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TWO-POINT CORRELATIONS OF SOUND PRESSURE IN THE FAR FIELD OF A JET: EXPERIMENT

By

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16. Abstract
Correlations of sound pressure between two microphones yield substantially more information than single microphone data; hence, they provide useful information about the nature and behavior of jet noise sources as a basis for theory development. The mapping of the space-time correlations of the pressure over a distant sphere enclosing a subsonic jet revealed a number of previously unaccounted for features essential for the interpretation of the radiation field and for the modeling of the flow field.

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TWO-POINT CORRELATIONS OF SOUND PRESSURE IN THE FAR FIELD OF A JET: EXPERIMENT

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INTRODUCTION

It is well known that present day turbulence measurements in subsonic jets are not detailed enough to give an accurate description of their noise sources. For noise prediction purposes one could start from far-field microphone measurements and deduce the equivalent acoustic sources in the jet. This procedure involves the solution of the so-called "inverse problem" and requires a knowledge of the correlations everywhere about the jet. The present investigation is aimed at providing these measurements which represent a continuation of those carried out at NASA Langley Research Center on a plane near the jet, references 1 and 2. Two-point space-time correlations of sound pressure about a far-field sphere surrounding the jet can clearly provide much more information than single microphone data. Also accurate information on the statistical outflow of acoustic energy from the sources in the jet can be extracted from such measurements. In addition, two-point correlations provide certain information concerning integral relationships of the sources in the jet, as a function of angles and time delay.

Surprisingly, this type of data has not been published in the literature with the exception of references 1 and 2. In the previous work it was pointed out from the analysis of a large body of experimental data on the space-time correlation of pressure gradients on an ideal plane near the jet, that the sound emanating from the flow is in the form of narrow beams. This kind of understanding could not be obtained from single microphone measurements alone. Present day jet noise theories invariably aim solely at the prediction of far-field noise directivity and spectrum, namely, $\overline{p^2}$ (θ, ϕ, f). This quantity can be measured by means of a single microphone. However, to gain knowledge of the sound wave patterns and noise source mechanisms through flow modeling or by the "inverse problem" the phase of the emitted noise from the jet is also required. This phase is lost in single-point pressure measurements. To perserve this information two-point space-time correlation data are indispensable.

The main objective of this presentation is to report on a set of experimental far-field cross correlation measurements from a subsonic axially symmetric jet. These measurements are taken over a large imaginary sphere surrounding the jet flow. Interpretation of the variation of the amplitude and phase of the measured data will be provided. Starting from Lighthill theory, certain integral representations of the cross correlation of the individual quadrupole field are described in the appendix. However, the actual evaluation of the source field from these equations must be done numerically. This work will be reported in detail at a later date.

Professor H. S. Ribner will present a companion paper at this meeting, his paper contains an alternative analytical treatment of far-field two-point cross correlation functions based on an extension of his original theory (ref. 3). He will also compare his theory with the measured data of this paper.

DESCRIPTION OF THE MEASUREMENTS

Two-point space-time correlation measurements were made inside an anechoic chamber about a sphere of radius $R = 4.389$ m with microphones located at (R, θ_1, ϕ_1) and (R, θ_2, ϕ_2) respectively, in spherical polar coordinates. Figure 1 shows the geometry of the far-field measurements. The jet was directed along the polar axis $(\theta = 0)$ with the nozzle at the origin. Two-point space-time correlations were carried out under the following conditions: (1) $\phi_1 = 0°$; $0 \leq \phi_2 \leq 180°$; $\theta_1 = \theta_2 = 30°$, 45°, 60°, 90°, 120°, and 135°; (2) $\phi_1 = \phi_2 = 0°$; $0 \leq \theta_2 \leq 180°$; $\theta_1 = 0°$, 30°, 45°, 60°, 90°, 120°, and 135°. Jet nozzles are standard convergent types with diameters D of 2.54 cm, 5.08 cm, and 7.62 cm operating over a range of velocities from 201.3 to 356.1 m/sec. The R/D ratio was 166 for the 2.54 cm jet. The jet temperature was ambient. Nineteen carefully phase-matched microphones were employed (1.27 cm in diameter condenser types). The array was designed such that the microphone distances were accurately controlled. The acoustic pressure was recorded on FM magnetic tape recorders within the band between 125 Hz to 40 KHz. The cross correlation and one-third octave band data were obtained by analog means through a playback system.

RESULTS AND DISCUSSION

The set of experimental results reported in the paper are taken at velocity $V = 252.3$ m/sec with a 2.54 cm diameter jet (R/D = 169). The broadband space-time correlations about the azimuthal angles were taken with $\phi_1 = 0$ while ϕ_2 varied from 0 to 180° (see fig. 1) and $\theta_1 = \theta_2$ were fixed at 30°, 60°, 90°, 125°, and 135°, respectively.

Typical plots of the broadband space-time correlations $R_{pp}(\theta_1, \theta_2, \phi_1, \phi_2, \tau)$ at $\theta_1 = \theta_2 = 30°$ and $60°$ are shown in figures 2 and 3. In addition, the variation of the normalized peak correlation at these angles $R_{pp}(\phi_1, \phi_2, \phi_1, \phi_2, \tau)/R_{pp}|_{\tau = \tau_{max}}$ as a function of ϕ_2 are shown in figures 4 and 5. Lastly, figures 6 and 7 display, in a polar plot, the peak correlations at all the measured azimuth angles. These figures, as well as results of a large body of data not shown here but including those taken at different nozzle diameters, reveal at least three important features:

1. The aximuthal cross correlation is positive and peaks at zero time delay when taken at small angles from the jet axis, i.e., $\theta \leq 30°$.
2. For measurements taken at angles at $\theta > 45°$ and at large separation distances, the azimuthal cross correlation shows also a negative peak which occurs at a finite time delay.
3. The polar plots of these correlations show a definite cusp at the origin, $\phi_1 = \phi_2 = 0$, unlike the polar plots for $\overline{p^2}$. These measurements do not identify any particular type of quadrupole as being predominant. The resulting broadband field is predominantly monodirectional.

Only a preliminary interpretation of the data is given here. Detailed discussions of the implications of the results of these measurements on the nature of the jet noise sources, especially with regard to being large and coherent versus localized and random, compact or noncompact, quadrupole, dipole or monopole in character, will be presented in a final report at a later date. However, the existence of the negative peak in the azimuthal cross correlation (fig. 3) is evidence against the presence of sources which emit noise coherently all around the jet. Large-scale sources, however, are found to be moderately correlated around the jet at small angles from the jet axis (fig. 2). The existence of a negative peak correlation is an indication that the sources are noncoherent and noncompact. For the example of figure 5, reducing the bandwidth of the cross correlation from 125 Hz - 40 KHz, to 125 Hz - 5 KHz increases the negative peak correlation approximately three times. This is evidence indicating that a model of moving random and incoherent (azimuthally) sources is compatible with present observations. Figure 4 also shows the variation of the peak correlation with velocity. For large separations the peak correlation decreases with jet velocity.

