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ESTIMATION OF PARAMETERS FOR TRUNCATED DISTRIBUTIONS

by

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PREFACE

The work described herein originated in the Methodology Group of Systems Analysis Branch, Systems Development Division. It was authorized by Project 1L162706A554, Smoke/Obscurants, was performed from 1 to 27 October 1980, and is part of the Chemical Systems Laboratory's (CSL) support of Technical Area 4-C, Smoke Technology, to develop methodology for operational assessment.

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## ESTIMATION OF PARAMETERS FOR TRUNCATED DISTRIBUTIONS

### 1. INTRODUCTION

The analysis of chemical warfare systems involves the use of distributions of droplet, particle, spot, and fragment sizes. Many field and laboratory tests are conducted to obtain data for the determination of such distributions. As a practical matter, the experimenter usually assumes the data are best characterized by a lognormal distribution, which is equivalent to assuming that the logarithm of the sizes is normally distributed. Then he proceeds to perform the routine calculations for the mean and standard deviation of the data and reports the results. If his experimental measurements span the range of possible sizes and the number of observations is sufficiently large, this procedure leads to acceptable results. However, many measuring devices are limited to a specific operating range, particularly on the low end, beyond which no data are obtainable. Since most experimenters are familiar with procedures for dealing with the effects of sample size on their estimates, this topic is not addressed further. On the other hand, many experimenters fail to recognize or consider properly the effect of such missing data. The purpose of this report is to describe the problem and present a method for determining the best estimates of the parameters of a truncated lognormal distribution.

### 2. THE PROBLEM

For the present purpose, it is assumed that a lognormal distribution of sizes of spherical liquid drops is adequate to represent the data collected in an experiment which counted the number of drops in each of a finite set of size intervals. The mathematical expression for the probability density function of the lognormal distribution is

$$f(d) = (d \ln \sigma_g \sqrt{2\pi})^{-1} \exp \left[ -1/2 \left( \frac{\ln d - \ln d_N}{\ln \sigma_g} \right)^2 \right]$$

where

- d = diameter of a drop
- $d_N$  = number median diameter (geometric mean)
- $\sigma_g$  = geometric standard deviation of the diameters

The objective of the experimenter is to obtain the best estimates of  $d_N$  and  $\sigma_g$ , or possibly the mass median diameter  $d_M$ , which is related to  $d_N$  by the expression

$$\ln d_M = \ln d_N + 3 \ln^2 \sigma_g \quad (2)$$

Suppose the experimental data obtained consist of the number  $n_i$  of drops in the  $i$ -th size interval such that  $d_{i-1} \leq d < d_i$  for  $i=1,2,\dots,k$  and  $d_0 > 0$ . No information is available for any  $d < d_0$ . If this truncation of the distribution at  $d_0$  is not considered, the results reported will be

$$\hat{d}_N = \exp \left\{ \frac{\sum_{i=1}^k N_i \ln \left[ \frac{1}{2} (d_{i-1} + d_i) \right]}{\sum_{i=1}^k N_i} \right\} \quad (3)$$

and

$$\hat{\sigma}_g = \exp \left\{ \left( \frac{\sum_{i=1}^k n_i \ln^2 \left[ \frac{(d_{i-1} + d_i)/(2d_N)}{2} \right]}{\sum_{i=1}^k n_i - 1} \right)^{1/2} \right\} \quad (4)$$

where the estimates  $\hat{d}_N$  and  $\hat{\sigma}_g$  may be far from the best estimates. Depending on the degree of truncation, the estimate of  $d_N$  will be too high, while that of  $\sigma_g$  will be too low by an undetermined amount.

### 3. A SOLUTION

In 1908, Pearson and Lee\* reported an algorithm for obtaining maximum likelihood estimates of the mean and standard deviation of a singly truncated normal distribution. Maximum likelihood estimates may be defined as those which describe the distribution of a random variable most likely to produce the set of observations of a random experiment. In many instances, these estimates are unbiased and of minimum variance; but, these properties, while most desirable, are not guaranteed.

The Pearson-Lee method consists of solving the equations derived by equating the first and second sample and population moments about the point of truncation. If the point of truncation is not known precisely, it is recommended that a point slightly less than the lowest observed size be used. The equations to be solved are

$$\sigma = \left[ \frac{z(x)}{1-\phi(x)} - x \right]^{-1} \frac{1}{u} \quad (5)$$

\* Pearson, Karl, and Lee, Alice. On the Generalized Probable Error in Multiple Normal Correlation, Biometrika 6, 59-68, (1908).

and

$$\frac{\hat{\sigma}}{\bar{u}} \left( \frac{\hat{\sigma}}{\bar{u}} - x \right) = \frac{\sum_{i=1}^k n_i u_i^2}{\bar{u}^2} \quad (6)$$

$$u = u^l - u_0^l \quad (7)$$

where  $u^l$  = original random variable

$u_0^l$  = truncation point ( $u_0^l \leq u^l$ )

$$\bar{u} = \frac{\sum_{i=1}^k n_i u_i}{\sum_{i=1}^k n_i} \quad (8)$$

$$x = \frac{u_0^l - \hat{m}}{\hat{\sigma}}, \text{ a standard deviate} \quad (9)$$

where  $\hat{m}$  = mean of the normal distribution (estimated)

