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Ingram Olkin, Friedrich Pukelsheim

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## The Distance between Two Random Vectors with Given Dispersion Matrices

I. Olkin

*Statistics Department*

*Sequoia Hall*

*Stanford University*

*Stanford, California 94305*

*and*

*Universität Freiburg im Breisgau*

*and*

F. Pukelsheim

*Institut für Mathematische Stochastik*

*Albert-Ludwigs-Universität*

*D-7800 Freiburg im Breisgau*

*Federal Republic of Germany*

### ABSTRACT

For two  $p$ -dimensional random vectors  $X$  and  $Y$  with dispersion matrices  $\Sigma_{11}$  and  $\Sigma_{22}$ , respectively, we determine that covariance matrix  $\Psi_0$  of  $X$  and  $Y$  that minimizes the  $L_2$ -distance between  $X$  and  $Y$ . There is a dual to this problem that is of interest in another context.

### 1. INTRODUCTION

Consider two  $p$ -variate normal distributions with zero means and positive definite dispersion matrices  $\Sigma_{11}$  and  $\Sigma_{22}$ . In the theory of strong approximations it is of interest to construct  $p$ -dimensional random vectors  $X$  and  $Y$  distributed according to  $N(0, \Sigma_{11})$  and  $N(0, \Sigma_{22})$ , respectively, such that the  $L_2$ -distance between  $X$  and  $Y$  is minimal.

Let

$$\Sigma = \begin{pmatrix} \Sigma_{11} & \Psi \\ \Psi' & \Sigma_{22} \end{pmatrix}$$

denote the dispersion matrix of  $(X, Y)$ . Then the problem is to minimize  $E \text{tr}(X - Y)'(X - Y) = \text{tr}(\Sigma_{11} + \Sigma_{22} - 2\Psi)$ . The restriction that  $\Sigma$  be nonnegative definite is equivalent to requiring that the Schur complement  $\Sigma_{11} - \Psi \Sigma_{22}^{-1} \Psi'$  be nonnegative definite. Consequently, under the assumption that  $\Sigma_{11} > 0, \Sigma_{22} > 0$ , the extremal problem becomes

$$\max_{\Sigma_{11} - \Psi \Sigma_{22}^{-1} \Psi' \geq 0} \text{tr} 2\Psi, \tag{1a}$$

where the Loewner ordering  $A \geq B$  ( $A > B$ ) means that  $A - B$  is nonnegative (positive) definite.

As a consequence of Theorem 3 we show that the problem (1) has a unique solution

$$\Psi_0 = \Sigma_{11} \Sigma_{22}^{1/2} (\Sigma_{22}^{1/2} \Sigma_{11} \Sigma_{22}^{1/2})^{-1/2} \Sigma_{22}^{1/2}, \tag{2}$$

where  $A^{1/2}$  denotes the unique positive definite square root of the positive definite matrix  $A$ .

When  $p = 1, \Psi_0 = \sqrt{\sigma_{11}\sigma_{22}}$ , so that the correlation between  $X$  and  $Y$  is 1. When  $\Sigma_{11}$  and  $\Sigma_{22}$  are diagonal,  $\Psi_0$  is diagonal, so that  $(X_1, Y_1), \dots, (X_p, Y_p)$  are independent bivariate random vectors that are perfectly correlated.

When  $X_1, \dots, X_p$  and  $Y_1, \dots, Y_p$  are equicorrelated with correlations  $\rho$  and  $\eta$ , respectively, then  $\Psi_0$  is a matrix with equal diagonal elements  $\psi_{ii} = a(\rho, \eta), i = 1, \dots, p$ , and equal off-diagonal elements  $\psi_{ij} = b(\rho, \eta), i \neq j = 1, \dots, p$ . The constants  $a(\rho, \eta)$  and  $b(\rho, \eta)$  are rather complicated functions of  $\rho$  and  $\eta$ .

We actually obtain a stronger result by assuming only nonnegative definiteness of  $\Sigma_{11}$  and  $\Sigma_{22}$ . This permits a comparison of random vectors  $X$  and  $Y$  of different lengths by appropriately including random variables degenerate at zero.

## 2. A DUALITY THEOREM

In another context Anderson and Olkin [1] consider the extremal problem

$$\min_{S > 0} \text{tr}(\Sigma_{11}S + \Sigma_{22}S^{-1}), \quad \Sigma_{11} > 0, \quad \Sigma_{22} > 0. \tag{1b}$$

It is interesting to note that the problems (1a) and (1b) are dual to each other. As a consequence we have a particularly simple way to investigate the optimal solutions. Since the set of matrices satisfying  $\Sigma_{11} - \Psi \Sigma_{22}^{-1} \Psi' \geq 0$  forms a convex set (see [2, p. 468]), the problem can also be considered from the more general programming theory as outlined in [3]. However, we need not use this route, since a direct argument establishes the duality.