The above conclusions are consistent with the real-time pressure measurements from circular and longitudinal arrays of microphones placed near the boundary of the jet, reference 4. These results show that the real-time pressure fluctuations are not observed to occur simultaneously around the circumference of the jet, and that the dominant period of these fluctuations changes significantly with distance downstream. A similar conclusion was made from the cross correlation measurements on a plane near the jet of references 1 and 2.

In the case of the vertical plane, the correlation related to the jet axis is sensitive to the effects of convection, refraction, scattering, and source distribution. These effects cause the peak correlation to occur at other than zero time delay. These results are illustrated in figure 8, taken with the fixed microphone at $\theta_1 = 30°$. This behavior is typical of all other angles. Peak correlation is found in the negative time delay region between 30° to 60° and in the positive time delay region between 0° and 30°. These results are clear evidence that the convection velocity of the flow plays an important part in the shifting of the peak correlations. Although not shown here, data measured at different jet velocities essentially substantiate this contention. In addition, the envelope of the correlation maxima does not depart significantly from the decay predicted by convection only. Source distribution, refraction, etc., also play their role in this shift. One can conclude that the sources of sound in the jet are well embedded in the flow. The correlation maxima in the region of positive time delay is caused by the interaction of sound with the stream direction of flow. The same effects are observed in the negative time delay, that is for angles greater than 30°.

Figures 9 and 10 show the variation of the normalized peak correlation with the angle θ_2 for the fixed microphone positions $\theta_1 = 30°$, 60°, 90°, 120°, and 135°. It was necessary to perform the correlation over a 360° arc because the radiation field is not symmetrical about the reference microphone. At $\theta_1 = 30°$ for example, one can observe two peaks, one at $\theta_2 = \theta_1$ and another at $\theta_2 = -\theta_1$. These figures also show a region of negative peak correlation similar to those obtained in the azimuthal plane at large separation distances. In addition, since correlations of the vertical plane with $\theta_1 = -\theta_2$ correspond to the correlation in the azimuthal plane at the 180° position, the two different sets of independent experimental measurements provide a good comparative reference to check the quality of the data.

CONCLUDING REMARKS

Measurements of the space-time correlations over an imaginary far-field sphere revealed a number of new features of the nature and behavior of subsonic jet noise sources. They show that sound radiated at small angles from the jet axis is probably generated by coherent sources while at large angles and at large separation distances for which the correlations are negative with finite time delay, the noise sources are most likely incoherent. This suggest that the turbulence structure of the jet is more coherent downstream than near the nozzle exit. The results of the present measurements can be used to describe the equivalent source distributions in a medium at rest by using the well-known radiation relationship between noise sources and far-field pressure cross correlations. This information is essential for the modeling of the jet acoustic source distribution. An analytical formulation of these relationships is briefly outlined in the appendix. The complete experimental and analytical investigation of this problem will be reported subsequently.

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4. Liu, C. H.; Maestrello, L.; and Gunzburger, M. D.: Simulation by Vortex Rings of the Unsteady Pressure Field Near a Jet. AIAA Paper No. 75-438, Second Aeroacoustics Conference, March 1975.

APPENDIX

THEORETICAL CONSIDERATION

Using Lighthill's theory one can identify the acoustic sources in a uniform medium at rest utilizing far-field cross correlation measurements. The present measurements contain new information not available from the usual point measurements in regard to noise generation and radiation. By making use of these measurements one can obtain a certain integral representation for each quadrupole source in terms of the angular dependence θ and ϕ and the time delay τ within the Lighthill theory.

Starting from Lighthill's theory one can derive the following far-field cross correlation. Using standard notation one can show that:

$$R_{pp}(\vec{x}_1, \vec{x}_2, \tau) = \frac{x_i x_j x_k x_1}{16\,\pi^2 \rho_o c_o^5 |x_1|^3 |x_2|^3} \iint \overline{Q}_{ijkl}\left(\vec{y}', \vec{y}'', \tau + \frac{\hat{x}_1 \cdot \vec{y}' - \hat{x}_2 \cdot \vec{y}''}{c_o}\right) d\vec{y}' d\vec{y}'' \qquad (1A)$$

where

$$\overline{Q}_{ijk\rho} = \overline{\frac{\partial^2}{\partial t^2} T_{ij}\left(\vec{y}', t - \frac{|x|}{c_o} + \frac{\hat{x}_1 \cdot \vec{y}'}{c_o}\right) \frac{\partial^2}{\partial t^2} T_{kl}\left(\vec{y}'', t + \tau - \frac{|x|}{c_o} + \frac{\hat{x}_2 \cdot \vec{y}''}{c_o}\right)}$$

$$\frac{\partial^4}{\partial \tau^4} \overline{P}_{ijkl}\left(\vec{y}', \vec{y}'', \tau + \frac{\hat{x}_1 \cdot \vec{y}' - \hat{x}_2 \cdot \vec{y}''}{c_o}\right)$$

Expanding $\overline{Q}_{ijkl}$ in a Taylor series of τ with respect to $\tau = 0$ one obtains:

$$\overline{Q}_{ijkl} = \overline{Q}_{ijkl}(\vec{y}', \vec{y}'', 0)$$

$$+ \dot{\overline{Q}}_{ijkl}(\vec{y}', \vec{y}'', 0)\,[\tau + \frac{\hat{x}_1 \cdot \vec{y}' - \hat{x}_2 \cdot \vec{y}''}{c_o}] \qquad (2A)$$

$$+ \frac{1}{2}\ddot{\overline{Q}}_{ijkl}(y', y'', 0)\,[\tau + \frac{\hat{x}_1 \cdot \vec{y}' - \hat{x}_2 \cdot \vec{y}''}{c_o}]^2$$

The vector product $\hat{x} \cdot \vec{y}$ can be expanded into spherical polar coordinates and by substituting (2A) into (1A) one can obtain:

$$\overline{Q}_{ijkl}(y', y'', \tau + \frac{\hat{x}_1 \cdot \vec{y}' - \hat{x}_2 \cdot \vec{y}''}{c_o})dy'dy''$$

$$= C_{ijkl} + \dot{C}_{ijkl}\,\tau + \dot{C}^{11}_{ijkl}\cos\theta_1 + \dot{C}^{12}_{ijkl}\sin\theta_1$$

$$+ \dot{C}^{21}_{ijkl}\cos\theta_2 + \dot{C}^{22}_{ijkl}\sin\theta_2\cos\phi_2 + \dot{C}^{23}_{ijkl}\sin\theta_2\sin\phi_2$$

$$+ \frac{1}{2}\{\tau^2\ddot{C}_{ijkl} + 2\tau\ddot{C}^{11}_{ijkl}\cos\theta_1 + 2\tau\ddot{C}^{12}_{ijkl}\sin\theta_1 \;\ldots.\} \qquad (3A)$$

where

$$C_{ijkl} = \iint \overline{Q}_{ijkl}(\vec{y}', \vec{y}'', 0)d\vec{y}'d\vec{y}''$$

$$\dot{C}_{ijkl} = \iint \dot{\overline{Q}}(\vec{y}', \vec{y}'', 0)d\vec{y}'d\vec{y}''$$

$$\dot{C}^{im}_{ijkl} = \iint \dot{\overline{Q}}(\vec{y}', \vec{y}'', 0)y'_m\, d\vec{y}'d\vec{y}''/c_o \qquad m = 1, 2$$

etc.

