

NAG Library Routine Document

D01AUF

Note: before using this routine, please read the Users' Note for your implementation to check the interpretation of ***bold italicised*** terms and other implementation-dependent details.

1 Purpose

D01AUF is an adaptive integrator, especially suited to oscillating, nonsingular integrands, which calculates an approximation to the integral of a function $f(x)$ over a finite interval $[a, b]$:

$$I = \int_a^b f(x) dx.$$

2 Specification

```
SUBROUTINE D01AUF(F, A, B, KEY, EPSABS, EPSREL, RESULT, ABSERR, W, LW,
1          IW, LIW, IFAIL)
      INTEGER          KEY, LW, IW(LIW), LIW, IFAIL
      double precision A, B, EPSABS, EPSREL, RESULT, ABSERR, W(LW)
      EXTERNAL         F
```

3 Description

D01AUF is based on the QUADPACK routine QAG (see Piessens *et al.* (1983)). It is an adaptive routine, offering a choice of six Gauss–Kronrod rules. A global acceptance criterion (as defined by Malcolm and Simpson (1976)) is used. The local error estimation is described in Piessens *et al.* (1983).

Because D01AUF is based on integration rules of high order, it is especially suitable for nonsingular oscillating integrands.

D01AUF requires a subroutine to evaluate the integrand at an array of different points and is therefore particularly efficient when the evaluation can be performed in vector mode on a vector-processing machine. Otherwise this algorithm with $KEY = 6$ is identical to that used by D01AKF.

4 References

Malcolm M A and Simpson R B (1976) Local versus global strategies for adaptive quadrature *ACM Trans. Math. Software* **1** 129–146

Piessens R (1973) An algorithm for automatic integration *Angew. Inf.* **15** 399–401

Piessens R, de Doncker–Kapenga E, Überhuber C and Kahaner D (1983) *QUADPACK, A Subroutine Package for Automatic Integration* Springer–Verlag

5 Parameters

1: F – SUBROUTINE, supplied by the user. *External Procedure*

F must return the values of the integrand f at a set of points.

The specification of F is:

```
SUBROUTINE F(X, FV, N)
      INTEGER          N
      double precision X(N), FV(N)
```

1:	X(N) – double precision array	<i>Input</i>
	<i>On entry:</i> the points at which the integrand f must be evaluated.	
2:	FV(N) – double precision array	<i>Output</i>
	<i>On exit:</i> FV(j) must contain the value of f at the point X(j), for $j = 1, 2, \dots, N$.	
3:	N – INTEGER	<i>Input</i>
	<i>On entry:</i> the number of points at which the integrand is to be evaluated. The actual value of N is equal to the number of points in the Kronrod rule (see specification of KEY).	

F must be declared as EXTERNAL in the (sub)program from which D01AUF is called. Parameters denoted as *Input* must **not** be changed by this procedure.

- 2: A – **double precision** *Input*
On entry: a , the lower limit of integration.
- 3: B – **double precision** *Input*
On entry: b , the upper limit of integration. It is not necessary that $a < b$.
- 4: KEY – INTEGER *Input*
On entry: indicates which integration rule is to be used.
 KEY = 1
 For the Gauss 7-point and Kronrod 15-point rule.
 KEY = 2
 For the Gauss 10-point and Kronrod 21-point rule.
 KEY = 3
 For the Gauss 15-point and Kronrod 31-point rule.
 KEY = 4
 For the Gauss 20-point and Kronrod 41-point rule.
 KEY = 5
 For the Gauss 25-point and Kronrod 51-point rule.
 KEY = 6
 For the Gauss 30-point and Kronrod 61-point rule.
Suggested value: KEY = 6.
Constraint: KEY = 1, 2, 3, 4, 5 or 6.
- 5: EPSABS – **double precision** *Input*
On entry: the absolute accuracy required. If EPSABS is negative, the absolute value is used. See Section 7.
- 6: EPSREL – **double precision** *Input*
On entry: the relative accuracy required. If EPSREL is negative, the absolute value is used. See Section 7.
- 7: RESULT – **double precision** *Output*
On exit: the approximation to the integral I .
- 8: ABSERR – **double precision** *Output*
On exit: an estimate of the modulus of the absolute error, which should be an upper bound for $|I - \text{RESULT}|$.

