

# NAG Library Function Document

## nag\_zhprfs (f07pvc)

### 1 Purpose

nag\_zhprfs (f07pvc) returns error bounds for the solution of a complex Hermitian indefinite system of linear equations with multiple right-hand sides,  $AX = B$ , using packed storage. 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_zhprfs (Nag_OrderType order, Nag_UploType uplo, Integer n,
                Integer nrhs, const Complex ap[], const Complex afp[],
                const Integer ipiv[], const Complex b[], Integer pdb, Complex x[],
                Integer pdx, double ferr[], double berr[], NagError *fail)
```

### 3 Description

nag\_zhprfs (f07pvc) returns the backward errors and estimated bounds on the forward errors for the solution of a complex Hermitian indefinite system of linear equations with multiple right-hand sides  $AX = B$ , using packed storage. The function handles each right-hand side vector (stored as a column of the matrix  $B$ ) independently, so we describe the function of nag\_zhprfs (f07pvc) 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*  $\beta$ . 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 3.2.1.3 in the Essential Introduction 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  $PUDU^H P^T$ , where  $U$  is upper triangular.  
**uplo** = Nag\_Lower  
 The lower triangular part of  $A$  is stored and  $A$  is factorized as  $PLDL^H P^T$ , 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:*  $n \geq 0$ .
- 4: **nrhs** – Integer *Input*  
*On entry:*  $r$ , the number of right-hand sides.  
*Constraint:* **nrhs**  $\geq 0$ .
- 5: **ap**[*dim*] – const Complex *Input*  
**Note:** the dimension, *dim*, of the array **ap** must be at least  $\max(1, n \times (n + 1)/2)$ .  
*On entry:* the  $n$  by  $n$  original Hermitian matrix  $A$  as supplied to nag\_zhptrf (f07prc).
- 6: **afp**[*dim*] – const Complex *Input*  
**Note:** the dimension, *dim*, of the array **afp** must be at least  $\max(1, n \times (n + 1)/2)$ .  
*On entry:* the factorization of  $A$  stored in packed form, as returned by nag\_zhptrf (f07prc).
- 7: **ipiv**[*dim*] – const Integer *Input*  
**Note:** the dimension, *dim*, of the array **ipiv** must be at least  $\max(1, n)$ .  
*On entry:* details of the interchanges and the block structure of  $D$ , as returned by nag\_zhptrf (f07prc).
- 8: **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;  
 $\max(1, n \times \mathbf{pdb})$  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  $B$ .
- 9: **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**  $\geq \max(1, \mathbf{nrhs})$ .

- 10: **x**[*dim*] – Complex *Input/Output*
- Note:** the dimension, *dim*, of the array **x** must be at least  
 $\max(1, \mathbf{pdx} \times \mathbf{nrhs})$  when **order** = Nag\_ColMajor;  
 $\max(1, \mathbf{n} \times \mathbf{pdx})$  when **order** = Nag\_RowMajor.
- The (*i*, *j*)th element of the matrix *X* is stored in  
 $\mathbf{x}[(j-1) \times \mathbf{pdx} + i - 1]$  when **order** = Nag\_ColMajor;  
 $\mathbf{x}[(i-1) \times \mathbf{pdx} + j - 1]$  when **order** = Nag\_RowMajor.
- On entry:* the *n* by *r* solution matrix *X*, as returned by nag\_zhptrs (f07psc).  
*On exit:* the improved solution matrix *X*.
- 11: **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**  $\geq \max(1, \mathbf{n})$ ;  
 if **order** = Nag\_RowMajor, **pdx**  $\geq \max(1, \mathbf{nrhs})$ .
- 12: **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*.
- 13: **berr**[**nrhs**] – double *Output*
- On exit:* **berr**[*j* – 1] contains the component-wise backward error bound  $\beta$  for the *j*th solution vector, that is, the *j*th column of *X*, for *j* = 1, 2, ..., *r*.
- 14: **fail** – NagError \* *Input/Output*
- The NAG error argument (see Section 3.6 in the Essential Introduction).

## 6 Error Indicators and Warnings

### NE\_ALLOC\_FAIL

Dynamic memory allocation failed.

### NE\_BAD\_PARAM

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

### NE\_INT

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

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

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

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

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

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

On entry, **pdx** =  $\langle \text{value} \rangle$ .

Constraint: **pdx**  $> 0$ .

**NE\_INT\_2**

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

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

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

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

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

Constraint: **pdx**  $\geq$  max(1, **n**).

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

Constraint: **pdx**  $\geq$  max(1, **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.

**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\_zhprfs (f07pvc) is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

nag\_zhprfs (f07pvc) 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 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 1 or 2 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\_dsprfs (f07phc).

**10 Example**

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

$$A = \begin{pmatrix} -1.36 + 0.00i & 1.58 + 0.90i & 2.21 - 0.21i & 3.91 + 1.50i \\ 1.58 - 0.90i & -8.87 + 0.00i & -1.84 - 0.03i & -1.78 + 1.18i \\ 2.21 + 0.21i & -1.84 + 0.03i & -4.63 + 0.00i & 0.11 + 0.11i \\ 3.91 - 1.50i & -1.78 - 1.18i & 0.11 - 0.11i & -1.84 + 0.00i \end{pmatrix}$$

and

$$B = \begin{pmatrix} 7.79 + 5.48i & -35.39 + 18.01i \\ -0.77 - 16.05i & 4.23 - 70.02i \\ -9.58 + 3.88i & -24.79 - 8.40i \\ 2.98 - 10.18i & 28.68 - 39.89i \end{pmatrix}.$$

Here  $A$  is Hermitian indefinite, stored in packed form, and must first be factorized by `nag_zhptrf` (f07prc).

## 10.1 Program Text