Our first theorem shows the interplay of the problems (1a) and (1b). However, we first require the following lemma.

LEMMA 1. Let  $\Sigma_{11} \geq 0$ ,  $\Sigma_{22} \geq 0$ . Then

$$\Sigma \equiv \begin{pmatrix} \Sigma_{11} & \Psi \\ \Psi' & \Sigma_{22} \end{pmatrix} \geq 0$$

if and only if  $\Psi \in \Omega$ , where

$$\Omega = \{ \Psi : \Sigma_{22} \Sigma_{22}^- \Psi' = \Psi', \Sigma_{11} - \Psi \Sigma_{22}^- \Psi' \geq 0 \}, \quad (3)$$

and  $\Sigma_{22}^-$  is any generalized inverse of  $\Sigma_{22}$ .

*Proof.* For the direct part, assume  $\Sigma \geq 0$  and suppose the vector  $y$  is in the nullspace of  $\Sigma_{22}$ . Then letting  $\lambda \neq 0$  tend to zero in

$$0 \leq (\lambda x', \lambda^{-1} y) \Sigma (\lambda x, \lambda^{-1} y)' = \lambda^2 x' \Sigma_{11} x + 2x' \Psi y$$

proves that  $\Psi y = 0$ . Thus,  $\text{nullspace}(\Sigma_{22}) \subseteq \text{nullspace}(\Psi)$ , or equivalently,  $\text{range}(\Psi') \subseteq \text{range}(\Sigma_{22})$ , which in turn is equivalent to  $\Sigma_{22} \Sigma_{22}^- \Psi' = \Psi'$ .

The second property is implied by

$$0 \leq \begin{pmatrix} I & -\Psi \Sigma_{22}^- \\ 0 & I \end{pmatrix} \begin{pmatrix} \Sigma_{11} & \Psi \\ \Psi' & \Sigma_{22} \end{pmatrix} \begin{pmatrix} I & 0 \\ -\Sigma_{22}^- \Psi' & I \end{pmatrix} = \begin{pmatrix} \Sigma_{11} - \Psi \Sigma_{22}^- \Psi' & 0 \\ 0 & \Sigma_{22} \end{pmatrix}.$$

The converse part follows from

$$0 \leq \begin{pmatrix} I & \Psi \Sigma_{22}^- \\ 0 & I \end{pmatrix} \begin{pmatrix} \Sigma_{11} - \Psi \Sigma_{22}^- \Psi' & 0 \\ 0 & \Sigma_{22} \end{pmatrix} \begin{pmatrix} I & 0 \\ \Sigma_{22}^- \Psi' & I \end{pmatrix} = \Sigma. \quad \blacksquare$$

As a consequence of Lemma 1, under the weaker assumption  $\Sigma_{11}^- \geq 0$ ,  $\Sigma_{22} \geq 0$ , the problem (1a) generalizes to

$$\max_{\Psi \in \Omega} \text{tr} 2\Psi. \quad (1a')$$

THEOREM 2 (Matrix inequality). For  $\Psi \in \Omega$  and for an arbitrary  $p \times p$  matrix  $R$  with generalized inverse  $R^-$ ,

$$R' \Sigma_{11} R + R^- \Sigma_{22} (R^-)' \geq R' \Psi (R^-) + R^- \Psi' R, \quad (4)$$

with equality if and only if

$$R'(\Sigma_{11} - \Psi \Sigma_{22}^- \Psi')R = 0, \tag{5a}$$

$$R'\Psi = R^- \Sigma_{22}. \tag{5b}$$

*Proof.* Let  $G$  denote any generalized inverse of  $R$ . The inequality (4) follows from the nonnegative definiteness of

$$(R', -G) \begin{pmatrix} \Sigma_{11} & \Psi \\ \Psi' & \Sigma_{22} \end{pmatrix} \begin{pmatrix} R \\ -G' \end{pmatrix}.$$

To show the case of equality, let

$$T = R'\Psi(\Sigma_{22}^{1/2})^-.$$

Then equality in (4) holds if and only if equality holds in

$$\begin{aligned} R'\Sigma_{11}R + G\Sigma_{22}G' &\geq R'\Sigma_{11}R + G\Sigma_{22}G' - TT' \\ &= R'\Psi G' + G\Psi'R + R'(\Sigma_{11} - \Psi \Sigma_{22}^- \Psi')R \\ &\geq R'\Psi G' + G\Psi'R. \end{aligned}$$