- 9: W(LW) – **double precision** array *Output*
On exit: details of the computation, as described in Section 8.
- 10: LW – INTEGER *Input*
On entry: the dimension of the array W as declared in the (sub)program from which D01AUF is called. The value of LW (together with that of LIW) imposes a bound on the number of sub-intervals into which the interval of integration may be divided by the routine. The number of sub-intervals cannot exceed LW/4. The more difficult the integrand, the larger LW should be.
Suggested value: LW = 800 to 2000 is adequate for most problems.
Constraint: LW $\geq$ 4.
- 11: IW(LIW) – INTEGER array *Output*
On exit: IW(1) contains the actual number of sub-intervals used. The rest of the array is used as workspace.
- 12: LIW – INTEGER *Input*
On entry: the dimension of the array IW as declared in the (sub)program from which D01AUF is called.
The number of sub-intervals into which the interval of integration may be divided cannot exceed LIW.
Suggested value: LIW = LW/4.
Constraint: LIW $\geq$ 1.
- 13: IFAIL – INTEGER *Input/Output*
On entry: IFAIL must be set to 0, -1 or 1. If you are unfamiliar with this parameter you should refer to Section 3.3 in the Essential Introduction for details.
On exit: IFAIL = 0 unless the routine detects an error (see Section 6).
For environments where it might be inappropriate to halt program execution when an error is detected, the value -1 or 1 is recommended. If the output of error messages is undesirable, then the value 1 is recommended. Otherwise, because for this routine the values of the output parameters may be useful even if IFAIL $\neq$ 0 on exit, the recommended value is -1. **When the value -1 or 1 is used it is essential to test the value of IFAIL on exit.**

6 Error Indicators and Warnings

If on entry IFAIL = 0 or -1, explanatory error messages are output on the current error message unit (as defined by X04AAF).

Note: D01AUF may return useful information for one or more of the following detected errors or warnings.

Errors or warnings detected by the routine:

IFAIL = 1

The maximum number of subdivisions allowed with the given workspace has been reached without the accuracy requirements being achieved. Look at the integrand in order to determine the integration difficulties. If necessary, another integrator, which is designed for handling the type of difficulty involved, must be used. Alternatively, consider relaxing the accuracy requirements specified by EPSABS and EPSREL, or increasing the amount of workspace.

IFAIL = 2

Round-off error prevents the requested tolerance from being achieved. Consider requesting less accuracy.

IFAIL = 3

Extremely bad local integrand behaviour causes a very strong subdivision around one (or more) points of the interval. The same advice applies as in the case of IFAIL = 1.

IFAIL = 4

On entry, KEY $\neq$ 1, 2, 3, 4, 5 or 6.

IFAIL = 5

On entry, LW < 4,
or LIW < 1.

7 Accuracy

D01AUF cannot guarantee, but in practice usually achieves, the following accuracy:

$$|I - \text{RESULT}| \leq \text{tol},$$

where

$$\text{tol} = \max\{|\text{EPSABS}|, |\text{EPSREL}| \times |I|\},$$

and EPSABS and EPSREL are user-specified absolute and relative error tolerances. Moreover, it returns the quantity ABSERR which, in normal circumstances, satisfies

$$|I - \text{RESULT}| \leq \text{ABSERR} \leq \text{tol}.$$

8 Further Comments

If IFAIL $\neq$ 0 on exit, then you may wish to examine the contents of the array W, which contains the end points of the sub-intervals used by D01AUF along with the integral contributions and error estimates over these sub-intervals.

Specifically, for $i = 1, 2, \dots, n$, let r_i denote the approximation to the value of the integral over the sub-interval $[a_i, b_i]$ in the partition of $[a, b]$ and e_i be the corresponding absolute error estimate. Then, $\int_{a_i}^{b_i} f(x) dx \simeq r_i$ and $\text{RESULT} = \sum_{i=1}^n r_i$. The value of n is returned in IW(1), and the values a_i , b_i , e_i and r_i are stored consecutively in the array W, that is:

