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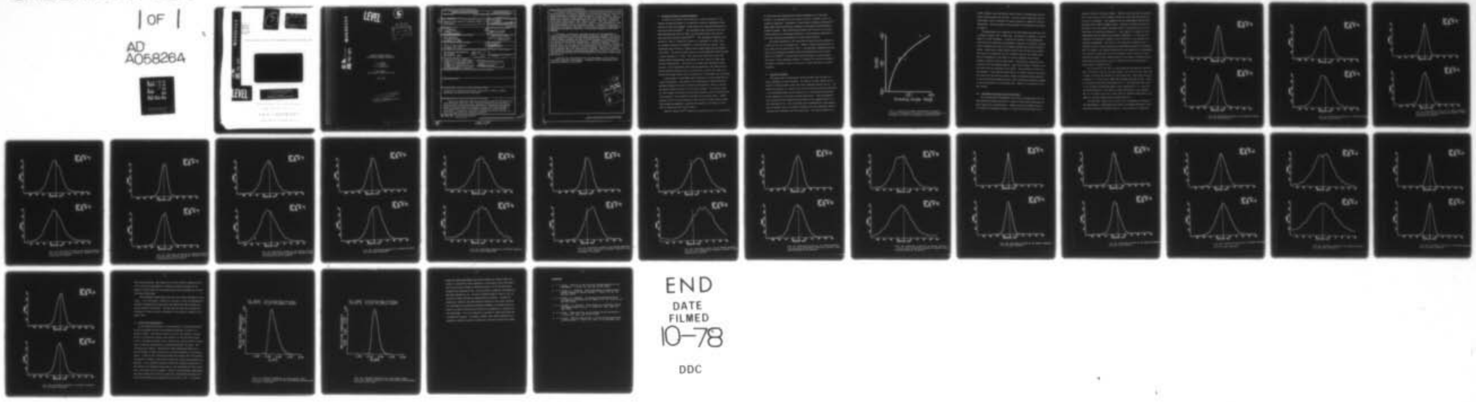

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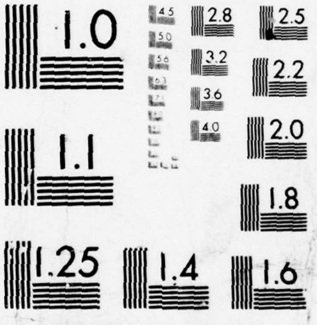
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PHYSICAL MODEL STUDIES
OF BISTATIC SURFACE SCATTERING

J. G. Zornig
J. Snyder
P. M. Schultheiss

Final Report
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This report summarizes the work accomplished under the referenced contract during the past year. Most results contained herein have been reported earlier in Yale University, Department of Engineering and Applied Science Technical Reports CS-9 (Bistatic Surface Scattering Strength at Short Wavelengths), and 7710 (Frequency Spreading in Forward Surface Scattering). In addition, this report contains some recent tentative results and observations not otherwise published.

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An extensive series of measurements of the scattering strength of a wind driven surface at an acoustic frequency of 1300 kHz were made in a model tank. These measurements encompassed grazing angles of 12 and 17 degrees. Wind speeds of 5.4 and 8.3 m./sec., and a variety of orientations to the wind and differential azimuths. The measurements were made using short, relatively narrow band probing signals under computer control. Data were converted to scattering strength using a flat surface reference and compensation for transducer beam patterns and data acquisition timing. A number of results were reported by this study in the form of observational conclusions regarding the magnitude and parametric sensitivity of scattering strength at short wavelengths.

A subsequent investigation concerned itself with the measurement of frequency spreading in forward ~~(differential azimuth = 180 deg.)~~ scattering. A new technique of channel probing using wideband test signals transmitted at frequent regular intervals was used to obtain estimates of frequency spread at a variety of wavelengths simultaneously. Rayleigh roughness parameters varying from 0.7 to 12. were studied both crosswind and downwind. The most dramatic result of the study was the demonstration under controlled conditions that spreading under conditions of exactly symmetric geometry is not necessarily symmetric about the insonification frequency. This report contains some additional frequency spreading measurements which correct errors in the originally reported data and test the sensitivity of the data to small alignment errors.

A technique has been developed for the measurement of wave slopes at very small horizontal displacements. Examples of slope measurements made using this technique are included.

I. Scattering Strength at High Frequencies

A series of experiments were conducted to obtain estimates of the surface scattering strength to be expected in bistatic transducer configurations at short wavelengths. These results were reported previously and have since been published(1). The experiments were conducted in the Yale Hydrocommunications Facility (HCF), an instrumented model tank facility which has been previously described(2,3). The experimental apparatus consisted of a pair of transducers mounted on a goniometer in a water tank, the surface of which was roughened by a fan generated air stream. These transducers were driven by a computer based signal generating and acquisition system. The probing signal used was a cosine modulated sinusoid having a center frequency of 1.3 MHz. This signal was chosen as the best compromise between simultaneous requirements for best signal to noise ratio and time discrimination. The choice of frequency was indicated by three factors: ease of generation with existing transducers, the expectation of high scattering strength levels, and the desire to obtain data under conditions which might permit direct validation of a facet model for the process.

A large number of experiments were conducted at various geometries and surface roughnesses. The results of the investigation, while providing a substantial empirical basis for further investigations, failed to confirm any present analytical model for scattering strength. The primary reason for this failure is believed to be an insufficiently accurate representation in the models of the probability distribution of surface slopes. Indeed precious little is known empirically about the PDF of steep surface slopes. This problem has generated a parallel investigation, the status of which will be summarized later in this report.

Technical Report CS-9(1) mentions an observed failure of scattered power to follow the often assumed inverse square spreading law in the cases studied. This phenomenon was not studied in detail, although it was confirmed by repetition. Fortunately a recent study by Mikeska and McKinney(4) using fixed random surfaces has confirmed this observation and studied the problem in detail. Their observations indicate that the use of the traditional definition of scattering strength as a scalar measure independent of the actual observational geometry is in many cases incorrect.

The results presented in the scattering strength study are lengthy and complex and will not be repeated here. However, between the publication of that report and the publication of Ref. 1, an additional comparison has been made of the backscatter strengths observed experimentally with the well-known law of Marsh(5) relating backscattering strength to grazing angle. The result of this comparison (Figure 1) indicated that the form of Marsh's prediction is roughly correct, but only for certain conditions of surface roughness.

