in each element of A and b such that x is the exact solution of a perturbed system

$$(A + \delta A)x = b + \delta b$$

$$|\delta a_{ij}| \leq \beta |a_{ij}| \quad \text{and} \quad |\delta b_i| \leq \beta |b_i|.$$

Then the function estimates a bound for the *component-wise forward error* in the computed solution, defined by:

$$\max_i |x_i - \hat{x}_i| / \max_i |x_i|$$

where \hat{x} is the true solution.

For details of the method, see the f07 Chapter Introduction.

4 References

Golub G H and Van Loan C F (1996) *Matrix Computations* (3rd Edition) Johns Hopkins University Press, Baltimore

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: **uplo** – Nag_UploType *Input*
On entry: specifies whether the upper or lower triangular part of A is stored and how A is to be factorized.
uplo = Nag_Upper
 The upper triangular part of A is stored and A is factorized as $U^H U$, where U is upper triangular.
uplo = Nag_Lower
 The lower triangular part of A is stored and A is factorized as LL^H , where L is lower triangular.
Constraint: **uplo** = Nag_Upper or Nag_Lower.
- 3: **n** – Integer *Input*
On entry: n , the order of the matrix A .
Constraint: **n** ≥ 0 .
- 4: **nrhs** – Integer *Input*
On entry: r , the number of right-hand sides.
Constraint: **nrhs** ≥ 0 .
- 5: **a**[*dim*] – const Complex *Input*
Note: the dimension, *dim*, of the array **a** must be at least $\max(1, \mathbf{pda} \times \mathbf{n})$.
On entry: the n by n original Hermitian positive definite matrix A as supplied to nag_zpotrf (f07frc).
- 6: **pda** – Integer *Input*
On entry: the stride separating row or column elements (depending on the value of **order**) of the matrix in the array **a**.
Constraint: **pda** $\geq \max(1, \mathbf{n})$.
- 7: **af**[*dim*] – const Complex *Input*
Note: the dimension, *dim*, of the array **af** must be at least $\max(1, \mathbf{pdaf} \times \mathbf{n})$.
On entry: the Cholesky factor of A , as returned by nag_zpotrf (f07frc).
- 8: **pdaf** – Integer *Input*
On entry: the stride separating row or column elements (depending on the value of **order**) of the matrix in the array **af**.
Constraint: **pdaf** $\geq \max(1, \mathbf{n})$.
- 9: **b**[*dim*] – const Complex *Input*
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 right-hand side matrix B .

- 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, **n**);
 if **order** = Nag_RowMajor, **pdb** \geq max(1, **nrhs**).
- 11: **x**[*dim*] – Complex *Input/Output*
Note: the dimension, *dim*, of the array **x** must be at least
 max(1, **pdx** \times **nrhs**) when **order** = Nag_ColMajor;
 max(1, **n** \times **pdx**) when **order** = Nag_RowMajor.
 The (*i*, *j*)th element of the matrix *X* is stored in
x[(*j* – 1) \times **pdx** + *i* – 1] when **order** = Nag_ColMajor;
x[(*i* – 1) \times **pdx** + *j* – 1] when **order** = Nag_RowMajor.
On entry: the *n* by *r* solution matrix *X*, as returned by nag_zpotrs (f07fsc).
On exit: the improved solution matrix *X*.
- 12: **pdx** – Integer *Input*
On entry: the stride separating row or column elements (depending on the value of **order**) in the array **x**.
Constraints:
 if **order** = Nag_ColMajor, **pdx** \geq max(1, **n**);
 if **order** = Nag_RowMajor, **pdx** \geq max(1, **nrhs**).
- 13: **ferr**[**nrhs**] – double *Output*
On exit: **ferr**[*j* – 1] contains an estimated error bound for the *j*th solution vector, that is, the *j*th column of *X*, for *j* = 1, 2, ..., *r*.
- 14: **berr**[**nrhs**] – double *Output*
On exit: **berr**[*j* – 1] contains the component-wise backward error bound β for the *j*th solution vector, that is, the *j*th column of *X*, for *j* = 1, 2, ..., *r*.
- 15: **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 3.2.1.2 in How to Use the NAG Library and its Documentation for further information.

