NAG Library Function Document
nag_censored_normal (g07bbc)

1 Purpose
nag_censored_normal (g07bbc) computes maximum likelihood estimates and their standard errors for arguments of the Normal distribution from grouped and/or censored data.

2 Specification
#include <nag.h>
#include <nagg07.h>
void nag_censored_normal (Nag_CEMethod method, Integer n, const double x[],
const double xc[], const Integer xci[], double *xmu, double *xsig,
double tol, Integer maxit, double *sexmu, double *sexsig, double *corr,
double *dev, Integer nobs[], Integer *nit, NagError *fail)

3 Description
A sample of size $n$ is taken from a Normal distribution with mean $\mu$ and variance $\sigma^2$ and consists of grouped and/or censored data. Each of the $n$ observations is known by a pair of values $(L_i, U_i)$ such that:

$$L_i \leq x_i \leq U_i.$$ 

The data is represented as particular cases of this form:

- exactly specified observations occur when $L_i = U_i = x_i$, 
- right-censored observations, known only by a lower bound, occur when $U_i \to \infty$, 
- left-censored observations, known only by an upper bound, occur when $L_i \to -\infty$, 
- and interval-censored observations when $L_i < x_i < U_i$.

Let the set $A$ identify the exactly specified observations, sets $B$ and $C$ identify the observations censored on the right and left respectively, and set $D$ identify the observations confined between two finite limits. Also let there be $r$ exactly specified observations, i.e., the number in $A$. The probability density function for the standard Normal distribution is

$$Z(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}x^2\right), \quad -\infty < x < \infty$$

and the cumulative distribution function is

$$P(X) = 1 - Q(X) = \int_{-\infty}^{X} Z(x) \, dx.$$ 

The log-likelihood of the sample can be written as:

$$L(\mu, \sigma) = -r \log \sigma - \frac{1}{2} \sum_A \{ (x_i - \mu)/\sigma \}^2 + \sum_B \log (Q(l_i)) + \sum_C \log (P(u_i)) + \sum_D \log (p_i)$$

where $p_i = P(u_i) - P(l_i)$ and $u_i = (U_i - \mu)/\sigma, \quad l_i = (L_i - \mu)/\sigma$.

Let

$$S(x_i) = \frac{Z(x_i)}{Q(x_i)} \quad S_l(l_i, u_i) = \frac{Z(l_i) - Z(u_i)}{p_i}$$

and
then the first derivatives of the log-likelihood can be written as:

\[
\frac{\partial L(\mu, \sigma)}{\partial \mu} = L_1(\mu, \sigma) = \sigma^{-1} \sum_A (x_i - \mu) + \sigma^{-1} \sum_B S(l_i) - \sigma^{-1} \sum_C S(-u_i) + \sigma^{-1} \sum_D S_l(l_i, u_i)
\]

and

\[
\frac{\partial L(\mu, \sigma)}{\partial \sigma} = L_2(\mu, \sigma) = -\sigma^{-1} + \sigma^{-1} \sum_A (x_i - \mu)^2 + \sigma^{-1} \sum_B l_i S(l_i) - \sigma^{-1} \sum_C u_i S(-u_i)
\]

\[-\sigma^{-1} \sum_D S_2(l_i, u_i)\]

The maximum likelihood estimates, \( \hat{\mu} \) and \( \hat{\sigma} \), are the solution to the equations:

\[
L_1(\hat{\mu}, \hat{\sigma}) = 0
\]

and

\[
L_2(\hat{\mu}, \hat{\sigma}) = 0
\]

and if the second derivatives \( \frac{\partial^2 L}{\partial \mu^2} \), \( \frac{\partial^2 L}{\partial \mu \partial \sigma} \) and \( \frac{\partial^2 L}{\partial \sigma^2} \) are denoted by \( L_{11} \), \( L_{12} \) and \( L_{22} \) respectively, then estimates of the standard errors of \( \hat{\mu} \) and \( \hat{\sigma} \) are given by:

\[
se(\hat{\mu}) = \sqrt{\frac{-L_{22}}{L_{11}L_{22} - L_{12}^2}}, \quad se(\hat{\sigma}) = \sqrt{\frac{-L_{11}}{L_{11}L_{22} - L_{12}^2}}
\]

and an estimate of the correlation of \( \hat{\mu} \) and \( \hat{\sigma} \) is given by:

\[
\frac{L_{12}}{\sqrt{L_{12}L_{22}}}
\]

To obtain the maximum likelihood estimates the equations (1) and (2) can be solved using either the Newton–Raphson method or the Expectation-maximization (EM) algorithm of Dempster et al. (1977).