Combining equation (1A) and (3A) and using the measurement of cross correlation (R_{pp}) one obtains a linear algebraic system. The problem now is solvable in terms of the angular distribution and time delay. Since the inversion must be done numerically, for simplicity, one can chose an angle, i.e., $\theta_1 = \theta_2 = 90°$. Then for an axially symmetric jet $\phi_1 = 0$ and $\phi_2 = \phi$. Due to symmetry of the jet it is possible to define only 18 types of basic directivity quadrupole, out of a possible 81 types. Furthermore, at the 90° angle only three types of quadrupoles contribute, namely:

$$2\ 2\ 2\ 2 \rightarrow \cos^2\phi$$

$$2\ 2\ 2\ 3 \rightarrow \cos\phi \sin\phi$$

$$2\ 2\ 3\ 3 \rightarrow \sin^2\phi$$

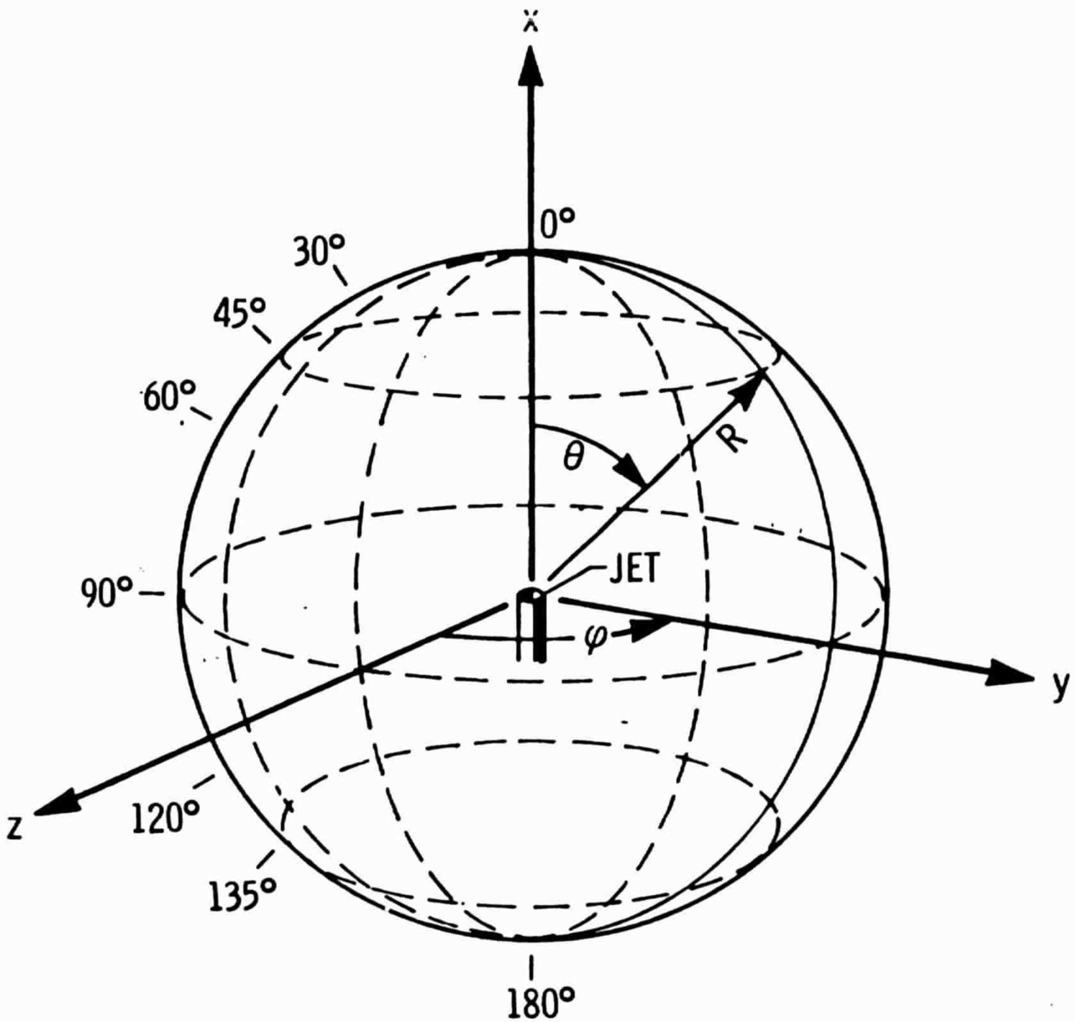

Figure 1. Geometry of the Far-Field Cross Correlation

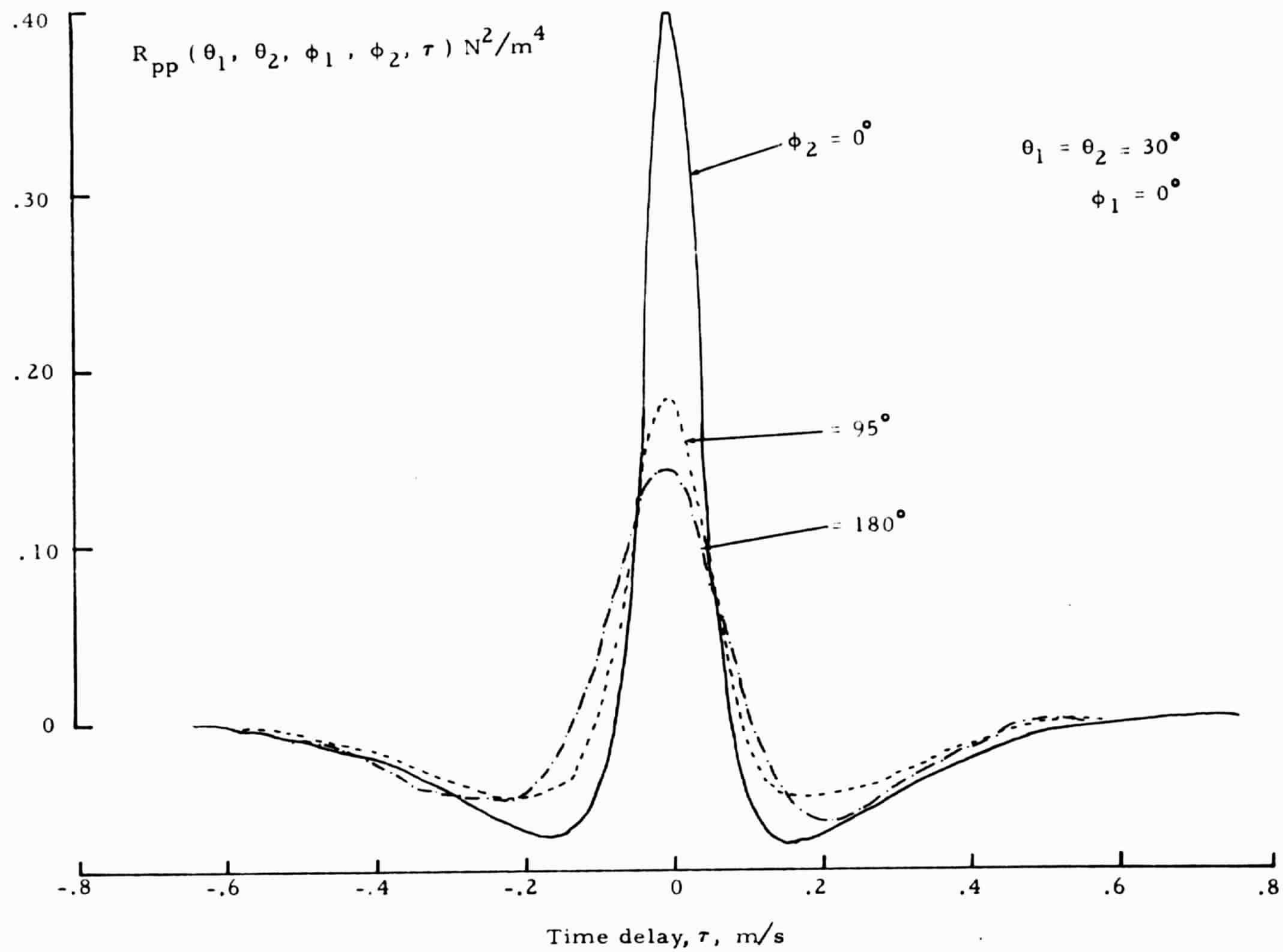

Figure 2.- Broadband Far-Field Space-Time Correlation