NE_BAD_PARAM

On entry, argument *value* had an illegal value.

NE_INT

On entry, **n** = $\langle value \rangle$.
 Constraint: **n** ≥ 0 .

On entry, **nrhs** = $\langle value \rangle$.
 Constraint: **nrhs** ≥ 0 .

On entry, **pda** = $\langle value \rangle$.
 Constraint: **pda** > 0 .

On entry, **pdaf** = $\langle value \rangle$.
 Constraint: **pdaf** > 0 .

On entry, **pdb** = $\langle value \rangle$.
 Constraint: **pdb** > 0 .

On entry, **pdx** = $\langle value \rangle$.
 Constraint: **pdx** > 0 .

NE_INT_2

On entry, **pda** = $\langle value \rangle$ and **n** = $\langle value \rangle$.
 Constraint: **pda** $\geq \max(1, \mathbf{n})$.

On entry, **pdaf** = $\langle value \rangle$ and **n** = $\langle value \rangle$.
 Constraint: **pdaf** $\geq \max(1, \mathbf{n})$.

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

On entry, **pdx** = $\langle value \rangle$ and **n** = $\langle value \rangle$.
 Constraint: **pdx** $\geq \max(1, \mathbf{n})$.

On entry, **pdx** = $\langle value \rangle$ and **nrhs** = $\langle value \rangle$.
 Constraint: **pdx** $\geq \max(1, \mathbf{nrhs})$.

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.

7 Accuracy

The bounds returned in **ferr** are not rigorous, because they are estimated, not computed exactly; but in practice they almost always overestimate the actual error.

8 Parallelism and Performance

nag_zporfs (f07fvc) is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

nag_zporfs (f07fvc) 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

For each right-hand side, computation of the backward error involves a minimum of $16n^2$ real floating-point operations. Each step of iterative refinement involves an additional $24n^2$ real operations. At most five steps of iterative refinement are performed, but usually only one or two steps are required.

Estimating the forward error involves solving a number of systems of linear equations of the form $Ax = b$; the number is usually 5 and never more than 11. Each solution involves approximately $8n^2$ real operations.

The real analogue of this function is nag_dporfs (f07fhc).

10 Example

This example solves the system of equations $AX = B$ using iterative refinement and to compute the forward and backward error bounds, where

$$A = \begin{pmatrix} 3.23 + 0.00i & 1.51 - 1.92i & 1.90 + 0.84i & 0.42 + 2.50i \\ 1.51 + 1.92i & 3.58 + 0.00i & -0.23 + 1.11i & -1.18 + 1.37i \\ 1.90 - 0.84i & -0.23 - 1.11i & 4.09 + 0.00i & 2.33 - 0.14i \\ 0.42 - 2.50i & -1.18 - 1.37i & 2.33 + 0.14i & 4.29 + 0.00i \end{pmatrix}$$

and

$$B = \begin{pmatrix} 3.93 - 6.14i & 1.48 + 6.58i \\ 6.17 + 9.42i & 4.65 - 4.75i \\ -7.17 - 21.83i & -4.91 + 2.29i \\ 1.99 - 14.38i & 7.64 - 10.79i \end{pmatrix}.$$

Here A is Hermitian positive definite and must first be factorized by nag_zpotrf (f07frc).

10.1 Program Text

```

/* nag_zporfs (f07fvc) Example Program.
 *
 * NAGPRODCODE Version.
 *
 * Copyright 2016 Numerical Algorithms Group.
 *
 * Mark 26, 2016.
 */

#include <stdio.h>
#include <nag.h>
#include <nag_stdlib.h>
#include <nagf07.h>
#include <nagx04.h>

int main(void)
{
    /* Scalars */
    Integer i, j, n, nrhs, pda, pdaf, pdb, pdx, ferr_len, berr_len;
    Integer exit_status = 0;
    Nag_UploType uplo;
    NagError fail;
    Nag_OrderType order;

    /* Arrays */
    char nag_enum_arg[40];
    Complex *a = 0, *af = 0, *b = 0, *x = 0;
    double *berr = 0, *ferr = 0;