**Newton–Raphson Method**

This consists of using approximate estimates \( \tilde{\mu} \) and \( \tilde{\sigma} \) to obtain improved estimates \( \tilde{\mu} + \delta \tilde{\mu} \) and \( \tilde{\sigma} + \delta \tilde{\sigma} \) by solving

\[
\delta \tilde{\mu} L_{11} + \delta \tilde{\sigma} L_{12} + L_1 = 0,
\]

\[
\delta \tilde{\mu} L_{12} + \delta \tilde{\sigma} L_{22} + L_2 = 0,
\]

for the corrections \( \delta \tilde{\mu} \) and \( \delta \tilde{\sigma} \).

**EM Algorithm**

The expectation step consists of constructing the variable \( w_i \) as follows:

\[
\text{if} \quad i \in A, \quad w_i = x_i
\]

\[
\text{if} \quad i \in B, \quad w_i = E(x_i \mid x_i > L_i) = \mu + \sigma S(l_i)
\]

\[
\text{if} \quad i \in C, \quad w_i = E(x_i \mid x_i < U_i) = \mu - \sigma S(-u_i)
\]
if $i \in D$, 
\[
 w_i = E(x_i \mid L_i < x_i < U_i) = \mu + \sigma S_1(l_i, u_i)
\]  
(6)

the maximization step consists of substituting (3), (4), (5) and (6) into (1) and (2) giving:
\[
\hat{\mu} = \sum_{i=1}^{n} \hat{w}_i / n
\]
and
\[
\hat{\sigma}^2 = \sum_{i=1}^{n} (\hat{w}_i - \hat{\mu})^2 / \left\{ r + \sum_{B} T(\hat{l}_i) + \sum_{C} T(-\hat{u}_i) + \sum_{D} T_{1}(\hat{l}_i, \hat{u}_i) \right\}
\]
(8)

where
\[
 T(x) = S(x)\{S(x) - x\}, \quad T_{1}(l, u) = S_{1}^{2}(l, u) + S_{2}(l, u)
\]
and where $\hat{w}_i$, $\hat{l}_i$ and $\hat{u}_i$ are $w_i$, $l_i$ and $u_i$ evaluated at $\hat{\mu}$ and $\hat{\sigma}$. Equations (3) to (8) are the basis of the EM iterative procedure for finding $\hat{\mu}$ and $\hat{\sigma}^2$. The procedure consists of alternately estimating $\hat{\mu}$ and $\hat{\sigma}^2$ using (7) and (8) and estimating $\{\hat{w}_i\}$ using (3) to (6).

In choosing between the two methods a general rule is that the Newton–Raphson method converges more quickly but requires good initial estimates whereas the EM algorithm converges slowly but is robust to the initial values. In the case of the censored Normal distribution, if only a small proportion of the observations are censored then estimates based on the exact observations should give good enough initial estimates for the Newton–Raphson method to be used. If there are a high proportion of censored observations then the EM algorithm should be used and if high accuracy is required the subsequent use of the Newton–Raphson method to refine the estimates obtained from the EM algorithm should be considered.

4 References

5 Arguments
1: method – Nag_CEMethod
\textit{Input}

\textit{On entry}: indicates whether the Newton–Raphson or EM algorithm should be used.

If method = Nag_CEMNR, then the Newton–Raphson algorithm is used.

If method = Nag_CE_EM, then the EM algorithm is used.

\textit{Constraint}: method = Nag_CEMNR or Nag_CE_EM.

2: n – Integer
\textit{Input}

\textit{On entry}: $n$, the number of observations.

\textit{Constraint}: $n \geq 2$.

3: x[n] – const double
\textit{Input}

\textit{On entry}: the observations $x_i$, $L_i$ or $U_i$, for $i = 1, 2, \ldots, n$.

If the observation is exactly specified – the exact value, $x_i$. 

Mark 25
If the observation is right-censored – the lower value, $L_i$.
If the observation is left-censored – the upper value, $U_i$.
If the observation is interval-censored – the lower or upper value, $L_i$ or $U_i$, (see $xc$).

4: $xc[n] \rightarrow$ const double

*Input*

*On entry:* if the $j$th observation, for $j = 1, 2, \ldots, n$ is an interval-censored observation then $xc[j-1]$ should contain the complementary value to $x[j-1]$, that is, if $x[j-1] < xc[j-1]$, then $xc[j-1]$ contains upper value, $U_i$, and if $x[j-1] > xc[j-1]$ then $xc[j-1]$ contains lower value, $L_i$. Otherwise if the $j$th observation is exact or right- or left-censored $xc[j-1]$ need not be set.