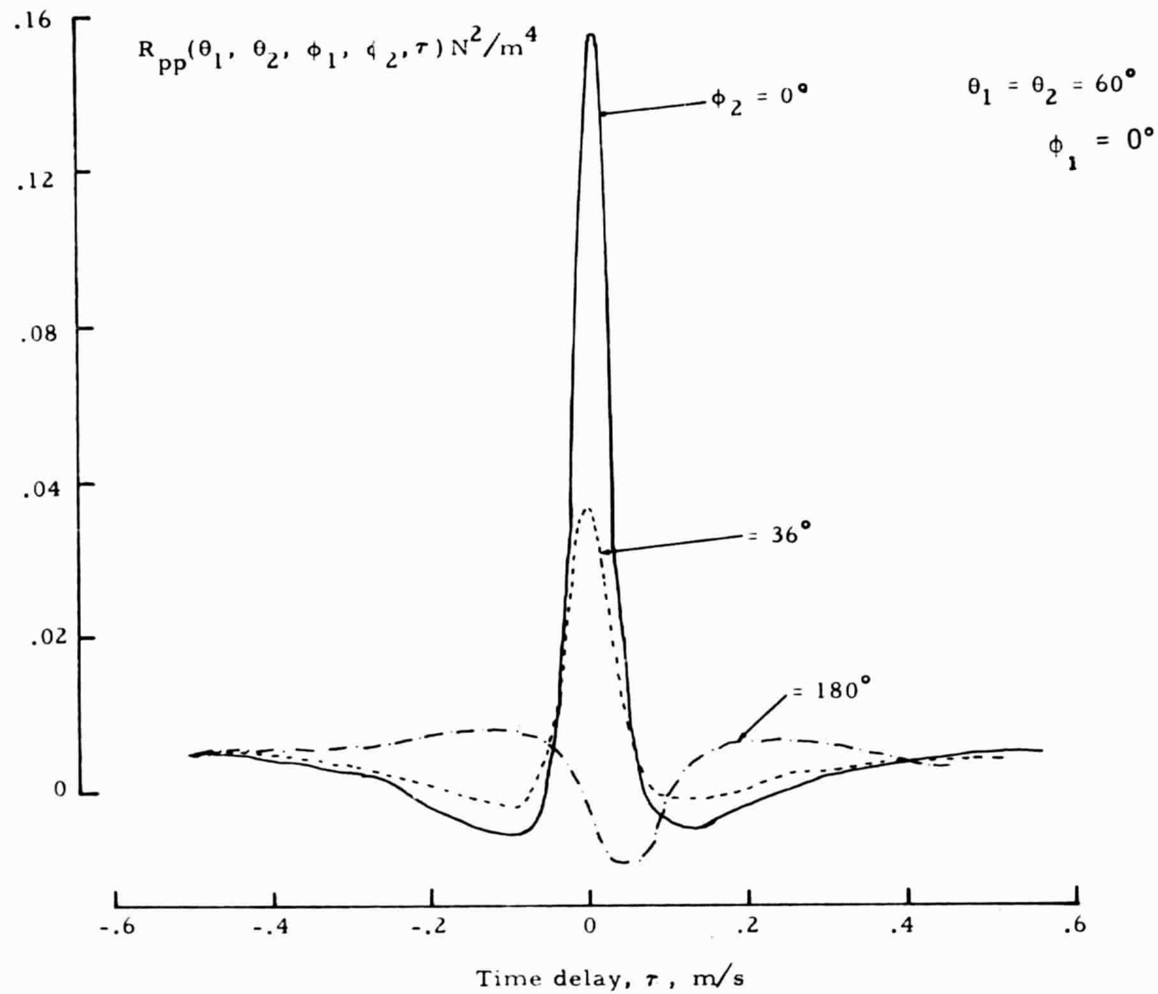

Figure 3. Broadband Far-Field Space-Time Correlation

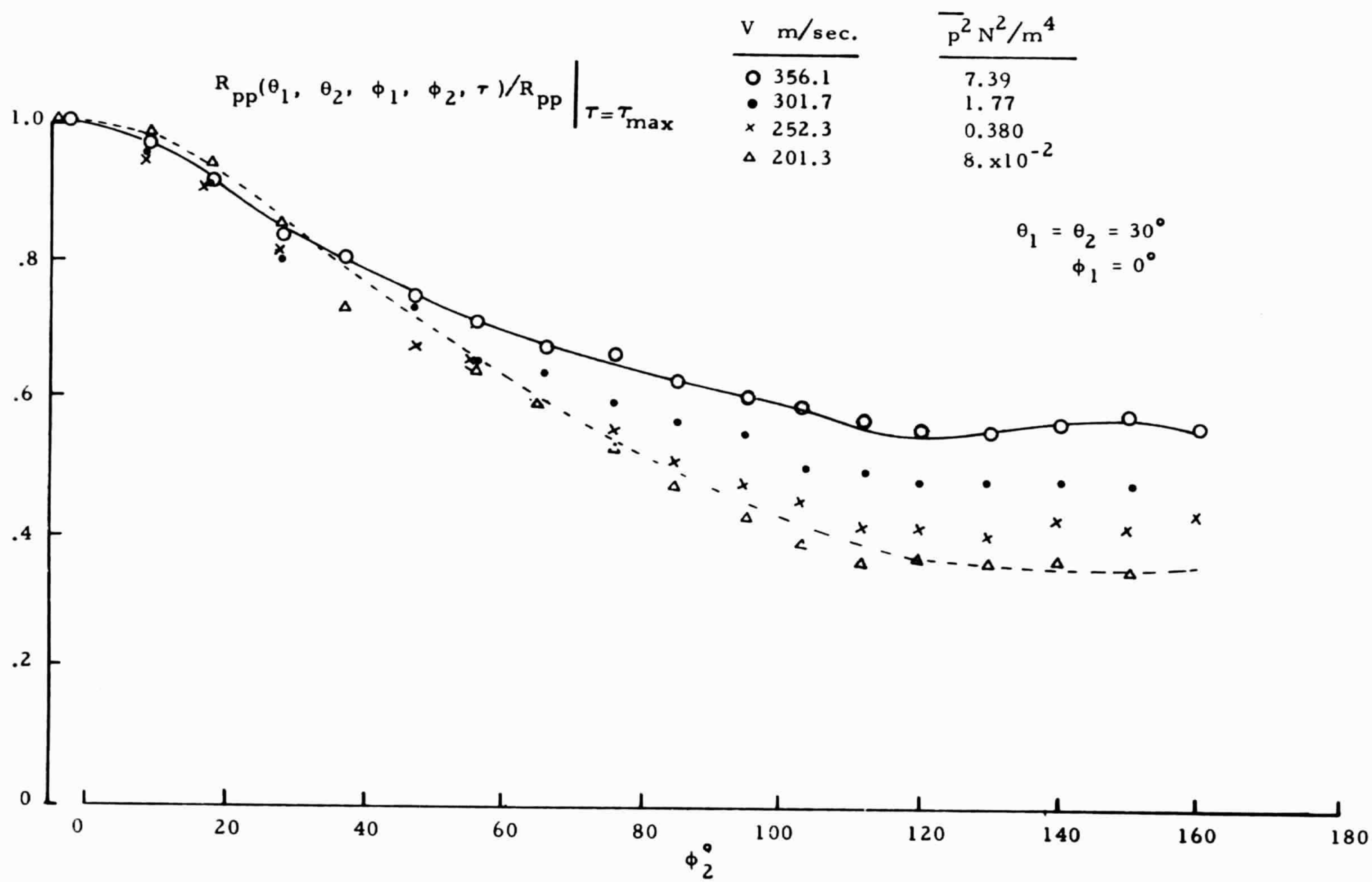

Figure 4. Normalized Cross Plot Peak Correlation

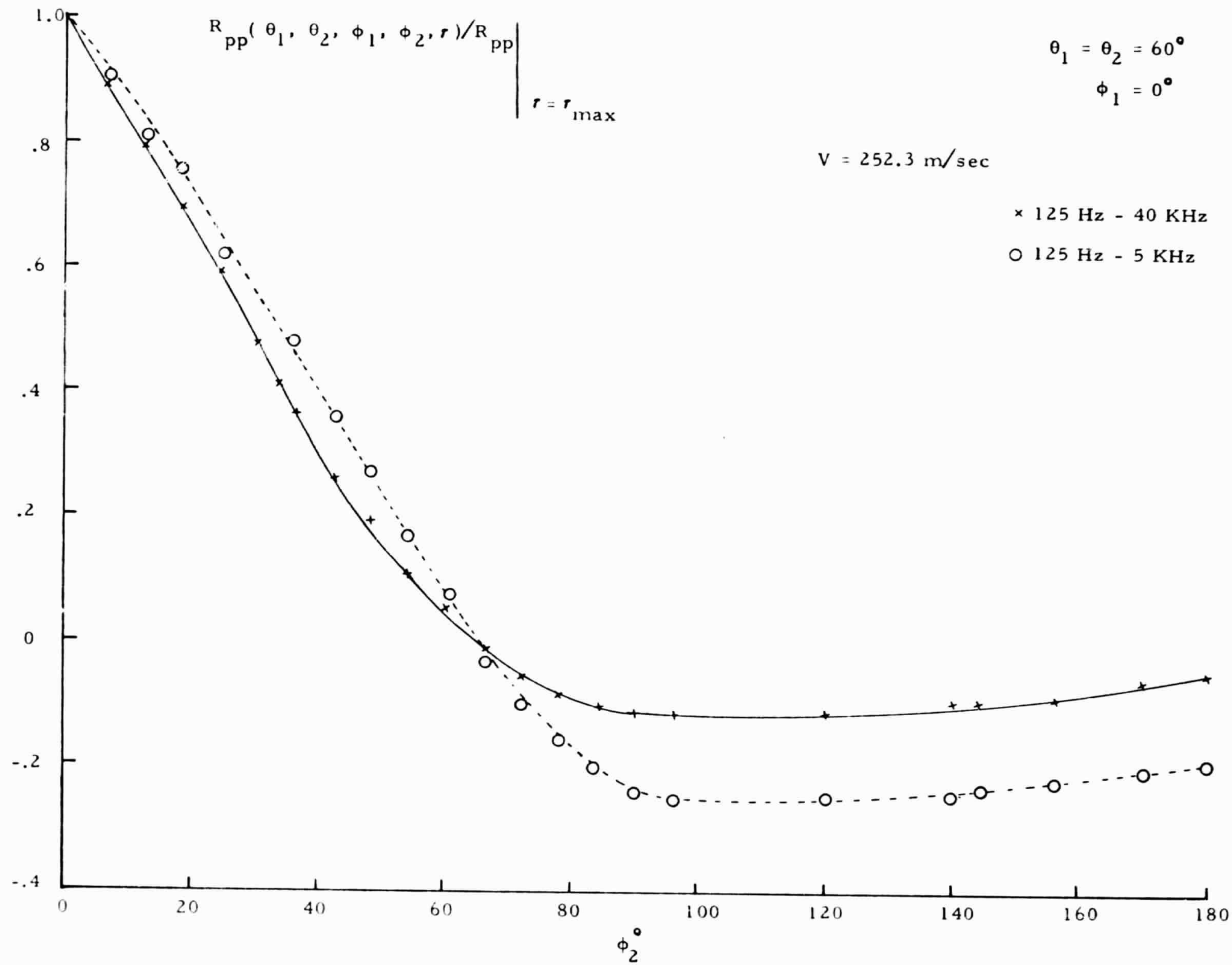

Figure 5. Normalized Cross Plot Peak Correlation

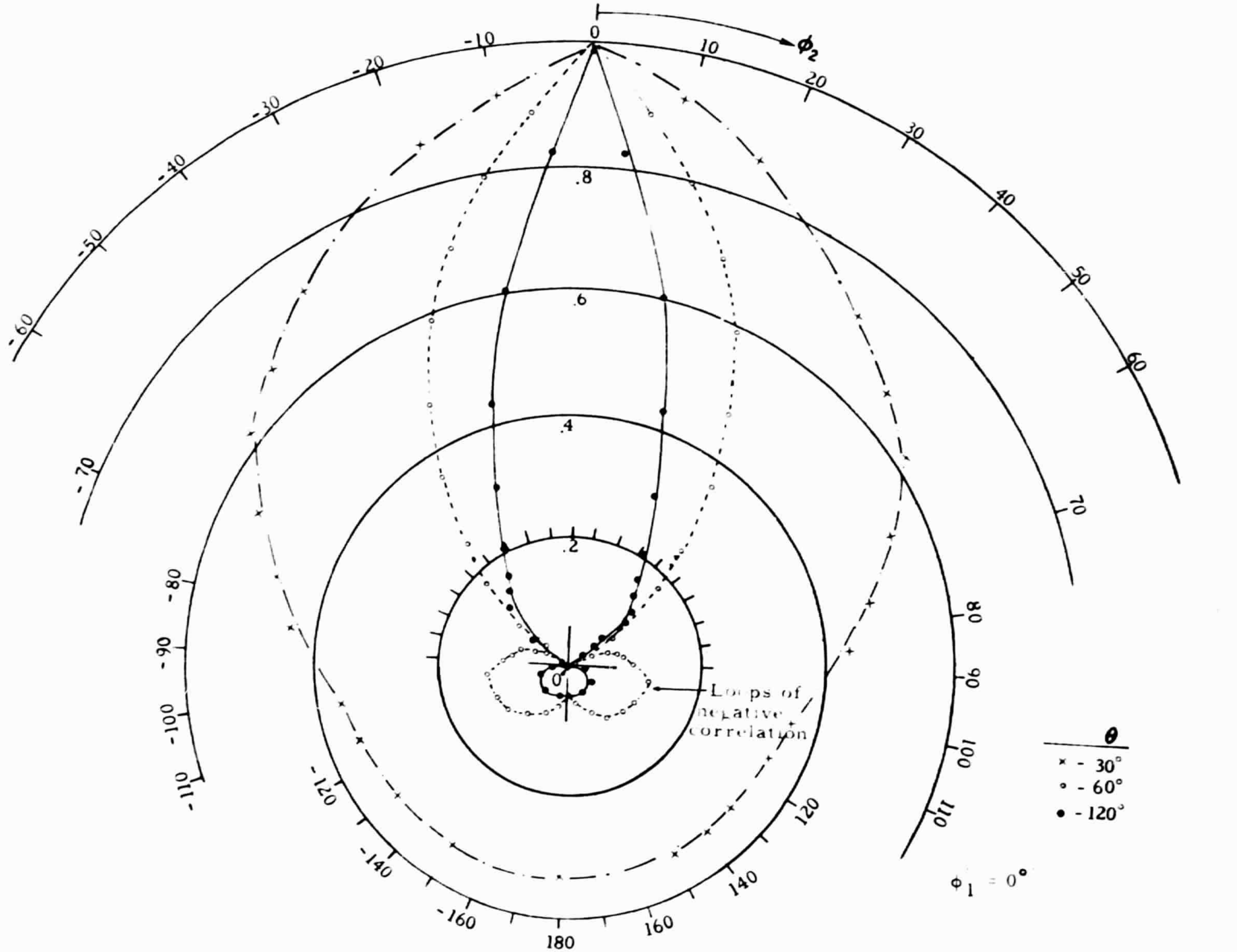

Figure 6. Polar Plot of the Normalized Peak Correlation $R_{pp}(\theta_1, \theta_2, \phi_1, \phi_2, \tau)/R_{pp}\big|_{\tau=\tau_{max}}$