```

```

#ifdef NAG_COLUMN_MAJOR
#define A(I, J)  a[(J-1)*pda + I - 1]
#define AF(I, J) af[(J-1)*pdaf + I - 1]
#define B(I, J)  b[(J-1)*pdb + I - 1]
#define X(I, J)  x[(J-1)*pdx + I - 1]
    order = Nag_ColMajor;
#else
#define A(I, J)  a[(I-1)*pda + J - 1]
#define AF(I, J) af[(I-1)*pdaf + J - 1]
#define B(I, J)  b[(I-1)*pdb + J - 1]
#define X(I, J)  x[(I-1)*pdx + J - 1]
    order = Nag_RowMajor;
#endif

    INIT_FAIL(fail);

    printf("nag_zporfs (f07fvc) 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 "%*[\n] ", &n, &nrhs);
#else
    scanf("%" NAG_IFMT "%" NAG_IFMT "%*[\n] ", &n, &nrhs);
#endif
#ifdef NAG_COLUMN_MAJOR
    pda = n;
    pdaf = n;
    pdb = n;
    pdx = n;
#else
    pda = n;
    pdaf = n;
    pdb = nrhs;
    pdx = nrhs;
#endif

    ferr_len = nrhs;
    berr_len = nrhs;

    /* Allocate memory */
    if (!(a = NAG_ALLOC(n * n, Complex)) ||
        !(af = NAG_ALLOC(n * n, Complex)) ||
        !(b = NAG_ALLOC(n * nrhs, Complex)) ||
        !(x = NAG_ALLOC(n * nrhs, Complex)) ||
        !(berr = NAG_ALLOC(berr_len, double)) ||
        !(ferr = NAG_ALLOC(ferr_len, double)))
    {
        printf("Allocation failure\n");
        exit_status = -1;
        goto END;
    }

    /* Read A and B from data file, and copy A to AF and B to X */
#ifdef _WIN32
    scanf_s("%39s%*[\n] ", nag_enum_arg, (unsigned)_countof(nag_enum_arg));
#else
    scanf("%39s%*[\n] ", nag_enum_arg);
#endif
    /* nag_enum_name_to_value (x04nac).
     * Converts NAG enum member name to value
     */
    uplo = (Nag_UploType) nag_enum_name_to_value(nag_enum_arg);

    if (uplo == Nag_Upper) {
        for (i = 1; i <= n; ++i) {
            for (j = i; j <= n; ++j)

```

```

#ifdef _WIN32
    scanf_s(" ( %lf , %lf )", &A(i, j).re, &A(i, j).im);
#else
    scanf(" ( %lf , %lf )", &A(i, j).re, &A(i, j).im);
#endif
}
#ifdef _WIN32
    scanf_s("%*[\n] ");
#else
    scanf("%*[\n] ");
#endif
}
else {
    for (i = 1; i <= n; ++i) {
        for (j = 1; j <= i; ++j)
#ifdef _WIN32
            scanf_s(" ( %lf , %lf )", &A(i, j).re, &A(i, j).im);
#else
            scanf(" ( %lf , %lf )", &A(i, j).re, &A(i, j).im);
#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 , %lf )", &B(i, j).re, &B(i, j).im);
#else
        scanf(" ( %lf , %lf )", &B(i, j).re, &B(i, j).im);
#endif
}
#ifdef _WIN32
    scanf_s("%*[\n] ");
#else
    scanf("%*[\n] ");
#endif
/* Copy A to AF and B to X */
if (uplo == Nag_Upper) {
    for (i = 1; i <= n; ++i) {
        for (j = i; j <= n; ++j) {
            AF(i, j).re = A(i, j).re;
            AF(i, j).im = A(i, j).im;
        }
    }
}
else {
    for (i = 1; i <= n; ++i) {
        for (j = 1; j <= i; ++j) {
            AF(i, j).re = A(i, j).re;
            AF(i, j).im = A(i, j).im;
        }
    }
}
for (i = 1; i <= n; ++i) {
    for (j = 1; j <= nrhs; ++j) {
        X(i, j).re = B(i, j).re;
        X(i, j).im = B(i, j).im;
    }
}

/* Factorize A in the array AF */
/* nag_zpotrf (f07frc).
 * Cholesky factorization of complex Hermitian
 * positive-definite matrix
 */
nag_zpotrf(order, uplo, n, af, pdaf, &fail);
if (fail.code != NE_NOERROR) {