```

/* nag_zhprfs (f07pvc) Example Program.
 *
 * Copyright 2001 Numerical Algorithms Group.
 *
 * Mark 7, 2001.
 */

#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, ap_len, afp_len;
    Integer      berr_len, ferr_len, pdb, pdx;
    Integer      exit_status = 0;
    NagError     fail;
    Nag_UploType uplo;
    Nag_OrderType order;
    /* Arrays */
    Integer      *ipiv = 0;
    char         nag_enum_arg[40];
    Complex      *afp = 0, *ap = 0, *b = 0, *x = 0;
    double       *berr = 0, *ferr = 0;

#ifdef NAG_COLUMN_MAJOR
#define A_LOWER(I, J) ap[(2*n-J)*(J-1)/2 + I - 1]
#define A_UPPER(I, J) ap[J*(J-1)/2 + 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_LOWER(I, J) ap[I*(I-1)/2 + J - 1]
#define A_UPPER(I, J) ap[(2*n-I)*(I-1)/2 + 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_zhprfs (f07pvc) Example Program Results\n\n");

    /* Skip heading in data file */
    scanf("%*[\n] ");
    scanf("%ld%ld%*[\n] ", &n, &nrhs);
    ap_len = n * (n + 1)/2;
    afp_len = n * (n + 1)/2;
    berr_len = nrhs;
    ferr_len = nrhs;
#ifdef NAG_COLUMN_MAJOR
    pdb = n;
    pdx = n;
#else
    pdb = nrhs;

```

```

pdx = nrhs;
#endif

/* Allocate memory */
if (!(ipiv = NAG_ALLOC(n, Integer)) ||
    !(afp = NAG_ALLOC(afp_len, Complex)) ||
    !(ap = NAG_ALLOC(ap_len, 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 AFP and B to X */
scanf(" %39s%*[\n] ", nag_enum_arg);
/* 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)
            scanf(" ( %lf , %lf )", &A_UPPER(i, j).re,
                &A_UPPER(i, j).im);
    }
    scanf("%*[\n] ");
}
else
{
    for (i = 1; i <= n; ++i)
    {
        for (j = 1; j <= i; ++j)
            scanf(" ( %lf , %lf )", &A_LOWER(i, j).re,
                &A_LOWER(i, j).im);
    }
    scanf("%*[\n] ");
}
for (i = 1; i <= n; ++i)
{
    for (j = 1; j <= nrhs; ++j)
        scanf(" ( %lf , %lf )", &B(i, j).re, &B(i, j).im);
}
scanf("%*[\n] ");

for (i = 1; i <= n * (n + 1) / 2; ++i)
{
    afp[i-1].re = ap[i-1].re;
    afp[i-1].im = ap[i-1].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 AFP */
/* nag_zhptrf (f07prc).
 * Bunch-Kaufman factorization of complex Hermitian
 * indefinite matrix, packed storage
 */
nag_zhptrf(order, uplo, n, afp, ipiv, &fail);
if (fail.code != NE_NOERROR)
{

```

```

        printf("Error from nag_zhptrf (f07prc).\n%s\n", fail.message);
        exit_status = 1;
        goto END;
    }
    /* Compute solution in the array X */
    /* nag_zhptrs (f07psc).
    * Solution of complex Hermitian indefinite system of linear
    * equations, multiple right-hand sides, matrix already
    * factorized by nag_zhptrf (f07prc), packed storage
    */
    nag_zhptrs(order, uplo, n, nrhs, afp, ipiv, x, pdx, &fail);
    if (fail.code != NE_NOERROR)
    {
        printf("Error from nag_zhptrs (f07psc).\n%s\n", fail.message);
        exit_status = 1;
        goto END;
    }
    /* Improve solution, and compute backward errors and */
    /* estimated bounds on the forward errors */
    /* nag_zhprfs (f07pvc).
    * Refined solution with error bounds of complex Hermitian
    * indefinite system of linear equations, multiple
    * right-hand sides, packed storage
    */
    nag_zhprfs(order, uplo, n, nrhs, ap, afp, ipiv, b, pdb,
               x, pdx, ferr, berr, &fail);
    if (fail.code != NE_NOERROR)
    {
        printf("Error from nag_zhprfs (f07pvc).\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(ipiv);
    NAG_FREE(afp);
    NAG_FREE(ap);
    NAG_FREE(b);
    NAG_FREE(x);
    NAG_FREE(berr);
    NAG_FREE(ferr);
    return exit_status;
}

```

## 10.2 Program Data

```
nag_zhprfs (f07pvc) Example Program Data
  4  2                                     :Values of n and nrhs
  Nag_Lower                               :Value of uplo
(-1.36, 0.00)
( 1.58,-0.90) (-8.87, 0.00)
( 2.21, 0.21) (-1.84, 0.03) (-4.63, 0.00)
( 3.91,-1.50) (-1.78,-1.18) ( 0.11,-0.11) (-1.84, 0.00) :End of matrix A
( 7.79,  5.48) (-35.39, 18.01)
(-0.77,-16.05) (  4.23,-70.02)
(-9.58,  3.88) (-24.79, -8.40)
( 2.98,-10.18) ( 28.68,-39.89)                                     :End of matrix B
```

## 10.3 Program Results

```
nag_zhprfs (f07pvc) Example Program Results

Solution(s)
           1           2
1 ( 1.0000,-1.0000) ( 3.0000,-4.0000)
2 (-1.0000, 2.0000) (-1.0000, 5.0000)
3 ( 3.0000,-2.0000) ( 7.0000,-2.0000)
4 ( 2.0000, 1.0000) (-8.0000, 6.0000)

Backward errors (machine-dependent)
  5.7e-17    5.8e-17
Estimated forward error bounds (machine-dependent)
  2.5e-15    3.1e-15
```

---