

# NAG Library Function Document

## nag\_ztprfs (f07uvc)

### 1 Purpose

nag\_ztprfs (f07uvc) returns error bounds for the solution of a complex triangular system of linear equations with multiple right-hand sides,  $AX = B$ ,  $A^T X = B$  or  $A^H X = B$ , using packed storage.

### 2 Specification

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

void nag_ztprfs (Nag_OrderType order, Nag_UploType uplo,
                Nag_TransType trans, Nag_DiagType diag, Integer n, Integer nrhs,
                const Complex ap[], const Complex b[], Integer pdb, const Complex x[],
                Integer pdx, double ferr[], double berr[], NagError *fail)
```

### 3 Description

nag\_ztprfs (f07uvc) returns the backward errors and estimated bounds on the forward errors for the solution of a complex triangular system of linear equations with multiple right-hand sides  $AX = B$ ,  $A^T X = B$  or  $A^H X = B$ , 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\_ztprfs (f07uvc) 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  $A$  is upper or lower triangular.  
**uplo** = Nag\_Upper  
 $A$  is upper triangular.  
**uplo** = Nag\_Lower  
 $A$  is lower triangular.  
*Constraint:* **uplo** = Nag\_Upper or Nag\_Lower.
- 3: **trans** – Nag\_TransType *Input*  
*On entry:* indicates the form of the equations.  
**trans** = Nag\_NoTrans  
The equations are of the form  $AX = B$ .  
**trans** = Nag\_Trans  
The equations are of the form  $A^T X = B$ .  
**trans** = Nag\_ConjTrans  
The equations are of the form  $A^H X = B$ .  
*Constraint:* **trans** = Nag\_NoTrans, Nag\_Trans or Nag\_ConjTrans.
- 4: **diag** – Nag\_DiagType *Input*  
*On entry:* indicates whether  $A$  is a nonunit or unit triangular matrix.  
**diag** = Nag\_NonUnitDiag  
 $A$  is a nonunit triangular matrix.  
**diag** = Nag\_UnitDiag  
 $A$  is a unit triangular matrix; the diagonal elements are not referenced and are assumed to be 1.  
*Constraint:* **diag** = Nag\_NonUnitDiag or Nag\_UnitDiag.
- 5: **n** – Integer *Input*  
*On entry:*  $n$ , the order of the matrix  $A$ .  
*Constraint:*  $n \geq 0$ .
- 6: **nrhs** – Integer *Input*  
*On entry:*  $r$ , the number of right-hand sides.  
*Constraint:* **nrhs**  $\geq 0$ .
- 7: **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  $n$  triangular matrix  $A$ , packed by rows or columns.  
The storage of elements  $A_{ij}$  depends on the **order** and **uplo** arguments as follows:  
if **order** = Nag\_ColMajor and **uplo** = Nag\_Upper,  
 $A_{ij}$  is stored in **ap**[( $j - 1$ )  $\times$   $j/2 + i - 1$ ], for  $i \leq j$ ;  
if **order** = Nag\_ColMajor and **uplo** = Nag\_Lower,  
 $A_{ij}$  is stored in **ap**[( $2n - j$ )  $\times$  ( $j - 1$ )/2 +  $i - 1$ ], for  $i \geq j$ ;  
if **order** = Nag\_RowMajor and **uplo** = Nag\_Upper,  
 $A_{ij}$  is stored in **ap**[( $2n - i$ )  $\times$  ( $i - 1$ )/2 +  $j - 1$ ], for  $i \leq j$ ;  
if **order** = Nag\_RowMajor and **uplo** = Nag\_Lower,  
 $A_{ij}$  is stored in **ap**[( $i - 1$ )  $\times$   $i/2 + j - 1$ ], for  $i \geq j$ .

If **diag** = Nag\_UnitDiag, the diagonal elements of AP are assumed to be 1, and are not referenced; the same storage scheme is used whether **diag** = Nag\_NonUnitDiag or **diag** = Nag\_UnitDiag.

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;  
 $\max(1, \mathbf{n} \times \mathbf{pdb})$  when **order** = Nag\_RowMajor.

The (*i*, *j*)th element of the matrix *B* is stored in

**b**[(*j* – 1) × **pdb** + *i* – 1] when **order** = Nag\_ColMajor;  
**b**[(*i* – 1) × **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** ≥ max(1, **n**);  
 if **order** = Nag\_RowMajor, **pdb** ≥ max(1, **nrhs**).

10: **x**[*dim*] – const Complex *Input*

**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

**x**[(*j* – 1) × **pdx** + *i* – 1] when **order** = Nag\_ColMajor;  
**x**[(*i* – 1) × **pdx** + *j* – 1] when **order** = Nag\_RowMajor.

*On entry:* the *n* by *r* solution matrix *X*, as returned by nag\_ztptrs (f07usc).

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** ≥ max(1, **n**);  
 if **order** = Nag\_RowMajor, **pdx** ≥ max(1, **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.  
See Section 3.2.1.2 in the Essential Introduction for further information.

### NE\_BAD\_PARAM

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

### NE\_INT

On entry,  $\mathbf{n} = \langle value \rangle$ .  
Constraint:  $\mathbf{n} \geq 0$ .

On entry,  $\mathbf{nrhs} = \langle value \rangle$ .  
Constraint:  $\mathbf{nrhs} \geq 0$ .

On entry,  $\mathbf{pdb} = \langle value \rangle$ .  
Constraint:  $\mathbf{pdb} > 0$ .

On entry,  $\mathbf{pdx} = \langle value \rangle$ .  
Constraint:  $\mathbf{pdx} > 0$ .

### NE\_INT\_2

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

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

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

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

### 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 the Essential Introduction 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 the Essential Introduction 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\_ztpfrs (f07uvc) is threaded by NAG for parallel execution in multithreaded implementations of the NAG Library.

nag\_ztpfrs (f07uvc) 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

A call to `nag_ztpfrs` (f07uvc), for each right-hand side, involves solving a number of systems of linear equations of the form  $Ax = b$  or  $A^Hx = b$ ; the number is usually 5 and never more than 11. Each solution involves approximately  $4n^2$  real floating-point operations.

The real analogue of this function is `nag_dtpfrs` (f07uhc).

## 10 Example

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

$$A = \begin{pmatrix} 4.78 + 4.56i & 0.00 + 0.00i & 0.00 + 0.00i & 0.00 + 0.00i \\ 2.00 - 0.30i & -4.11 + 1.25i & 0.00 + 0.00i & 0.00 + 0.00i \\ 2.89 - 1.34i & 2.36 - 4.25i & 4.15 + 0.80i & 0.00 + 0.00i \\ -1.89 + 1.15i & 0.04 - 3.69i & -0.02 + 0.46i & 0.33 - 0.26i \end{pmatrix}$$

and

$$B = \begin{pmatrix} -14.78 - 32.36i & -18.02 + 28.46i \\ 2.98 - 2.14i & 14.22 + 15.42i \\ -20.96 + 17.06i & 5.62 + 35.89i \\ 9.54 + 9.91i & -16.46 - 1.73i \end{pmatrix},$$

using packed storage for  $A$ .

### 10.1 Program Text