II. Frequency Spreading

The second area of investigation during the past year has been frequency spreading in forward scatter. The results of these studies are reported in Technical Report #7710 (New report numbering system) and (6). The study has consisted of a review of the current status of analytical modelling of the spreading process and an extensive set of experimental measurements of the phenomenon in the physical modelling facility. These measurements were conducted using impulsive probing signals and an apparatus similar to that described in (2). The test signals were transmitted at a rate greater than the Nyquist rate of the channel fading so that the phenomenon could be characterized completely from the sampled data. The probing signals them-

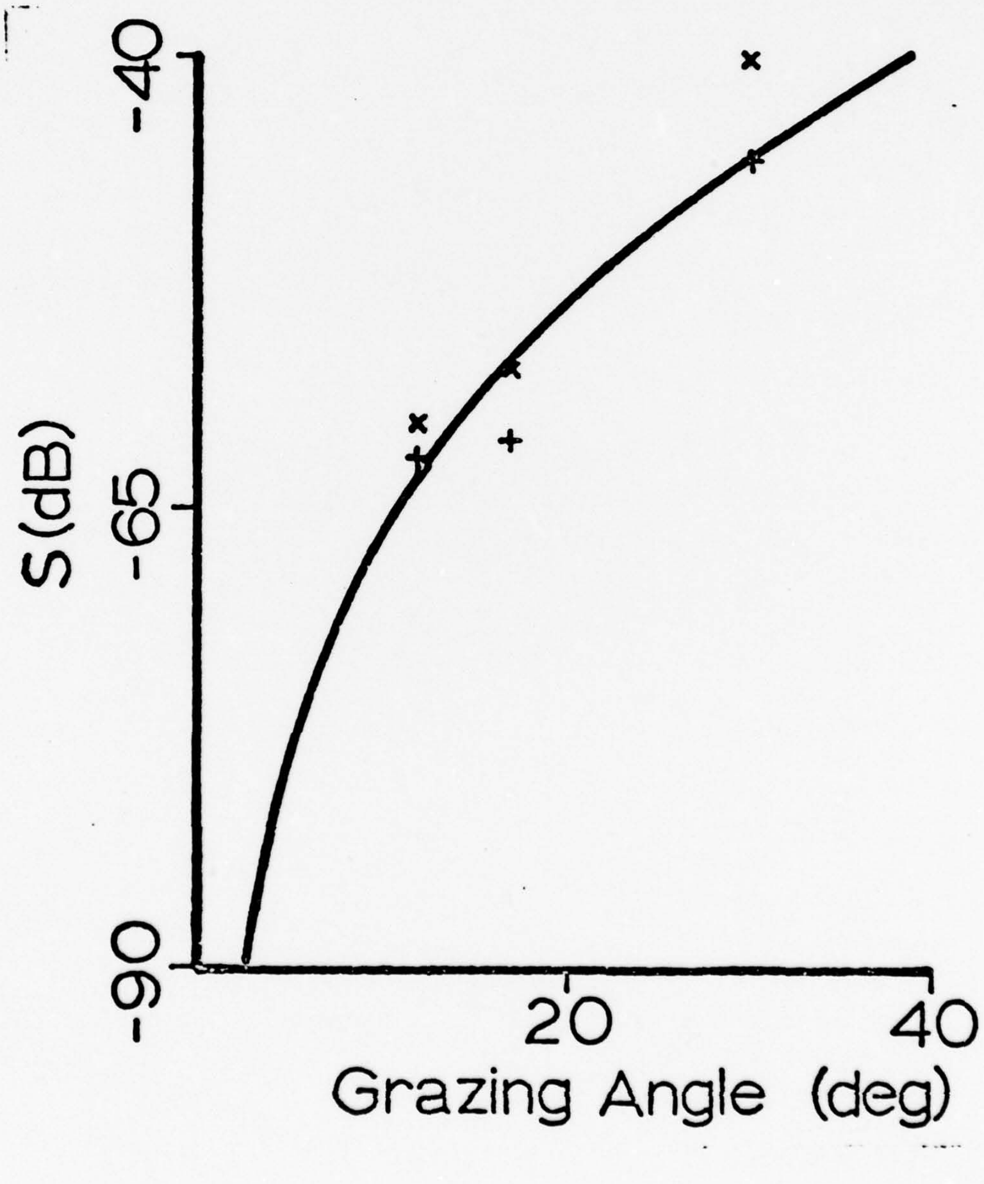

FIG. 1. Measured Surface backscatter strengths at wind 4 (8.3m/sec) at upwind (x) and crosswind (+) compared to Marsh's expression S=-36+40log tan

selves, however, were sufficiently short so that no reverberation from one pulse could interfere with the next. The data records were doubly Fourier transformed to give an estimate of Doppler spread at a number of "carrier" frequencies. The exact method of data analysis is discussed in the Technical Report.

The measurements were conducted at two wind speeds and directions over a frequency range of 256. to 1060. kHz. The series was repeated at grazing angles of 17 and 30 degrees. In general the results of the experimental study were self consistent and repeatable. They were, in addition, qualitatively consistent with some of the results derived from current analytical models. Specifically, these theories predict that the form of the spread spectrum due to scattering will be a modified image of the temporal spectrum of waveheights at low values of surface roughness and a shifted Gaussian of greater width at high values. These general predictions were consistent with the measured spectra. There were, however, features in the data which were not explained by any theory. Most important of these was the asymmetry of the measured spread spectra in exactly symmetric geometries. This feature of the data has raised a number of questions among proponents of various analytical models and led to some confirming experiments designed to test the precision of the reported work. These will be reported in the next section.

