Employing Vague Prior Information in the Construction of Confidence Sets

GEORGE CASELLA AND JIUNN TZON HWANG

Cornell University

Communicated by A. Cohen

In the problem of estimating the mean, $\theta$, of a multivariate normal distribution, an experimenter will often be able to give some vague prior specifications about $\theta$. This information is used to construct confidence sets centered at improved estimators of $\theta$. These sets are shown to have uniformly (in $\theta$) higher coverage probability than the usual confidence set (a sphere centered at the observations), with no increase in volume. Further, through the use of a modified empirical Bayes argument, a variable radius confidence set is constructed which provides a uniform reduction of volume. Strong numerical evidence is presented which shows that the empirical Bayes set also dominates the usual confidence set in coverage probability. All these improved sets provide substantial gains if the prior information is correct. Also considered are extensions to the unknown variance case, and a discussion of applications to the one-way analysis of variance. In particular, a procedure is presented which uniformly improves upon Scheffé's method of estimation of contrasts. © 1987 Academic Press, Inc.

1. INTRODUCTION

In the past twenty years, much progress has been made with the problem of improving on the usual point estimator of a multivariate normal mean. However, only recently has there been progress with the problem of improving upon the usual confidence set. Let $X \sim N(\theta, \sigma^2I)$ where, for now, $\sigma^2$ is assumed to be known. The usual confidence set is a $p$-dimensional sphere centered at $X$ with radius $c\sigma$, i.e.,

$$C^0_{X,c} = \{ \theta : |\theta - X| \leq c\sigma \}.$$

Received March, 1984; revised April 2, 1986.
Key words and phrases: Multivariate normal mean, Stein Estimation, empirical Bayes, Analysis of variance.

79
The constant \( c \) is chosen to satisfy \( P(X^2 \leq c^2) = 1 - \alpha \), which implies that \( P(\theta \in C^0_{X,\sigma}) = 1 - \alpha \) and \( C^0_{X,\sigma} \) has coverage probability \( 1 - \alpha \).

The usual confidence set \( C^0_{X,\sigma} \) is minimax in the sense that among all the confidence sets with coverage probability at least \( 1 - \alpha \), \( C^0_{X,\sigma} \) minimizes the maximum volume. Despite this optimality property (and many others), it has been shown independently by Brown [4] and Joshi [11] that \( C^0_{X,\sigma} \) can be improved upon provided \( p \geq 3 \). They showed that if \( p \geq 3 \), there exists another confidence set \( C^{BJ} \) dominating \( C^0_{X,\sigma} \) in the sense that

(a) \( P_\theta(\theta \in C^{BJ}) \geq P_\theta(\theta \in C^0_{X,\sigma}) \),

(b) \( \text{volume } C^{BJ} \leq \text{volume } C^0_{X,\sigma} \),

with strict inequality holding in either (a) or (b) for a set of positive Lebesgue measure of \( \theta \) or \( X \), respectively.

More recently, Faith [8] derived an alternative confidence set by considering a version of a Bayes credible set. Berger [1] also developed alternative confidence sets. Starting with a prior that gives admissible minimax point estimators, Berger constructed confidence ellipsoids centered at the posterior mean and oriented by the posterior covariance matrix. Berger and Faith both presented convincing analytical and numerical evidence that their confidence sets dominate \( C^0_{X,\sigma} \).

Hwang and Casella [9, 10] consider simpler confidence sets; spheres recentered at the positive part James–Stein estimator. These confidence sets are shown to dominate \( C^0_{X,\sigma} \). In particular, Hwang and Casella [9] give the first analytical proof that their confidence sets dominate \( C^0_{X,\sigma} \). Later, Hwang and Casella [10] provide another, simpler proof which strengthens these domination results. These stronger results form a base on which the results of this paper are built.

Even though \( C^0_{X,\sigma} \) can be improved upon uniformly, it is impossible to significantly improve on \( C^0_{X,\sigma} \) everywhere. (This is due to the minimaxity of \( C^0_{X,\sigma} \).) So far, all the improved confidence sets proposed yield significant improvement over \( C^0_{X,\sigma} \) (either by increasing coverage probability or decreasing volume) only when \( \theta \) and \( X \) are near a fixed point. Naturally, an experimenter would choose the fixed point to be the most likely value of \( \theta \) (or the prior guess of \( \theta \)) so that there is a good chance of realizing a substantial gain by using the improved confidence set.

In some situations, however, there may only be vague prior information concerning the most likely value of \( \theta \). In particular, it may be thought that \( \theta \) lies in a linear subspace of the parameter space, perhaps described by the equation \( H\theta = 0 \), where \( H \) is a known matrix. (In the point estimation problem, Bock [2, 3] has many interesting results concerning these and other forms of vague prior information.)

One useful type of prior information, particularly in the analysis of
variance, is the specification that the $\theta_j$'s are equal to a common, unknown value. (This is the null hypothesis in the one-way analysis of variance.) We interpret this type of vague prior information as stating that the $\theta_j$ are close to each other, but it is not clear what is the common likely value. In such situations, all of the above confidence sets may improve upon $C_{x,\alpha}$ only slightly, and one might as well use $C_{x,\alpha}^\circ$.

In this paper we consider confidence sets that are recentered at estimators of the form

$$
\delta^4(X) = AX + \left\{ 1 - \frac{a\sigma^2}{\| (I - A) X \|^2} \right\}^+ [(I - A) X],
$$

estimators which shrink toward a linear subspace. We pay particular attention to the matrix $A = (1/p) 11'$, where $1$ is a $p \times 1$ vector of ones. The resulting estimator is

$$
\delta^4(X) = \bar{x}1 + \left\{ 1 - \frac{a\sigma^2}{\| X - \bar{x}1 \|^2} \right\}^+ (X - \bar{x}1),
$$

where $\bar{x} = (1/p) \sum_{i=1}^p X_i$, which is the positive-part version of the estimator first derived by Lindley [14]. This estimator shrinks toward the estimate of the common mean, $\bar{x}$, and it is well known that, as a point estimator, $\delta^4(X)$ dominates $X$ (under sum of squared errors loss), provided $0 < a \leq 2(p - 3)$. It is also known that $\delta^4(X)$ yields significant improvement over $X$ as long as $\sum (\theta_i - \bar{\theta})^2/\sigma^2$ is small, where $\bar{\theta} = (1/p) \sum \theta_i$. Therefore, $\delta^4(X)$ is a particularly pertinent point estimator when it is thought that the $\theta_j$'s are close to each other. The same is true of the confidence sets based on $\delta^4$, as will be shown in this paper.

In Section 2, we prove that a confidence set recentered at $\delta^4$ (with radius $\alpha$) dominates $C_{x,\alpha}^\circ$. Generalized confidence sets centered at an improved estimator shrinking toward an arbitrary linear subspace are also constructed. Applications to the one-way analysis of variance model, and other models, are discussed.

Section 3 develops (using an empirical Bayes approach) confidence sets centered at $\delta^4$ with radius uniformly smaller than the usual confidence set. Numerical evidence shows that the coverage probability of these sets is at least $1 - \alpha$. When $\sigma^2$ is unknown, but an independent estimate, $s^2$, of $\sigma^2$ is available, we modify these sets by replacing $\sigma^2$ by its estimate. Numerical evidence also confirms the superiority of this adaptive empirical Bayes confidence set over the usual confidence set (based on $X$ and $s^2$). Section 4 discusses applications of these results to the multiple comparisons problem. In particular, it is shown that Scheffé's procedure can be improved upon uniformly (in the sense that, for the same confidence level, intervals with smaller radii are constructed).
2. Fixed Radius Confidence Sets

2.1. Improved Confidence Sets for the Mean

In this section we consider fixed radius confidence sets centered at estimators which shrink toward a linear subspace. For a fairly general class of confidence sets we obtain dominance results similar to those of Hwang and Casella [10]: that is, we prove that these recentered sets have uniformly higher coverage probability than the usual confidence set.

Let \( X \) be an observation from a \( p \)-variate normal distribution with mean vector \( \theta \) and covariance matrix \( \sigma^2 I \). (Generalization to an arbitrary, known covariance matrix \( \Sigma \) is straightforward, and will be treated later in this section.) Define the estimator \( \delta^+ (X) \) by

\[
\delta^+ (X) = \left[ 1 - \left( a \sigma^2 / |X|^2 \right) \right]^+ X,
\]

where \( a \) is a positive constant, \( "^+" \) denotes positive part, and \( |\cdot|^2 \) is the Euclidean norm. This is the well-known positive-part James–Stein estimator, which shrinks the maximum likelihood estimator towards zero.

We consider estimators of the form

\[
\delta^A (X) = AX + \delta^+ \left[ (I - A) X \right],
\]

where \( A \) is a \( p \times p \) symmetric, idempotent matrix, and confidence sets of the form

\[
C_{\delta^A} = \{ \theta : |\theta - \delta^A (X)| \leq c \sigma \}.
\]

The choice of the matrix \( A \) is usually based on prior information, reflecting the belief that \( AX \) is a reasonable estimator of \( \theta \). If \( 0 \leq a \leq 2(p - q - 2) \), where \( q \) is the rank of \( A \), \( \delta^A (X) \) is a minimax estimator of \( \theta \) under squared error loss. Moreover, the region of significant risk improvement is the region where \( |(I - A) \theta| / \sigma \) is small. Comparing this to the estimator \( \delta^+ (X) \), which yields significant risk improvement only when \( |\theta| / \sigma \) is small, shows that \( \delta^A (X) \) has a wider region of significant improvement, and is very efficient if the prior belief is true.