In the case of equality, (5a) holds and  $T = 0$ , which is equivalent to (5b). ■

In order to connect Theorem 2 with the problem (1b), let  $S = RR'$  satisfy the condition  $\text{range}(\Sigma_{22}) \subseteq \text{range}(S)$ , that is,

$$SS^- \Sigma_{22} = \Sigma_{22},$$

where  $S^-$  is any generalized inverse of  $S$ . Accordingly, assuming merely  $\Sigma_{11} \geq 0, \Sigma_{22} \geq 0$ , we modify the problem (1b) to

$$\min_{s \in \mathfrak{S}} \text{tr}(\Sigma_{11}S + \Sigma_{22}S^-), \tag{1b'}$$

where

$$\mathfrak{S} = \{S : S \geq 0, SS^- \Sigma_{22} = \Sigma_{22}\}. \tag{6}$$

**COROLLARY 3 (Mutual boundedness).** *For all matrices  $\Psi \in \Omega$  and  $S \in \mathfrak{S}$ , the inequality*

$$\text{tr}(\Sigma_{11}S + \Sigma_{22}S^-) \geq \text{tr} 2\Psi \tag{7}$$

holds, with equality if and only if

$$S\Sigma_{11}S = \Sigma_{22} = S\Psi. \quad (8)$$

*Proof.* Fix  $S^-$  and  $S = RR'$ . Then  $G = R'S^-$  is a generalized inverse of  $R$ , and by (6),

$$\Sigma_{22}G'G = \Sigma_{22}S^-RR'S^- = \Sigma_{22}S^-SS^- = \Sigma_{22}S^-.$$

Hence, from (4)

$$\begin{aligned} \text{tr}(\Sigma_{11}S + \Sigma_{22}S^-) &= \text{tr}(\Sigma_{11}RR' + \Sigma_{22}G'G) \\ &\geq \text{tr}(\Psi G'R' + RG\Psi') = 2\text{tr}RG\Psi' = 2\text{tr}SS^-\Psi'. \end{aligned}$$

But, because  $\Psi \in \Omega$  and (6) holds,

$$\Psi' = \Sigma_{22}\Sigma_{22}^-\Psi' = SS^-\Sigma_{22}\Sigma_{22}^-\Psi' = SS^-\Psi'. \quad (9)$$

The condition (5b) implies that  $S\Psi = \Sigma_{22}$ , which when inserted in (5a) yields  $S\Sigma_{11}S = \Sigma_{22}$ . Thus equality in (7) forces (8), whereas the converse is immediate from (9). ■

From (8) it follows that equality in (7) holds only if  $\text{rank}(\Sigma_{22}) = \text{rank}(S\Sigma_{11}S) \leq \text{rank}(\Sigma_{11})$ . The rank assumption can be made without loss of generality; however, we require the slightly stronger assumption that  $\text{range}(\Sigma_{22}) \subseteq \text{range}(\Sigma_{11})$  in the following duality theorem.

**THEOREM 4 (Duality).** *If  $\text{range}(\Sigma_{22}) \subseteq \text{range}(\Sigma_{11})$  then the problems (1a') and (1b') share the same optimal value*

$$\max_{\Psi \in \Omega} \text{tr} 2\Psi = \min_{S \in \mathfrak{S}} \text{tr}(\Sigma_{11}S + \Sigma_{22}S^-) = 2\text{tr}(\Sigma_{22}^{1/2}\Sigma_{11}\Sigma_{22}^{1/2})^{1/2}, \quad (10)$$

with solutions

$$\Psi_0 = \Sigma_{11}\Sigma_{22}^{1/2} \left[ (\Sigma_{22}^{1/2}\Sigma_{11}\Sigma_{22}^{1/2})^{1/2} \right]^- \Sigma_{22}^{1/2} \equiv \Sigma_{11}S_0, \quad (11a)$$

$$S_0 = \Sigma_{22}^{1/2} \left[ (\Sigma_{22}^{1/2}\Sigma_{11}\Sigma_{22}^{1/2})^{1/2} \right]^- \Sigma_{22}^{1/2}. \quad (11b)$$

If  $\text{range}(\Sigma_{22}) = \text{range}(\Sigma_{11})$ , then  $\Psi_0$  is the unique solution of the problem (1a'), and  $S_0$  is the unique solution of problem (1b') that satisfies  $\text{range}(S_0) = \text{range}(\Sigma_{22})$ .