III. Supplemental Frequency Spread Measurements

The aforementioned disagreements of the Doppler measurements with current mathematical models has led to a number of discussions concerning possible reasons for the differences. Foremost among the probable causes is the tendency of mathematical models to assume particularly simple and unrealistic forms for the water surface. However, trial calculations revealed that in some situations the symmetry results of theory were very sensitive to errors in alignment. This suggested that the experimental results might have been due to small alignment errors. Therefore a series of trial runs was made to test the results obtained earlier for sensitivity and accuracy. These data are enclosed as Figures 2-7. They consist of a series of three measurements each at upwind and crosswind orientations. In each case one transducer was displaced 5 degrees in each direction to test sensitivity to azimuthal misalignment. The result of this test was to indicate that: 1) frequency spread in upwind scattering is relatively insensitive to misalignment, 2) spread in the crosswind direction is quite sensitive to misalignment but accurately aligned data are still asymmetric, and 3) an error in data reduction was made in the original series for the upwind, 30 degree grazing angle case which resulted in a mirror reflection of the reported data in range (sign of frequency shift).

The correction of this error in data reduction motivated the remeasurement of the Wind 2 case for the same geometry, which was the only other case in which an upshift was reported for the upwind case. These data are given as Figure 8. As can be seen, these data had been reflected as well. These two corrections have been incorporated in (6). This simplifies the results of the frequency spread measurements rather significantly, i.e. crosswind scattering results in a net upshift, upwind scattering in a net downshift. This is, of course, still not a result which is explained analytically, but admits to a rather simpler empirical generalization.

The next step, clearly, was to take a look at downwind scattering for the same geometry. Measurements were taken at 30 degrees and Winds 2 and 4 which are given here as Figures 9 and 10. As can be seen, no consistent