The performance of the confidence set \( C_{\delta^A} \) parallels that of \( \delta^A (X) \). As will be seen in Theorem 2.1, for suitable choices of \( a \), \( C_{\delta^A} \) dominates \( C_{\delta^0} \) in coverage probability. It is also shown that the coverage probability depends on \( \theta \) only through \( |(I - A) \theta| / \sigma \). This, and, for \( q = 1 \), the numerical results reported in Tables II and III, show that the region where \( C_{\delta^A} \) significantly improves upon \( C^0 \) is widened in a way similar to the point estimation case. Consequently, \( C_{\delta^A} \) is very useful if the prior information is correct, and still dominates \( C_{X_{\delta^0}} \) even if the prior information is incorrect.

As mentioned before, we will also focus on the special case \( A = (1/p) 11' \),
where \( I \) is a \( p \times 1 \) vector of ones. This choice of \( A \) reflects the belief that the \( \theta_i \)'s are close together (or exchangeable), which is the case if the ANOVA null hypothesis is true. The resulting estimator is

\[
\delta^L(X) = \bar{x}1 + \delta^+(X - \bar{x}1),
\]  

(2.4)

the positive-part Lindley estimator. The coverage probability of the associated confidence set

\[
C_{\delta^L} = \{ \theta : |\theta - \delta^L(X)| \leq c\sigma \}
\]  

(2.5)

depends on \( \theta \) only through \( \sum p (\theta_i - \theta)^2 / \sigma^2 \). Thus, similar to \( \delta^+(X) \), \( \delta^L(X) \) significantly widens the region of improvement, obtaining maximal improvement when the \( \theta_i \)'s are close together.

We now proceed to establish the dominance of \( C_{\delta^L} \) over \( C^{10}_{X,\sigma} \) by extending the results of Hwang and Casella [10], who give conditions for the dominance of \( C_{\delta^+} = \{ \theta : |\theta - \delta^+(X)| \leq c\sigma \} \) over \( C^{10}_{X,\sigma} \). Define the functions \( G_q(a, c) \) and \( H_q(a, c) \) by

\[
G_q(a, c) = \left[ \left( \frac{c}{\sqrt{2}} + \frac{\sqrt{c^2 + a}}{\sqrt{a}} \right) \right]^{p - q - 2} e^{-c\sqrt{a^2},}
\]

\[
H_q(a, c) = \left[ \left( \frac{c + \sqrt{c^2 + a}}{\sqrt{a}} \right) \right]^{p - q - 1} e^{-c\sqrt{a}} \left[ \frac{\sqrt{c^2 + 4a - c}}{2\sqrt{a}} \right].
\]  

(2.6)

**Lemma 2.1** [10]. If \( p \geq 3 \), the confidence set

\[
C_{\delta^+} = \{ \theta : |\theta - \delta^+(X)| \leq c\sigma \}
\]  

(2.7)

has higher coverage probability than \( C^{10}_{X,\sigma} \) for every \( \theta \) provided \( a > 0 \) and \( c > 0 \) satisfy \( G_q(a, c) \geq 1 \) and \( H_q(a, c) \geq 1 \).

The dominance of \( C_{\delta^L} \) over \( C^{10}_{X,\sigma} \) can now be established by using a transformation to reduce the problem to that of Lemma 2.1.

**Theorem 2.1.** Let \( A \) be a symmetric, idempotent matrix of rank \( q \), \( p - q > 2 \). The confidence set \( C_{\delta^L} \) has higher coverage probability than \( C^{10}_{X,\sigma} \) for every \( \theta \) provided \( 0 < a \leq a_0 \), where \( a_0 \) is the minimum of the two unique solutions to

\[
G_q(a, c) = 1 \quad \text{and} \quad H_q(a, c) = 1.
\]  

(2.8)

Consequently, since \( C_{\delta^L} \) and \( C^{10}_{X,\sigma} \) have the same volume, \( C_{\delta^L} \) uniformly dominates \( C^{10}_{X,\sigma} \). Furthermore, the coverage probability of \( C_{\delta^L} \) depends on \( \theta \) only through \( |(I - A) \theta| / \sigma \).
TABLE I

Values of $a_0$ for $q = 1$

<table>
<thead>
<tr>
<th>$p$</th>
<th>$a = 0.10$</th>
<th>$a = 0.05$</th>
<th>$p$</th>
<th>$a = 0.10$</th>
<th>$a = 0.05$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.669</td>
<td>0.633</td>
<td>15</td>
<td>9.888</td>
<td>9.675</td>
</tr>
<tr>
<td>5</td>
<td>1.517</td>
<td>1.458</td>
<td>16</td>
<td>10.731</td>
<td>10.510</td>
</tr>
<tr>
<td>6</td>
<td>2.392</td>
<td>2.281</td>
<td>17</td>
<td>11.574</td>
<td>11.345</td>
</tr>
<tr>
<td>7</td>
<td>3.211</td>
<td>3.083</td>
<td>18</td>
<td>12.418</td>
<td>12.182</td>
</tr>
<tr>
<td>8</td>
<td>4.036</td>
<td>3.893</td>
<td>19</td>
<td>13.263</td>
<td>13.020</td>
</tr>
<tr>
<td>9</td>
<td>4.865</td>
<td>4.710</td>
<td>20</td>
<td>14.109</td>
<td>13.859</td>
</tr>
<tr>
<td>10</td>
<td>5.697</td>
<td>5.531</td>
<td>21</td>
<td>14.955</td>
<td>14.699</td>
</tr>
<tr>
<td>11</td>
<td>6.532</td>
<td>6.355</td>
<td>22</td>
<td>15.802</td>
<td>15.539</td>
</tr>
<tr>
<td>12</td>
<td>7.369</td>
<td>7.182</td>
<td>23</td>
<td>16.650</td>
<td>16.381</td>
</tr>
<tr>
<td>13</td>
<td>8.207</td>
<td>8.011</td>
<td>24</td>
<td>17.498</td>
<td>17.223</td>
</tr>
</tbody>
</table>

Remark. Values of $a_0$ for $q = 1$ and $a = 0.1$ and 0.05 are given in Table I. These values of $a_0$ do not reach the value $p - 3$, which is the standard choice for the point estimation problem. However, by comparing Tables II and III, it can be seen that the differences in coverage probabilities are minimal.

Proof. Without loss of generality, let $\sigma^2 = 1$ (simply make the transformation $Y = X/\sigma$). Write

$$|\theta - \delta^4(x)|^2 = |[A\theta - AX] + (I - A) \theta - \delta^+ [(I - A) X]|^2$$

$$= |A(\theta - X)|^2 + |(I - A) \theta - \delta^+ [(I - A) X]|^2, \quad (2.9)$$

TABLE II

Coverage Probabilities of the Set $C_{\alpha}^\prime$ with $a = a_0$, $\alpha = 0.10$

<table>
<thead>
<tr>
<th>$p$</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\theta - \delta</td>
<td>/\sigma$</td>
<td>0.940</td>
<td>0.991</td>
<td>0.998</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>1.000</td>
<td>0.995</td>
<td>0.997</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>0.927</td>
<td>0.985</td>
<td>0.994</td>
<td>0.998</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>0.905</td>
<td>0.956</td>
<td>0.988</td>
<td>0.997</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td></td>
<td>0.902</td>
<td>0.930</td>
<td>0.962</td>
<td>0.983</td>
<td>0.994</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>0.890</td>
<td>0.895</td>
<td>0.920</td>
<td>0.946</td>
<td>0.961</td>
<td>0.974</td>
</tr>
<tr>
<td></td>
<td>0.900</td>
<td>0.903</td>
<td>0.908</td>
<td>0.914</td>
<td>0.920</td>
<td>0.927</td>
</tr>
<tr>
<td></td>
<td>0.900</td>
<td>0.901</td>
<td>0.904</td>
<td>0.905</td>
<td>0.901</td>
<td>0.901</td>
</tr>
<tr>
<td></td>
<td>0.900</td>
<td>0.900</td>
<td>0.901</td>
<td>0.901</td>
<td>0.901</td>
<td>0.901</td>
</tr>
</tbody>
</table>
where the second equality follows from the fact that \( A \) is symmetric idem-
potent and consequently satisfies \( A'(I-A) = 0 \). Furthermore, there exists
an orthogonal matrix \( P \) satisfying \( PAP' = D_q \), where \( D_q \) is a diagonal
matrix whose first \( q \) diagonal elements are 1 and last \( p-q \) are zero. Define
\[ Y = PX, \quad \eta = P\theta. \] (2.10)

