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ASYMPTOTIC RISK COMPARISON OF IMPROVED ESTIMATORS FOR NORMAL COVARIANCE MATRIX

By

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Asymptotic risks of the empirical Bayes estimators $\hat{\Sigma}_H$ by Haff [5] for a covariance matrix Σ in a p-dimensional normal distribution are computed and compared with that of James and Stein's minimax estimators $\hat{\Sigma}_{JS}$. For $p\geqq 6$, it is shown that $\hat{\Sigma}_{JS}$ are always better than $\hat{\Sigma}_H$ asymptotically, though the leading terms are the same. New estimators which dominate $\hat{\Sigma}_{JS}$ for some Σ in any p asymptotically are proposed. Some numerical comparisons are given. Exact risks for ordinary estimators $\hat{\Sigma}_O$ and minimax estimators $\hat{\Sigma}_{JS}$ are also computed and compared with asymptotic ones for which the approximations are shown to be excellent.

1. Introduction

Let S have a Wishart distribution with unknown scale matrix Σ and n degrees of freedom, for which we shall write $S: W_p(n, \Sigma)$ and assume $n>p+1$. Let $\hat{\Sigma}$ be an estimator of Σ. The loss function is taken to be

$$L_1(\hat{\Sigma}, \Sigma)=\operatorname{tr}\hat{\Sigma}\Sigma^{-1}-\log|\hat{\Sigma}\Sigma^{-1}|-p \tag{1.1}$$

or

$$L_2(\hat{\Sigma}, \Sigma)=\frac{1}{2}\operatorname{tr}(\hat{\Sigma}\Sigma^{-1}-I)^2. \tag{1.2}$$

The L_1 loss is equivalent to the likelihood ratio statistic for testing the hypothesis $\Sigma=\Sigma_0$ against all alternatives. The L_2 loss can also be used as a test statistic for the same problem as in Nagao [10]. The factor 1/2 in the L_2 loss is not essential. However we wish to retain it, since L_1 loss tends to $\operatorname{tr}(\hat{\Sigma}\Sigma^{-1}-I)^2/2$, when $\hat{\Sigma}$ is close to Σ. The risk function is given by $R_i(\hat{\Sigma}, \Sigma)=E[L_i(\hat{\Sigma}, \Sigma)]$ for $i=1$ or 2. Haff [5] proved that among the scalar multiples of S, the best estimator under L_1 is $\hat{\Sigma}_O^{(1)}=S/n$ and that under L_2 it is given by $\hat{\Sigma}_O^{(2)}=S/(n+p+1)$, which we call ordinary estimators. Then he considered the posterior mean of Σ for a prior distribution $W_p[n', (\gamma C)^{-1}]$ for Σ^{-1} with unknown scalar $\gamma>0$ and known p.d. matrix

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C. It is given by $E[\Sigma|S,\gamma]=(S+\gamma C)/(n+n'-p-1)$. In the process of estimating γ by maximizing approximate marginal likelihood of S, he obtained $ut(u)$ for $u=1/\mathrm{tr}(S^{-1}C)$ as an estimator for γ, where $t(\cdot)$ is nonincreasing. He then proved that under L_1 the estimator

$$\hat{\Sigma}_H^{(1)}=\frac{1}{n}[S+ut(u)C] \tag{1.3}$$

for $0\leqq t(u)\leqq 2(p-1)/n$, dominates $\hat{\Sigma}_O^{(1)}=S/n$ for any $n>p+1$ and under L_2 the estimator

$$\hat{\Sigma}_H^{(2)}=\frac{1}{n+p+1}(S+utC) \tag{1.4}$$

for $0\leqq t\leqq 2(p-1)/(n-p+3)$, dominates $\hat{\Sigma}_O^{(2)}=S/(n+p+1)$ for any $n>p+1$. It was also shown that if $t(u)$ in (1.3) is constant, the best choice of $t(u)$ is $(p-1)/n$ and that the best choice of t in (1.4) is $(p-1)/(n-p+3)$. In this paper we always take these optimal values for t and call them Haff's estimators $\hat{\Sigma}_H^{(1)}$ and $\hat{\Sigma}_H^{(2)}$ respectively.

A minimax estimator for Σ was earlier obtained by James and Stein [7], giving

$$\hat{\Sigma}_{JS}^{(i)}=K\Delta^{(i)}K' \tag{1.5}$$

for the loss L_i ($i=1$ or 2), where the lower triangular matrix K with positive diagonal elements is obtained from $S=KK'$ and $\Delta^{(i)}=diag[\Delta_1^{(i)},\cdots,\Delta_p^{(i)}]$. For the L_1 loss, they proved that $\Delta_j^{(1)}=1/(n+p+1-2j)$ and reported that they were unable to get explicit form of $\Delta_j^{(2)}$. Sharma [13] derived the linear equations for $\Delta_j^{(2)}$, from which numerical values are computed for given n and p. They were also obtained earlier by Selliah [12].

The primary purpose of this paper is to compare the asymptotic risk of Haff's estimator $\hat{\Sigma}_H^{(i)}$ with that of James and Stein's estimator $\hat{\Sigma}_{JS}^{(i)}$ under L_i for $i=1$ or 2. Under L_2, we have derived an asymptotic form of $\Delta_j^{(2)}$ for large n. It is shown that the leading terms of the asymptotic risks for $\hat{\Sigma}_H^{(i)}$ and $\hat{\Sigma}_{JS}^{(i)}$ are the same and that the next term for $\hat{\Sigma}_H^{(i)}$ is less than that of $\hat{\Sigma}_{JS}^{(i)}$ only for $2\leqq p\leqq 5$ and for some Σ. If $p\geqq 6$, the second term of the asymptotic expansion of $R_i(\hat{\Sigma}_H^{(i)},\Sigma)$ is always larger than that of $R_i(\hat{\Sigma}_{JS}^{(i)},\Sigma)$ for all Σ.

Secondly we shall propose new estimators for Σ by minimizing risks empirically, which are given by

$$\hat{\Sigma}^{(1)}=\frac{1}{n}\left[S+b\frac{\mathrm{tr}\,CS^{-1}}{\mathrm{tr}(CS^{-1})^2}C\right],\quad 0\leqq b\leqq\frac{2(p-1)}{n} \tag{1.6}$$

for L_1 loss and

$$\hat{\Sigma}^{(2)}=\frac{1}{n+p+1}\left[S+b\frac{\mathrm{tr}\,CS^{-1}}{\mathrm{tr}(CS^{-1})^2}C\right],\quad 0\leqq b\leqq\frac{2(p-1)}{n} \tag{1.7}$$

for L_2 loss. It is shown that our new estimator $\hat{\Sigma}^{(1)}$ dominates $\hat{\Sigma}_O^{(1)}$ for all $n>p+1$ and that $\hat{\Sigma}^{(2)}$ dominates $\hat{\Sigma}_O^{(2)}$ asymptotically. The result also holds for more general form of $\hat{\Sigma}^{(1)}$, that is, the constant b in (1.6) can be replaced by $t(\cdot)$ in (1.3) for $u=\mathrm{tr}\, CS^{-1}/\mathrm{tr}(CS^{-1})^2$. However we prefer to (1.6) to simplify later discussions. The leading term of the asymptotic risk is the same as that of $\hat{\Sigma}_{JS}^{(i)}$ and the second term is less than that of $\hat{\Sigma}_{JS}^{(i)}$ for some Σ and for all $p>1$. Eliminating the leading term, the range of $R_i(\hat{\Sigma}^{(i)}, \Sigma)$ is much wider below than $R_i(\hat{\Sigma}_H^{(i)}, \Sigma)$ asymptotically. However the absolute difference $R_i(\hat{\Sigma}^{(i)}, \Sigma)-R_i(\hat{\Sigma}_{JS}^{(i)}, \Sigma)$ or $R_i(\hat{\Sigma}_H^{(i)}, \Sigma)-R_i(\hat{\Sigma}_{JS}^{(i)}, \Sigma)$ is not so large.

To get some idea for the errors of asymptotic approximations, the terms of order n^{-3} (third terms) are computed for $R_i(\hat{\Sigma}_H^{(i)}, \Sigma)$ and $R_i(\hat{\Sigma}^{(i)}, \Sigma)$. The exact risks of $\hat{\Sigma}_{JS}^{(i)}$ are computed and asymptotic values up to order n^{-3} are compared. For $2\leqq p\leqq 6$ and $n\geqq 16$, asymptotic values for $\hat{\Sigma}_{JS}^{(i)}$ are accurate for three (two) significant digits for L_1 (L_2) loss in most cases examined. The rates of the reduction of the risks of $\hat{\Sigma}_H^{(i)}(\hat{\Sigma}^{(i)})$ with respect to $\hat{\Sigma}_O^{(i)}$ are shown to be the highest 8%(20%) for $i=1$, $n\geqq 16$ and 4%(11%) for $i=2$, $n\geqq 32$ respectively within our examples computed in Tables.

2. Derivation of new estimators

Since our goal is to find an estimator $\hat{\Sigma}$ which minimizes the risk, we shall look for a solution in a form $\hat{\Sigma}^{(1)}=(S+\gamma C)/n$ for L_1 or $\hat{\Sigma}^{(2)}=(S+\gamma C)/(n+p+1)$ for L_2. The risk for L_1 is given by

$$R_1(\hat{\Sigma}^{(1)}, \Sigma)=\frac{\gamma}{n}\mathrm{tr}\, C\Sigma^{-1}-E[\log|\frac{1}{n}(S+\gamma C)\Sigma^{-1}|]. \tag{2.1}$$

Hence the derivative with respect to γ is

$$\frac{1}{n}\mathrm{tr}\, C\Sigma^{-1}-E[\mathrm{tr}(\gamma I+SC^{-1})^{-1}], \tag{2.2}$$

where the expectation is taken by S having $W_p(n, \Sigma)$ distribution. At $\gamma=0$, the derivative has a negative value $-(p+1)\,\mathrm{tr}\, C\Sigma^{-1}/\{n(n-p-1)\}$, since $E(S^{-1})=\Sigma^{-1}/(n-p-1)$, by Kshirsagar [9], for example. This shows that the risk will be smaller if we take γ positive near zero. Assume that γ is small and put the derivative (2.2) equal to zero. We get an equation for γ, an approximate solution of which is given by

$$\gamma=(p+1)\frac{\mathrm{tr}\, C\Sigma^{-1}}{\mathrm{tr}(C\Sigma^{-1})^2}, \tag{2.3}$$

which yields the estimator (1.6). The estimator (1.7) for L_2 is similarly derived.

The constant factor b is restricted so that it dominates ordinary estimator $\hat{\Sigma}_O^{(i)}$, which will be discussed later.