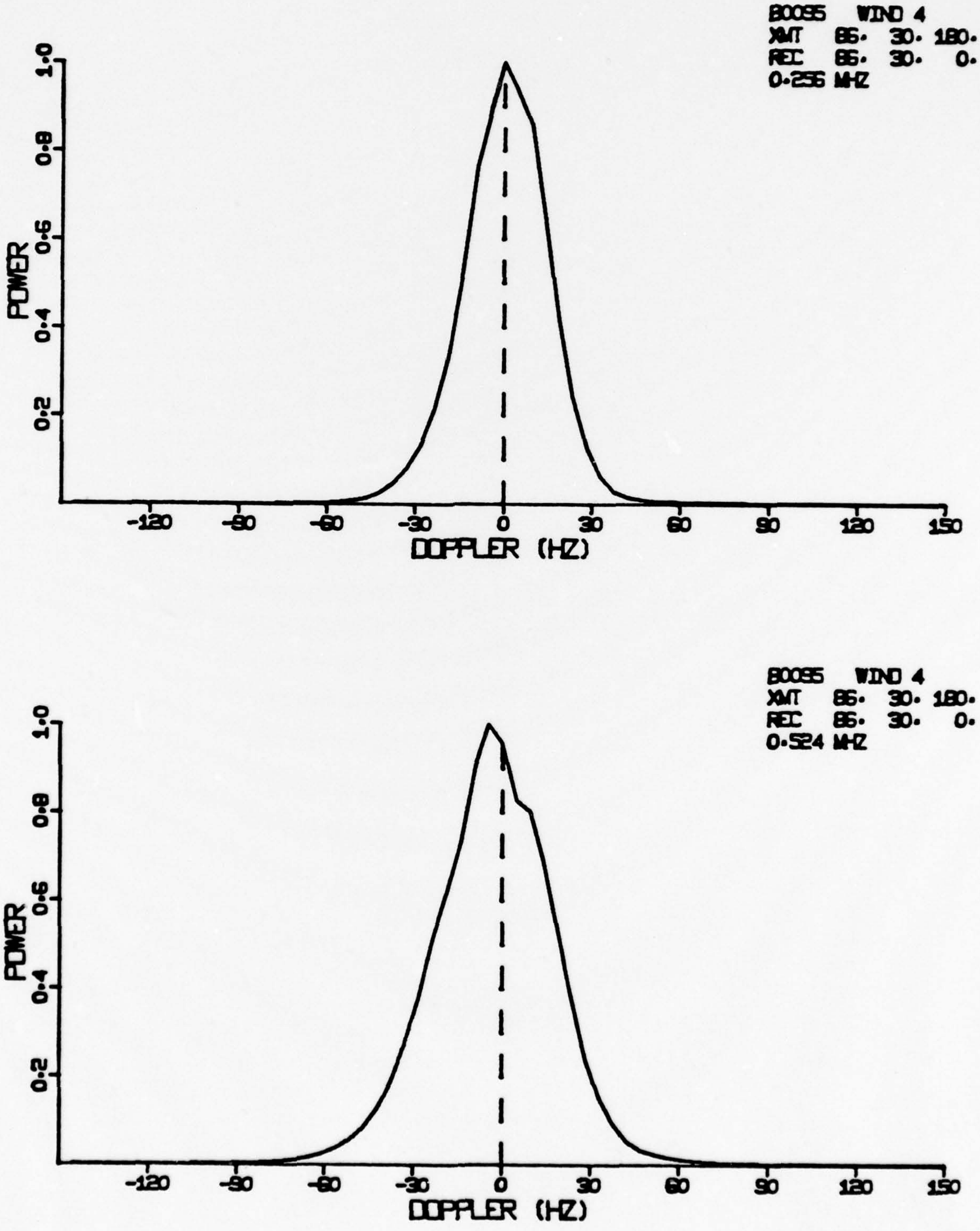

FIG. 2a. Frequency spread at 30 degree grazing, 8.3 m/s wind, upwind

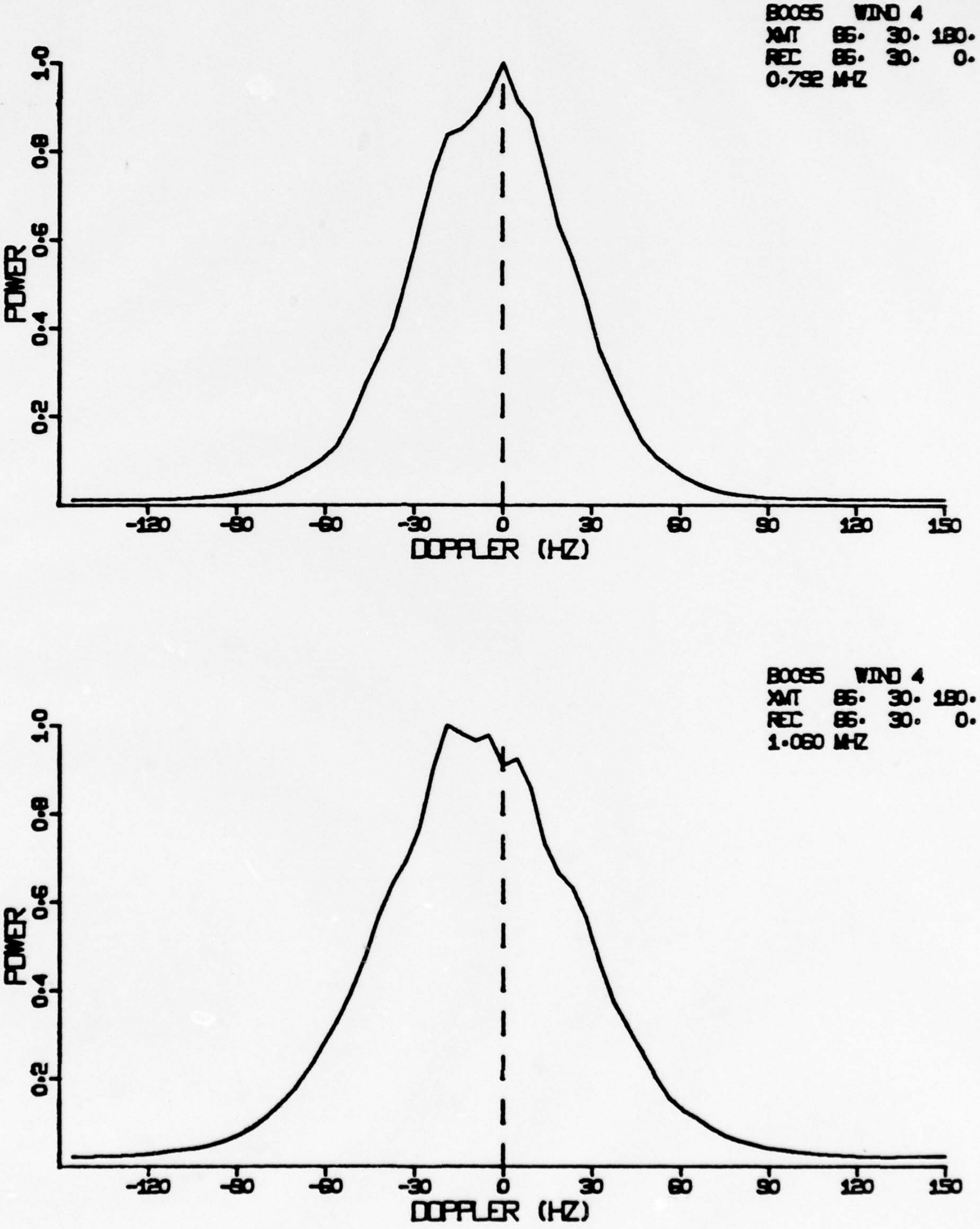

FIG. 2b. Frequency spread at 30 degree grazin
8.3 m/s wind, upwind

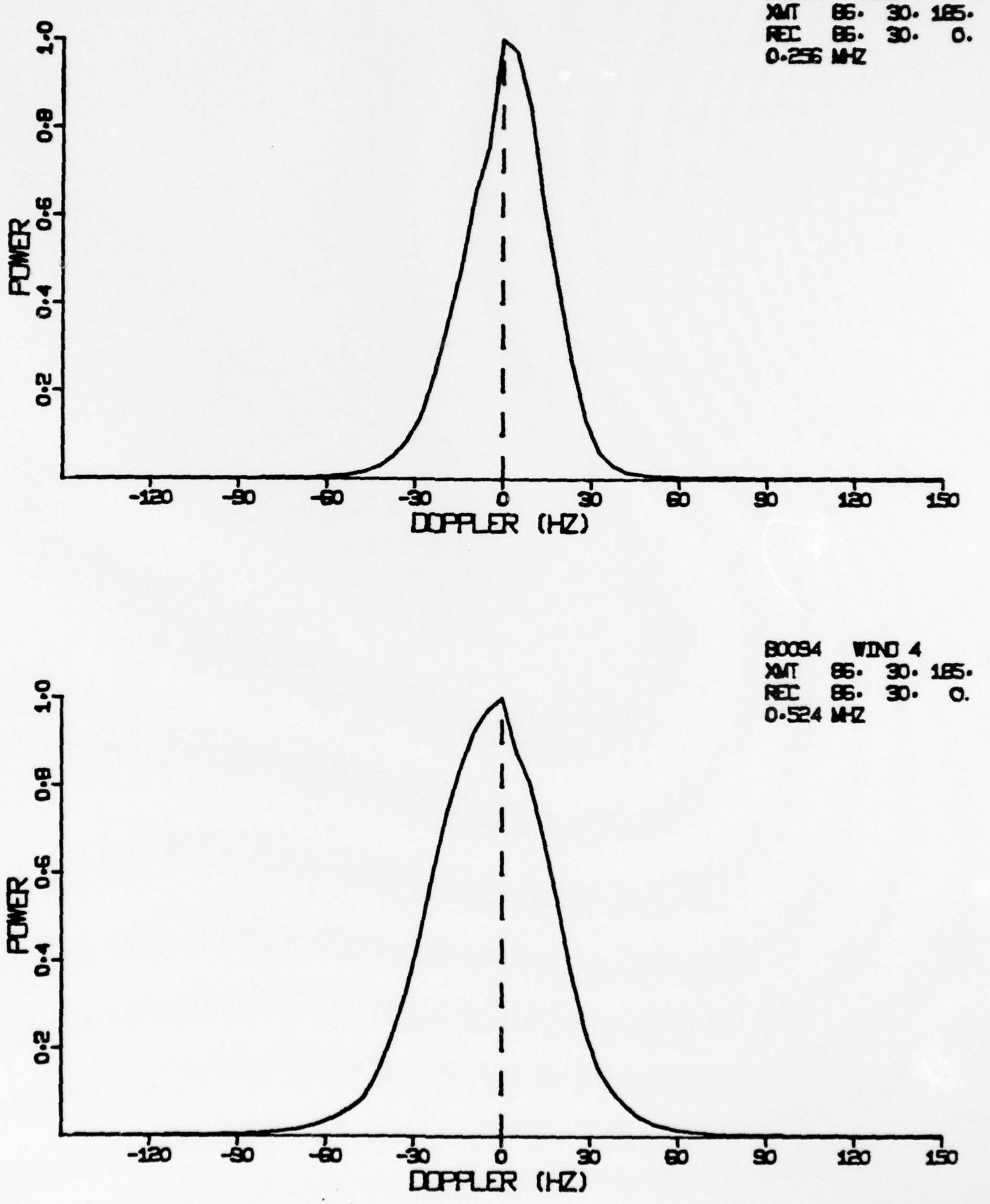

FIG. 3a. Frequency spread at 30 degree grazing, 8.3 m/s wind, upwind, projector rotated 5 deg. clockwise in azimuth