It follows that \( Y \sim N(\eta, I) \) and we have
\[ |\theta - \delta^A(X)|^2 = \sum_{i=1}^{q} (\eta_i - Y_i)^2 + \sum_{i=q+1}^{p} \{\eta_i - [1 - (a/S_Y)]^+ Y_i\}^2, \] (2.11)
where \( S_Y = \sum_{i=q+1}^{p} Y_i^2 \). Using the facts that the \( Y_i \)'s are independent and
\( \sum_{i=1}^{q} (\eta_i - Y_i)^2 \sim \chi^2_q \), we have
\[ P_\eta[|\theta - \delta^A(X)|^2 \leq c^2] = \int_0^{c^2} P_\eta \left( \sum_{i=q+1}^{p} \{\eta_i - [1 - (a/S_Y)]^+ Y_i\}^2 \leq t \right) g_q(t) \, dt, \] (2.12)
where \( g_q(t) \) is the pdf of a \( \chi^2_q \) random variable. The theorem will be
established if we can show that for every \( b \) satisfying \( 0 < b^2 \leq c^2 \),
\[ P_\eta \left( \sum_{i=q+1}^{p} \{\eta_i - [1 - (a/S_Y)]^+ Y_i\}^2 \leq b^2 \right) > P_\eta \left( \sum_{i=q+1}^{p} (\eta_i - Y_i)^2 \leq b^2 \right), \] (2.13)
since substituting the right-hand side of (2.13) for the integrand in (2.12) yields

\[ P_\theta(|\theta - \delta^*(X)|^2 \leq c^2) \geq \int_0^c P_\eta \left( \sum_{i=q+1}^p (\eta_i - Y_i)^2 \leq c^2 - t \right) g_\eta(t) \, dt \]

\[ = P_\theta(|\theta - X|^2 \leq c^2). \quad (2.14) \]

To establish (2.13) we use Lemma 2.1. Since \( (Y_{q+1}, \ldots, Y_p) \) is distributed as a \((p-q)\)-variate normal random variable with mean \((\eta_{q+1}, \ldots, \eta_p)\) and identity covariance matrix, by Lemma 2.1 it is sufficient to establish that \( G_\eta(a, b) \geq 1 \) and \( H_\eta(a, b) \geq 1 \) for \( 0 < a \leq a_0 \) and \( 0 < b^2 \leq c^2 \).

We will only give details for the proof that \( G_\eta(a, b) \geq 1 \) for \( 0 < b^2 \leq c^2 \), the proof being similar for \( H_\eta(a, c) \). Note that, for each value of \( b \), the function \( G_\eta(a, b) \) is decreasing in \( a \). Hence, it is sufficient to establish that \( G_\eta(a^*, b) \geq 1 \), where \( a^* \) satisfies \( G_\eta(a^*, c) = 1 \). It is straightforward to check that \( \frac{\partial}{\partial a} \log G_\eta(a, b) \) is strictly decreasing in \( b \). Hence, \( G_\eta(a^*, b) \) either strictly decreases to zero in \( b \) or strictly increases to a unique maximum and then strictly decreases to zero. However, the former case is impossible since \( G_\eta(a^*, 0) = G_\eta(a^*, c) = 1 \). Hence, the latter case implies \( G_\eta(a^*, b) > 1 \) for \( 0 < b^2 < c^2 \).

Finally, from (2.12), an orthogonal transformation will show that the coverage probability is a function only of \( \sum_{i=q+1}^p \eta_i^2 = ||I - A||^2 \).

It is straightforward to extend the results of Theorem 2.1 to the case when \( X \) has an arbitrary, known covariance matrix \( \Sigma \). In this case, the usual confidence set is

\[ C_\Sigma = \{ \theta : (\theta - X)' \Sigma^{-1}(\theta - X) \leq c^2 \}. \quad (2.15) \]

For a given matrix \( A \), define \( A^* \) by

\[ A^* = \Sigma^{1/2} A \Sigma^{-1/2} \quad (2.16) \]

and

\[ \delta^{A^*}(X) = A^*X + \left( 1 - \frac{a}{X'(I - A^*)' \Sigma^{-1}(I - A^*) X} \right)^+ (I - A^*) X. \quad (2.17) \]

The confidence set associated with \( \delta^{A^*}(X) \) is

\[ C_{\delta^{A^*}} = \{ \theta : [\theta - \delta^{A^*}(X)]' \Sigma^{-1} [\theta - \delta^{A^*}(X)] \leq c^2 \}. \quad (2.18) \]

The following corollary shows that \( C_{\delta^{A^*}} \) is a uniform improvement over \( C_\Sigma \).
**Corollary 2.1.** The confidence set $C_{\delta^*}$ has uniformly higher coverage probability than $C_{0,2}$ provided

(i) $A$ is symmetric, idempotent of rank $q$, $p - q > 2$, and

(ii) $0 < a \leq a_0$, where $a_0$ is the unique solution to (2.8).

**Proof.** The transformation $Y = \Sigma^{-1/2}X$ reduce this to the case of Theorem 2.1.

2.2. Applications

In this section we consider various cases of the estimators and confidence sets constructed in Section 2.1. We pay particular attention to the type of prior information which may be useful in achieving the greatest possible improvement.

**Example 1.** The unbalanced one-way analysis of variance. In a one-way ANOVA model, it is assumed that there are $p$ treatments characterized by the levels $\theta_1, \ldots, \theta_p$, and there are $n_i$ i.i.d. $N(\theta_i, \sigma^2)$ observations $X_{1i}, \ldots, X_{ni}$. The variance, $\sigma^2$, is assumed to be known.

By sufficiency, we can consider only procedures depending on $X_i = (1/n_i) \sum_{j=1}^{n_i} X_{ij}$, $1 \leq i \leq p$. The vector $\vec{X} = (\bar{X}_1, \ldots, \bar{X}_p)'$ has a multivariate normal distribution with mean $(\theta_1, \ldots, \theta_p)'$ and covariance matrix $\Sigma = \sigma^2 D_n^{-1}$, $D_n = \text{diag}(n_1, \ldots, n_p)$. The usual confidence set is

$$C_{\bar{X}, \sigma} = \{\theta : (\theta - \bar{X})' D_n (\theta - \bar{X}) \leq c^2 \sigma^2\}.$$  

(2.19)

Corollary 2.1 provides better confidence sets, however.

Consider the situation when prior information indicates $\theta_j$'s are very likely to be close. Under the assumption that $\theta_i = \theta_j$, $\forall i, j$, the classical estimator (the uniformly minimum variance unbiased estimator and the maximum likelihood estimator) of the common value $\theta$ is $\bar{x} = (1/N) \sum_{i=1}^{p} \sum_{j=1}^{n_i} X_{ij}$, where $N = \sum n_i$. In this situation, the reasonable estimator to use is one which shrinks $\bar{X}$ to an estimate of the common $\theta$. If we take $A = D_n^{1/2} 11' D_n^{1/2}/N$, we have $A^* = 11' D_n/N$, and

$$\delta^*(\bar{X}) = \bar{x}1 + \left[1 - \frac{a \sigma^2}{\sum_{i=1}^{p} n_i (\bar{X}_i - \bar{x})^2} \right]^+ (\bar{X} - \bar{x}1),$$

(2.20)

a version of the positive-part Lindley estimator. Note that $A$ is a symmetric, idempotent matrix, and hence Corollary 2.1 shows that the confidence set

$$C_{\delta^*} = \{\theta : [\theta - \delta^*(\bar{X})]' D_n [\theta - \delta^*(\bar{X})] \leq c^2 \sigma^2\}$$

(2.21)

uniformly dominates $C_{\bar{X}, \sigma}$ provided $0 \leq a \leq a_0$, where $a_0$ is the largest value
which satisfies \( G_1(a, c) \geq 1 \) and \( H_1(a, c) \geq 1 \). For \( a = 0.1 \) and 0.05, the values of \( a_0 \) are given in Table 1.

Another, somewhat more vague, prior specification which may be useful is to suppose that \( \theta \) is a multiple of a known vector, i.e., \( \theta = a r \), where \( a \) is an unknown scalar and \( r \) is a known vector. If \( r = 1 \), this case reduces to the previous situation. Under the model \( \theta = a r \), the classical estimator (i.e., the uniformly minimum unbiased estimator and the maximum likelihood estimator) of \( \theta \) is

\[
\delta'(\bar{X}) = r r' \Sigma^{-1} \bar{X}/r' \Sigma^{-1} r
\]

(2.22)

with \( i \)th component

\[
\delta'_i(\bar{X}) = r_i \Sigma, r_i, n_i, \bar{X}_i/\Sigma, n_i, r_i^2.
\]

It is therefore reasonable to consider \( \delta^{A'} \) that shrinks \( \bar{X} \) toward \( \delta'(\bar{X}) \). If we choose

\[
A = D_n^{1/2} r r' D_n^{1/2}/r' D_n r,
\]

(2.23)

which is symmetric and idempotent, we have \( A^* = D_n^{-1/2} A D_n^{1/2} = r r' D_n r/r' D_n r \). Corollary 2.1 then shows that a confidence set of the form (2.21) centered at

\[
\delta^{A'}(X) = \delta'(\bar{X}) + \left[ 1 - \frac{a \sigma^2}{\sum_{i=1}^n \bar{n}_i [\bar{X}_i - \delta'_i(\bar{X})]^2} \right]^{1/2} \left[ \bar{X} - \delta'(\bar{X}) \right]
\]

dominates one centered at \( \delta'(\bar{X}) \).

**Example 2.** \( \theta \) lies in a linear subspace. We now consider a more general form of restriction, one in which the prior information indicates that \( \theta \) lies in a linear subspace of the parameter space. This example includes the case of the general linear model (with known variance) as a special case, if \( X \), below, is taken to be the least squares estimator.