$\hat{\sigma}$  = estimated normal standard distribution

$$z(x) = (\sqrt{2\pi})^{-1} \exp(-x^2/2) \quad (10)$$

$$\phi(x) = \int_{-\infty}^x z(t) dt \quad (11)$$

By solving equation (5) for  $\hat{\sigma}/\bar{u}$  and substituting in equation (6), a nonlinear equation in  $x$  arises. Once  $x$  is determined by some means,  $\hat{\sigma}$  can be obtained from equation (5) and  $\hat{m}$  from solving equation (9). Cohen and Woodward\* have published tables for solution of the equations, and we have prepared a computer program in BASIC (see the Appendix) for numerical solution.

In terms of the lognormal distribution of our problem

$$\begin{aligned} u^l &= \ln d, \\ u_0^l &= \ln d_0, \\ u &= \ln (d/d_0), \\ \hat{\sigma} &= \exp(\hat{\sigma}), \text{ and} \\ \hat{d}_N &= \exp(\hat{m}) \end{aligned}$$

\* Cohen, A.C., and Woodward, John. Tables of Pearson-Lee-Fisher Functions of Singly Truncated Normal Distribution. Biometrics 9, 489-497 (1953).

#### 4. ILLUSTRATIVE EXAMPLE

An aerosol sample injected into a particle counter produced the data shown in table 1. The smallest particle resolved was 0.15  $\mu\text{m}$  in diameter. One can see that the data are truncated just below the mode of the distribution, this implies that neglect of the truncation could produce a significant error. In fact, the estimates obtained by the blind application of routine formulas are  $\hat{d}_N = 0.200$  and  $\hat{\sigma}_g = 1.20$ . If we apply the Pearson-Lee algorithm as implemented in the computer program, we get  $\hat{d}_N = 0.186$  and  $\hat{\sigma}_g = 1.26$ , and note that the differences in the estimates are in the expected directions.

Table 1. Experimental Observations

| <u>Point No.</u> | <u>Size Range</u> | <u>Count</u> | <u>Point No.</u> | <u>Size Range</u> | <u>Count</u> |
|------------------|-------------------|--------------|------------------|-------------------|--------------|
| 1                | 0.15 - 0.16       | 375          | 16               | 0.305 - 0.330     | 21           |
| 2                | 0.16 - 0.17       | 408          | 17               | 0.330 - 0.355     | 10           |
| 3                | 0.17 - 0.18       | 428          | 18               | 0.355 - 0.380     | 6            |
| 4                | 0.18 - 0.19       | 384          | 19               | 0.380 - 0.405     | 3            |
| 5                | 0.19 - 0.20       | 379          | 20               | 0.405 - 0.430     | 2            |
| 6                | 0.20 - 0.21       | 333          | 21               | 0.430 - 0.455     | 1            |
| 7                | 0.21 - 0.22       | 279          | 22               | 0.455 - 0.480     | 0            |
| 8                | 0.22 - 0.23       | 207          | 23               | 0.480 - 0.505     | 1            |
| 9                | 0.23 - 0.24       | 203          | 24               | 0.505 - 0.530     | 0            |
| 10               | 0.24 - 0.25       | 139          | 25               | 0.530 - 0.555     | 0            |
| 11               | 0.25 - 0.26       | 176          | 26               | 0.555 - 0.580     | 0            |
| 12               | 0.26 - 0.27       | 113          | 27               | 0.580 - 0.605     | 0            |
| 13               | 0.27 - 0.28       | 75           |                  |                   |              |
| 14               | 0.28 - 0.29       | 65           |                  |                   |              |
| 15               | 0.29 - 0.30       | 51           |                  |                   |              |

#### 5. SUMMARY

A method has been found and implemented to obtain estimates of the parameters of truncated normal and lognormal distributions. Emphasis is placed on the importance of recognizing the truncation of data by measuring devices and on the ease with which the problem can be solved.

## APPENDIX

### A Computer Program for Estimating the Parameters of a Truncated Lognormal Distribution

A computer program has been written to implement the Pearson-Lee method of estimating the parameters of a normal distribution and to apply the technique to data from a lognormal distribution. The program is written in BASIC for the Tektronix (TEK) 4051 Graphics Calculator. The interactive mode is used to prompt the demand terminal user for the proper input sequence. Because the TEK 4051 has an internal tape unit, provision is made for data storage and retrieval from unit 33. Statements may be removed from unit 33 and used with other terminals or host computers. The program also calculates estimates of the parameters using a method by Cohen which uses the third moments about the truncation point. Use of third moments is believed to introduce inaccuracies which become apparent in the large deviations from the Pearson-Lee maximum likelihood estimates. A listing of the program appears at the end of the appendix.