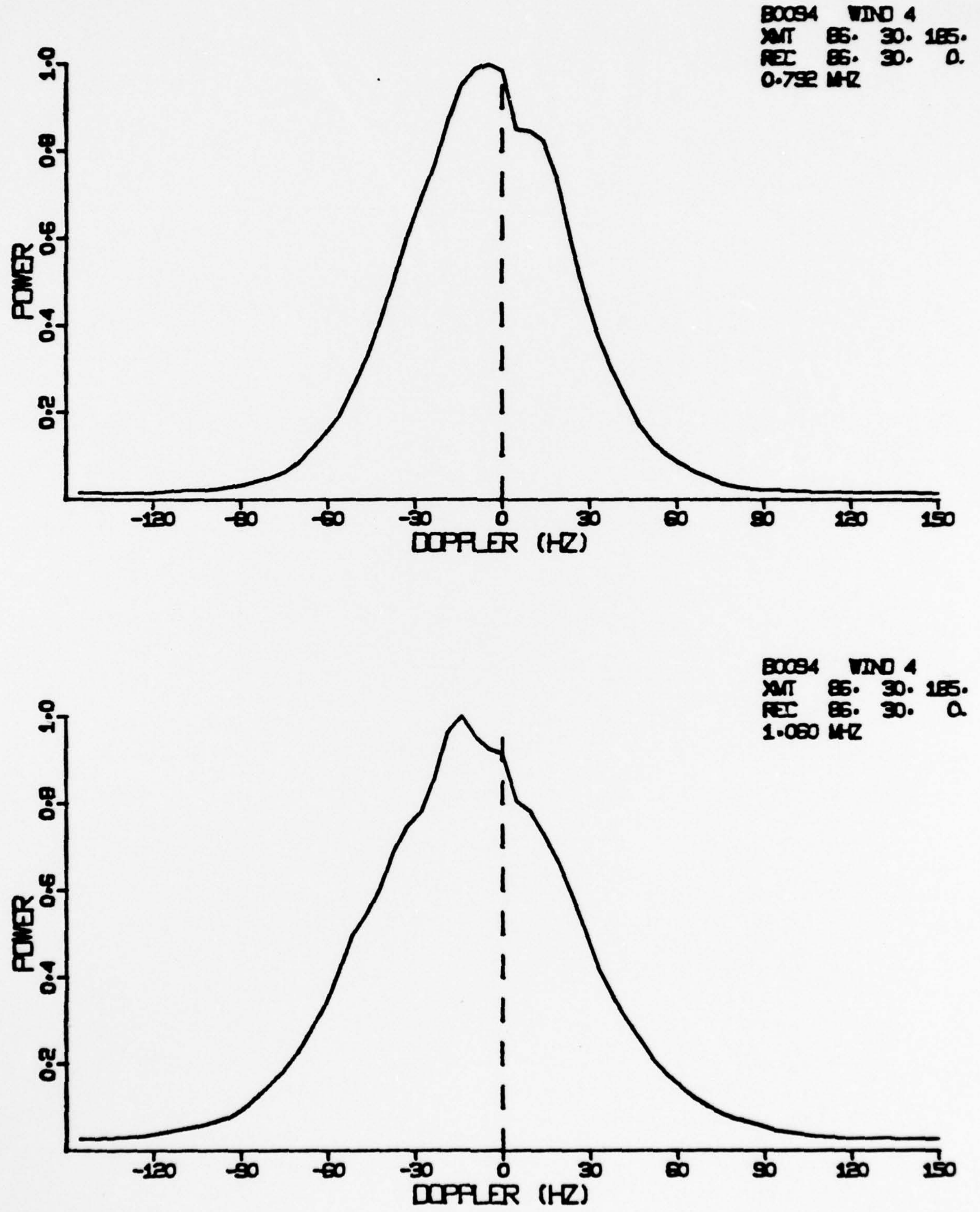

FIG. 3b. Frequency spread at 30 degree grazing, 6.3 m/s wind, upwind, projector rotated 5 deg. clockwise in azimuth