Assume \( X \sim N(\theta, \Sigma) \), where \( \Sigma \) is a nonsingular known matrix. Suppose that the prior information indicates that \( \theta \) lies in the plane

\[
L_H = \{ \theta : H \theta = 0 \},
\]

where \( H \) is a \( k \times p \) matrix with rank \( k \). Assuming \( \theta \in L_H \), it can be shown that the classical estimator (the uniformly minimum variance unbiased estimator and the maximum likelihood estimator) of \( \theta \) is \( A^* X \) with

\[
A^* = I - \Sigma H' (H \Sigma H')^{-1} H.
\]
In Corollary 2.1, let $A = I - \Sigma^{-1/2}H'(H\Sigma H')^{-1}H\Sigma^{1/2}$, which is symmetric and idempotent. The resulting estimator is

$$\delta^A(X) = A^*X + \left[1 - \frac{a}{X'HH'(H\Sigma H')^{-1}HX}\right]^+ \Sigma H'(H\Sigma H')^{-1}HX,$$

and it follows that the confidence set centered at this estimator uniformly dominates the one centered at $A^*X$ provided $0 < a \leq a_0$, where $a_0$ satisfies $G_{\mu}(a, c) \geq 1$ and $H_k(a, c) \geq 1$.

If, instead, prior belief indicates that $\theta$ is near $L_H = \{\theta : H\theta = m\}$, which is assumed to be a nonempty set with $H$ being as above and $m$ a known $k$-component vector, we can proceed as follows. Assume that $\theta_0 \in L_H$; i.e., $H\theta_0 = m$. By transforming $X' = X - \theta_0$ and $\theta' = \theta - \theta_0$, the problem is reduced to the above setting. It then follows that an improved confidence set can be constructed by centering at the estimator

$$\delta^A(x) = \left[X - \Sigma H'(H\Sigma H')^{-1}(HX - m)\right]$$

$$+ \left[1 - \frac{a}{(HX - m)'(H\Sigma H)(HX - m)}\right]^+ \times \Sigma H'(H\Sigma H')^{-1}(HX - m).$$

3. Variable Radius Confidence Sets

The confidence sets considered in Section 2 are all of fixed radius and, hence, afford no volume reduction over the usual set. Although sets such as $C_{\mu}$ of (2.5) yield uniformly higher coverage probability, an experiment must report the same confidence coefficient as reported if the usual set, $C_{D_\mu}$, had been used. Thus, to the experimenter, there is no tangible evidence that $C_{D_\mu}$ should be preferred over $C_{D_0}$.

Since the coverage probability of $C_{D_\mu}$ can be much greater than that of $C_{D_0}$, there seems to be room for decreasing its volume without giving up dominance in coverage probability. The construction of such confidence sets is the focus of this section.

We confine our attention to the estimator

$$\delta^B(X) = \hat{x}I + \left(1 - \frac{a\sigma^2}{\Sigma(X' - \hat{x})^2}\right)^+ (X' - \hat{x}I), \quad (3.1)$$

the positive-part Lindley estimator. Through the use of transformations like those in Section 2, the results of this section can be generalized to include estimators such as $\delta^A$ of (2.2), and associated confidence sets. However, we will not consider such generalizations here.

In Section 3.1 we derive, through the use of a modified empirical Bayes
argument, a variable radius confidence set based on $\delta^1(X)$. It is shown that
this set has uniformly smaller volume than the usual confidence set and, in
fact, can provide significant volume reduction. Also, the exact formula for
the coverage probability is derived. Although dominance in coverage
probability is not demonstrated analytically, strong numerical evidence is
presented which shows that the empirical Bayes confidence set is superior
to the usual set. Section 3.2 deals with the case of unknown $\sigma^2$, where
the empirical Bayes sets are modified by replacing $\sigma^2$ by an estimate. Again,
these sets yield a reduction in volume, and (based on numerical evidence)
also dominate the usual confidence set in coverage probability.

3.1. Empirical Bayes Confidence Sets

We now consider confidence sets of the form
\[ \{ \theta : |\theta - \delta^1(X)|^2 \leq \nu(X, \sigma) \}, \]  \hspace{1cm} (3.2)
where $\nu$ is a nondecreasing function of $|X - \bar{x}I|$. It is a difficult task to find
a function $\nu$ that will yield a confidence set dominating the usual one in
coverage probability. To get some idea of what form such a function will
take, we use an empirical Bayes argument. We begin by deriving a Bayes
rule against the loss function
\[ L_k(\theta, C) = k \text{ Volume (} C \text{)} - I_c(\theta), \]  \hspace{1cm} (3.3)
where $I_c(\theta) = 1$ if $\theta \in C$ and zero otherwise. For this loss function, the usual
confidence set
\[ C^0_{X, \sigma} = \{ \theta : |\theta - X| \leq c\sigma \} \]
is minimax if $k = k_0 = \exp(-c^2/2\sigma^2)/(2\pi\sigma^2)^{p/2}$. Since $k_0$ is the only value of
$k$ for which $C^0_{X, \sigma}$ is minimax, it seems reasonable to use this value in deriving
a Bayes rule. Furthermore, Casella and Hwang [6, Theorems 2.1, 2.2,
and 2.3] argue that a rule that is minimax with respect to $L_k$ is likely to
dominate $C^0_{X, \sigma}$.

An empirical Bayes argument has been previously used [5] to derive
confidence sets centered at the positive-part James–Stein estimator. There,
normal priors were used in a way parallel to the derivation of the
James–Stein point estimator in Efron and Morris [7]. More recently,
Morris [15] has used empirical Bayes arguments to construct improved
confidence intervals. Our goal here is to derive confidence sets centered at
$\delta^1(X)$ so, naturally, we consider Lindley's two-stage prior, namely
\[ X | \theta, \sigma^2 \sim N(\theta, \sigma^2 I) \]
\[ \theta | \mu, \tau^2 \sim N(\mu I, \tau^2 I) \]
\[ \mu \sim \text{Uniform}(-\infty, \infty). \]  \hspace{1cm} (3.4)
The improper prior on the scalar \( \mu \) can be interpreted as an approximation to an \( n(0, \lambda^2) \) density, where \( \lambda^2 \) is much larger than \( \sigma^2 \) or \( \tau^2 \).

From Joshi [12] or Faith [8], it follows that the Bayes rule against \( L_k \) is

\[
C^B = \{ \theta : \pi(\theta \mid X) \geq k \},
\]

where \( \pi(\theta \mid X) \) is the posterior density of \( \theta \). Direct calculation shows that the posterior distribution is \( \mathcal{N} [\delta^B(X), \Sigma] \), where

\[
\delta^B(X) = \bar{x}I + \frac{\tau^2}{\sigma^2 + \tau^2} (X - \bar{x}I),
\]

\[
\Sigma^{-1} = \left( \frac{1}{\sigma^2 + \frac{\tau^2}{\tau^2}} \right) V^{-1}, \quad V^{-1} = I - \frac{\sigma^2}{\rho(\sigma^2 + \tau^2)} \mathbf{1}\mathbf{1}'.
\]

Setting \( k = k_0 \), the Bayes rule against \( L_{k_0} \) can be written (after some algebra) as

\[
C^B = \{ \theta : [\theta - \delta^B(X)]' V^{-1} [\theta - \delta^B(X)] \leq v^B(\tau^2, \sigma^2) \}
\]

where

\[
v^B(\tau^2, \sigma^2) = \frac{\sigma^2 \tau^2}{\sigma^2 + \tau^2} \left\{ \frac{c^2 - (p - 1) \log(\tau^2/(\tau^2 + \sigma^2))}{c^2} \right\}.
\]

The prior variance, \( \tau^2 \), is usually unknown, and the empirical Bayesian will replace \( \tau^2 \) by an estimate taken from the marginal density of \( X \). Marginally, \( \sum_{i=1}^{p} (X_i - \bar{x})^2 \sim (\sigma^2 + \tau^2) \chi^2_{p-1} \), and it follows that

\[
E \left\{ \frac{1}{\Sigma(X_i - \bar{x})^2} \right\} = \frac{\tau^2}{\tau^2 + \sigma^2}.
\]

The empirical Bayes strategy is to replace \( \tau^2/(\tau^2 + \sigma^2) \) in \( v^B \) by its unbiased estimate. However, the unbiased estimate may be negative, which is undesirable. Hence, we truncate the unbiased estimate, and replace \( v^B \) by the modified empirical Bayes estimate

\[
v^*(X, \sigma) = \sigma^2 T [c^2 - (p - 1) \log T]
\]

where

\[
T = \begin{cases} 
1 - \frac{(p - 3) \sigma^2}{\Sigma(X_i - \bar{x})^2} & \text{if } \frac{\Sigma(X_i - \bar{x})^2}{\sigma^2} \geq c^2 \\
1 - \frac{p - 3}{c^2} & \text{if } \frac{\Sigma(X_i - \bar{x})^2}{\sigma^2} < c^2
\end{cases}
\]
We assume that $c^2 > p - 3$ so that $\log T$ is defined. This an extremely minor assumption since $c^2 = p - 3$ would give $C^2_{\theta,\sigma}$ a confidence coefficient of approximately 0.3.