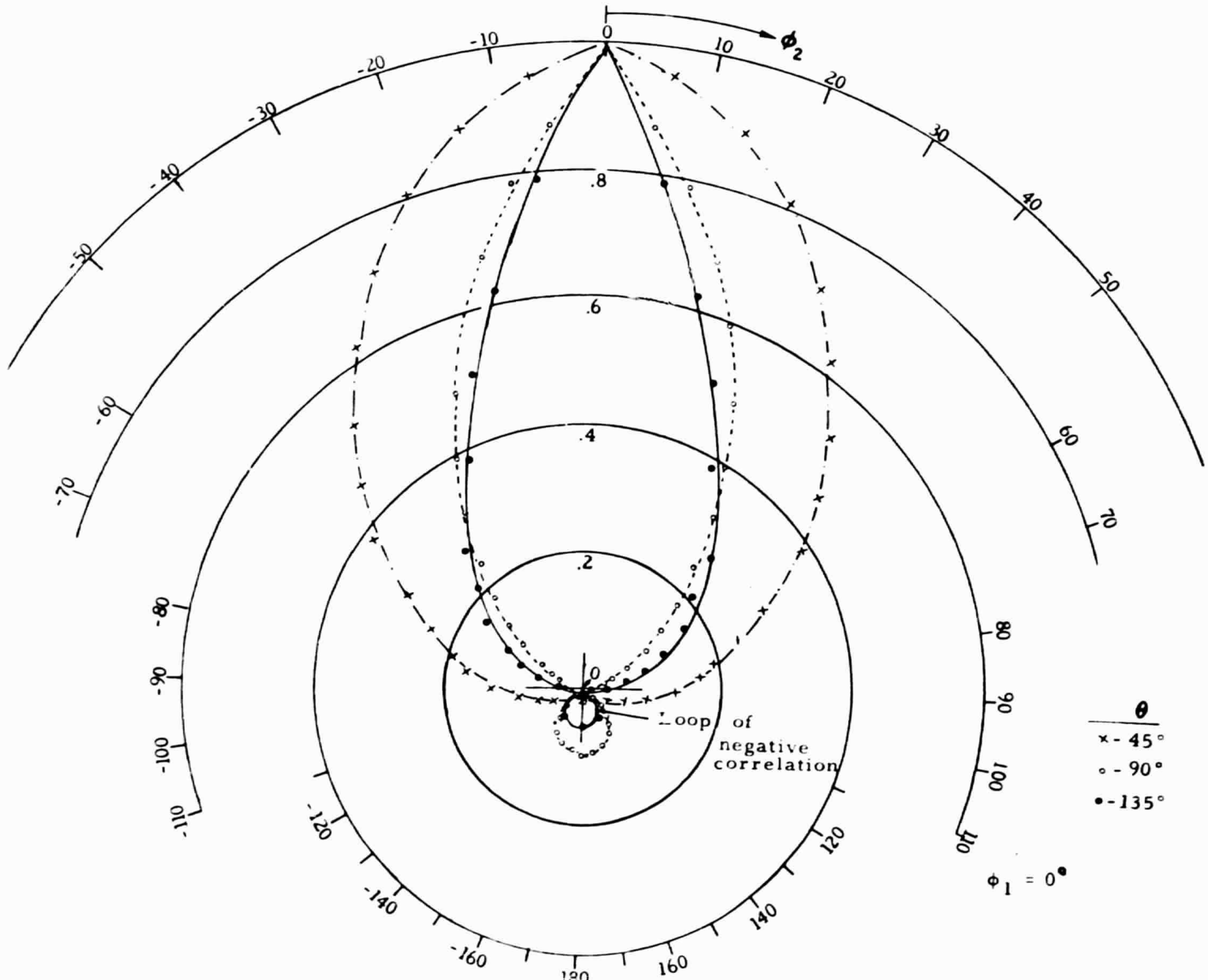

Figure 7. Polar Plot of the Normalized Peak Correlation $R_{pp}(\theta_1, \theta_2, \phi_1, \phi_2, \tau)/R_{pp}\Big|_{\tau=\tau_{max}}$