```

```

    printf("Error from nag_zpotrf (f07frc).\n%s\n", fail.message);
    exit_status = 1;
    goto END;
}
/* Compute solution in the array X */
/* nag_zpotrs (f07fsc).
 * Solution of complex Hermitian positive-definite system of
 * linear equations, multiple right-hand sides, matrix
 * already factorized by nag_zpotrf (f07frc)
 */
nag_zpotrs(order, uplo, n, nrhs, af, pdaf, x, pdx, &fail);
if (fail.code != NE_NOERROR) {
    printf("Error from nag_zpotrs (f07fsc).\n%s\n", fail.message);
    exit_status = 1;
    goto END;
}
/* Improve solution, and compute backward errors and */
/* estimated bounds on the forward errors */
/* nag_zporfs (f07fvc).
 * Refined solution with error bounds of complex Hermitian
 * positive-definite system of linear equations, multiple
 * right-hand sides
 */
nag_zporfs(order, uplo, n, nrhs, a, pda, af, pdaf, b, pdb, x, pdx,
           ferr, berr, &fail);
if (fail.code != NE_NOERROR) {
    printf("Error from nag_zporfs (f07fvc).\n%s\n", fail.message);
    exit_status = 1;
    goto END;
}
/* Print solution */
/* nag_gen_complx_mat_print_comp (x04dbc).
 * Print complex general matrix (comprehensive)
 */
fflush(stdout);
nag_gen_complx_mat_print_comp(order, Nag_GeneralMatrix, Nag_NonUnitDiag, n,
                             nrhs, x, pdx, Nag_BracketForm, "%7.4f",
                             "Solution(s)", Nag_IntegerLabels,
                             0, Nag_IntegerLabels, 0, 80, 0, 0, &fail);
if (fail.code != NE_NOERROR) {
    printf("Error from nag_gen_complx_mat_print_comp (x04dbc).\n%s\n",
           fail.message);
    exit_status = 1;
    goto END;
}
printf("\nBackward errors (machine-dependent)\n");
for (j = 1; j <= nrhs; ++j)
    printf("%11.1e%s", berr[j - 1], j % 4 == 0 ? "\n" : " ");
printf("\nEstimated forward error bounds (machine-dependent)\n");
for (j = 1; j <= nrhs; ++j)
    printf("%11.1e%s", ferr[j - 1], j % 4 == 0 ? "\n" : " ");
printf("\n");
END:
NAG_FREE(a);
NAG_FREE(af);
NAG_FREE(b);
NAG_FREE(x);
NAG_FREE(berr);
NAG_FREE(ferr);
return exit_status;
}

```

10.2 Program Data

```

nag_zporfs (f07fvc) Example Program Data
  4 2                                     :Values of n and nrhs
  Nag_Lower                               :Value of uplo
(3.23, 0.00)
(1.51, 1.92) ( 3.58, 0.00)
(1.90,-0.84) (-0.23,-1.11) ( 4.09, 0.00)

```



```
(0.42,-2.50) (-1.18,-1.37) ( 2.33, 0.14) ( 4.29, 0.00) :End of matrix A
( 3.93, -6.14) ( 1.48,  6.58)
( 6.17,  9.42) ( 4.65, -4.75)
(-7.17,-21.83) (-4.91,  2.29)
( 1.99,-14.38) ( 7.64,-10.79) :End of matrix B
```

10.3 Program Results

nag_zporfs (f07fvc) Example Program Results

Solution(s)

```

           1           2
1 ( 1.0000,-1.0000) (-1.0000, 2.0000)
2 (-0.0000, 3.0000) ( 3.0000,-4.0000)
3 (-4.0000,-5.0000) (-2.0000, 3.0000)
4 ( 2.0000, 1.0000) ( 4.0000,-5.0000)
```

Backward errors (machine-dependent)

```
5.9e-17  4.8e-17
```

Estimated forward error bounds (machine-dependent)

```
6.0e-14  7.2e-14
```