Now consider the left-hand side of the inequality in (3.7). Direct calculation shows

$$[\theta - \delta^B(X)]' V^{-1} [\theta - \delta^B(X)] = |\theta - \delta^B(X)|^2 - \frac{p\sigma^2}{\tau^2 + \sigma^2} (\bar{x} - \theta)^2. \quad (3.12)$$

If we use the empirical Bayes strategy on (3.12), this will lead us to a very complicated confidence set. It not only will be hard to interpret (it may not be convex), but also its coverage probability will be quite hard to evaluate. Thus, we take a simpler alternative, and merely drop the last term in (3.12) (which also decreases the volume of the confidence set). Upon replacing $\delta^B(X)$ by its estimate, $\delta^E(X)$, we obtain our recommended confidence set

$$C^E_{\theta,\sigma} = \{\theta: |\theta - \delta^E(X)|^2 \leq v^E(X, \sigma)\}. \quad (3.13)$$

The coverage probability of $C^E_{\theta,\sigma}$ can be evaluated by using a decomposition similar to that used in Section 2, Theorem 2.1. Taking $\sigma^2 = 1$ we have

$$P_0(\theta \in C^E_{\theta,\sigma}) = \int_0^1 P_\eta \{ |\eta - \delta^+(Y)|^2 \leq [v^*(|Y|) - t]^+ \} \, g_1(t) \, dt. \quad (3.14)$$

where $Y \sim N_{p-1}(\eta, I)$, $\eta = \theta - \theta 1$, $\delta^+(Y) = [1 - (p-3)/|Y|^2]^+ Y$, $g_1(t)$ is the density of a $\chi^2_1$ random variable, and

$$v^*(|Y|) = \left( 1 - \frac{p-3}{\max \{|Y|^2, c^2\}} \right) \left[ c^2 - (p-1) \log \left( 1 - \frac{p-3}{\max \{|Y|^2, c^2\}} \right) \right].$$

To evaluate the integrand of (3.14), transform to the spherical coordinates $r = |Y|, \cos \beta = \eta Y/|\eta||Y|$. We then have

$$\{ |\eta - \delta^+(Y)|^2 \leq [v^*(|Y|) - t]^+ \}$$

$$= \{ r^2 \gamma^2(r) - 2 \gamma(r) |\eta| \cos \beta + |\eta|^2 \leq [v^*(r) - t]^+ \}, \quad (3.15)$$

where $\gamma(r) = [1 - (a/r^2)]^+$.

Some algebra will show that this last set can be written as

$$\{(r, \beta) : r \in S_{a, r}, \cos \beta > h(r, t)\}, \quad (3.16)$$

where $S_{a, r}$ is either an interval, or the union of two disjoint intervals, and is defined by

$$S_{a, r} = \{ r : \{ |\eta| - [r - (a/r)]^+ \}^2 \leq [v^*(r) - t]^+ \}. \quad (3.17)$$
and

\[
h(r, t) = \begin{cases} 
\max \left\{ \frac{r^2 \gamma^2(r) + |\eta|^2 - \left[ \theta^*(r) - t \right]^+}{2r |\eta| \gamma(r)}, \ -1 \right\} & \text{if } r\gamma(r) \neq 0 \\
-1 & \text{if } r\gamma(r) = 0.
\end{cases}
\]

(3.18)

We thus have the following representation for the coverage probability of \( C_{X,\sigma}^E \).

**Theorem 3.1.** If \( p \geq 3 \), for \( |\theta - \theta| > 0 \),

\[
P_\theta(\theta \in C_{X,\sigma}^E) = K \int_0^1 \int_{S_{\eta}} \cos^{-1}(h) \, r^p (\sin \beta)^{p-3} \\
\times \exp \left\{ -(r^2 - 2r |\eta| \cos \beta + |\eta|^2) / 2 \right\} g(t) \, d\beta \, dt, \tag{3.19}
\]

where \( K = \sqrt{\pi} \Gamma[(p-2)/2] 2^{(p-3)/2} \). \( \eta = |\theta - \theta| / \sigma \), and \( g(t) \) is the density of a \( \chi^2_1 \) random variable. If \( |\theta - \theta| = 0 \), then \( P_\theta(\theta \in C_{X,\sigma}^E) = \int_0^1 P[\chi^2_1 \leq r^+(0, t)] g(t) \, dt \), where \( r^+(\eta, t) = \max \{ r : r \in S_{\eta} \} \).

**Proof.** If \( |\theta - \theta| = 0 \), the set \( \{ Y : |\eta - \delta^+(Y)|^2 \leq \left[ \theta^*(|Y|) - t \right]^+ \} \) clearly contains \( Y = 0 \). Hence \( S_{\eta} \) is an interval and the result follows. The result for \( |\theta - \theta| > 0 \) is easily established by carrying out the spherical transformation.

If \( \theta^E \) is constant, as in Section 2, then it is possible to express (3.17) as an interval. The fact that this cannot be done when \( \theta^E \) is nonconstant is the major reason why dominance of \( C_{X,\sigma}^E \) over \( C_{X,\sigma}^0 \) in coverage probability cannot be established analytically. Formula (3.19) has been evaluated numerically, however. For \( a = p - 3 \) and \( a = 0.1 \), coverage probabilities of \( C_{X,\sigma}^E \) are presented in Table IV. We choose to use \( a = p - 3 \), rather than \( a = a_0 \), because this value produces a better point estimator than \( a = a_0 \), and is more readily available to an experimenter. The numerical evidence shows that, with the exception of \( p = 4 \) and \( a = 0.1 \), \( C_{X,\sigma}^E \) provides a uniform improvement over \( C_{X,\sigma}^0 \). Moreover, the failure of \( C_{X,\sigma}^E \) is so slight (for example, a minimum coverage probability of 0.891 for \( a = 0.1 \)) that for all intents and purposes, \( C_{X,\sigma}^E \) can be regarded as a \( 1 - \alpha \) confidence set.

The important feature of \( C_{X,\sigma}^E \), however, is that it provides a reduction in volume over \( C_{X,\sigma}^0 \). This is established in the following theorem.

**Theorem 3.2.** If \( c^2 > p - 1 \), the radius of \( C_{X,\sigma}^E \) is uniformly (in \( |X - \bar{X}| \)) smaller than that of \( C_{X,\sigma}^0 \). Hence, \( C_{X,\sigma}^E \) has uniformly smaller volume.
TABLE IV
Coverage Probabilities of the Empirical Bayes Confidence Set $C_{x_x}^E$, $\alpha = 0.10$

<table>
<thead>
<tr>
<th>$\theta - \theta_1/\sigma$</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.937</td>
<td>0.987</td>
<td>0.997</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>1</td>
<td>0.934</td>
<td>0.985</td>
<td>0.996</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>2</td>
<td>0.920</td>
<td>0.976</td>
<td>0.993</td>
<td>0.998</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>3</td>
<td>0.892</td>
<td>0.950</td>
<td>0.984</td>
<td>0.995</td>
<td>0.998</td>
<td>0.999</td>
</tr>
<tr>
<td>4</td>
<td>0.891</td>
<td>0.906</td>
<td>0.941</td>
<td>0.968</td>
<td>0.991</td>
<td>0.997</td>
</tr>
<tr>
<td>6</td>
<td>0.896</td>
<td>0.902</td>
<td>0.921</td>
<td>0.939</td>
<td>0.952</td>
<td>0.961</td>
</tr>
<tr>
<td>8</td>
<td>0.898</td>
<td>0.903</td>
<td>0.916</td>
<td>0.933</td>
<td>0.950</td>
<td>0.961</td>
</tr>
<tr>
<td>10</td>
<td>0.898</td>
<td>0.902</td>
<td>0.912</td>
<td>0.925</td>
<td>0.938</td>
<td>0.950</td>
</tr>
<tr>
<td>20</td>
<td>0.899</td>
<td>0.900</td>
<td>0.903</td>
<td>0.907</td>
<td>0.912</td>
<td>0.917</td>
</tr>
<tr>
<td>50</td>
<td>0.899</td>
<td>0.900</td>
<td>0.900</td>
<td>0.901</td>
<td>0.902</td>
<td>0.903</td>
</tr>
<tr>
<td>100</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
</tr>
</tbody>
</table>

Proof. From (3.10),

$$v^E(X, \sigma) = \sigma^2 T[c^2 - (p - 1) \log T],$$

where $T$ is defined in (3.11). Differentiation shows $(\partial v^E/\partial T) > 0$, which implies that $v^E$ is a nondecreasing function of $T$. Since $T$ is a nondecreasing function of $|X - \bar{x}|$, and $0 < T \leq 1$, it follows that $v^E$ is nondecreasing in $|X - \bar{x}|$, and is bounded by $c^2 \sigma^2$.