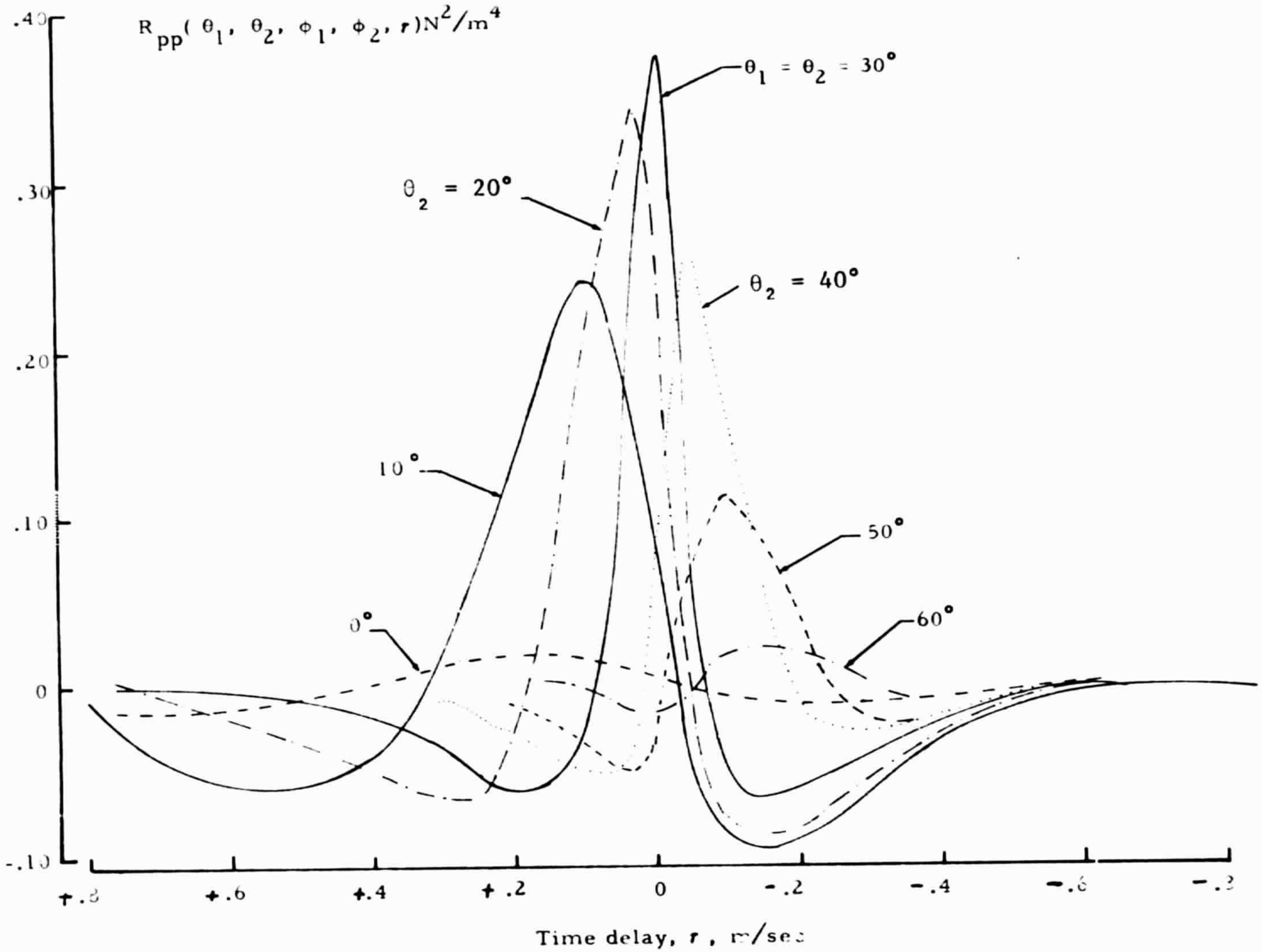

Figure 8. Broadband Space-Time Correlation

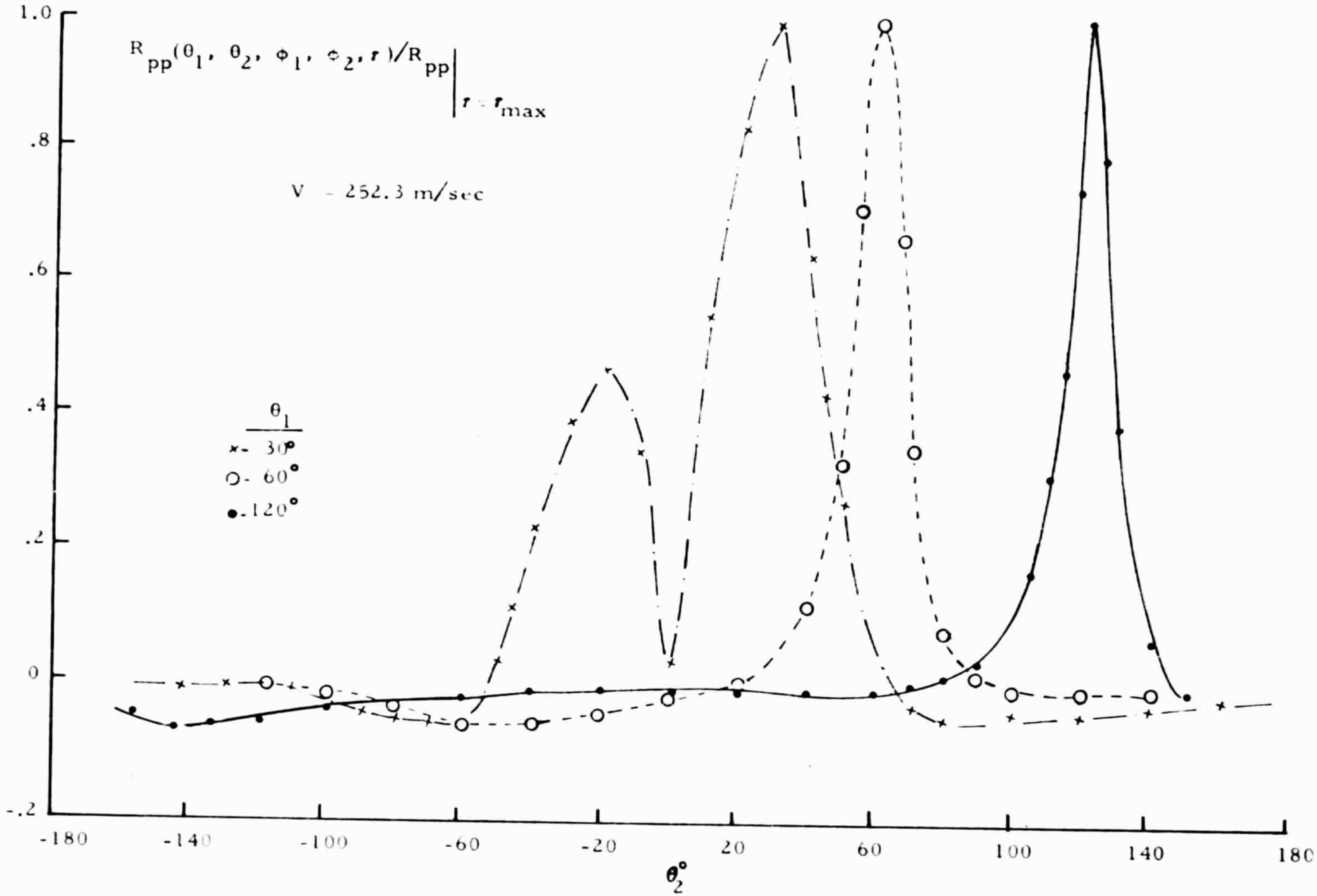