3. Risks of ordinary and James and Stein's minimax estimators

Using the Bartlett's decomposition (Giri [3], page 126) of Wishart matrix S when $\Sigma=I$, we get

$$R_1(\hat{\Sigma}_O^{(1)}, \Sigma)=p \log n-\sum_{j=1}^{p} E[\log \chi^2_{n-j+1}], \tag{3.1}$$

where χ^2_m denotes the χ^2 variate with m degrees of freedom. Using digamma function $\psi(x)=d \log \Gamma(x)/dx$, we can rewrite it

$$p \log \frac{n}{2}-\sum_{j=1}^{p} \psi\left(\frac{n-j+1}{2}\right). \tag{3.2}$$

If n is an integer larger than one, we know that

$$\psi(n)=1+\frac{1}{2}+\cdots+\frac{1}{n-1}-\gamma \tag{3.3}$$

for Euler's constant $\gamma=0.57721\ 56649\ 01532\ 9\cdots$ (Abramowitz and Stegun [1]). For half integer argument ($n\geqq 1$),

$$\psi\left(n+\frac{1}{2}\right)=-\gamma-2 \log 2+2\left(1+\frac{1}{3}+\cdots+\frac{1}{2n-1}\right). \tag{3.4}$$

These are sufficient for the computation of $R_1(\hat{\Sigma}_O^{(1)}, \Sigma)$. If n is large, an asymptotic formula for ψ is available, which is derived from Stirling's formula (Kendall [8], page 245)

$$\psi(x+h)=\log x+\frac{h-1/2}{x}+\sum_{r=1}^{n} \frac{(-1)^r B_{r+1}(h)}{x^{r+1}(r+1)}+O\left(\frac{1}{x^{n+2}}\right), \tag{3.5}$$

where $B_r(h)$ are the Bernoulli polynomials given by $B_2(h)=h^2-h+1/6$, $B_3(h)=h^3-(3/2)h^2+(1/2)h$. This yields

$$R_1(\hat{\Sigma}_O^{(1)}, \Sigma)=\frac{p(p+1)}{2n}+\frac{p(2p^2+3p-1)}{12n^2}+\frac{p(p^2-1)(p+2)}{12n^3}+O(n^{-4}). \tag{3.6}$$

Some numerical values of $R_1(\hat{\Sigma}_O^{(1)}, \Sigma)$ are computed based on (3.2)$\sim$(3.4) and compared with the asymptotic values (3.6) for $p=2\sim 6$ and $n=8\sim 128$. They are shown in Table 1. We can see that the asymptotic approximations are excellent, namely, for $n\geqq 16$ and $p\leqq 6$, the values are accurate with three significance digits.

Under L_2 loss, Haff [5] noted that

$$R_2(\hat{\Sigma}_O^{(2)}, \Sigma)=\frac{p(p+1)}{2(n+p+1)}, \tag{3.7}$$

Table 1. Values of $R_1(\hat{\Sigma}_O^{(1)}, \Sigma)$

		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=2$	$O(n^{-1})$	.37500	.187500	.093750	.046875	.023438
	$O(n^{-2})$	.03385	.008464	.002116	.000529	.000132
	$O(n^{-3})$	.00391	.000488	.000061	.000008	.000001
	approx.	.4128	.19645	.095927	.047412	.023571
	exact	.413314	.196484	.095929	.047412	.023571
$p=3$	$O(n^{-1})$	.75000	.37500	.187500	.093750	.046875
	$O(n^{-2})$	.10156	.02539	.006348	.001587	.000397
	$O(n^{-3})$	.01953	.00244	.000305	.000038	.000005
	approx.	.871	.4028	.19415	.095375	.047276
	exact	.876824	.403141	.194171	.095376	.047277
$p=4$	$O(n^{-1})$	1.2500	.62500	.312500	.156250	.078125
	$O(n^{-2})$	.2240	.05599	.013997	.003499	.000875
	$O(n^{-3})$	.0586	.00732	.000916	.000114	.000014
	approx.	1.533	.6883	.32741	.159864	.079014
	exact	1.559962	.689672	.327490	.159868	.079015
$p=5$	$O(n^{-1})$	1.8750	.9375	.46875	.234375	.117188
	$O(n^{-2})$	.4167	.1042	.02604	.006510	.001628
	$O(n^{-3})$	.1367	.0171	.00214	.000267	.000033
	approx.	2.43	1.059	.4969	.24115	.118848
	exact	2.52347	1.06300	.497161	.241166	.118849
$p=6$	$O(n^{-1})$	2.6250	1.3125	.65626	.328125	.164063
	$O(n^{-2})$	.6953	.1738	.04346	.010864	.002716
	$O(n^{-3})$	.2734	.0342	.00427	.000534	.000067
	approx.	3.59	1.521	.7040	.33952	.166845
	exact	3.87328	1.53134	.704554	.339557	.166847

which is asymptotically the same as $R_1(\hat{\Sigma}_O^{(1)}, \Sigma)$ for large n. This is the reason why we prefer multiplier 1/2 in the definition of L_2 loss in (1.2). Unlike the simple form of (3.7), the asymptotic approximations

$$R_2(\hat{\Sigma}_O^{(2)}, \Sigma)=\frac{p(p+1)}{2n}-\frac{p(p+1)^2}{2n^2}+\frac{p(p+1)^3}{2n^3}+O(n^{-4}) \tag{3.8}$$

are not so excellent as $R_1(\hat{\Sigma}_O^{(1)}, \Sigma)$. For example, the exact value of $R_2(\hat{\Sigma}_O^{(2)}, \Sigma)$ in (3.7) for $p=2$ and $n=16$ is 0.15789, while the asymptotic value of (3.8) gives 0.15894 which is accurate for three significant digits. From Table 1, the corresponding exact value of $R_1(\hat{\Sigma}_O^{(1)}, \Sigma)$ is 0.19648 and the asymptotic value is 0.19645 which is accurate for one more digit than $R_2(\hat{\Sigma}_O^{(2)}, \Sigma)$. This is the case with other values of parameters n and p.

Next we shall evaluate the risks of the minimax estimators by James and Stein [7]. By considering a best equivariant estimator $\phi(LSL')=L\phi(S)L'$ for the transformation group of lower triangular matrices L with positive diagonal elements, they obtained a minimax estimator of (1.5) under L_1 loss and derived

$$R_1(\hat{\Sigma}_{JS}^{(1)}, \Sigma)=\sum_{j=1}^{p}\log(n+p-2j+1)-\sum_{j=1}^{p}E[\log\chi^2_{n-j+1}]. \tag{3.9}$$

Using digamma function $\psi(x)$, this can be simplified as

$$\sum_{j=1}^{p}\log\frac{1}{2}(n+p-2j+1)-\sum_{j=1}^{p}\psi\left(\frac{n-j+1}{2}\right), \tag{3.10}$$

which is useful for numerical computations. The asymptotic form of (3.10) is obtained by (3.5), giving

$$R_1(\hat{\Sigma}_{JS}^{(1)},\Sigma)=\frac{p(p+1)}{2n}+\frac{p(3p+1)}{12n^2}+\frac{p(p^2-1)(p+2)}{12n^3}+O(n^{-4}). \tag{3.11}$$

In Table 2 exact and asymptotic values of $R_1(\hat{\Sigma}_{JS}^{(1)},\Sigma)$ are compared. It is found that for $n\geqq 16$ and $p\leqq 6$, the asymptotic values are accurate for three significant digits, which is the same conclusion as for $R_1(\hat{\Sigma}_O^{(1)},\Sigma)$. Since equivariant estimators contain best scalar multiple of S, namely, $\hat{\Sigma}_O^{(1)}$, inequality $R_1(\hat{\Sigma}_{JS}^{(1)},\Sigma)<R_1(\hat{\Sigma}_O^{(1)},\Sigma)$ holds as a matter of fact. If we take difference of the risks by asymptotic form, we get

$$R_1(\hat{\Sigma}_{JS}^{(1)},\Sigma)-R_1(\hat{\Sigma}_O^{(1)},\Sigma)=-\frac{p(p^2-1)}{6n^2}+O(n^{-4}), \tag{3.12}$$

which is negative for $p\geqq 2$, neglecting the higher order terms. This suggests the

Table 2. Exact and asymptotic values of $R_1(\hat{\Sigma}_{JS}^{(1)},\Sigma)$

		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=2$	$O(n^{-1})$	.37500	.187500	.093750	.046875	.023438
	$O(n^{-2})$	.01823	.004557	.001139	.000285	.000071
	$O(n^{-3})$	.00391	.000488	.000061	.000008	.000001
	approx.	.3971	.19255	.094950	.047167	.023510
	exact	.39757	.19257	.094952	.047168	.023510
$p=3$	$O(n^{-1})$	.75000	.37500	.187500	.093750	.046875
	$O(n^{-2})$	.03906	.00977	.002441	.000610	.000153
	$O(n^{-3})$	.01953	.00244	.000305	.000038	.000005
	approx.	.809	.3872	.19025	.094398	.047033
	exact	.81229	.38739	.190257	.094399	.047032
$p=4$	$O(n^{-1})$	1.2500	.62500	.312500	.156250	.078125
	$O(n^{-2})$	.0677	.01693	.004232	.001058	.000265
	$O(n^{-3})$	.0586	.00732	.000916	.000114	.000014
	approx.	1.376	.6493	.31765	.157422	.078404
	exact	1.3927	.64997	.31768	.157425	.078404
$p=5$	$O(n^{-1})$	1.8750	.9375	.46875	.234375	.117188
	$O(n^{-2})$	.1042	.0260	.00651	.001628	.000407
	$O(n^{-3})$	.1367	.0171	.00214	.000267	.000033
	approx.	2.12	.981	.4774	.236270	.117628
	exact	2.1713	.98271	.47750	.236275	.117628
$p=6$	$O(n^{-1})$	2.6250	1.3125	.65625	.328125	.164063
	$O(n^{-2})$	.1484	.0371	.00928	.002319	.000580
	$O(n^{-3})$	.2734	.0342	.00427	.000534	.000067
	approx.	3.05	1.384	.6698	.33098	.164709
	exact	3.2107	1.3889	.67003	.330991	.164710

validity of the asymptotic comparisons.

Under L_2 loss, the exact $\Delta^{(2)}$ is not available. However Selliah [12] and Sharma [13] show that $\Delta=[\Delta_1^{(2)}, \cdots, \Delta_p^{(2)}]'$, satisfies linear equations $A\Delta=b$, where $p\times p$ matrix A and p-vector b are given by

$$A=\begin{pmatrix} (n+p-1)(n+p+1) & n+p-3 & \cdots\cdots & n-p+1 \\ n+p-3 & (n+p-3)(n+p-1) & \cdots\cdots & n-p+1 \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ n-p+1 & n-p+1 & \cdots\cdots & (n-p+1)(n-p+3) \end{pmatrix} \tag{3.13}$$

$$b=(n+p-1,\ n+p-3, \cdots, n-p+1)'.$$

With this Δ, the risk is given by

$$R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)=\frac{1}{2}p-\frac{1}{2}\sum_{j=1}^{p}(n-2j+p+1)\Delta_j^{(2)}. \tag{3.14}$$

We can see by checking the exact values of $\Delta^{(1)}$ and $\Delta^{(2)}$ that the choice of $\Delta_j^{(1)}$ is always larger than $\Delta_j^{(2)}$ and the risks of $\hat{\Sigma}_{JS}^{(1)}$ are larger than that of $\hat{\Sigma}_{JS}^{(2)}$. The best scalar multiple $1/n$ for L_1 loss and $1/(n+p+1)$ for L_2 loss lie always smaller than the middle of $\Delta_1, \cdots, \Delta_p$. Sharma [13] gives the values of $R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)$ for $p=2$ and $n=5(5)30$. Using (3.13), we can evaluate Δ for large n, giving

$$\begin{aligned}\Delta_j^{(2)}=&\frac{1}{n}-\frac{2}{n^2}(p+1-j)+\frac{1}{n^3}[4(p+1)^2-(8p+9)j+5j^2]\\ &+\frac{1}{3n^4}[-2(p+1)(11p^2+22p+12)+(66p^2+150p+85)j\\ &-3(28p+33)j^2+38j^3]+O(n^{-5})\end{aligned} \tag{3.15}$$

and

$$R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)=\frac{p(p+1)}{2n}-\frac{p(p+1)(2p+1)}{3n^2}+\frac{p^2(p+1)^2}{n^3}+O(n^{-4}). \tag{3.16}$$

Note that optimal scalar multiplier for S is $1/n$ under L_1 loss and $1/(n+p+1)$ under L_2 loss. Asymptotic expansion of $\Delta_j^{(1)}=1/(n+p+1-2j)$ replaced n by $n+p+1$ yields the same terms as in (3.15) up to order n^{-2}. The difference of the risks, $R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)-R_2(\hat{\Sigma}_{O}^{(2)}, \Sigma)$ in the asymptotic form is exactly the same as (3.12) up to $O(n^{-2})$. In Table 3, exact and asymptotic values of $R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)$ are shown based on (3.14) and (3.16). We can see that the asymptotic approximations are worse than $R_1(\hat{\Sigma}_{JS}^{(1)}, \Sigma)$ and are comparative for $R_2(\hat{\Sigma}_{O}^{(2)}, \Sigma)$. This suggests that the loss L_1 is favourable for the asymptotic approximations. The maximum rate of reduction of risks for $\hat{\Sigma}_{JS}^{(1)}$ with respect to $\hat{\Sigma}_{O}^{(1)}$ within Tables 1 and 2 is given by 17% for $n=8$ and $p=6$. However the corresponding rate for L_2 loss in Table 3 is only 5%.