Two comments are needed to guide the program user:

1. The test identification can be a string of 72 characters.
2. The size requested should be the midpoint of the size range represented.

```

1 GO TO 100
4 GOSUB 840
5 PRINT X,Z,P,H,H1,F,F1
6 GO TO 1100
8 GO TO 1030
12 GO TO 110
16 GO TO 730
100 INIT
110 PAGE
120 PRINT "ENTER NO. OF OBSERVATIONS :";
130 INPUT N0
140 PRINT "ENTER LOWER BOUND OF DATA :";
150 INPUT D0
160 PRINT "ENTER TEST IDENTIFICATION"
170 INPUT A$
180 RESTORE 200
190 READ N,S1,S2,S3,S4,S5,R9
200 DATA 0,0,0,0,0,0,0
210 IF N0=0 THEN 390
220 PRINT "ENTER INPUT FILE NO. (0 FOR KEYBOARD, -FILE FOR SAVE): ";
230 INPUT F2
240 IF F2=0 THEN 260
250 FIND ABS(F2)
260 PRINT "ENTER DATA PAIRS, (SIZE,FREQ.) : "
270 DIM D2(N0),M2(N0)
280 M0=N0
290 FOR I=1 TO N0
300 IF F2<=0 THEN 330
310 INPUT @33:D2(I),M2(I)
320 GO TO 360
330 INPUT D2(I),M2(I)
340 IF F2=0 THEN 360
350 PRINT @33:D2(I),M2(I)
360 NEXT I

```

```

370 PAGE
375 PRINT A$
380 PRINT "POINT NO.", "SIZE RANGE", "COUNT"
390 FOR I=1 TO M0
395 IF R9<1 THEN 430
400 FOR J=1 TO R9
410 IF I=M3(J) THEN 510
420 NEXT J
430 N=N+M2(I)
440 S1=S1+M2(I)*LOG(D2(I))
450 S2=S2+M2(I)*LOG(D2(I))^2
460 S3=S3+M2(I)*LOG(D2(I)/D0)
470 S4=S4+M2(I)*LOG(D2(I)/D0)^2
480 S5=S5+M2(I)*LOG(D2(I)/D0)^3
490 IF N0=0 THEN 510
500 PRINT I, D2(I), M2(I)
510 NEXT I
520 D1=EXP(S1/N)
530 S=EXP(SQR((S2-N*LOG(D1))^2)/(N-1))
540 PRINT "STATISTICS OF RAW DATA"
550 PRINT
560 PRINT "GEOMETRIC MEAN = ";D1
570 PRINT "GEOMETRIC STD. DEV. = ";S
580 PRINT
590 PRINT
600 X=(LOG(D0)-LOG(D1))/LOG(S)
610 RESTORE 640
620 C=N*S4/S3^2
630 READ G,E
640 DATA 30,1.0E-8
650 GOSUB 950
660 GOSUB 840
670 S9=EXP(S3/H^H)
680 D9=EXP(LOG(D0)-X*LOG(S9))
690 PRINT "STATISTICS USING PEARSON-LEE METHOD"

```

```

700 PRINT "ADJUSTED GEOMETRIC MEAN = ";D9
710 PRINT "ADJUSTED GEOM. STD. DEV. = ";S9
720 P1=S3/N
730 P2=S4/N
740 P3=S5/N
750 PRINT "STATISTICS USING COHEN METHOD"
760 PRINT "ADJ. GEOM. MEAN=";EXP(LOG(D0)-(2*P1*P2-P3)/(2*P1+2-P2+2))
770 PRINT "ADJ. STD. DEV.=";EXP(SQR((P1*P3-P2+2)/(2*P1+2-P2)))
780 PRINT A$
790 GO TO 1100
800 B=1/SQR(2*PI)
810 Z=B*EXP(-0.5*X+2)
820 X9=X*(X=>0)-X*(X<0)
830 T9=1/(1+0.33267*X9)
840 P9=1-Z*T9*(0.4361836+T9*(-0.1201676+T9*0.937298))
850 P=P9*(1-2*(X<0))/(X<0)
860 H=1/(Z/(1-P))-X
870 H1=H+2*(Z*(Z-X*(1-P))/(1-P)+2-1)*-1
880 F=H*(H-X)-C
890 F1=2*X*H1-X*H1-H
900 RETURN
910 N9=1
920 GOSUB 840
930 X=X-F/F1
940 IF ABS(F/F1)/ABS(X)<E THEN 1020
950 IF N9>C THEN 1020
960 N9=N9+1
970 GO TO 960
980 RETURN
990 PRINT "ENTER NO. OF POINTS TO REMOVE,FOLLOWED BY INDICES OF POINTS"
1000 INPUT R9

```

```
1045 DELETE M3  
1050 DIM M3(R9)  
1060 FOR J=1 TO R9  
1070 INPUT M3(J)  
1080 NEXT J  
1090 GO TO 370  
1100 END
```

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