$$a_i = W(i),$$

$$b_i = W(n + i),$$

$$e_i = W(2n + i) \text{ and}$$

$$r_i = W(3n + i).$$

9 Example

This example computes

$$\int_0^{2\pi} x \sin(30x) \cos x \, dx.$$

9.1 Program Text

```

*      D01AUF Example Program Text
*      Mark 14 Revised. NAG Copyright 1989.
*      .. Parameters ..
      INTEGER          NOUT
      PARAMETER        (NOUT=6)
      INTEGER          LW, LIW
      PARAMETER        (LW=800,LIW=LW/4)
*      .. Scalars in Common ..
      INTEGER          KOUNT
*      .. Local Scalars ..
      DOUBLE PRECISION A, ABSERR, B, EPSABS, EPSREL, PI, RESULT
      INTEGER          IFAIL, KEY
*      .. Local Arrays ..
      DOUBLE PRECISION W(LW)
      INTEGER          IW(LIW)
*      .. External Functions ..
      DOUBLE PRECISION X01AAF
      EXTERNAL         X01AAF
*      .. External Subroutines ..
      EXTERNAL         D01AUF, F
*      .. Common blocks ..
      COMMON           /TELNUM/KOUNT
*      .. Executable Statements ..
      WRITE (NOUT,*) 'D01AUF Example Program Results'
      PI = X01AAF(0.0D0)
      EPSABS = 0.0D0
      EPSREL = 1.0D-03
      A = 0.0D0
      B = 2.0D0*PI
      KEY = 6
      KOUNT = 0
      IFAIL = 1

*      CALL D01AUF(F,A,B,KEY,EPSABS,EPSREL,RESULT,ABSERR,W,LW,IW,LIW,
+          IFAIL)
*
      IF (IFAIL.GE.0) THEN
        WRITE (NOUT,*)
        WRITE (NOUT,99999) 'A      - lower limit of integration = ', A
        WRITE (NOUT,99999) 'B      - upper limit of integration = ', B
        WRITE (NOUT,99998) 'EPSABS - absolute accuracy requested = ',
+          EPSABS
        WRITE (NOUT,99998) 'EPSREL - relative accuracy requested = ',
+          EPSREL
        WRITE (NOUT,*)
        IF (IFAIL.NE.0) WRITE (NOUT,99996) 'IFAIL = ', IFAIL
        IF (IFAIL.LE.3) THEN
          WRITE (NOUT,99997)
+          'RESULT - approximation to the integral = ', RESULT
          WRITE (NOUT,99998)
+          'ABSERR - estimate of the absolute error = ', ABSERR
          WRITE (NOUT,99996)
+          'KOUNT - number of function evaluations = ', KOUNT
          WRITE (NOUT,99996) 'IW(1) - number of subintervals used = '
+          , IW(1)
        END IF
      ELSE
        WRITE (NOUT,*)
        WRITE (NOUT,99995) ' ** D01AUF returned with IFAIL = ', IFAIL
      END IF

*
99999 FORMAT (1X,A,F10.4)
99998 FORMAT (1X,A,E9.2)
99997 FORMAT (1X,A,F9.5)
99996 FORMAT (1X,A,I4)
99995 FORMAT (1X,A,I5)
      END
*
      SUBROUTINE F(X,FV,N)

```

```
*      .. Scalar Arguments ..
      INTEGER          N
*      .. Array Arguments ..
      DOUBLE PRECISION FV(N), X(N)
*      .. Scalars in Common ..
      INTEGER          KOUNT
*      .. Local Scalars ..
      INTEGER          I
*      .. Intrinsic Functions ..
      INTRINSIC        COS, SIN
*      .. Common blocks ..
      COMMON            /TELNUM/KOUNT
*      .. Executable Statements ..
      KOUNT = KOUNT + N
      DO 20 I = 1, N
        FV(I) = X(I)*(SIN(30.0D0*X(I)))*COS(X(I))
20  CONTINUE
      RETURN
      END
```

9.2 Program Data

None.

9.3 Program Results

D01AUF Example Program Results

```
A      - lower limit of integration =    0.0000
B      - upper limit of integration =    6.2832
EPSABS - absolute accuracy requested =  0.00E+00
EPSREL - relative accuracy requested =  0.10E-02

RESULT - approximation to the integral = -0.20967
ABSERR - estimate of the absolute error =  0.45E-13
KOUNT  - number of function evaluations =  427
IW(1)  - number of subintervals used =    4
```