Table 3. Exact and asymptotic values of $R_2(\hat{\Sigma}^{(2)}_{JS}, \Sigma)$

		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=2$	$O(n^{-1})$	.37500	.18750	.093750	.046875	.023438
	$O(n^{-2})$	—.15625	—.03906	—.009766	—.002441	—.000610
	$O(n^{-3})$	.07031	.00879	.001099	.000137	.000017
	approx.	.289	.1572	.0851	.04457	.022844
	exact	.26697	.15559	.084970	.044563	.022844
$p=3$	$O(n^{-1})$	.75000	.37500	.18750	.093750	.046875
	$O(n^{-2})$	—.43750	—.10938	—.02734	—.006836	—.001709
	$O(n^{-3})$	.28125	.03516	.00440	.000549	.000069
	approx.	.59	.301	.1646	.08746	.045235
	exact	.48250	.29211	.16393	.087422	.045232
$p=4$	$O(n^{-1})$	1.2500	.62500	.31250	.15625	.078125
	$O(n^{-2})$	—.9375	—.23438	—.05859	—.01465	—.003662
	$O(n^{-3})$	.7813	.09766	.01221	.00153	.000191
	approx.	1.09	.488	.266	.1431	.07465
	exact	.73548	.45918	.26397	.14298	.074644
$p=5$	$O(n^{-1})$	1.8750	.9375	.46875	.23438	.117188
	$O(n^{-2})$	—1.7188	—.4297	—.10742	—.02686	—.006714
	$O(n^{-3})$	1.7578	.2197	.02747	.00343	.000429
	approx.	1.9	.73	.389	.2110	.11090
	exact	1.0189	.65233	.38311	.21056	.11088
$p=6$	$O(n^{-1})$	2.625	1.3125	.65625	.32813	.164063
	$O(n^{-2})$	—2.844	—.7109	—.17773	—.04443	—.011108
	$O(n^{-3})$	3.445	.4307	.05383	.00673	.000841
	approx.	3.2	1.03	.532	.2904	.15380
	exact	1.3283	.86807	.51965	.28952	.15374

4. Risks under L_1 loss

4.1. Risk of Haff's estimator. As Sharma [13] noted, the exact values of the risks of Haff's estimators are difficult to compute. Asymptotic evaluation of them gives some useful information. We shall put $C=I$ in (1.3) without loss of generality and assume that $t(u)=b$=constant, namely, the estimator

$$\hat{\Sigma}^{(1)}_H=\frac{1}{n}\left(S+\frac{b}{\operatorname{tr} S^{-1}}I\right) \tag{4.1}$$

is considered for L_1 loss. The difference of risks can be written by

$$\begin{aligned}(4.2)\qquad & R_1(\hat{\Sigma}^{(1)}_H, \Sigma)-R_1(\hat{\Sigma}^{(1)}_O, \Sigma)\\ &=\frac{b}{n}E\left[\frac{\operatorname{tr}\Sigma^{-1}}{\operatorname{tr} S^{-1}}\right]-E\left[\log\left|I+\frac{b}{\operatorname{tr} S^{-1}}S^{-1}\right|\right],\end{aligned}$$

which is bounded from above by

$$\frac{b}{n}E\left[\frac{\operatorname{tr}\Sigma^{-1}}{\operatorname{tr} S^{-1}}\right]-b+\frac{b^2}{2}E\left[\frac{\operatorname{tr} S^{-2}}{(\operatorname{tr} S^{-1})^2}\right]. \tag{4.3}$$

By the Wishart identity due to Haff [5], we get

$$E\left[\frac{\operatorname{tr}\Sigma^{-1}}{\operatorname{tr}S^{-1}}\right]=n-p-1+2E\left[\frac{\operatorname{tr}S^{-2}}{(\operatorname{tr}S^{-1})^2}\right]. \tag{4.4}$$

This yields an upper bound of (4.2)

$$\frac{b}{n}\left(-p-1+2+\frac{nb}{2}\right), \tag{4.5}$$

which is negative if and only if $0\leqq b\leqq 2(p-1)/n$, and the minimum value is attained by $b=(p-1)/n$. This is the special case of Theorem 4.3 by Haff [5]. We impose this restriction on b. Note that $b=O(n^{-1})$ and $Y=\sqrt{n}(S/n-\Sigma)$ converges in law to a $p(p+1)/2$ variate normal distribution with mean zero. We can evaluate (4.2) asymptotically as

$$\frac{b}{n}\left\{E\left[\frac{\operatorname{tr}\Sigma^{-1}}{\operatorname{tr}S^{-1}}\right]-n+\frac{nb}{2}E\left[\frac{\operatorname{tr}S^{-2}}{(\operatorname{tr}S^{-1})^2}\right]-\frac{b^2n}{3}\frac{\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-1})^3}\right\}+O(n^{-4}). \tag{4.6}$$

In getting the last term of (4.6), we should take $E[\operatorname{tr}S^{-3}/(\operatorname{tr}S^{-1})^3]$, which can be evaluated by writing $S/n=\Sigma+Y/\sqrt{n}$ and noting that $E(Y)=0$ and $Y=O_p(1)$, giving $\operatorname{tr}\Sigma^{-3}/(\operatorname{tr}\Sigma^{-1})^3+O(n^{-1})$. Now we need the following lemma to complete our asymptotic expansion.

LEMMA 4.1. *Let S have a Wishart distribution $W_p(n,\Sigma)$. Then*

$$E\left[\frac{\operatorname{tr}S^{-2}}{(\operatorname{tr}S^{-1})^2}\right]=\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}+\frac{1}{n}\left\{6\frac{(\operatorname{tr}\Sigma^{-2})^2}{(\operatorname{tr}\Sigma^{-1})^4}-8\frac{\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-1})^3}+\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}+1\right\}+O(n^{-2}). \tag{4.7}$$

PROOF. From the Wishart identity, we get

$$E\left[\frac{\operatorname{tr}S^{-2}}{(\operatorname{tr}S^{-1})^2}\operatorname{tr}\Sigma^{-1}\right]=4E\left[\frac{(\operatorname{tr}S^{-2})^2}{(\operatorname{tr}S^{-1})^3}-\frac{\operatorname{tr}S^{-3}}{(\operatorname{tr}S^{-1})^2}\right]+(n-p-1)E\left[\frac{\operatorname{tr}S^{-2}}{\operatorname{tr}S^{-1}}\right]. \tag{4.8}$$

$$E\left[\frac{\operatorname{tr}S^{-2}}{\operatorname{tr}S^{-1}}\operatorname{tr}\Sigma^{-1}\right]=2E\left[\frac{(\operatorname{tr}S^{-2})^2}{(\operatorname{tr}S^{-1})^2}-2\frac{\operatorname{tr}S^{-3}}{\operatorname{tr}S^{-1}}\right]+(n-p-1)E[\operatorname{tr}S^{-2}]. \tag{4.9}$$

By Haff [4], we know that

$$\begin{aligned}E[\operatorname{tr}S^{-2}]&=\frac{(\operatorname{tr}\Sigma^{-1})^2}{(n-p)(n-p-1)(n-p-3)}+\frac{\operatorname{tr}\Sigma^{-2}}{(n-p)(n-p-3)}\\&=\frac{1}{n^2}\operatorname{tr}\Sigma^{-2}+\frac{2p+3}{n^3}\operatorname{tr}\Sigma^{-2}+\frac{1}{n^3}(\operatorname{tr}\Sigma^{-1})^2+O(n^{-4}).\end{aligned} \tag{4.10}$$

Combined with these formulas, we get the desired result (4.7).
Substituting (4.4) and (4.7) into (4.6) and using (3.12) we get

THEOREM 4.1. *An asymptotic expansion of the difference of risks between Haff's estimator* $\hat{\Sigma}_H^{(1)}$ *defined by* (4.1) *with* $b=(p-1)/n$ *and James and Stein's minimax estimator* $\hat{\Sigma}_{JS}^{(1)}$ *for* L_1 *loss is given by*

$$
\begin{aligned}
R_1(\hat{\Sigma}_H^{(1)}, \Sigma)-R_1(\hat{\Sigma}_{JS}^{(1)}, \Sigma)=&\frac{p-1}{6n^2}\left\{(p+1)(p-6)+3(p+3)\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}\right\}\\
&+\frac{(p-1)(p+3)}{2n^3}\left\{6\frac{(\operatorname{tr}\Sigma^{-2})^2}{(\operatorname{tr}\Sigma^{-1})^4}-8\frac{\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-1})^3}+\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}+1\right\}\\
&-\frac{(p-1)^3}{3n^3}\frac{\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-1})^3}+O(n^{-4}).
\end{aligned}
\tag{4.11}
$$

We can see that the term of $O(n^{-2})$ in (4.11) is always positive, if $p\geqq 6$. This shows that the risk of $\hat{\Sigma}_H^{(1)}$ is always larger than that of $\hat{\Sigma}_{JS}^{(1)}$ asymptotically, if $p\geqq 6$. Note that

$$\frac{1}{p}\leqq\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}\leqq 1. \tag{4.12}$$

The lower and upper bounds of $O(n^{-2})$ in (4.11) are given by

$$\frac{1}{6}(p-1)\left(p^2-5p-3+\frac{9}{p}\right) \quad\text{and}\quad \frac{1}{6}(p-1)(p^2-2p+3). \tag{4.13}$$

Some numerical values are given in the following:

Ranges of $O(n^{-2})$ in (4.11).