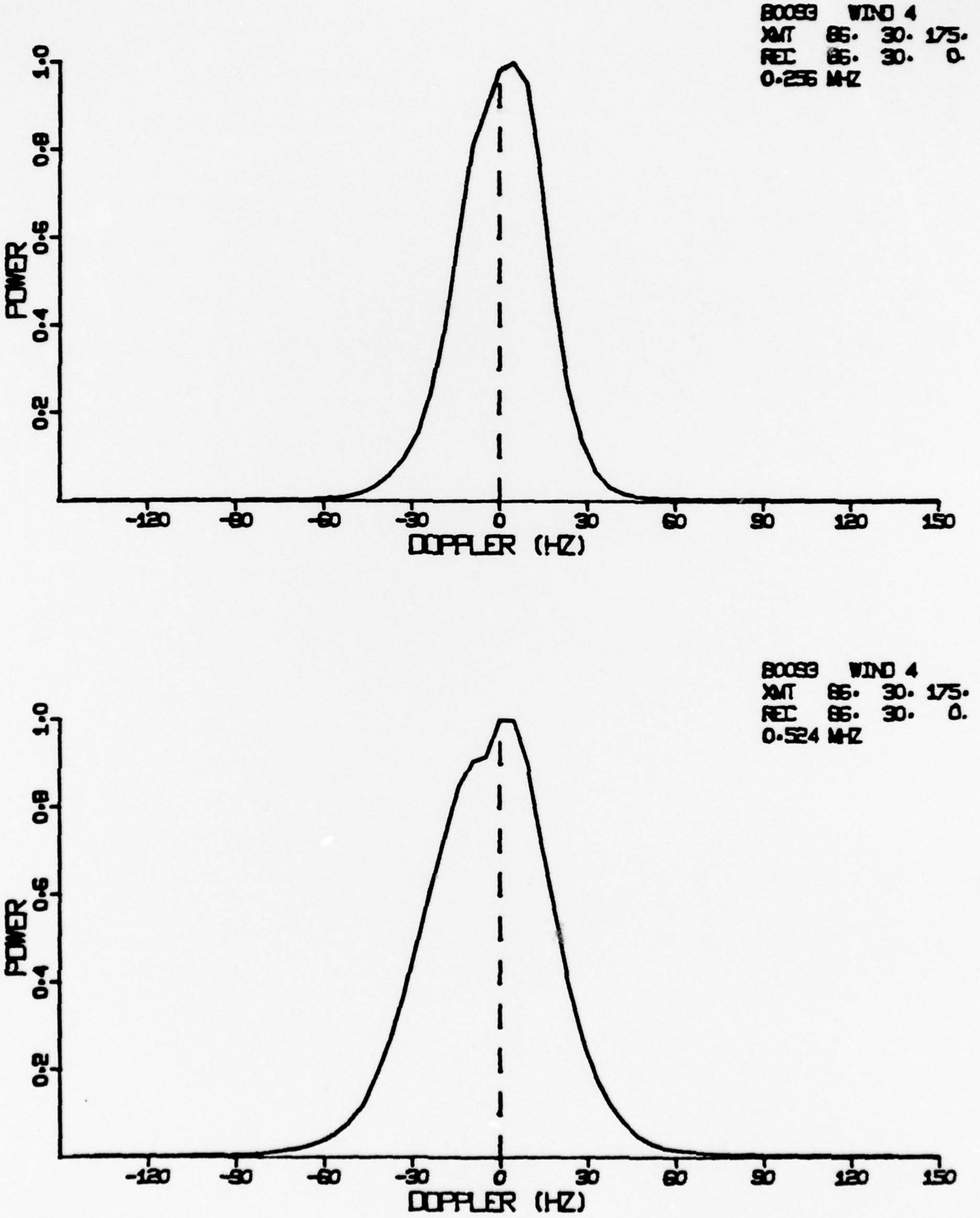

FIG. 4a. Frequency spread at 30 degree grazing, 8.3 m/s wind, upwind, projector rotated 5 deg. counterclockwise in azimuth

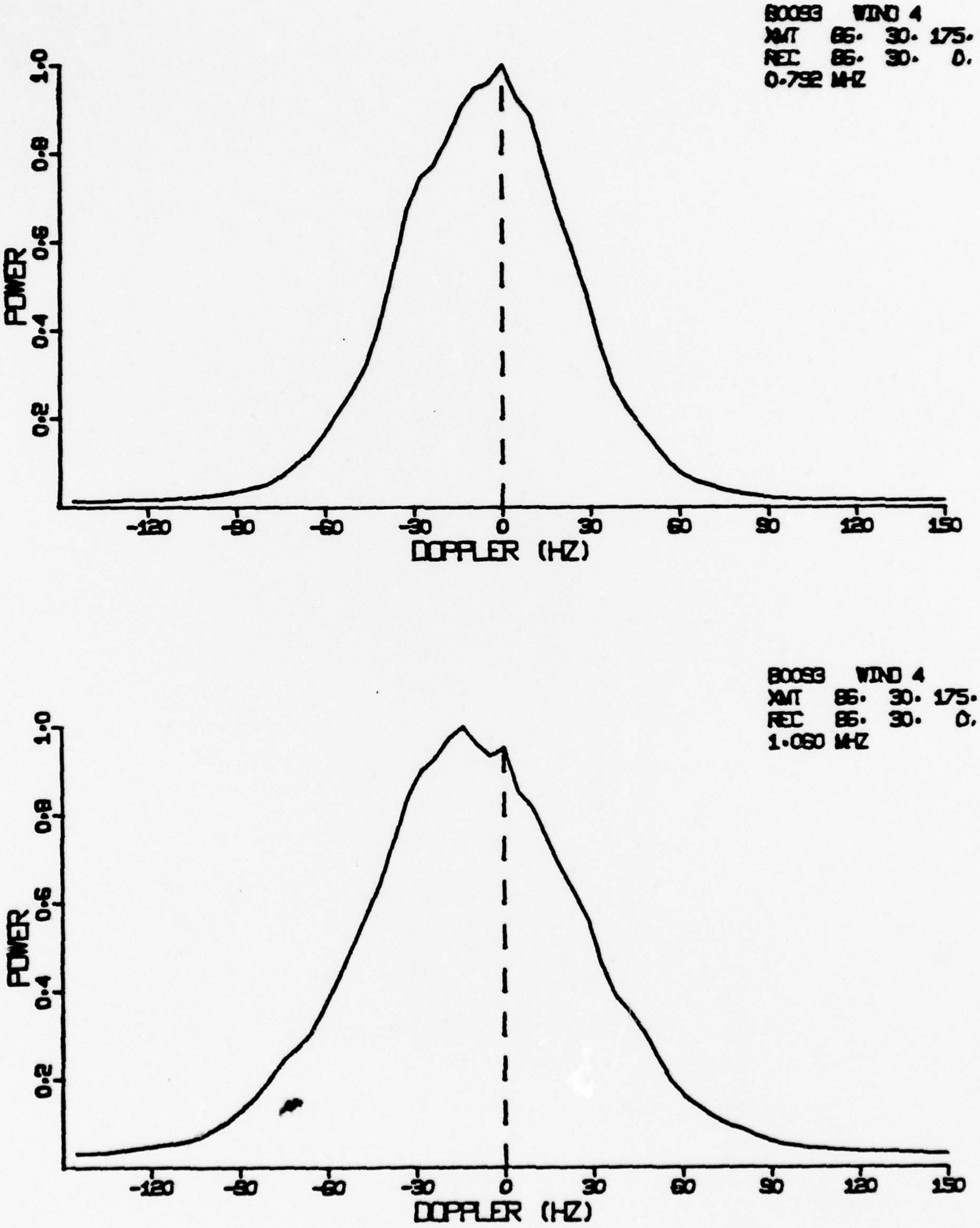

FIG. 4b. Frequency spread at 30 degree grazing, 8.3 m/s wind, upwind, projector rotated 5 deg. counterclockwise in azimuth