*Proof.* Because of the assumption  $\text{range}(\Sigma_{22}) \subseteq \text{range}(\Sigma_{11})$ , the matrices  $\Psi_0$  and  $S_0$  are invariant under the choice of the generalized inverse  $\left[ \left( \Sigma_{22}^{1/2} \Sigma_{11} \Sigma_{22}^{1/2} \right)^{1/2} \right]^{-}$ . The matrices  $\Psi_0$  and  $S_0$  defined by (11) are clearly feasible for the problems (1a') and (1b') and satisfy (8), thus proving (10).

To establish uniqueness, an argument similar to that in the proof of Lemma 1 shows that any  $\Psi \in \Omega$  satisfies  $\text{range}(\Psi) \subseteq \text{range}(\Sigma_{11})$ . Hence, if  $\text{range}(\Sigma_{11}) = \text{range}(\Sigma_{22})$  and  $S \in \tilde{S}$ , then  $\text{range}(\Psi) \subseteq \text{range}(S)$ , and  $SS^{-}\Psi = \Psi$ . In particular, from (8), any two optimal solutions  $\Psi_0$  and  $\tilde{\Psi}_0$  of problem (1') satisfy  $S_0\Psi_0 = \Sigma_{22} = S_0\tilde{\Psi}_0$ , which yields

$$\Psi_0 = S_0 S_0^{-} \Psi_0 = S_0^{-} S_0 \Psi_0 = S_0^{-} \Sigma_{22} = S_0^{-} S_0 \tilde{\Psi}_0 = S_0 S_0^{-} \tilde{\Psi}_0 = \tilde{\Psi}_0.$$

Finally, any two optimal solutions  $S_0$  and  $\tilde{S}_0$  of (1b') satisfy  $S_0\Psi_0 = \Sigma_{22} = \tilde{S}_0\Psi_0$ . Suppose, in addition, that  $\text{range}(S_0) = \text{range}(\tilde{S}_0) = \text{range}(\Sigma_{22})$ . From the above we have that  $\text{range}(\Psi) \subseteq \text{range}(\Sigma_{22})$ , whereas (8) implies that  $\text{rank}(\Sigma_{22}) \leq \text{rank}(\Psi)$ . Thus,  $\text{range}(\Sigma_{22}) = \text{range}(\Psi_0)$ , and

$$S_0 = S_0\Psi\Psi_0^{-} = \Sigma_{22}\Psi_0^{-} = \tilde{S}_0\Psi_0\Psi_0^{-} = \tilde{S}_0. \quad \blacksquare$$

**NOTE.** If  $z \perp \text{range}(\Sigma_{22}) = \text{range}(\Sigma_{11})$ , then  $S_0 + zz'$  also satisfies (8), and hence is also optimal, which shows that the condition  $\text{range}(S_0) = \text{range}(\Sigma_{22})$  cannot be relaxed.

**REMARK.** When  $\text{range}(\Sigma_{11}) = \text{range}(\Sigma_{22})$ , the problem (1a') can also be formulated with the Schur complement  $\Sigma_{22} - \Psi'\Sigma_{11}^{-}\Psi$ . Accordingly, an alternative representation of its unique optimal solution is

$$\Psi'_0 = \Sigma_{22} \Sigma_{11}^{1/2} \left[ \left( \Sigma_{11}^{1/2} \Sigma_{22} \Sigma_{11}^{1/2} \right)^{1/2} \right]^{-} \Sigma_{11}^{1/2}.$$

If  $\lambda_1(A), \dots, \lambda_p(A)$  denote the characteristic roots of  $A$ , then the optimal value (9) becomes

$$\begin{aligned} 2 \text{tr} \left( \Sigma_{22}^{1/2} \Sigma_{11} \Sigma_{22}^{1/2} \right)^{1/2} &= 2 \sum_1^p \lambda_i \left[ \left( \Sigma_{22}^{1/2} \Sigma_{11} \Sigma_{22}^{1/2} \right)^{1/2} \right] \\ &= 2 \sum_1^p \lambda_i^{1/2} \left( \Sigma_{22}^{1/2} \Sigma_{11} \Sigma_{22}^{1/2} \right) = 2 \sum_1^p \lambda_i^{1/2} (\Sigma_{11} \Sigma_{22}), \end{aligned}$$

which provides a more symmetric expression in  $\Sigma_{11}$  and  $\Sigma_{22}$ .

*Note added in proof.* During the proof stage the authors note the appearance of a paper dealing with the same problem, though motivated from a slightly different point of view. The reference is D. C. Dowson and B. V. Landau, the Fréchet distance between multivariate normal distributions, *J. Multivariate Anal.* 12:450–455 (1982).

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