$p=2$	$p=3$	$p=4$	$p=5$	$p=6$
$\left(-\frac{3}{4},\frac{1}{2}\right)$	$(-2, 2)$	$\left(-\frac{19}{8},\frac{11}{2}\right)$	$\left(-\frac{4}{5},12\right)$	$\left(\frac{15}{4},\frac{45}{2}\right)$

The risk is unchanged for any scalar multiple of Σ. Some numerical values based on (4.11) are given in Table 4. The term of $O(n^{-3})$ gives some idea for the error of our asymptotic approximation. For $\Sigma^{-1}=\lambda\, diag(1, 1, \cdots, 1)$, the lower bound of (4.12) is attained and for $\Sigma^{-1}\to\lambda\, diag(1, 0, \cdots, 0)$, the upper bound is approached. In Table 4 we write $\Sigma^{-1}=\lambda(1, \cdots, 1)$ instead of $\Sigma^{-1}=\lambda\, diag(1, \cdots, 1)$ for abbreviation. Inspection of Table 4 shows that for $p\geqq 6$, the risk differences are positive and that for $p=5$ and $\Sigma^{-1}=\lambda\, diag(1, \cdots, 1)$, the values are positive for $n=8$ and $n=16$, while they are negative for $n\geqq 32$. Precisely speaking they are positive for $n\leqq 21$ and negative for $n\geqq 22$. Whether this is due to the poor accuracy of the asymptotic approximation for small n is not clear. For $p\leqq 4$ and $\Sigma^{-1}=\lambda\, diag(1, \cdots, 1)$, the values are all negative. Thus $p=5$ is the boundary. $\hat{\Sigma}_H^{(1)}$ is better than $\hat{\Sigma}_{JS}^{(1)}$ for these type of Σ if $p\leqq 5$. For $0\leqq b\leqq 2(p-1)/n$, inequality $R_1(\hat{\Sigma}_H^{(1)}, \Sigma)<R_1(\hat{\Sigma}_0^{(1)}, \Sigma)$ holds

exactly. This can be verified also by the asymptotic consideration, namely, we have

$$(4.14)\qquad R_1(\hat{\Sigma}_H^{(1)}, \Sigma)-R_1(\hat{\Sigma}_O^{(1)}, \Sigma)$$
$$=\frac{p-1}{n^2}\left[-(p+1)+\frac{1}{2}(p+3)\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}\right]+O(n^{-3}).$$

The term of $O(n^{-2})$ is always negative because of (4.12). This gives again a weak support as in (3.12) for the usefulness of the asymptotic comparison, when exact inequality between risks is not known. From Tables 1 and 4, we can compute the rates of the reduction of the risks of Haff's estimator $\hat{\Sigma}_H^{(1)}$ with respect to the

Table 4. Asymptotic values of $R_1(\hat{\Sigma}_H^{(1)}, \Sigma)-R_1(\hat{\Sigma}_{JS}^{(1)}, \Sigma)$

Σ^{-1}		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=2$ $\lambda(1,1)$	$O(n^{-2})$	−.011719	−.002930	−.000732	−.000183	−.000046
	$O(n^{-3})$	.004720	.000590	.000074	.000009	.000001
	approx.	−.0070	−.00234	−.000659	−.000174	−.000045
$\lambda(1,2)$	$O(n^{-2})$	−.009549	−.002387	−.000597	−.000149	−.000037
	$O(n^{-3})$	.003400	.000425	.000053	.000007	.000001
	approx.	−.0061	−.00196	−.000544	−.000143	−.000036
$\lambda(1,10)$	$O(n^{-2})$	.001356	.000339	.000085	.000021	.000005
	$O(n^{-3})$	−.000496	−.000062	−.000008	−.000001	−.000000
	approx.	.00086	.000277	.000077	.000020	.000005
$\lambda(1,0)$	$O(n^{-2})$	.007813	.001953	.000488	.000122	.000031
	$O(n^{-3})$	−.000651	−.000081	−.000010	−.000001	−.000000
	approx.	.00716	.001872	.000478	.000121	.000030
$p=3$ $\lambda(1,1,1)$	$O(n^{-2})$	−.031250	−.007813	−.001953	−.000488	−.000122
	$O(n^{-3})$	.012442	.001555	.000194	.000024	.000003
	approx.	−.019	−.0063	−.00176	−.000464	−.000119
$\lambda(1,2,3)$	$O(n^{-2})$	−.026042	−.006510	−.001628	−.000407	−.000102
	$O(n^{-3})$	.010417	.001302	.000163	.000020	.000003
	approx.	−.016	−.0052	−.00146	−.000387	−.000099
$\lambda(1,10,10^2)$	$O(n^{-2})$	.014358	.003590	.000897	.000224	.000056
	$O(n^{-3})$	−.003847	−.000481	−.000060	−.000008	−.000001
	approx.	.0105	.00311	.000837	.000217	.000055
$\lambda(1,0,0)$	$O(n^{-2})$	.031250	.007813	.001953	.000488	.000122
	$O(n^{-3})$	−.005208	−.000651	−.000081	−.000010	−.000001
	approx.	.0260	.00716	.001872	.000478	.000121
$p=4$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	−.037109	−.009277	−.002319	−.000580	−.000145
	$O(n^{-3})$	.021973	.002747	.000343	.000043	.000005
	approx.	−.015	−.0065	−.00198	−.000537	−.000140
$\lambda(1,2,3,4)$	$O(n^{-2})$	−.028906	−.007227	−.001807	−.000452	−.000113
	$O(n^{-3})$	.019570	.002446	.000306	.000038	.000005
	approx.	−.009	−.0048	−.00150	−.000413	−.000108
$\lambda(1,10,10^2,10^3)$	$O(n^{-2})$	.056135	.014034	.003508	.000877	.000219
	$O(n^{-3})$	−.012895	−.001612	−.000201	−.000025	−.000003
	approx.	.043	.0124	.00331	.000852	.000216
$\lambda(1,0,0,0)$	$O(n^{-2})$	.085938	.021484	.005371	.001343	.000336
	$O(n^{-3})$	−.017578	−.002197	−.000275	−.000034	−.000004
	approx.	.068	.0193	.00510	.001308	.000331

Table 4. (continued)

Σ^{-1}		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=5$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	$-.012500$	$-.003125$	$-.000781$	$-.000195$	$-.000049$
	$O(n^{-3})$	.033333	.004167	.000521	.000065	.000008
	approx.	.021	.0010	$-.00026$	$-.000130$	$-.000041$
$\lambda(1,2,\cdots,5)$	$O(n^{-2})$	$-.001389$	$-.000347$	$-.000087$	$-.000022$	$-.000005$
	$O(n^{-3})$	.030648	.003831	.000479	.000060	.000007
	approx.	.029	.0035	.00039	.000038	.000002
$\lambda(1,10,\cdots,10^4)$	$O(n^{-2})$	.142050	.035512	.008878	.002220	.000555
	$O(n^{-3})$	$-.030504$	$-.003813$	$-.000477$	$-.000060$	$-.000007$
	approx.	.112	.0317	.00840	.002160	.000547
$\lambda(1,0,\cdots,0)$	$O(n^{-2})$	.187500	.046875	.011719	.002930	.000732
	$O(n^{-3})$	$-.041667$	$-.005208$	$-.000651$	$-.000081$	$-.000010$
	approx.	.146	.0417	.01107	.002848	.000722
$p=6$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	.058594	.014648	.003662	.000916	.000229
	$O(n^{-3})$	.046568	.005821	.000728	.000091	.000011
	approx.	.105	.0205	.00439	.001006	.000240
$\lambda(1,2,\cdots,6)$	$O(n^{-2})$	.072545	.018136	.004534	.001134	.000283
	$O(n^{-3})$	.043624	.005453	.000682	.000085	.000011
	approx.	.116	.0236	.00522	.001219	.000294
$\lambda(1,10,\cdots,10^5)$	$O(n^{-2})$	.287643	.071911	.017978	.004494	.001124
	$O(n^{-3})$	$-.059523$	$-.007440$	$-.000930$	$-.000116$	$-.000015$
	approx.	.228	.0645	.01705	.00438	.001109
$\lambda(1,0,\cdots,0)$	$O(n^{-2})$	.351563	.087891	.021973	.005493	.001373
	$O(n^{-3})$	$-.081380$	$-.010173$	$-.001272$	$-.000159$	$-.000020$
	approx.	.270	.078	.0207	.00533	.001353

maximum likelihood estimator $\hat{\Sigma}_O^{(1)}$, namely $100\times\{R_1(\hat{\Sigma}_O^{(1)},\Sigma)-R_1(\hat{\Sigma}_H^{(1)},\Sigma)\}/R_1(\hat{\Sigma}_O^{(1)},\Sigma)$, which range above to 8% for $n\geqq 16$. The rates of the reduction of the risks of $\hat{\Sigma}_H^{(1)}$ with respect to $\hat{\Sigma}_{JS}^{(1)}$ range only from -5.6% to 1.6% for $n\geqq 16$ in Table 4.

4.2. Risk of new estimator. Now we shall consider the risk of a new estimator $\hat{\Sigma}^{(1)}$ given in (1.6). We can write the risk difference

$$R_1(\hat{\Sigma}^{(1)},\Sigma)-R_1(\hat{\Sigma}_O^{(1)},\Sigma) = \frac{b}{n}(\operatorname{tr}\Sigma^{-1})E\left[\frac{\operatorname{tr}S^{-1}}{\operatorname{tr}S^{-2}}\right]-E\left[\log\left|I+\frac{b\operatorname{tr}S^{-1}}{\operatorname{tr}S^{-2}}S^{-1}\right|\right]. \tag{4.15}$$

By the Wishart identity, we get

$$E\left[\frac{\operatorname{tr}S^{-1}}{\operatorname{tr}S^{-2}}\operatorname{tr}\Sigma^{-1}\right]=4E\left[\frac{\operatorname{tr}S^{-3}\operatorname{tr}S^{-1}}{(\operatorname{tr}S^{-2})^2}\right]-2+(n-p-1)E\left[\frac{(\operatorname{tr}S^{-1})^2}{\operatorname{tr}S^{-2}}\right]. \tag{4.16}$$

Using (4.16), the risk difference is bounded from above by

$$\frac{b}{n}\left\{4E\left[\frac{\operatorname{tr}S^{-3}\operatorname{tr}S^{-1}}{(\operatorname{tr}S^{-2})^2}\right]-2+\left(\frac{bn}{2}-p-1\right)E\left[\frac{(\operatorname{tr}S^{-1})^2}{\operatorname{tr}S^{-2}}\right]\right\}. \tag{4.17}$$

Note that

$$2\frac{\operatorname{tr} S^{-3}\operatorname{tr} S^{-1}}{(\operatorname{tr} S^{-2})^2}\leqq 1+\frac{(\operatorname{tr} S^{-1})^2}{\operatorname{tr} S^{-2}}, \tag{4.18}$$

where the equality holds if and only if $S^{-1}=\lambda\, diag(1,0,\cdots,0)$ except for permutation of the diagonal elements. The upper bound (4.17) is further simplified as

$$\frac{b}{n}\left(\frac{bn}{2}-p+1\right)E\left[\frac{(\operatorname{tr} S^{-1})^2}{\operatorname{tr} S^{-2}}\right]. \tag{4.19}$$

Hence $\hat{\Sigma}^{(1)}$ dominates $\hat{\Sigma}_O^{(1)}$ if $0\leqq b\leqq 2(p-1)/n$ and the minimum of (4.19) is attained by $b=(p-1)/n$. The choice of b is the same as for the Haff's estimator.

To get asymptotic expansion of the risk difference (4.15), we can rewrite it as in (4.6) by

$$\begin{aligned}\frac{b}{n}&\left\{\left(\frac{nb}{2}-p-1\right)E\left[\frac{(\operatorname{tr} S^{-1})^2}{\operatorname{tr} S^{-2}}\right]-2+4E\left[\frac{\operatorname{tr} S^{-3}\operatorname{tr} S^{-1}}{(\operatorname{tr} S^{-2})^2}\right]\right\}\\ &-\frac{b^3}{3}\frac{(\operatorname{tr}\Sigma^{-1})^3\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-2})^3}+O(n^{-4}).\end{aligned} \tag{4.20}$$

To evaluate each expectation asymptotically, we need the following lemma.