TABLE V
Ratio of the Radii of $C_{x_x}^E$ to $C_{x_x}^o$ for $\alpha = 0.10$

<table>
<thead>
<tr>
<th>$\rho$</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.958</td>
<td>0.883</td>
<td>0.847</td>
<td>0.823</td>
<td>0.804</td>
<td>0.789</td>
</tr>
<tr>
<td>1</td>
<td>0.958</td>
<td>0.883</td>
<td>0.847</td>
<td>0.823</td>
<td>0.804</td>
<td>0.789</td>
</tr>
<tr>
<td>2</td>
<td>0.958</td>
<td>0.883</td>
<td>0.847</td>
<td>0.823</td>
<td>0.804</td>
<td>0.789</td>
</tr>
<tr>
<td>3</td>
<td>0.964</td>
<td>0.883</td>
<td>0.847</td>
<td>0.823</td>
<td>0.804</td>
<td>0.789</td>
</tr>
<tr>
<td>4</td>
<td>0.980</td>
<td>0.907</td>
<td>0.847</td>
<td>0.823</td>
<td>0.804</td>
<td>0.789</td>
</tr>
<tr>
<td>6</td>
<td>0.991</td>
<td>0.964</td>
<td>0.937</td>
<td>0.906</td>
<td>0.868</td>
<td>0.818</td>
</tr>
<tr>
<td>8</td>
<td>0.995</td>
<td>0.980</td>
<td>0.968</td>
<td>0.935</td>
<td>0.941</td>
<td>0.926</td>
</tr>
<tr>
<td>10</td>
<td>0.997</td>
<td>0.988</td>
<td>0.980</td>
<td>0.973</td>
<td>0.966</td>
<td>0.959</td>
</tr>
<tr>
<td>20</td>
<td>0.999</td>
<td>0.997</td>
<td>0.995</td>
<td>0.994</td>
<td>0.993</td>
<td>0.991</td>
</tr>
<tr>
<td>50</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
</tbody>
</table>
To get an idea of the amount of possible improvement, Table V gives values of the ratio of the radii of $C^E_{X,\sigma}$ to $C^0_{X,\sigma}$, i.e.,

$$
\frac{\text{Radius of } C^E_{X,\sigma}}{\text{Radius of } C^0_{X,\sigma}} = \left( \frac{T_c \left( c^2 - (p - 1) \log T_c \right)}{c^2} \right)^{1/2}.
$$

(3.20)

As can be seen in Table V, the amount of possible improvement can be substantial if $|X - \bar{x}1|$ is small. We also note that, in terms of volume reduction (rather than radius reduction) the improvement is even greater. The ratio of volumes is obtained by raising (3.20) to the $p$th power and, hence, is smaller than the ratio of the radii.

3.2. The Case of Unknown Variance

We assume now that $\sigma^2$ is unknown, but an estimate $s^2$ of $\sigma^2$, independent of $X$, is available, where $s^2 \sim (\sigma^2/\nu) \chi^2_\nu$. The usual $1 - \alpha$ confidence set for $\theta$ is

$$
C^0_{X,s} = \{ \theta : |\theta - \bar{X}|^2 \leq s^2 c^2 \},
$$

(3.21)

where $c^2$ satisfies $P(F_{p,v} \leq c^2/p) = 1 - \alpha$, where $F_{p,v}$ denotes an $F$-random variable with $p$ and $v$ degrees of freedom.

In order to obtain an improved confidence set, it should be possible to proceed as in Section 3.1, and consider a modified empirical Bayes set. However, it is no longer clear as to which priors would lead us to reasonable empirical Bayes sets. An obvious choice would be to use a conjugate prior, but such calculations lead to enormously complicated sets with no easily discernible optimality properties. One disconcerting fact is the following: consider the simple known variance case $X|\theta \sim N(\theta, \sigma^2 I)$ and $\theta|\tau^2 \sim N(0, \tau^2 I)$. As $\tau^2 \rightarrow \infty$, the Bayes set converges to $C^0_{X,s}$ and the Bayes risk converges to the risk of $C^0_{X,s}$. This no longer occurs in the unknown variance case. For the conjugate priors ($\theta|\sigma^2, \tau^2 \sim N(0, \sigma^2 \tau^2 I), \sigma^2 \sim \text{Inverse Gamma}$) as $\tau^2 \rightarrow \infty$, neither the Bayes set nor the Bayes risk converges to that of $C^0_{X,s}$.

Thus, we consider the simpler alternative of replacing $\sigma^2$ in $C^E_{X,\sigma}$ by its estimate, $s^2$, and form the confidence set

$$
C^E_{X,s} = \{ \theta : |\theta - \bar{x}1(X, s)|^2 \leq \nu(X, s) \},
$$

(3.22)

where

$$
\nu(X, s) = s^2 T_c \left[ c^2 - (p - 1) \log T_c \right],
$$

$$
T_c = \begin{cases} 
1 - \frac{a_s s^2}{\Sigma(X_i - \bar{x})^2} & \text{if } \frac{\Sigma(X_i - \bar{x})^2}{s^2} \geq c^2, \\
1 - \frac{a_s}{c^2} & \text{if } \frac{\Sigma(X_i - \bar{x})^2}{s^2} < c^2,
\end{cases}
$$

(3.23)
\[ \delta^L(X, s) = \bar{x}1 + \left( 1 - \frac{a_v s^2}{\sum (x_i - \bar{x})^2} \right)^+ (X - \bar{x}1), \]

and

\[ a_v = v(p - 3)/(v + 2). \]

The choice \( a = a_v \) again reflects the fact that \( a_v \) results in an optimal point estimator. Also, if we assume the structure of (3.4) and merely regard \( \sigma^2 \) as a nuisance parameter, we have (similar to (3.9))

\[ \lim_{v \to \infty} E \left[ 1 - \frac{a_v s^2}{\sum (x_i - \bar{x})^2} \right] = \frac{\tau^2}{\tau^2 + \sigma^2}. \]  

(3.24)

Thus, \( C_{x,s}^E \) retains somewhat of an empirical Bayes flavor.

Again, dominance of coverage probability of \( C_{x,s}^E \) over \( C_{x,s}^0 \) could not be obtained analytically. The major reason for this is the same as in the known variance case: the limits of integration could not be solved explicitly. However, the exact formula of the coverage probability of \( C_{x,s}^E \) is straightforward to derive, and can be easily obtained for the formula for the coverage probability of \( C_{x,s}^E \).

**Theorem 3.3.** The coverage probability of \( C_{x,s}^E \) is

\[ P_{\theta}(\theta \in C_{x,s}^E) = \int_0^\infty P[|\theta - \delta^L(X,t)|^2 \leq v^E(X,t)] \ g_v(t) \ dt, \]  

(3.25)

where \( g_v(t) \) is the density of a \( \chi^2 \) random variable, and \( \delta^L \) and \( v^E \) are given in (3.23).

**Proof.** The formula follows immediately from the independence of \( X \) and \( s^2. \)

The integrand in Eq. (3.25) can be evaluated using Theorem 3.1. Values of the coverage probability have been evaluated numerically for \( p = 4, 10, \) \( v = 2, 5, 10, 20, 30, \) and \( \alpha = 0.1, \) and are presented in Table VI. With the exception of \( p = 4, \) and a few other cases (not reported here) where \( v = 2, \) \( C_{x,s}^E \) demonstrates almost uniform dominance in coverage probability over \( C_{x,s}^0. \) Again, when \( C_{x,s}^E \) fails, the failure is so slight that it is reasonable to treat \( C_{x,s}^E \) as a \( 1 - \alpha \) confidence set.

\( C_{x,s}^E \) does provide a uniform reduction in volume over \( C_{x,s}^0 \) and, similar to Theorem 3.2, we have the following theorem.

**Theorem 3.4.** If \( c^2 > p - 1, \) then Volume(\( C_{x,s}^E \)) < Volume(\( C_{x,s}^0 \)) for all values of \( X \) and \( s^2. \)
TABLE VI
Coverage Probabilities for the Set $C_{x,s}^e$, $\alpha = 0.1$

| $|\theta - \theta_1|/\sigma$ | \(p = 4\) | \(p = 10\) |
|---------------------------|--------|--------|
|                           | $n$    | $\theta_1$ | $\theta_1$ | $\theta_1$ | $\theta_1$ |
|                           | 2      | 5       | 10        | 20        | 30        |
| 0                         | 0.901  | 0.909   | 0.918     | 0.926     | 0.929     |
| 1                         | 0.901  | 0.907   | 0.916     | 0.923     | 0.926     |
| 2                         | 0.900  | 0.903   | 0.907     | 0.912     | 0.914     |
| 4                         | 0.900  | 0.898   | 0.897     | 0.895     | 0.894     |
| 6                         | 0.900  | 0.899   | 0.898     | 0.897     | 0.897     |
| 8                         | 0.900  | 0.899   | 0.899     | 0.899     | 0.899     |
| 10                        | 0.900  | 0.899   | 0.900     | 0.900     | 0.900     |
| 15                        | 0.900  | 0.899   | 0.900     | 0.900     | 0.900     |
| 20                        | 0.900  | 0.899   | 0.900     | 0.900     | 0.900     |

Proof. From (3.23), it is clear that the ratio of the radii of $C_{x,s}^e$ to $C_{x,s}^0$ (and hence the ratio of the volumes) is a function of the data only through $\Sigma(X_i - \bar{x})^2/s^2$. The theorem is then established in a manner similar to that of Theorem 3.2.

Selected values of the radius ratio are presented in Table VII. While the reduction in volume is not as much as for the known variance case, $C_{x,s}^e$ can provide good volume reduction if $\Sigma(X_i - \bar{x})^2/s^2$ is small.