*Note:* if $x[j-1] = xc[j-1]$ then the observation is ignored.

5: $ic[n] \rightarrow$ const Integer

*Input*

*On entry:* $ic[i-1]$ contains the censoring codes for the $i$th observation, for $i = 1, 2, \ldots, n$.

If $ic[i-1] = 0$, the observation is exactly specified.
If $ic[i-1] = 1$, the observation is right-censored.
If $ic[i-1] = 2$, the observation is left-censored.
If $ic[i-1] = 3$, the observation is interval-censored.

*Constraint:* $ic[i-1] = 0, 1, 2$ or $3$, for $i = 1, 2, \ldots, n$.

6: $xmu \rightarrow$ double *

*Input/Output*

*On entry:* if $xsig > 0.0$ the initial estimate of the mean, $\mu$; otherwise $xmu$ need not be set.

*On exit:* the maximum likelihood estimate, $\hat{\mu}$, of $\mu$.

7: $xsig \rightarrow$ double *

*Input/Output*

*On entry:* specifies whether an initial estimate of $\mu$ and $\sigma$ are to be supplied.

$xsig > 0.0$

$xsig$ is the initial estimate of $\sigma$ and $xmu$ must contain an initial estimate of $\mu$.

$xsig \leq 0.0$

Initial estimates of $xmu$ and $xsig$ are calculated internally from:

(a) the exact observations, if the number of exactly specified observations is $\geq 2$; or
(b) the interval-censored observations; if the number of interval-censored observations is $\geq 1$; or
(c) they are set to 0.0 and 1.0 respectively.

*On exit:* the maximum likelihood estimate, $\hat{\sigma}$, of $\sigma$.

8: $tol \rightarrow$ double

*Input*

*On entry:* the relative precision required for the final estimates of $\mu$ and $\sigma$. Convergence is assumed when the absolute relative changes in the estimates of both $\mu$ and $\sigma$ are less than $tol$.

If $tol = 0.0$, then a relative precision of 0.000005 is used.

*Constraint:* machine precision $\leq tol < 1.0$ or $tol = 0.0$.

9: $maxit \rightarrow$ Integer

*Input*

*On entry:* the maximum number of iterations.

If $maxit \leq 0$, then a value of 25 is used.
10:  sexmu – double *
    *Output
    On exit: the estimate of the standard error of $\hat{\mu}$.

11:  sexsig – double *
    *Output
    On exit: the estimate of the standard error of $\hat{\sigma}$.

12:  corr – double *
    *Output
    On exit: the estimate of the correlation between $\hat{\mu}$ and $\hat{\sigma}$.

13:  dev – double *
    *Output
    On exit: the maximized log-likelihood, $L(\hat{\mu}, \hat{\sigma})$.

    *Output
    On exit: the number of each different types of each observation;
    nobs[0] contains number of right-censored observations.
    nobs[1] contains number of left-censored observations.
    nobs[2] contains number of interval-censored observations.
    nobs[3] contains number of exactly specified observations.

15:  nit – Integer *
    *Output
    On exit: the number of iterations performed.

16:  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 *value* had an illegal value.

**NE_CONVERGENCE**

Method has not converged in *value* iterations.

**NE_DIVERGENCE**

Process has diverged.

**NE_EM_PROCESS**

The EM process has failed.

**NE_INT**

On entry, $n = \langle value \rangle$.
Constraint: $n \geq 2$.  

Mark 25  
g07bbc.5
NE_INT_ARRAY
On entry, ic[value] is invalid, it contains (value).

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.

NE_OBSERVATIONS
On entry, effective number of observations < 2.

NE_REAL
On entry, tol is invalid: tol = (value).

NE_STANDARD_ERRORS
Standard errors cannot be computed.

7 Accuracy
The accuracy is controlled by the argument tol.
If high precision is requested with the EM algorithm then there is a possibility that, due to the slow convergence, before the correct solution has been reached the increments of \( \hat{\mu} \) and \( \hat{\sigma} \) may be smaller than tol and the process will prematurely assume convergence.

8 Parallelism and Performance
Not applicable.

9 Further Comments
The process is deemed divergent if three successive increments of \( \mu \) or \( \sigma \) increase.

10 Example
A sample of 18 observations and their censoring codes are read in and the Newton–Raphson method used to compute the estimates.