LEMMA 4.2. *Let S have a Wishart distribution $W_p(n,\Sigma)$. Then*

$$\begin{aligned}&E\left[\frac{(\operatorname{tr} S^{-1})^2}{\operatorname{tr} S^{-2}}\right]\\ &=\frac{(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}}+\frac{1}{n}\left[8\frac{\operatorname{tr}\Sigma^{-4}(\operatorname{tr}\Sigma^{-1})^2}{(\operatorname{tr}\Sigma^{-2})^3}-\frac{(\operatorname{tr}\Sigma^{-1})^4}{(\operatorname{tr}\Sigma^{-2})^2}\right.\\ &\quad\left.-8\frac{\operatorname{tr}\Sigma^{-3}\operatorname{tr}\Sigma^{-1}}{(\operatorname{tr}\Sigma^{-2})^2}-\frac{(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}}+2\right]+O(n^{-2}),\end{aligned} \tag{4.21}$$

$$\begin{aligned}&E\left[\frac{\operatorname{tr} S^{-1}\operatorname{tr} S^{-3}}{(\operatorname{tr} S^{-2})^2}\right]\\ &=\frac{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-2})^2}+\frac{1}{n}\left[24\frac{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}\operatorname{tr}\Sigma^{-4}}{(\operatorname{tr}\Sigma^{-2})^4}\right.\\ &\quad-\frac{2}{(\operatorname{tr}\Sigma^{-2})^3}\{(\operatorname{tr}\Sigma^{-1})^3\operatorname{tr}\Sigma^{-3}+12\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-5}\\ &\quad+4(\operatorname{tr}\Sigma^{-3})^2\}+\frac{1}{(\operatorname{tr}\Sigma^{-2})^2}\{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}+6\operatorname{tr}\Sigma^{-4}\}\\ &\quad\left.+\frac{3(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}}\right]+O(n^{-2}).\end{aligned} \tag{4.22}$$

Unlike Lemma 4.1, it seems to be impossible to prove Lemma 4.2 from the Wishart identity only. We obtained it by another method used by Ito [6], Siotani [14], Okamoto [11], Sugiura [15], Fujikoshi [2] and others, that is, for analytic function $f(S)$, it holds

$$E\left[f\left(\frac{1}{n}S\right)\right]=f(\Sigma)+\frac{1}{n}\operatorname{tr}(\Sigma\partial)^2 f(\Lambda)|_{\Lambda=\Sigma}+O(n^{-2}), \tag{4.23}$$

where ∂ is a matrix of differential operators and its (i, j) element is given by $(1/2)(1+\delta_{ij})(\partial/\partial\lambda_{ij})$ for $\Lambda=(\lambda_{ij})$. The following lemma is useful for the repeated application of (4.23).

LEMMA 4.3. *Let E_{ij} $(i\neq j)$ be $p\times p$ matrix having $1/2$ at the (i, j) and (j, i) positions and zero at other positions. Let E_{ii} be diagonal matrix having 1 at i-th diagonal and zero otherwise. Then for any symmetric matrices $A=(a_{ij})$ and $B=(b_{ij})$,*

$$\begin{aligned}&\sum_{i,j}\lambda_i\lambda_j \operatorname{tr} AE_{ij}\operatorname{tr} BE_{ij}=\sum_{i,j}\lambda_i\lambda_j a_{ij}b_{ij}\\ &\sum_{i,j}\lambda_i\lambda_j\operatorname{tr} AE_{ij}BE_{ij}=\frac{1}{2}\sum_{i,j}\lambda_i\lambda_j a_{ij}b_{ij}+\frac{1}{2}\sum_i\lambda_i a_{ii}\sum_j\lambda_j b_{jj}.\end{aligned} \tag{4.24}$$

Applying Lemma 4.2 to (4.20), we get

THEOREM 4.2. *An asymptotic expansion of the difference of risks between new estimator $\hat{\Sigma}^{(1)}$ defined by (1.6) with $b=(p-1)/n$ and James and Stein's minimax estimator $\hat{\Sigma}^{(1)}_{JS}$ for L_1 loss is given by*

$$\begin{aligned}R_1(\hat{\Sigma}^{(1)},\Sigma)-R_1(\hat{\Sigma}^{(1)}_{JS},\Sigma)=&\frac{p(p^2-1)}{6n^2}+\frac{p-1}{n^2}\left[-2+4\frac{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-2})^2}\right.\\ &\left.-\frac{p+3}{2}\frac{(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}}\right]+\frac{p-1}{n^3}\left[96\frac{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}\operatorname{tr}\Sigma^{-4}}{(\operatorname{tr}\Sigma^{-2})^4}\right.\\ &-\frac{1}{(\operatorname{tr}\Sigma^{-2})^3}\left\{\left(8+\frac{(p-1)^2}{3}\right)(\operatorname{tr}\Sigma^{-1})^3\operatorname{tr}\Sigma^{-3}+96\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-5}\right.\\ &\left.+32(\operatorname{tr}\Sigma^{-3})^2+4(p+3)(\operatorname{tr}\Sigma^{-1})^2\operatorname{tr}\Sigma^{-4}\right\}\\ &+\frac{1}{(\operatorname{tr}\Sigma^{-2})^2}\left\{4(p+4)\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}+24\operatorname{tr}\Sigma^{-4}+\frac{p+3}{2}(\operatorname{tr}\Sigma^{-1})^4\right\}\\ &\left.+\left(12+\frac{p+3}{2}\right)\frac{(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}}-p-3\right]+O(n^{-4}).\end{aligned} \tag{4.25}$$

By the inequalities (4.12) and (4.18), the term of $O(n^{-2})$ in (4.25) ranges from

(4.26) $$-\frac{1}{3}(p-1)(p^2+4p-6) \quad \text{to} \quad \frac{1}{6}(p-1)(p^2-2p+3).$$

The lower bound is obtained by noting that $(\mathrm{tr}\,\Sigma^{-1})^2/\mathrm{tr}\,\Sigma^{-2}\leqq p$ and $\mathrm{tr}\,\Sigma^{-1}\,\mathrm{tr}\,\Sigma^{-3}/(\mathrm{tr}\,\Sigma^{-2})^2\geqq 1$, where both equalities are satisfied by $\Sigma^{-1}=\lambda I$. The upper bound is the same as for $\hat{\Sigma}_H^{(1)}$ given in (4.13), while the lower bound is smaller than that of $\hat{\Sigma}_H^{(1)}$, and is always negative. Some numerical values are given below. The lower bound is considerably smaller than (4.13).

Ranges of $O(n^{-2})$ in (4.25).

$p=2$	$p=3$	$p=4$	$p=5$	$p=6$
$\left(-2, \frac{1}{2}\right)$	$(-10, 2)$	$\left(-26, \frac{11}{2}\right)$	$(-52, 12)$	$\left(-90, \frac{45}{2}\right)$

The upper bound is approached as $\Sigma^{-1}\to\lambda\, diag(1, 0, \cdots, 0)$ or any permutation of the diagonal elements of it. This shows that $\hat{\Sigma}^{(1)}$ is better than $\hat{\Sigma}_{JS}^{(1)}$ for $\Sigma^{-1}=\lambda I$ and worse for $\Sigma^{-1}=\lambda\, diag(1, 0, \cdots, 0)$, which is the same conclusion as in Haff's estimator $\hat{\Sigma}_H^{(1)}$. However the lower bound is always negative for $\hat{\Sigma}^{(1)}$ and it is not dominated by $\hat{\Sigma}_{JS}^{(1)}$ for any p if n is large.

Some numerical values based on Theorem 4.2 are given in Table 5, in contrast to Table 4. For $n=8$ and $\Sigma^{-1}=\lambda I$, the positive risk differences are observed, which is probably due to the error of asymptotic approximation for small n. It is found that for $\Sigma^{-1}=\lambda I$ and $\lambda\, diag(1, 2, \cdots, p)$, $\hat{\Sigma}^{(1)}$ is better than $\hat{\Sigma}_H^{(1)}$; for $\Sigma^{-1}=\lambda\, diag(1, 10, \cdots, 10^{p-1})$, $\hat{\Sigma}^{(1)}$ is slightly worse than $\hat{\Sigma}_H^{(1)}$; for $\Sigma^{-1}=\lambda\, diag(1, 0, \cdots, 0)$, the asymptotic differences are consistent up to $O(n^{-3})$. The last statement can be confirmed by putting $\Sigma^{-1}=\lambda\, diag(1, 0, \cdots, 0)$ in Theorems 4.1 and 4.2. From Tables 1, 2 and 5, we can compute the rates of the reduction of the risks of $\hat{\Sigma}^{(1)}$ with respect to $\hat{\Sigma}_O^{(1)}$, namely, $100\times\{R_1(\hat{\Sigma}_O^{(1)}, \Sigma)-R_1(\hat{\Sigma}^{(1)}, \Sigma)\}/R_1(\hat{\Sigma}_O^{(1)}, \Sigma)$ which range above to 20% for $n\geqq 16$. This may be compared with 8% for $\hat{\Sigma}_H^{(1)}$. If we compare the rates of $\hat{\Sigma}^{(1)}$

Table 5. Asymptotic values of $R_1(\hat{\Sigma}^{(1)}, \Sigma)-R_1(\hat{\Sigma}_{JS}^{(1)}, \Sigma)$

Σ^{-1}			$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=2$	$\lambda(1, 1)$	$O(n^{-2})$	$-.031250$	$-.007813$	$-.001953$	$-.000488$	$-.000122$
		$O(n^{-3})$	$.033854$	$.004232$	$.000529$	$.000066$	$.000008$
		approx.	$.003$	$-.0036$	$-.00142$	$-.000422$	$-.000114$
	$\lambda(1, 2)$	$O(n^{-2})$	$-.018438$	$-.004609$	$-.001152$	$-.000288$	$-.000072$
		$O(n^{-3})$	$.008778$	$.001097$	$.000137$	$.000017$	$.000002$
		approx.	$-.0097$	$-.0035$	$-.00102$	$-.000271$	$-.000070$
	$\lambda(1, 10)$	$O(n^{-2})$	$.005040$	$.001260$	$.000315$	$.000079$	$.000020$
		$O(n^{-3})$	$-.001753$	$-.000219$	$-.000027$	$-.000003$	$-.000000$
		approx.	$.0033$	$.00104$	$.000288$	$.000075$	$.000019$
	$\lambda(1, 0)$	$O(n^{-2})$	$.007813$	$.001953$	$.000488$	$.000122$	$.000031$
		$O(n^{-3})$	$-.000651$	$-.000081$	$-.000010$	$-.000001$	$-.000000$
		approx.	$.00716$	$.001872$	$.000478$	$.000121$	$.000030$

Table 5. (continued)