4. ESTIMATION OF CONTRASTS IN THE ONE-WAY ANALYSIS OF VARIANCE

Often, in the analysis of variance, an experimenter is not only interested in testing the overall hypothesis that the treatment means are equal, but also in testing or estimating linear combinations of the means. The confidence sets developed in the previous two sections can be readily adapted to such situations. In fact, the variable radius confidence sets of Section 3
TABLE VII  
Ratio of the Radii of $C_{s,y}$ to $C_{0,y}$, $\alpha = 0.1$

| $|X - \bar{s}|/s$ | 2  | 5  | 10 | 20 | 30 |
|----------------|----|----|----|----|----|
| $p = 4$        |    |    |    |    |    |
| 0              | 0.994 | 0.980 | 0.971 | 0.965 | 0.963 |
| 1              | 0.994 | 0.980 | 0.971 | 0.965 | 0.963 |
| 2              | 0.994 | 0.980 | 0.971 | 0.965 | 0.963 |
| 4              | 0.994 | 0.982 | 0.981 | 0.981 | 0.980 |
| 6              | 0.994 | 0.992 | 0.992 | 0.991 | 0.991 |
| 8              | 0.996 | 0.996 | 0.995 | 0.995 | 0.995 |
| 10             | 0.998 | 0.997 | 0.997 | 0.997 | 0.997 |
| 15             | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 |
| 20             | 0.999 | 0.999 | 0.999 | 0.999 | 0.999 |

$\psi = 0.996$

$p = 10$

| 0              | 0.983 | 0.942 | 0.913 | 0.892 | 0.884 |
| 1              | 0.983 | 0.942 | 0.913 | 0.892 | 0.884 |
| 2              | 0.983 | 0.942 | 0.913 | 0.892 | 0.884 |
| 4              | 0.983 | 0.947 | 0.946 | 0.946 | 0.946 |
| 6              | 0.983 | 0.971 | 0.971 | 0.972 | 0.972 |
| 8              | 0.984 | 0.982 | 0.982 | 0.982 | 0.982 |
| 10             | 0.993 | 0.992 | 0.992 | 0.992 | 0.993 |
| 15             | 0.996 | 0.996 | 0.996 | 0.996 | 0.996 |

provide a procedure that is a uniform improvement over the S-method of Scheffé [16].

Recall the setup of the one-way analysis of variance, mentioned in Section 2, Example 1. For any $p \times 1$ vector $a$, we call $\psi(a) = \Sigma a_i \theta_i$ a comparison of the means $\theta_1, \ldots, \theta_p$. In addition, if $\Sigma a_i = 0$, $\psi(a)$ is called a contrast. The classic estimator of $\psi(a)$ is $\psi_x(a) = \Sigma a_i \bar{X}_i$. The multiple comparison procedure of Scheffé [16], the S-method, can be summarized as follows.

**THEOREM 4.1 (Scheffé).**

(a) The probability is $1 - \alpha$ that simultaneously

$$|\psi_x(a) - \psi(a)| \leq (p F_{p-1, \chi^2} / (\Sigma a_i^2 / n))^{1/2}$$

(4.1)

for all vectors $a$.

(b) The probability is $1 - \alpha$ that simultaneously

$$|\psi_x(a) - \psi(a)| \leq ((p - 1) F_{p-2, \chi^2} / \Sigma a_i^2 / n))^{1/2}$$

(4.2)

for all vectors $a$ such that $\Sigma a_i = 0$. 
The Scheffé intervals can be used either for estimation or testing. They are very flexible in their ability to handle all contrasts, and to provide exact probability statements even for unbalanced data. The major drawback of the Scheffé intervals is that they are very conservative. For example, if one is only interested in pairwise differences, it would be better to use Tukey's procedure (sometimes referred to as the Q-method), which provides shorter intervals for the same α level (see also [13]).

The Scheffé intervals are based on a confidence ellipse centered at the observations. Since the confidence sets detailed in Sections 2 and 3 are improvements over this ellipse, we expect intervals based on these sets to improve upon the Scheffé intervals.

For an estimator \( \delta(\bar{X}, s) \) of \( \theta \), define \( \psi_\delta(a) \) by

\[
\psi_\delta(a) = \Sigma a_\delta(\bar{X}, s).
\]  

We have the following theorem, which shows the relationship between the improved confidence sets and improved intervals.

**Theorem 4.2.** Let \( D_n = \text{diag}(n_1, \ldots, n_p) \). If the confidence set

\[
C_\delta = \{ \theta : (\theta - \delta(\bar{X}, s))' D_n (\theta - \delta(\bar{X}, s)) \leq v^e(\bar{X}, s) \}
\]  

is a \( 1 - \alpha \) confidence set, then the probability is \( 1 - \alpha \) that simultaneously

\[
|\psi_\delta(a) - \psi_\theta(a)| \leq [v^e(\bar{X}, s) \Sigma a_i^2/n_i]^{1/2}
\]

for all vectors \( a \).

**Proof.**

\[
P\{|\psi_\delta(a) - \psi_\theta(a)|^2 \leq v^e(\bar{X}, s) \Sigma a_i^2/n_i \text{ for all } a\}
\]

\[
= P\left\{ \max_a a'[\theta - \delta(\bar{X}, s)] [\theta - \delta(\bar{X}, s)]' a \leq v^e(\bar{X}, s) \right\}
\]

\[
= P\{[\theta - \delta(\bar{X}, s)]' D_n [\theta - \delta(\bar{X}, s)] \leq v^e(\bar{X}, s)\}.
\]

Generalization of this theorem, and the rest of the results in this section, for the case when the covariance matrix is not diagonal is straightforward and will not be dealt with explicitly.
We now will use Theorem 4.2 to construct intervals based on the confidence set \( C_{X,s}^B \) of Section 3. For the analysis of variance setup of this section, the appropriate version of \( C_{X,s}^B \) is

\[
C_{X,s}^B = \{ \theta : (\theta - \delta^L(\bar{X}, s))' D_n (\theta - \delta^L(\bar{X}, s)) \leq v^B(\bar{X}, s) \},
\]

where \( \delta^L(\bar{X}, s) \) and \( v^B(\bar{X}, s) \) are defined as in (3.23) with the exceptions that \( \Sigma(X_i - \bar{x})^2 \) is replaced by \( \Sigma n_i(X_i - \bar{x})^2 \) and \( c^2 \) is replaced by \( pF_{a,p-n} \). If \( C_{X,s}^B \) is a \( 1 - \alpha \) confidence set, then the probability is \( 1 - \alpha \) that simultaneously

\[
|\psi_0(a) - \psi_{sa}(a)| \leq [v^B(\bar{X}, s) \Sigma a_i^2/n_i]^{1/2}
\]

for all vectors \( a \). Theorem 3.4 guarantees that if \( pF_{a,p-n} > p - 1 \), then \( v^B(\bar{X}, s) \leq s^2 pF_{a,p-n} \). Hence, by comparing (4.1) to (4.7), it follows that the intervals of (4.7) are uniformly shorter than the Scheffé intervals. Of course, it was not demonstrated analytically that \( C_{X,s}^B \) is a \( 1 - \alpha \) confidence set. However, the numerical evidence for this case is quite strong (with the exceptions noted in Section 3).

To get an idea of the possible improvement that the intervals in (4.7) can provide over the corresponding \( S \)-intervals given in (4.1), Table VII can be used. For a given \( p \), the entries in Table VII give the ratio of the lengths of the intervals in (4.7) to the corresponding Scheffé intervals in (4.1).

For the case of simultaneous estimation of contrasts, the argument is similar, the only difference being that the intervals are taken from a \( p - 1 \) dimensional ellipse. (The space of all contrasts is a \( (p - 1) \)-dimensional subspace of the \( p \)-dimensional parameter space.) Similar to Theorem 4.2, we have the following theorem for contrasts, which we state without proof.

**Theorem 4.3.** Let \( \bar{X} \sim N(\theta, D_n^{-1}) \). Define the \( p \times (p - 1) \) matrix \( Q \) by \( Q = (I_{p-1}, -1)' \), and let \( \dot{Y} = Q'X', \eta = Q'\theta \). If the confidence set

\[
C_Y = \{ \eta : [\eta - Q'\delta(\bar{X}, s)]' (Q'D_n^{-1}Q)^{-1} [\eta - Q'\delta(\bar{X}, s)] \leq v^B(\bar{X}, s) \}
\]

is a \( 1 - \alpha \) confidence set, then the probability is \( 1 - \alpha \) that simultaneously

\[
|\psi_0(a) - \psi_{sa}(a)| \leq [v^B(\bar{X}, s) \Sigma a_i^2/n_i]^{1/2}
\]

for all vectors \( a \) such that \( \Sigma a_i = 0 \).

For this case our recommended confidence set, and hence simultaneous intervals for all contrasts can again be described by (3.23) with two exceptions. We again replace \( \Sigma(X_i - \bar{x})^2 \) with \( \Sigma n_i(X_i - \bar{x})^2 \), but now we replace \( c^2 \) by \( (p - 1) F_{a,p-n-1}.r \).

To see more clearly how we arrive at this new modification \( v^B \) for the
case of contrasts, we can calculate explicitly the ellipse (4.8) of Theorem 4.3 when we use the estimator \( \delta^2(\bar{X}, s) \). It is easy to check that

\[
Q' \delta^2(\bar{X}, s) = \left( a_s s^2 \right)^+ \left( \frac{Y}{Y' (Q' D_n^{-1} Q)^{-1} Y} \right)
\]

\( Y = \delta(Y) \),

since \( Q' \tilde{x} = 0 \) and \( \Sigma_n (\tilde{x}, -\tilde{x})^2 = Y' (Q' D_n^{-1} Q)^{-1} Y \). Furthermore, \( Y = Q' X \) is distributed as a \((p - 1)\)-dimensional normal random variable with mean \( \eta = Q' \theta \) and covariance matrix \( \Sigma_Y = \sigma^2 (Q' D_n^{-1} Q)^{-1} \). Thus, the intervals in (4.9) will have simultaneous coverage probability at least \( 1 - \alpha \) if the \((p - 1)\)-dimensional confidence set

\[
C_Y = \left\{ \eta: [\eta - \delta(Y)]' \Sigma_Y [\eta - \delta(Y)] \leq v^2(Y, s) \right\}
\]

(4.10) is a \( 1 - \alpha \) confidence set.