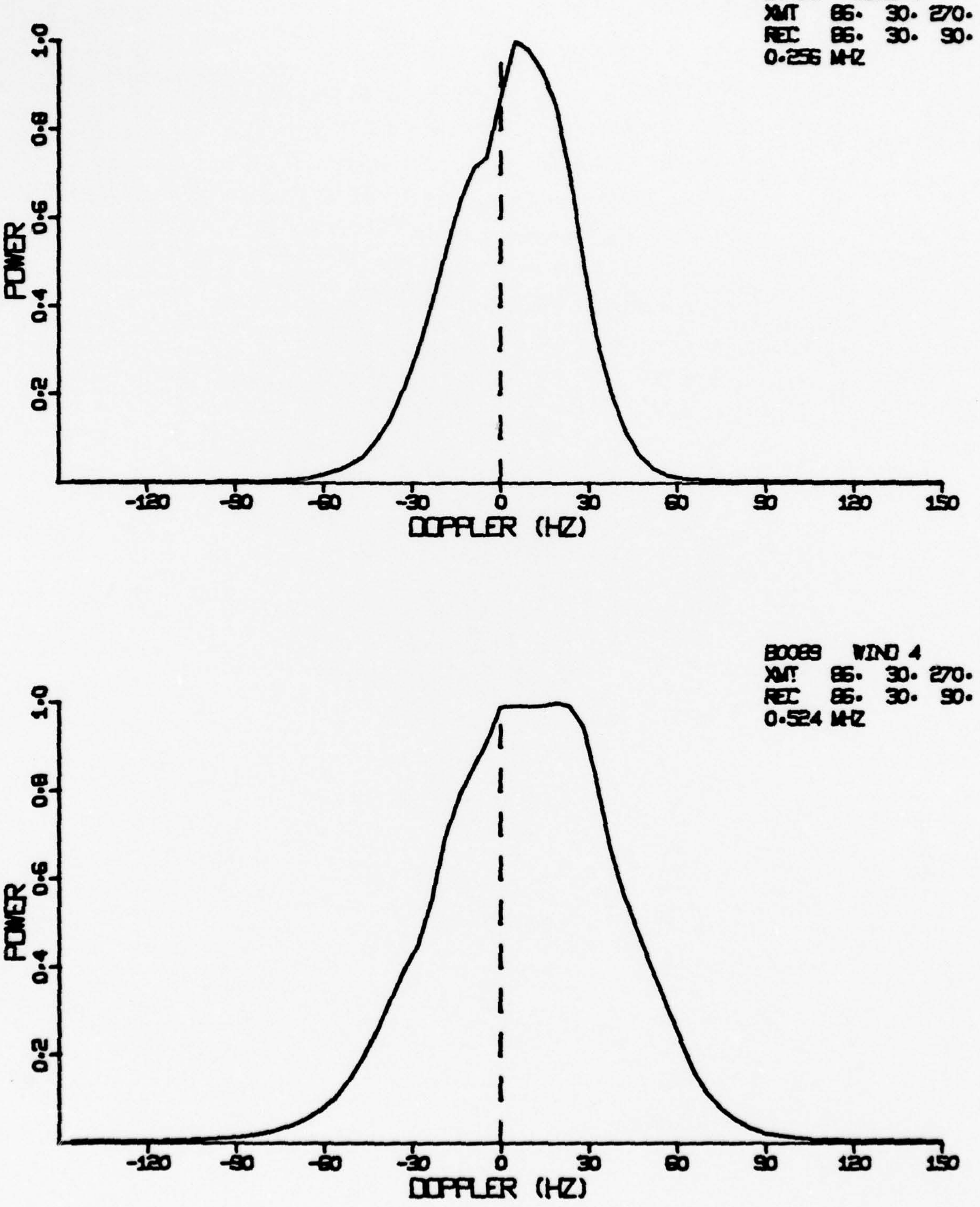

FIG. 5a. Frequency spread at 30 degree grazing, 8.3 m/s wind, crosswind

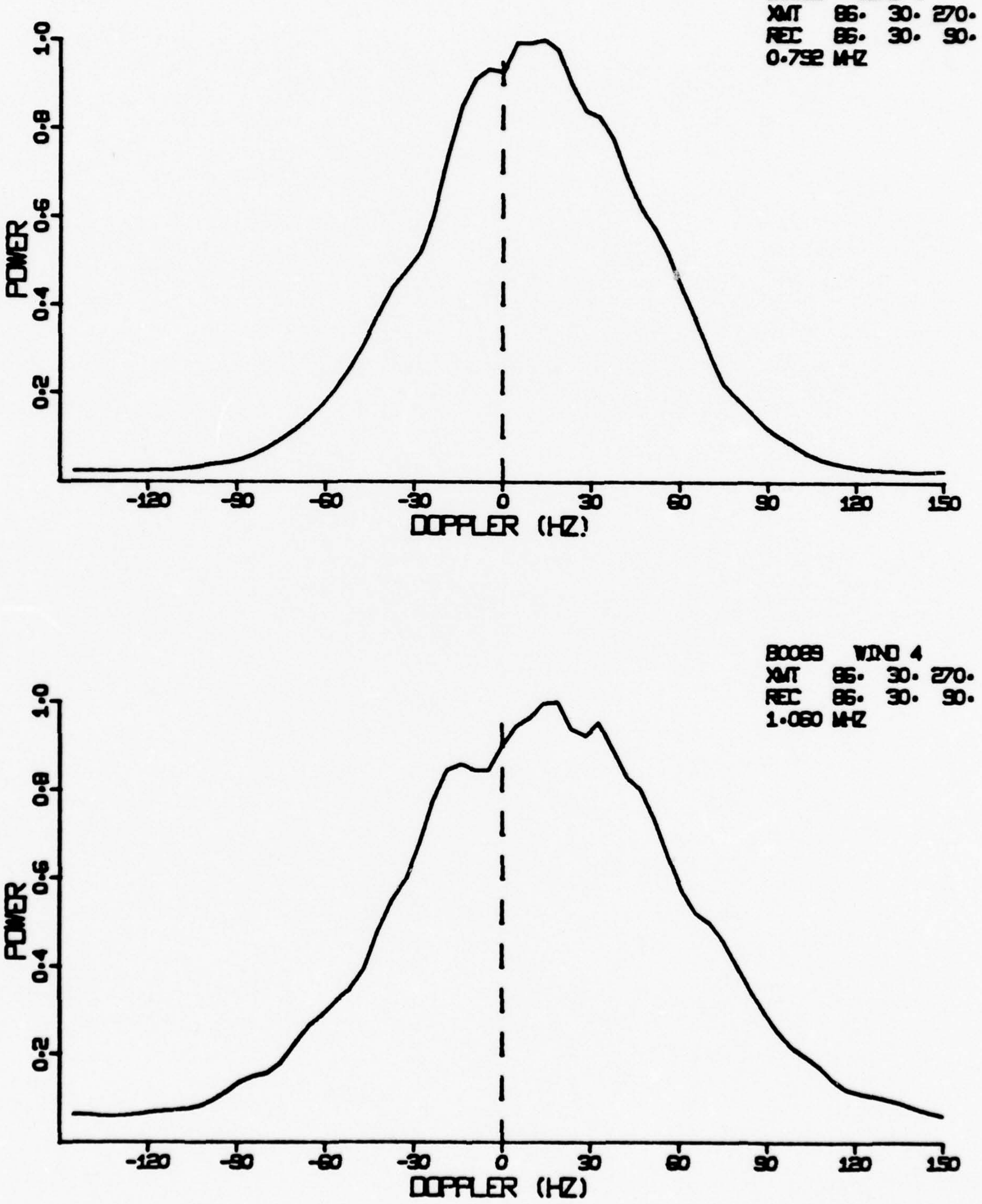

FIG. 5b. Frequency spread at 30 degree