Σ^{-1}		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=3$ $\lambda(1,1,1)$	$O(n^{-2})$	$-.156250$	$-.039063$	$-.009766$	$-.002441$	$-.000610$
	$O(n^{-3})$	$.153646$	$.019206$	$.002401$	$.000300$	$.000038$
	approx.	$-.003$	$-.020$	$-.0074$	$-.00214$	$-.000573$
$\lambda(1,2,3)$	$O(n^{-2})$	$-.103316$	$-.025829$	$-.006457$	$-.001614$	$-.000404$
	$O(n^{-3})$	$.069561$	$.008695$	$.001087$	$.000136$	$.000017$
	approx.	$-.034$	$-.0171$	$-.0054$	$-.00148$	$-.000387$
$\lambda(1,10,10^2)$	$O(n^{-2})$	$.021771$	$.005443$	$.001361$	$.000340$	$.000085$
	$O(n^{-3})$	$-.009179$	$-.001147$	$-.000143$	$-.000018$	$-.000002$
	approx.	$.0126$	$.0043$	$.00122$	$.000322$	$.000083$
$\lambda(1,0,0)$	$O(n^{-2})$	$.031250$	$.007813$	$.001953$	$.000488$	$.000122$
	$O(n^{-3})$	$-.005208$	$-.000651$	$-.000081$	$-.000010$	$-.000001$
	approx.	$.0260$	$.00716$	$.001872$	$.000478$	$.000121$
$p=4$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	$-.406250$	$-.101563$	$-.025391$	$-.006348$	$-.001587$
	$O(n^{-3})$	$.404297$	$.050537$	$.006317$	$.000790$	$.000099$
	approx.	$-.002$	$-.051$	$-.0191$	$-.00556$	$-.001488$
$\lambda(1,2,3,4)$	$O(n^{-2})$	$-.276042$	$-.069010$	$-.017253$	$-.004313$	$-.001078$
	$O(n^{-3})$	$.204965$	$.025621$	$.003203$	$.000400$	$.000050$
	approx.	$-.07$	$-.043$	$-.0140$	$-.00391$	$-.001208$
$\lambda(1,10,10^2,10^3)$	$O(n^{-2})$	$.066391$	$.016598$	$.004149$	$.001037$	$.000259$
	$O(n^{-3})$	$-.027263$	$-.003408$	$-.000426$	$-.000053$	$-.000007$
	approx.	$.039$	$.0132$	$.00372$	$.000984$	$.000253$
$\lambda(1,0,0,0)$	$O(n^{-2})$	$.085938$	$.021484$	$.005371$	$.001343$	$.000336$
	$O(n^{-3})$	$-.017578$	$-.002197$	$-.000275$	$-.000034$	$-.000004$
	approx.	$.068$	$.0193$	$.00510$	$.001308$	$.000331$
$p=5$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	$-.812500$	$-.203125$	$-.050781$	$-.012695$	$-.003174$
	$O(n^{-3})$	$.841667$	$.105208$	$.013151$	$.001644$	$.000205$
	approx.	$.03$	$-.10$	$-.038$	$-.0111$	$-.00297$
$\lambda(1,2\cdots,5)$	$O(n^{-2})$	$-.556302$	$-.139075$	$-.034769$	$-.008692$	$-.002173$
	$O(n^{-3})$	$.435419$	$.054427$	$.006803$	$.000850$	$.000106$
	approx.	$-.12$	$-.085$	$-.0280$	$-.00784$	$-.00207$
$\lambda(1,10,\cdots,10^4)$	$O(n^{-2})$	$.154470$	$.038618$	$.009654$	$.002414$	$.000603$
	$O(n^{-3})$	$-.061226$	$-.007653$	$-.000957$	$-.000120$	$-.000015$
	approx.	$.093$	$.0310$	$.00870$	$.00229$	$.000588$
$\lambda(1,0,\cdots,0)$	$O(n^{-2})$	$.187500$	$.046875$	$.011719$	$.002930$	$.000732$
	$O(n^{-3})$	$-.041667$	$-.005208$	$-.000651$	$-.000081$	$-.000010$
	approx.	$.146$	$.0417$	$.01107$	$.002848$	$.000722$
$p=6$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	-1.406250	$-.351563$	$-.087891$	$-.021973$	$-.005493$
	$O(n^{-3})$	1.529948	$.191243$	$.023905$	$.002988$	$.000374$
	approx.	$.1$	$-.16$	$-.064$	$-.0190$	$-.00512$
$\lambda(1,2,\cdots,6)$	$O(n^{-2})$	$-.963619$	$-.240905$	$-.060226$	$-.015057$	$-.003764$
	$O(n^{-3})$	$.782396$	$.097799$	$.012225$	$.001528$	$.000191$
	approx.	$-.18$	$-.143$	$-.048$	$-.0135$	$-.00357$
$\lambda(1,10,\cdots,10^5)$	$O(n^{-2})$	$.301591$	$.075398$	$.018849$	$.004712$	$.001178$
	$O(n^{-3})$	$-.116287$	$-.014536$	$-.001817$	$-.000227$	$-.000028$
	approx.	$.19$	$.061$	$.0170$	$.00449$	$.001150$
$\lambda(1,0,\cdots,0)$	$O(n^{-2})$	$.351563$	$.087891$	$.021973$	$.005493$	$.001373$
	$O(n^{-3})$	$-.081380$	$-.010173$	$-.001272$	$-.000159$	$-.000020$
	approx.	$.270$	$.078$	$.0207$	$.00533$	$.001353$

with respect to $\hat{\Sigma}^{(1)}_{JS}$, we get the range from -5.6% to 12% in Table 5 for $n\geqq16$. The rates for $\hat{\Sigma}^{(1)}$ with respect to $\hat{\Sigma}^{(1)}_{H}$ range from -0.4% to 12% for $n\geqq16$.

5. Risks under L_2 loss

5.1. Risk of Haff's estimator. We shall now consider the estimator

$$\hat{\Sigma}_H^{(2)}=\frac{1}{n+p+1}\left[S+\frac{b}{\operatorname{tr} S^{-1}}I\right] \tag{5.1}$$

proposed by Haff [5], where C is taken to be I in (1.4) without loss of generality. The loss function is given by (1.2), throughout Section 5. It is known by Haff [5] that the best scalar multiple of S is given by $\hat{\Sigma}_O^{(2)}=S/(n+p+1)$. The difference of risks can be written by

$$\begin{aligned}&R_2(\hat{\Sigma}_H^{(2)},\Sigma)-R_2(\hat{\Sigma}_O^{(2)},\Sigma)\\ &=\frac{b}{2(n+p+1)^2}E\left[\frac{2}{\operatorname{tr} S^{-1}}\operatorname{tr}\{S\Sigma^{-2}-(n+p+1)\Sigma^{-1}\}+\frac{b\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr} S^{-1})^2}\right].\end{aligned} \tag{5.2}$$

To evaluate each expectation, we need the following equations due to Haff [5] derived from the Wishart identity.

$$E\left[\frac{\operatorname{tr} S\Sigma^{-2}}{\operatorname{tr} S^{-1}}\right]=nE\left[\frac{\operatorname{tr}\Sigma^{-1}}{\operatorname{tr} S^{-1}}\right]+2E\left[\frac{\operatorname{tr} S^{-1}\Sigma^{-1}}{(\operatorname{tr} S^{-1})^2}\right]. \tag{5.3}$$

$$E\left[\frac{\operatorname{tr} S^{-1}\Sigma^{-1}}{(\operatorname{tr} S^{-1})^2}\right]=(n-p-2)E\left[\frac{\operatorname{tr} S^{-2}}{(\operatorname{tr} S^{-1})^2}\right]+4E\left[\frac{\operatorname{tr} S^{-3}}{(\operatorname{tr} S^{-1})^3}\right]-1. \tag{5.4}$$

$$E\left[\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr} S^{-1})^2}\right]=4E\left[\frac{\operatorname{tr} S^{-2}\Sigma^{-1}}{(\operatorname{tr} S^{-1})^3}\right]+(n-p-1)E\left[\frac{\operatorname{tr} S^{-1}\Sigma^{-1}}{(\operatorname{tr} S^{-1})^2}\right]. \tag{5.5}$$

Together with (4.4) and Lemma 4.1, we can rewrite (5.2) as

$$\begin{aligned}&\frac{b}{(n+p+1)^2}\left[-n(p+1)+\left\{2n-4p-4-bn(p+1)+\frac{bn^2}{2}\right\}\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}+(p+1)^2\right.\\ &\qquad\left.-8\frac{\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-1})^3}+3(bn+4)\frac{(\operatorname{tr}\Sigma^{-2})^2}{(\operatorname{tr}\Sigma^{-1})^4}\right]+O(n^{-4}).\end{aligned} \tag{5.6}$$

Assuming that $b=O(1/n)$, the term of $O(n^{-2})$ in (5.6) is

$$-n(p+1)+2n\left(1+\frac{bn}{4}\right)\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}\leqq -n(p+1)+2n\left(1+\frac{bn}{4}\right). \tag{5.7}$$

The condition that the R. H. S. of (5.7) is negative is given by $b\leqq 2(p-1)/n$ which is in contrast with the exact result $b\leqq 2(p-1)/(n-p+3)$ in Haff [5]. The equality in (5.7) is attained by $\Sigma^{-1}=\lambda\, diag(1,0,\cdots,0)$, for which the value of (5.6) is minimized by

$$b=\frac{(n-p+1)(p-1)}{n^2-2(p-2)n}=\frac{1}{n}(p-1)\left(1+\frac{p-3}{n}\right)+O(n^{-3}). \tag{5.8}$$

Again the result is the same as the optimal choice $b=(p-1)/(n-p+3)$ by Haff [5] asymptotically. Note that

$$R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)-R_2(\hat{\Sigma}_{O}^{(2)}, \Sigma) = -\frac{p(p^2-1)}{6n^2}+\frac{p(p+1)^2(p-1)}{2n^3}+O(n^{-4}). \tag{5.9}$$

We get

THEOREM 5.1. *An asymptotic expansion of the difference of risks between Haff's estimator* $\hat{\Sigma}_H^{(2)}$ *defined by* (5.1) *and James and Stein's minimax estimator* $\hat{\Sigma}_{JS}^{(2)}$ *for* L_2 *loss is given by*

$$\begin{aligned} R_2(\hat{\Sigma}_H^{(2)}, \Sigma)-R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)&=\frac{p-1}{6n^2}\left[(p+1)(p-6)+3(p+3)\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}\right] \\ &+\frac{p-1}{n^3}\left[\frac{1}{2}(p+1)^2(6-p)-\Delta(p+1)+3(p+3)\frac{(\operatorname{tr}\Sigma^{-2})^2}{(\operatorname{tr}\Sigma^{-1})^4}\right. \\ &\left.+(p+1)(\Delta-2p-6)\frac{\operatorname{tr}\Sigma^{-2}}{(\operatorname{tr}\Sigma^{-1})^2}-8\frac{\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-1})^3}\right]+O(n^{-4}), \end{aligned} \tag{5.10}$$

where $b=(p-1)(1+\Delta/n)/n$ *and an optimal choice of* Δ *is* $p-3$.

The term of $O(n^{-2})$ in (5.10) is the same as that of $R_1(\hat{\Sigma}_H^{(1)}, \Sigma)-R_1(\hat{\Sigma}_{JS}^{(1)}, \Sigma)$ in Theorem 4.1. However the term of $O(n^{-3})$ is different which yields poor asymptotic approximations as can be seen in Table 6 compared with Table 4. For instance, when $n=16$, $p=6$ and $\Sigma^{-1}=\lambda I$, the approximate value of $R_2(\hat{\Sigma}_H^{(2)}, \Sigma)-R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)$ is equal to -0.032. However we can not say that this is negative, because of the error that may arise in the asymptotic approximations. The corresponding value for $\hat{\Sigma}_H^{(1)}$ is 0.0205 from Table 4 and we are certain that this is positive. One might think that an asymptotic expansion with respect to $n+p+1$ is better for $\hat{\Sigma}_H^{(2)}$, because of (3.7). We can easily rewrite (5.10) in terms of powers of $n+p+1$ instead of n. For the above example we get the term of order $(n+p+1)^{-2}$ is equal to 0.007089 and the term of order $(n+p+1)^{-3}$ is equal to -0.011290. The approximate value is -0.004201, which is different from -0.032. However still the second term is larger than the first in absolute value. If we increase $n=128$ in this example, the approximate value is 0.000150, the corresponding value in Table 6 is 0.000138. Hence these values are reliable. The fact that the asymptotic approximations are better for L_1 loss than for L_2 loss, is ascertained again. From Tables 3 and 6, the rates of the reduction of the risks of $\hat{\Sigma}_H^{(2)}$ with respect to $\hat{\Sigma}_O^{(2)}$ can be computed, the range of which is given by $0\%\sim4\%$ for $n\geqq32$ in Table 6.