```

/* nag_ztpfrs (f07uvc) Example Program.
 *
 * Copyright 2014 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    ap_len, i, j, n, nrhs;
    Integer    berr_len, ferr_len, pdb, pdx;
    Integer    exit_status = 0;
    Nag_UploType uplo;
    NagError   fail;
    Nag_OrderType order;
    /* Arrays */
    char       nag_enum_arg[40];
    Complex    *ap = 0, *b = 0, *x = 0;
    double     *berr = 0, *ferr = 0;

#ifdef NAG_COLUMN_MAJOR
#define A_UPPER(I, J) ap[J*(J-1)/2 + I - 1]
#define A_LOWER(I, J) ap[(2*n-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;
#endif

```

```

#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_ztprfs (f07uvc) Example Program Results\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
    berr_len = nrhs;
    ferr_len = nrhs;
    ap_len = n * (n + 1)/2;
#ifdef NAG_COLUMN_MAJOR
    pdb = n;
    pdx = n;
#else
    pdb = nrhs;
    pdx = nrhs;
#endif

    /* Allocate memory */
    if (!(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 B to X */
#ifdef _WIN32
    scanf_s(" %39s%*[\n] ", nag_enum_arg, _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_UPPER(i, j).re,
                    &A_UPPER(i, j).im);
#else
                scanf(" ( %lf , %lf )", &A_UPPER(i, j).re,
                    &A_UPPER(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_LOWER(i, j).re,
                    &A_LOWER(i, j).im);
#else
            scanf(" ( %lf , %lf )", &A_LOWER(i, j).re,
                    &A_LOWER(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
    }
    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;
        }
    }
}
/* Compute solution in the array X */
/* nag_ztptrs (f07usc).
 * Solution of complex triangular system of linear
 * equations, multiple right-hand sides, packed storage
 */
nag_ztptrs(order, uplo, Nag_NoTrans, Nag_NonUnitDiag, n,
           nrhs, ap, x, pdx, &fail);
if (fail.code != NE_NOERROR)
{
    printf("Error from nag_ztptrs (f07usc).\n%s\n", fail.message);
    exit_status = 1;
    goto END;
}

/* Compute backward errors and estimated bounds on the */
/* forward errors */
/* nag_ztprfs (f07uvc).
 * Error bounds for solution of complex triangular system of
 * linear equations, multiple right-hand sides, packed
 * storage
 */
nag_ztprfs(order, uplo, Nag_NoTrans, Nag_NonUnitDiag, n,
           nrhs, ap, b, pdb, x, pdx, ferr, berr, &fail);
if (fail.code != NE_NOERROR)
{
    printf("Error from nag_ztprfs (f07uvc).\n%s\n", fail.message);
}

```

```

        exit_status = 1;
        goto END;
    }

    /* Print solution */
    printf("\n");
    /* nag_gen_complex_mat_print_comp (x04dbc).
     * Print complex general matrix (comprehensive)
     */
    fflush(stdout);
    nag_gen_complex_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_complex_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(ap);
    NAG_FREE(b);
    NAG_FREE(x);
    NAG_FREE(berr);
    NAG_FREE(ferr);

    return exit_status;
}

```

## 10.2 Program Data

```

nag_ztprfs (f07uvc) Example Program Data
  4  2                                     :Values of n and nrhs
  Nag_Lower                               :Value of uplo
(  4.78,  4.56)
(  2.00,-0.30) (-4.11,  1.25)
(  2.89,-1.34) (  2.36,-4.25) (  4.15,  0.80)
(-1.89,  1.15) (  0.04,-3.69) (-0.02,  0.46) (  0.33,-0.26) :End of matrix A
(-14.78,-32.36) (-18.02,  28.46)
(  2.98, -2.14) ( 14.22,  15.42)
(-20.96, 17.06) (  5.62,  35.89)
(  9.54,  9.91) (-16.46, -1.73)                               :End of matrix B

```

## 10.3 Program Results

```

nag_ztprfs (f07uvc) Example Program Results

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

Backward errors (machine-dependent)
  6.2e-17    2.7e-17
Estimated forward error bounds (machine-dependent)
  2.9e-14    3.2e-14

```

---