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Conditional Means and Covariances
of Normal Variables with
Singular Covariance Matrix

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CONDITIONAL MEANS AND COVARIANCES OF NORMAL
VARIABLES WITH SINGULAR COVARIANCE MATRIX

by

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Let (ξ, η) be a partitioned zero mean normal random vector with covariance matrix $\begin{pmatrix} A & B' \\ B & C \end{pmatrix}$ where $\text{cov}(\xi) = A$ and $\text{cov}(\eta) = C$, with $\text{cov}(\)$ meaning the covariance matrix of the random vector enclosed. The usual way of getting the conditional mean and covariance matrix of ξ , given that $\eta = \beta$, is to divide the joint density of ξ and η by that of η . The following is an alternative method which is more general, in that it does not require that ξ and η have a joint density, or even that η have a density.

This is the result we want to prove: The conditional mean and covariance of ξ , given that $\eta = \beta$, are

$$E(\xi|\eta = \beta) = \beta C^+ B, \quad \text{cov}(\xi|\eta = \beta) = A - B' C^+ B$$

where C^+ is the pseudoinverse of C , that is, if $C = T'T$ with T $r \times m$ of rank r , then $C^+ = T'(TT')^{-2}T$. If C^{-1} exists, then $C^+ = C^{-1}$. The pseudoinverse of a symmetric matrix, although perhaps not under that name, is well known and has been used in statistics for some time. For a recent discussion and references, see [1].

Let $E = T'(TT')^{-1}T = C^+C = CC^+$ be the projector of the row space of C . Note that $CE = C$, and hence for any matrix F whose rows are in the row space of C , $FE = F$. In particular, B' in the covariance matrix above satisfies $B'E = B'$, since the rows of B' are in the row space of C . (The general covariance matrix

may be assumed to have the form $\begin{pmatrix} S' \\ U' \end{pmatrix} (SU) = \begin{pmatrix} S'S & S'U \\ U'S & U'U \end{pmatrix}$, and the row space of $S'U$ lies in the row space of U , which has the same row space as $U'U$.)

We will derive the formulas for conditional mean and covariance of ξ , given $\eta = \beta$, by representing ξ in such a way that it is obvious what conditioning on η means. We need only the fact that the sum of two normal random vectors is normal, and that if η has covariance C , then ηM has covariance $M'CM$. Let ζ be a zero mean normal random vector which is independent of η and which has covariance $A - B'C^+B$. (This is a valid covariance matrix, for example, that of $\xi - \eta C^+B$.) Then $\xi = \zeta + \eta C^+B$ is our representation for ξ , since the covariance matrix of $(\xi, \eta) = (\zeta, \eta) \begin{pmatrix} I & 0 \\ C^+B & I \end{pmatrix}$ is

$$\begin{pmatrix} I & B'C^+ \\ 0 & I \end{pmatrix} \begin{pmatrix} A - B'C^+B & 0 \\ 0 & C \end{pmatrix} \begin{pmatrix} I & 0 \\ C^+B & I \end{pmatrix} = \begin{pmatrix} A & B' \\ B & C \end{pmatrix}.$$

Since ζ and η are independent, it is obvious that the conditional mean of $\zeta + \eta C^+B$, given that $\eta = \beta$, is βC^+B , and that the conditional covariance is that of ζ . Hence our general result: If (ξ, η) is a zero mean normal vector with $\text{cov}(\xi, \eta) = \begin{pmatrix} A & B' \\ B & C \end{pmatrix}$, $\text{cov}(\xi) = A$, and $\text{cov}(\eta) = C$, then the expected value and covariance of ξ , given that $\eta = \beta$, are

$$E(\xi | \eta = \beta) = \beta C^+B, \quad \text{cov}(\xi | \eta = \beta) = A - B'C^+B$$

where C^+ is the pseudoinverse of C , that is, $C^+ = C^{-1}$ if C^{-1} exists, otherwise, if $C = T'T$ with T $r \times m$ of rank r , then $C^+ = T'(TT')^{-2}T$.

REFERENCE

- [1] Greville, T. N. E. The pseudoinverse of a rectangular or singular matrix and its application to the solution of systems of linear equations. SIAM Review, Vol. 1, No. 1, January 1959, p. 38-43.