Table 6. Asymptotic values of $R_2(\hat{\Sigma}_H^{(2)}, \Sigma)-R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)$

Σ^{-1}		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=2$ $\lambda(1,1)$	$O(n^{-2})$	−.011719	−.002930	−.000732	−.000183	−.000046
	$O(n^{-3})$	.012207	.001526	.000191	.000024	.000003
	approx.	.0005	−.0014	−.00054	−.000159	−.000043
$\lambda(1,2)$	$O(n^{-2})$	−.009549	−.002387	−.000597	−.000149	−.000037
	$O(n^{-3})$	.009042	.001130	.000141	.000018	.000002
	approx.	−.0005	−.0013	−.00046	−.000132	−.000035
$\lambda(1,10)$	$O(n^{-2})$	.001356	.000339	.000085	.000021	.000005
	$O(n^{-3})$	−.004123	−.000515	−.000064	−.000008	−.000001
	approx.	−.0028	−.00018	.000020	.000013	.000004
$\lambda(1,0)$	$O(n^{-2})$	.007813	.001953	.000488	.000122	.000031
	$O(n^{-3})$	−.009766	−.001221	−.000153	−.000019	−.000002
	approx.	−.0020	.0007	.00034	.000103	.000028
$p=3$ $\lambda(1,1,1)$	$O(n^{-2})$	−.031250	−.007813	−.001953	−.000488	−.000122
	$O(n^{-3})$	.035590	.004449	.000556	.000070	.000009
	approx.	.004	−.0034	−.00134	−.000419	−.000113
$\lambda(1,2,3)$	$O(n^{-2})$	−.026042	−.006510	−.001628	−.000407	−.000102
	$O(n^{-3})$	.026259	.003282	.000410	.000051	.000006
	approx.	.0002	−.0032	−.00122	−.000356	−.000095
$\lambda(1,10,10^2)$	$O(n^{-2})$	.014358	.003590	.000897	.000224	.000056
	$O(n^{-3})$	−.035581	−.004448	−.000556	−.000069	−.000009
	approx.	−.021	−.0009	.00034	.000155	.000047
$\lambda(1,0,0)$	$O(n^{-2})$	.031250	.007813	.001953	.000488	.000122
	$O(n^{-3})$	−.054688	−.006836	−.000854	−.000107	−.000013
	approx.	−.023	.0010	.00110	.00038	.000109
$p=4$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	−.037109	−.009277	−.002319	−.000580	−.000145
	$O(n^{-3})$	.026733	.003342	.000418	.000052	.000007
	approx.	−.010	−.0059	−.00190	−.000528	−.000138
$\lambda(1,2,3,4)$	$O(n^{-2})$	−.028906	−.007227	−.001807	−.000452	−.000113
	$O(n^{-3})$	.009316	.001165	.000146	.000018	.000002
	approx.	−.0196	−.0061	−.00166	−.000433	−.000111
$\lambda(1,10,10^2,10^3)$	$O(n^{-2})$	.056135	.014034	.003508	.000877	.000219
	$O(n^{-3})$	−.146300	−.018288	−.002286	−.000286	−.000036
	approx.	−.09	−.004	.0012	.00059	.000184
$\lambda(1,0,0,0)$	$O(n^{-2})$	.085938	.021484	.005371	.001343	.000336
	$O(n^{-3})$	−.187500	−.023438	−.002930	−.000366	−.000046
	approx.	−.10	−.002	.0024	.00098	.000290
$p=5$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	−.012500	−.003125	−.000781	−.000195	−.000049
	$O(n^{-3})$	−.079375	−.009922	−.001240	−.000155	−.000019
	approx.	−.092	−.0130	−.0020	−.00035	−.000068
$\lambda(1,2,\cdots,5)$	$O(n^{-2})$	−.001389	−.000347	−.000087	−.000022	−.000005
	$O(n^{-3})$	−.106505	−.013313	−.001664	−.000208	−.000026
	approx.	−.11	−.014	−.0018	−.00023	−.000031
$\lambda(1,10,\cdots,10^4)$	$O(n^{-2})$	.142050	.035512	.008878	.002220	.000555
	$O(n^{-3})$	−.410155	−.051269	−.006409	−.000801	−.000100
	approx.	−.27	−.016	.0025	.00142	.00046
$\lambda(1,0,\cdots,0)$	$O(n^{-2})$	.187500	.046875	.011719	.002930	.000732
	$O(n^{-3})$	−.484375	−.060547	−.007568	−.000946	−.000118
	approx.	−.30	−.014	.0042	.00198	.00061

Table 6. (continued)

Σ^{-1}		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=6$ $\lambda(1,\cdots,1)$	$O(n^{-2})$ $O(n^{-3})$ approx.	.058594 −.370822 −.31	.014648 −.046353 −.032	.003662 −.005794 −.0021	.000916 −.000724 .00019	.000229 −.000091 .000138
$\lambda(1,2,\cdots,6)$	$O(n^{-2})$ $O(n^{-3})$ approx.	.072545 −.409160 −.38	.018136 −.051145 −.033	.004534 −.006393 −.0019	.001134 −.000799 .00033	.000283 −.000100 .00018
$\lambda(1,10,\cdots,10^5)$	$O(n^{-2})$ $O(n^{-3})$ approx.	.287643 −.924538 −.64	.071911 −.115567 −.04	.017978 −.014446 .004	.004494 −.001806 .0027	.001124 −.000226 .00090
$\lambda(1,0,\cdots,0)$	$O(n^{-2})$ $O(n^{-3})$ approx.	.351563 −1.044922 −.7	.087891 −.130615 −.04	.021973 −.016327 .006	.005493 −.002041 .0035	.001373 −.000255 .00112

5.2. Risk of new estimator. Finally we shall consider the estimator (1.7) for $C=I$ without loss of generality, namely,

$$\hat{\Sigma}^{(2)}=\frac{1}{n+p+1}\left(S+\frac{b\operatorname{tr}S^{-1}}{\operatorname{tr}S^{-2}}I\right). \tag{5.11}$$

The risk difference can be written by

$$\begin{aligned}R_2(\hat{\Sigma}^{(2)},\Sigma)-R_2(\hat{\Sigma}_O^{(2)},\Sigma)=\frac{b}{(n+p+1)^2}\,E\Bigg[&\frac{\operatorname{tr}S^{-1}}{\operatorname{tr}S^{-2}}\operatorname{tr}\{S\Sigma^{-1}-(n+p+1)I\}\Sigma^{-1}\\&+\frac{b}{2}\left(\frac{\operatorname{tr}S^{-1}}{\operatorname{tr}S^{-2}}\right)^2\operatorname{tr}\Sigma^{-2}\Bigg].\end{aligned} \tag{5.12}$$

Each expectation can be computed by the following relations obtained from the Wishart identity in Haff [5].

$$\begin{aligned}E\left[\frac{\operatorname{tr}S^{-1}\operatorname{tr}S^{-2}\Sigma^{-1}}{(\operatorname{tr}S^{-2})^2}\right]=&\,2E\left[4\frac{\operatorname{tr}S^{-1}\operatorname{tr}S^{-5}}{(\operatorname{tr}S^{-2})^3}-\frac{\operatorname{tr}S^{-4}}{(\operatorname{tr}S^{-2})^2}\right]\\&-2E\left[\frac{(\operatorname{tr}S^{-1})^2}{\operatorname{tr}S^{-2}}\right]+(n-p-3)E\left[\frac{\operatorname{tr}S^{-1}\operatorname{tr}S^{-3}}{(\operatorname{tr}S^{-2})^2}\right].\end{aligned} \tag{5.13}$$

$$E\left[\frac{\operatorname{tr}S^{-1}\Sigma^{-1}}{\operatorname{tr}S^{-2}}\right]=n-p-2-E\left[\frac{(\operatorname{tr}S^{-1})^2}{\operatorname{tr}S^{-2}}\right]+4E\left[\frac{\operatorname{tr}S^{-4}}{(\operatorname{tr}S^{-2})^2}\right]. \tag{5.14}$$

$$\begin{aligned}E\left[\frac{(\operatorname{tr}S^{-1})^2}{(\operatorname{tr}S^{-2})^2}\operatorname{tr}S^{-1}\Sigma^{-1}\right]=&\,(n-p-2)E\left[\frac{(\operatorname{tr}S^{-1})^2}{\operatorname{tr}S^{-2}}\right]-E\left[\frac{(\operatorname{tr}S^{-1})^4}{(\operatorname{tr}S^{-2})^2}\right]\\&+8E\left[\frac{(\operatorname{tr}S^{-1})^2\operatorname{tr}S^{-4}}{(\operatorname{tr}S^{-2})^3}\right]-4E\left[\frac{\operatorname{tr}S^{-1}\operatorname{tr}S^{-3}}{(\operatorname{tr}S^{-2})^2}\right].\end{aligned} \tag{5.15}$$

For example, the first term of the expectation in the R. H. S. of (5.12) can be expressed by the Whisart identity as

$$nE\left[\frac{\operatorname{tr} S^{-1}}{\operatorname{tr} S^{-2}}\operatorname{tr}\Sigma^{-1}\right]-(n-p-1)(n+p+1)E\left[\frac{(\operatorname{tr} S^{-1})^2}{\operatorname{tr} S^{-2}}\right]+4E\left[\frac{\operatorname{tr} S^{-1}\operatorname{tr} S^{-2}\Sigma^{-1}}{(\operatorname{tr} S^{-2})^2}\right]$$
$$-2E\left[\frac{\operatorname{tr} S^{-1}\Sigma^{-1}}{\operatorname{tr} S^{-2}}\right]-4(n+p+1)E\left[\frac{\operatorname{tr} S^{-1}\operatorname{tr} S^{-3}}{(\operatorname{tr} S^{-2})^2}\right]+2(n+p+1),$$

which can be reduced further by (5.13), (5.14) and (4.16). Assuming that $b=O(n^{-1})$, we can finally rewrite (5.12) as

$$\begin{aligned}\frac{b}{(n+p+1)^2}\Bigg[&-2n+n\left(\frac{b}{2}n-p-1\right)E\left[\frac{(\operatorname{tr} S^{-1})^2}{\operatorname{tr} S^{-2}}\right]+4nE\left[\frac{\operatorname{tr} S^{-1}\operatorname{tr} S^{-3}}{(\operatorname{tr} S^{-2})^2}\right]\\&+4p+6+\left\{(p+1)^2-6-\frac{b}{2}n(2p+3)\right\}\frac{(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}}-16\frac{\operatorname{tr}\Sigma^{-4}}{(\operatorname{tr}\Sigma^{-2})^2}\\&-4(bn+2p+4)\frac{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-2})^2}+32\frac{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-5}}{(\operatorname{tr}\Sigma^{-2})^3}\\&+8bn\frac{(\operatorname{tr}\Sigma^{-1})^2\operatorname{tr}\Sigma^{-4}}{(\operatorname{tr}\Sigma^{-2})^3}-\frac{bn}{2}\frac{(\operatorname{tr}\Sigma^{-1})^4}{(\operatorname{tr}\Sigma^{-2})^2}\Bigg]+O(n^{-4}).\end{aligned}\tag{5.16}$$

By (4.18) the term of $O(n^{-2})$ in (5.16) is bounded from above by

$$\left\{\frac{1}{2}bn^2-n(p+1)+2n\right\}\frac{(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}},\tag{5.17}$$

which is negative only if $b\leqq 2(p-1)/n$. The upper bound (5.17) is attained for $\Sigma^{-1}=\lambda\, diag(1,0,\cdots,0)$ or any permutation of the diagonal elements of it. For this Σ^{-1}, the risk difference (5.16) can be written by

$$\frac{b}{(n+p+1)^2}\left\{\frac{1}{2}bn^2-n(p-1)+(p-1)^2-(p-2)bn\right\}+O(n^{-4}),\tag{5.18}$$

which is minimized by $b=(p-1)(1+\Delta/n)/n$ for $\Delta=p-3$ asymptotically. This optimal choice of b is the same as for $\hat{\Sigma}_H^{(2)}$. Using (5.9), we get