Figure 9. Normalized Cross Plot Peak Correlation

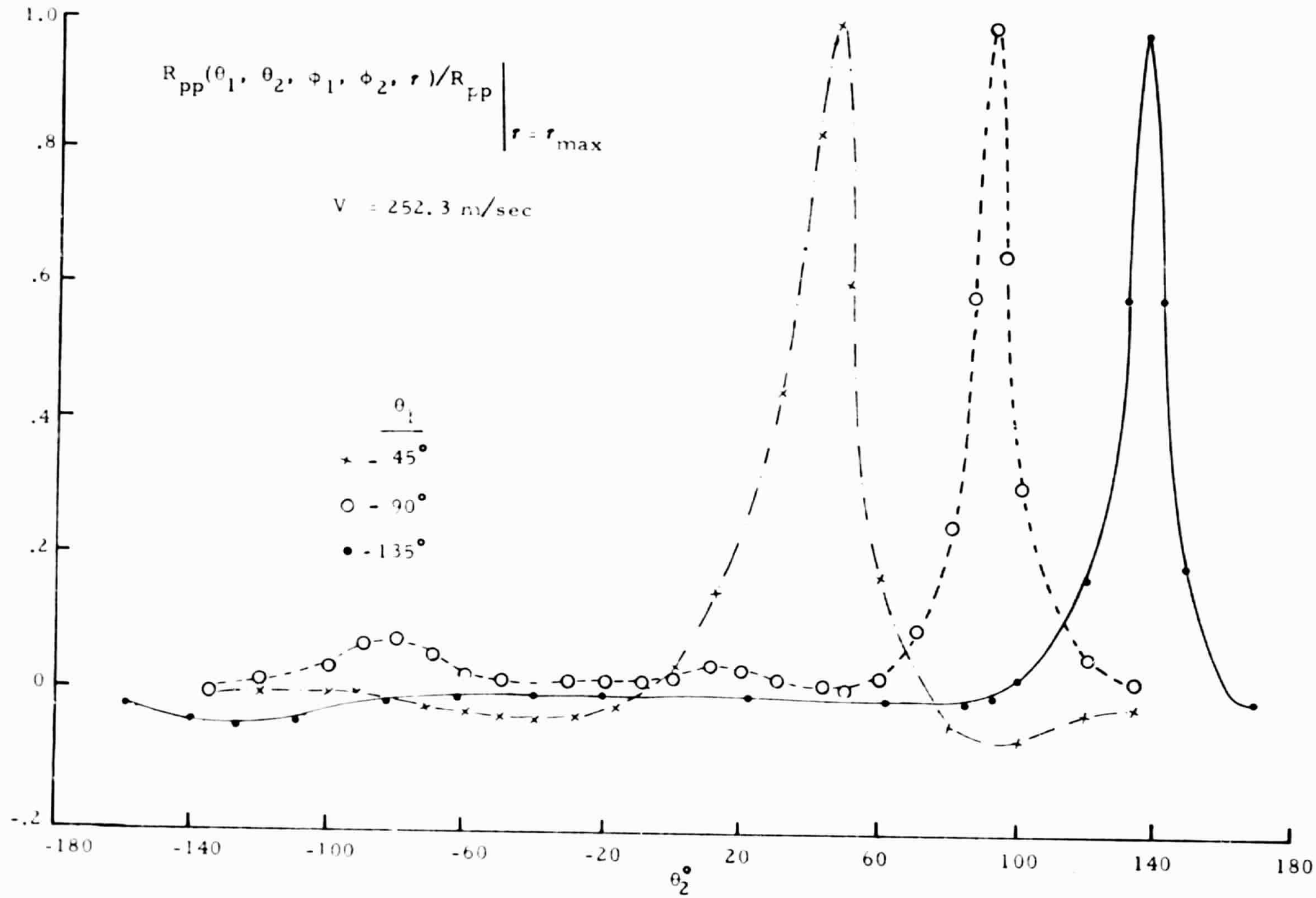

Figure 10. Normalized Cross Plot Peak Correlation