10.1 Program Text
/* nag_censored_normal (g07bbc) Example Program. *
 * Copyright 2014 Numerical Algorithms Group.
 */
#include <stdio.h>
#include <string.h>
#include <nag.h>
#include <nag_stdlib.h>
#include <nagg07.h>
int main(void) {
  /* Scalars */
  double    corr, dev, sexmu, sexsig, tol, xmu, xsig;
  Integer   exit_status, i, maxit, n, nit;
  /* Arrays */
  char      nag_enum_arg[40];
  double    *x = 0, *xc = 0;
  Integer   *ic = 0, *nobs = 0;
  Nag_CEMethod method;
  NagError   fail;

  INIT_FAIL(fail);

  exit_status = 0;
  printf("nag_censored_normal (g07bbc) Example Program Results\n");

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

  /* nag_enum_name_to_value (x04nac).
   * Converts NAG enum member name to value
   */
  method = (Nag_CEMethod) nag_enum_name_to_value(nag_enum_arg);

  /* Allocate memory */
  if (!(x = NAG_ALLOC(n, double)) ||
      !(xc = NAG_ALLOC(n, double)) ||
      !(ic = NAG_ALLOC(n, Integer)) ||
      !(nobs = NAG_ALLOC(4, Integer)))
  {
    printf("Allocation failure\n");
    exit_status = -1;
    goto END;
  }

  for (i = 1; i <= n; ++i)
    #ifdef _WIN32
      scanf_s("%lf%lf%nAG_IPMT" %39s %lf%lf%nAG_IPMT"%[\n]", &n, nag_enum_arg,
           _countof(nag_enum_arg), &xmu, &xsig, &tol, &maxit);
    #else
      scanf("%lf%lf%nAG_IPMT" %39s %lf%lf%nAG_IPMT"%[\n]", &n, nag_enum_arg,
           &xmu, &xsig, &tol, &maxit);
    #endif
  /* nag_censored_normal (g07bbc).
   * Computes maximum likelihood estimates for parameters of
   * the Normal distribution from grouped and/or censored data
   */
  nag_censored_normal(method, n, x, xc, ic, &xmu, &xsig, tol, maxit,
                      &sexmu, &sexsig, &corr, &dev, nobs, &nit, &fail);

  if (fail.code != NE_NOERROR)
  {
    printf("Error from nag_censored_normal (g07bbc).\n%s\n", fail.message);
  
  
  END: }

  return exit_status;
}
exit_status = 1;
goto END;
}

printf("n");
printf(" Mean = %8.4f\n", xmu);
printf(" Standard deviation = %8.4f\n", xsig);
printf(" Standard error of mean = %8.4f\n", sexmu);
printf(" Standard error of sigma = %8.4f\n", sexsig);
printf(" Correlation coefficient = %8.4f\n", corr);
printf(" Number of right censored observations = %2"NAG_IFMT"\n",
   nobs[0]);
printf(" Number of left censored observations = %2"NAG_IFMT"\n",
   nobs[1]);
printf(" Number of interval censored observations = %2"NAG_IFMT"\n",
   nobs[2]);
printf(" Number of exactly specified observations = %2"NAG_IFMT"\n",
   nobs[3]);
printf(" Number of iterations = %2"NAG_IFMT"\n", nit);
printf(" Log-likelihood = %8.4f\n", dev);

END:
NAG_FREE(x);
NAG_FREE(xc);
NAG_FREE(ic);
NAG_FREE(nobs);

return exit_status;
}

10.2 Program Data
nag_censored_normal (g07bbc) Example Program Data
18 Nag_CE_NR 4.0 1.0 0.00005 50
4.5 0.0 0 5.4 0.0 0 3.9 0.0 0 5.1 0.0 0 4.6 0.0 0 4.8 0.0 0
2.9 0.0 0 6.3 0.0 0 5.5 0.0 0 4.6 0.0 0 4.1 0.0 0 5.2 0.0 0
3.2 0.0 1 4.0 0.0 1 3.1 0.0 1 5.1 0.0 2 3.8 0.0 2 2.2 2.5 3

10.3 Program Results
nag_censored_normal (g07bbc) Example Program Results
Mean = 4.4924
Standard deviation = 1.0196
Standard error of mean = 0.2606
Standard error of sigma = 0.1940
Correlation coefficient = 0.0160
Number of right censored observations = 3
Number of left censored observations = 2
Number of interval censored observations = 1
Number of exactly specified observations = 12
Number of iterations = 5
Log-likelihood = -22.2817