THEOREM 5.2. *An asymptotic expansion of the difference of risks between estimator $\hat{\Sigma}^{(2)}$ defined by* (5.11) *with $b=(p-1)(1+\Delta/n)/n$ and James and Stein's estimator $\hat{\Sigma}_{JS}^{(2)}$ for L_2 loss is given by*

$$\begin{aligned}&R_2(\hat{\Sigma}^{(2)},\Sigma)-R_2(\hat{\Sigma}_{JS}^{(2)},\Sigma)\\&=\frac{p-1}{6n^2}\left[(p-3)(p+4)-3(p+3)\frac{(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}}+24\frac{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-2})^2}\right]\\&\quad+\frac{p-1}{n^3}\Bigg[-\frac{1}{2}(p+1)(p^2+p-14)-2\Delta+(p^2+6p+13-2\Delta)\frac{(\operatorname{tr}\Sigma^{-1})^2}{\operatorname{tr}\Sigma^{-2}}\\&\quad+4(\Delta-4p-1)\frac{\operatorname{tr}\Sigma^{-1}\operatorname{tr}\Sigma^{-3}}{(\operatorname{tr}\Sigma^{-2})^2}+8\frac{\operatorname{tr}\Sigma^{-4}}{(\operatorname{tr}\Sigma^{-2})^2}+2\frac{(\operatorname{tr}\Sigma^{-1})^4}{(\operatorname{tr}\Sigma^{-2})^2}\end{aligned}\tag{5.19}$$

$$-\frac{4}{(\mathrm{tr}\,\Sigma^{-2})^3}\{-(p-5)(\mathrm{tr}\,\Sigma^{-1})^2\,\mathrm{tr}\,\Sigma^{-4}+16\,\mathrm{tr}\,\Sigma^{-1}\,\mathrm{tr}\,\Sigma^{-5}$$

$$+2(\mathrm{tr}\,\Sigma^{-1})^3\,\mathrm{tr}\,\Sigma^{-3}+8(\mathrm{tr}\,\Sigma^{-3})^2\}$$

$$\left.+96\frac{\mathrm{tr}\,\Sigma^{-1}\,\mathrm{tr}\,\Sigma^{-3}\,\mathrm{tr}\,\Sigma^{-4}}{(\mathrm{tr}\,\Sigma^{-2})^4}\right]+O(n^{-4}).$$

An optimal choice of Δ is given by $p-3$.

Note that the term of $O(n^{-2})$ for $\hat{\Sigma}^{(2)}$ in (5.19) is the same as the corresponding term of Theorem 4.2 for $\hat{\Sigma}^{(1)}$. Also the term of $O(n^{-2})$ for $\hat{\Sigma}_H^{(2)}$ in Theorem 5.1 is the same as that of Theorem 4.1 for $\hat{\Sigma}_H^{(1)}$. Hence the ranges of $O(n^{-2})$ in (4.13) and (4.26) hold also for $\hat{\Sigma}_H^{(2)}$ and $\hat{\Sigma}^{(2)}$. Asymptotically, the range for $\hat{\Sigma}^{(2)}$ is wider below than that for $\hat{\Sigma}_H^{(2)}$. Some numerical values of the risk differences for $\hat{\Sigma}^{(2)}$ are shown in Table 7. Comparing with Table 6, we can see that for $\Sigma^{-1}=\lambda I$ and $\lambda\,diag(1, 2, \cdots, p)$, $\hat{\Sigma}^{(2)}$ is better considerably; for $\Sigma^{-1}=\lambda\,diag(1, 10, \cdots, 10^{p-1})$, $\hat{\Sigma}_H^{(2)}$ is better and for $\Sigma^{-1}=\lambda\,diag(1, 0, \cdots, 0)$, they are the same. The last statement can be checked by putting $\Sigma^{-1}=\lambda\,diag(1, 0, \cdots, 0)$ in (5.10) and (5.19). Comparing with Table 5, we can see that the asymptotic approximations are poor for $\hat{\Sigma}^{(2)}$. Again the positive values for $\Sigma^{-1}=\lambda I$ and negative values for $\Sigma^{-1}=$

Table 7. Asymptotic values of $R_2(\hat{\Sigma}^{(2)}, \Sigma)-R_2(\hat{\Sigma}_{JS}^{(2)}, \Sigma)$

Σ^{-1}			$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=2$	$\lambda(1, 1)$	$O(n^{-2})$	—.031250	—.007813	—.001953	—.000488	—.000122
		$O(n^{-3})$	.039063	.004883	.000610	.000076	.000010
		approx.	.008	—.0029	—.00134	—.000412	—.000113
	$\lambda(1, 2)$	$O(n^{-2})$	—.018438	—.004609	—.001152	—.000288	—.000072
		$O(n^{-3})$	.014372	.001796	.000225	.000028	.000004
		approx.	—.004	—.0028	—.00093	—.000260	—.000069
	$\lambda(1, 10)$	$O(n^{-2})$	.005040	.001260	.000315	.000079	.000020
		$O(n^{-3})$	—.007077	—.000885	—.000111	—.000014	—.000002
		approx.	—.0020	.00038	.00020	.000065	.000018
	$\lambda(1, 0)$	$O(n^{-2})$	.007813	.001953	.000488	.000122	.000031
		$O(n^{-3})$	—.009766	—.001221	—.000153	—.000019	—.000002
		approx.	—.0020	.0007	.00034	.000103	.000028
$p=3$	$\lambda(1, 1, 1)$	$O(n^{-2})$	—.156250	—.039063	—.009766	—.002441	—.000610
		$O(n^{-3})$	.236979	.029622	.003703	.000463	.000058
		approx.	.08	—.009	—.0061	—.00198	—.000552
	$\lambda(1, 2, 3)$	$O(n^{-2})$	—.103316	—.025829	—.006457	—.001614	—.000404
		$O(n^{-3})$	.128827	.016103	.002013	.000252	.000031
		approx.	.26	—.010	—.0044	—.00136	—.000372
	$\lambda(1, 10, 10^2)$	$O(n^{-2})$	.021771	.005443	.001361	.000340	.000085
		$O(n^{-3})$	—.042109	—.005264	—.000658	—.000082	—.000010
		approx.	—.020	.0002	.00070	.000258	.000075
	$\lambda(1, 0, 0)$	$O(n^{-2})$	.031250	.007813	.001953	.000488	.000122
		$O(n^{-3})$	—.054688	—.006836	—.000854	—.000107	—.000013
		approx.	—.023	.0010	.00110	.00038	.000109

Table 7. (continued)

Σ^{-1}		$n=8$	$n=16$	$n=32$	$n=64$	$n=128$
$p=4$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	$-.406250$	$-.101563$	$-.025391$	$-.006348$	$-.001587$
	$O(n^{-3})$	$.708984$	$.088623$	$.011078$	$.001385$	$.000173$
	approx.	$.30$	$-.013$	$-.014$	$-.0050$	$-.00141$
$\lambda(1,2,3,4)$	$O(n^{-2})$	$-.276042$	$-.069010$	$-.017253$	$-.004313$	$-.001078$
	$O(n^{-3})$	$.419957$	$.052495$	$.006562$	$.000820$	$.000103$
	approx.	$.14$	$-.017$	$-.0107$	$-.00349$	$-.00098$
$\lambda(1,10,10^2,10^3)$	$O(n^{-2})$	$.066391$	$.016598$	$.004149$	$.001037$	$.000259$
	$O(n^{-3})$	$-.155830$	$-.019479$	$-.002435$	$-.000304$	$-.000038$
	approx.	$-.09$	$-.003$	$.0017$	$.00073$	$.000221$
$\lambda(1,0,0,0)$	$O(n^{-2})$	$.085938$	$.021484$	$.005371$	$.001343$	$.000336$
	$O(n^{-3})$	$-.187500$	$-.023438$	$-.002930$	$-.000366$	$-.000046$
	approx.	$-.10$	$-.002$	$.0024$	$.00098$	$.000290$
$p=5$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	$-.812500$	$-.203125$	$-.050781$	$-.012695$	$-.003174$
	$O(n^{-3})$	1.590625	$.198828$	$.024854$	$.003107$	$.000388$
	approx.	$.8$	$-.004$	$-.026$	$-.0096$	$-.00279$
$\lambda(1,2,\cdots,5)$	$O(n^{-2})$	$-.556302$	$-.139075$	$-.034769$	$-.008692$	$-.002173$
	$O(n^{-3})$	$.968478$	$.121060$	$.015132$	$.001892$	$.000236$
	approx.	$.41$	$-.02$	$-.020$	$-.0068$	$-.00194$
$\lambda(1,10,\cdots,10^4)$	$O(n^{-2})$	$.154470$	$.038618$	$.009654$	$.002414$	$.000603$
	$O(n^{-3})$	$-.421797$	$-.052725$	$-.006591$	$-.000824$	$-.000103$
	approx.	$-.27$	$-.014$	$.0031$	$.00159$	$.00050$
$\lambda(1,0,\cdots,0)$	$O(n^{-2})$	$.187500$	$.046875$	$.011719$	$.002930$	$.000732$
	$O(n^{-3})$	$-.484375$	$-.060547$	$-.007568$	$-.000946$	$-.000118$
	approx.	$-.30$	$-.014$	$.0042$	$.00198$	$.00061$
$p=6$ $\lambda(1,\cdots,1)$	$O(n^{-2})$	-1.406250	$-.351563$	$-.087891$	$-.021973$	$-.005493$
	$O(n^{-3})$	3.040365	$.380046$	$.047506$	$.005938$	$.000742$
	approx.	1.6	$.03$	$-.040$	$-.0160$	$-.00475$
$\lambda(1,2,\cdots,6)$	$O(n^{-2})$	$-.963619$	$-.240905$	$-.060226$	$-.015057$	$-.003764$
	$O(n^{-3})$	1.865664	$.233208$	$.029151$	$.003644$	$.000455$
	approx.	$.9$	$-.01$	$-.031$	$-.0114$	$-.00331$
$\lambda(1,10,\cdots,10^5)$	$O(n^{-2})$	$.301591$	$.075398$	$.018849$	$.004712$	$.001178$
	$O(n^{-3})$	$-.936962$	$-.117120$	$-.014640$	$-.001830$	$-.000229$
	approx.	$-.64$	$-.04$	$.004$	$.0029$	$.00095$
$\lambda(1,0,\cdots,0)$	$O(n^{-2})$	$.351563$	$.087891$	$.021973$	$.005493$	$.001373$
	$O(n^{-3})$	-1.044922	$-.130615$	$-.016327$	$-.002041$	$-.000255$
	approx.	$-.7$	$-.04$	$.006$	$.0035$	$.00112$

$\lambda\, diag(1,0,\cdots,0)$ when $n=8$ or 16 in Table 7 are doubtful. From Tables 3 and 7, we can compute the rates of the reduction of the risks for $\hat{\Sigma}^{(2)}$ with respect to $\hat{\Sigma}_O^{(2)}$, which range above to 11% for $n\geqq 32$. This may be compared with 4% for $\hat{\Sigma}_H^{(2)}$. Comparing the rates for $\hat{\Sigma}^{(2)}$ with respect to $\hat{\Sigma}_H^{(2)}$, the range is given by $-0.2\%\sim 7\%$ for $n\geqq 32$ in Table 7. Also the rates for $\hat{\Sigma}^{(2)}$ with respect to $\hat{\Sigma}_{JS}^{(2)}$ range $-1.2\%\sim 8\%$ while the rates for $\hat{\Sigma}_H^{(2)}$ with respect to $\hat{\Sigma}_{JS}^{(2)}$ range only $-1.2\%\sim 0.8\%$ for $n\geqq 32$.

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