Note that the estimator \( \delta(Y) \) shrinks \( Y \) toward zero rather than toward a linear subspace, and thus the associated confidence set is a special case of the sets in Sections 2 and 3, obtained by taking the matrix \( A = 0 \). Also, if \( \sigma^2 \)

---

**TABLE VIII**

Coverage Probabilities for the Simultaneous Intervals Given in (4.9), \( \alpha = 0.10 \)

<table>
<thead>
<tr>
<th>( \nu )</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>( [\Sigma_n(\theta_i - \delta)^2 / \sigma^2]^{1/2} )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p = 4 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.902</td>
<td>0.912</td>
<td>0.924</td>
<td>0.933</td>
<td>0.937</td>
</tr>
<tr>
<td>1</td>
<td>0.902</td>
<td>0.911</td>
<td>0.923</td>
<td>0.932</td>
<td>0.936</td>
</tr>
<tr>
<td>2</td>
<td>0.901</td>
<td>0.906</td>
<td>0.914</td>
<td>0.921</td>
<td>0.926</td>
</tr>
<tr>
<td>4</td>
<td>0.899</td>
<td>0.899</td>
<td>0.898</td>
<td>0.897</td>
<td>0.896</td>
</tr>
<tr>
<td>6</td>
<td>0.899</td>
<td>0.899</td>
<td>0.899</td>
<td>0.899</td>
<td>0.898</td>
</tr>
<tr>
<td>8</td>
<td>0.900</td>
<td>0.900</td>
<td>0.899</td>
<td>0.899</td>
<td>0.899</td>
</tr>
<tr>
<td>10</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
</tr>
<tr>
<td>15</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
</tr>
<tr>
<td>20</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
<td>0.900</td>
</tr>
<tr>
<td>( p = 10 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.904</td>
<td>0.930</td>
<td>0.959</td>
<td>0.979</td>
<td>0.986</td>
</tr>
<tr>
<td>1</td>
<td>0.903</td>
<td>0.928</td>
<td>0.956</td>
<td>0.977</td>
<td>0.984</td>
</tr>
<tr>
<td>2</td>
<td>0.902</td>
<td>0.923</td>
<td>0.948</td>
<td>0.970</td>
<td>0.978</td>
</tr>
<tr>
<td>4</td>
<td>0.901</td>
<td>0.911</td>
<td>0.925</td>
<td>0.935</td>
<td>0.938</td>
</tr>
<tr>
<td>6</td>
<td>0.901</td>
<td>0.905</td>
<td>0.911</td>
<td>0.916</td>
<td>0.907</td>
</tr>
<tr>
<td>8</td>
<td>0.900</td>
<td>0.903</td>
<td>0.907</td>
<td>0.910</td>
<td>0.911</td>
</tr>
<tr>
<td>10</td>
<td>0.900</td>
<td>0.902</td>
<td>0.904</td>
<td>0.907</td>
<td>0.908</td>
</tr>
<tr>
<td>15</td>
<td>0.900</td>
<td>0.901</td>
<td>0.902</td>
<td>0.903</td>
<td>0.904</td>
</tr>
<tr>
<td>20</td>
<td>0.900</td>
<td>0.900</td>
<td>0.901</td>
<td>0.902</td>
<td>0.902</td>
</tr>
</tbody>
</table>
is known, then the coverage probability of \( C_Y \) can be obtained from Theorem 3.1 by merely setting \( t = 0 \) in (3.17) and (3.18), and eliminating the integral over \( t \) in (3.19). For the case of unknown \( \sigma^2 \), one proceeds as in Theorem 3.3, and integrates this probability against the \( \chi^2 \) density. It is also easy to verify that the coverage probability of \( C_Y \) depends on the unknown parameters only through \( \eta^2 \Sigma^{-1} \eta = \theta^t Q (Q^t D Q)^{-1} = \Sigma p_i (\theta_i - \bar{\theta})^2 / \sigma^2 \). (Sets such as \( C_Y \), which are centered at estimators that shrink toward a known point rather than a linear subspace, are treated in more detail in Casella and Hwang [5].)

The coverage probability of \( C_Y \), and hence of the associated intervals, has been evaluated numerically for \( p = 4, 10 \), \( v = 2, 3, 5, 10, 20, 30 \), and \( a = 0.1 \), and are presented in Table VIII. With the exception of a few cases when \( p = 4 \) or \( v = 2 \), the coverage probability of \( C_Y \) is above 0.90. Again, the few failures are so slight that it is reasonable to consider \( C_Y \) a 1 - \( \alpha \) procedure.

If we apply Theorem 3.4 to the intervals associated with \( C_Y \), we find that a sufficient condition for these intervals to be uniformly shorter than the

### Table IX

<table>
<thead>
<tr>
<th>( v )</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Sigma_p (\bar{X} - \bar{\theta})^2 / \sigma^2 )^1/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p = 4 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.992</td>
<td>0.976</td>
<td>0.966</td>
<td>0.961</td>
<td>0.958</td>
</tr>
<tr>
<td>1</td>
<td>0.992</td>
<td>0.976</td>
<td>0.966</td>
<td>0.961</td>
<td>0.958</td>
</tr>
<tr>
<td>2</td>
<td>0.992</td>
<td>0.976</td>
<td>0.966</td>
<td>0.961</td>
<td>0.958</td>
</tr>
<tr>
<td>4</td>
<td>0.992</td>
<td>0.984</td>
<td>0.983</td>
<td>0.983</td>
<td>0.983</td>
</tr>
<tr>
<td>6</td>
<td>0.994</td>
<td>0.993</td>
<td>0.993</td>
<td>0.993</td>
<td>0.993</td>
</tr>
<tr>
<td>8</td>
<td>0.997</td>
<td>0.996</td>
<td>0.996</td>
<td>0.996</td>
<td>0.996</td>
</tr>
<tr>
<td>10</td>
<td>0.998</td>
<td>0.997</td>
<td>0.997</td>
<td>0.997</td>
<td>0.997</td>
</tr>
<tr>
<td>15</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>20</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>( p = 10 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.981</td>
<td>0.937</td>
<td>0.907</td>
<td>0.886</td>
<td>0.877</td>
</tr>
<tr>
<td>1</td>
<td>0.981</td>
<td>0.937</td>
<td>0.907</td>
<td>0.886</td>
<td>0.877</td>
</tr>
<tr>
<td>2</td>
<td>0.981</td>
<td>0.937</td>
<td>0.907</td>
<td>0.886</td>
<td>0.877</td>
</tr>
<tr>
<td>4</td>
<td>0.981</td>
<td>0.937</td>
<td>0.907</td>
<td>0.886</td>
<td>0.877</td>
</tr>
<tr>
<td>6</td>
<td>0.981</td>
<td>0.949</td>
<td>0.949</td>
<td>0.951</td>
<td>0.952</td>
</tr>
<tr>
<td>8</td>
<td>0.981</td>
<td>0.972</td>
<td>0.973</td>
<td>0.974</td>
<td>0.975</td>
</tr>
<tr>
<td>10</td>
<td>0.984</td>
<td>0.982</td>
<td>0.983</td>
<td>0.984</td>
<td>0.984</td>
</tr>
<tr>
<td>15</td>
<td>0.993</td>
<td>0.992</td>
<td>0.992</td>
<td>0.993</td>
<td>0.993</td>
</tr>
<tr>
<td>20</td>
<td>0.996</td>
<td>0.996</td>
<td>0.996</td>
<td>0.996</td>
<td>0.996</td>
</tr>
</tbody>
</table>
CONSTRUCTION OF CONFIDENCE SETS

The corresponding Scheffé intervals is \( F_{a, p - 1, v} > 1 \). The ratio of the radii of these intervals is given by

\[
\left[ \frac{v^E(X, s) \sum a_i^2/n_i}{(p - 1) s^2 F_{a, p - 1, v} \sum a_i^2/n_i} \right]^{1/2} = \left[ T_v \left( 1 - \frac{\log T_v}{F_{a, p - 1, v}} \right) \right]^{1/2}, \tag{4.11}
\]

where \( T_v \) is described following Theorem 4.3. Values of this ratio for \( p = 4, 10, v = 2, 5, 10, 20, 30 \), and \( \alpha = 0.10 \) have been calculated, and are given in Table IX. The reduction in length is quite respectable, and is even greater than for the case of estimation of contrasts (compare Tables VII and IX).

The results of this section also apply to the case of known variance. The relevant intervals are obtained by letting \( v \to \infty \), in the expressions given in this section. (As \( v \to \infty \), \( s^2 \to \sigma^2 \), and \( p F_{a, p, v} \to \chi^2_{a, p} \).) The results also apply to the fixed radius confidence sets of Section 2, for which it was proved that the coverage probability is bounded below by \( 1 - \alpha \). For these confidence sets, it follows from Theorem 4.2 that the simultaneous intervals constructed will have confidence coefficient \( 1 - \alpha \). Although these intervals will uniformly improve upon the Scheffé intervals in terms of coverage probability, they will, of course, have the same length.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation Grants DMS-8501973 and MCS80–03568 at Cornell University.

REFERENCES


Printed by the St. Catherine Press Ltd., Tempelhof 41, Bruges, Belgium