grazing, 8.3 m/s wind, crosswind

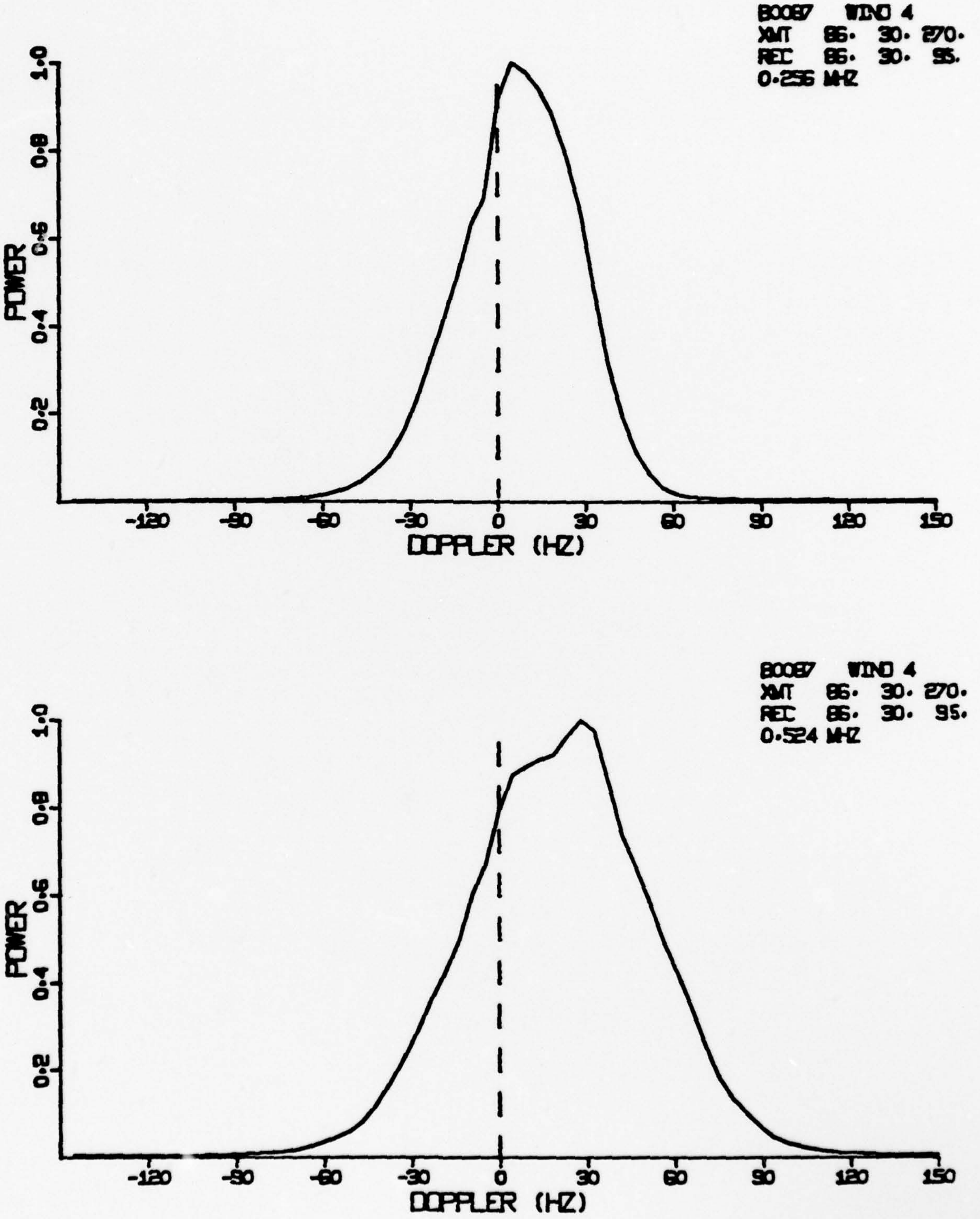

FIG. 6a. Frequency spread at 30 degree grazing, 8.3 m/s wind, crosswind, receiver rotated 5 deg. clockwise in azimuth

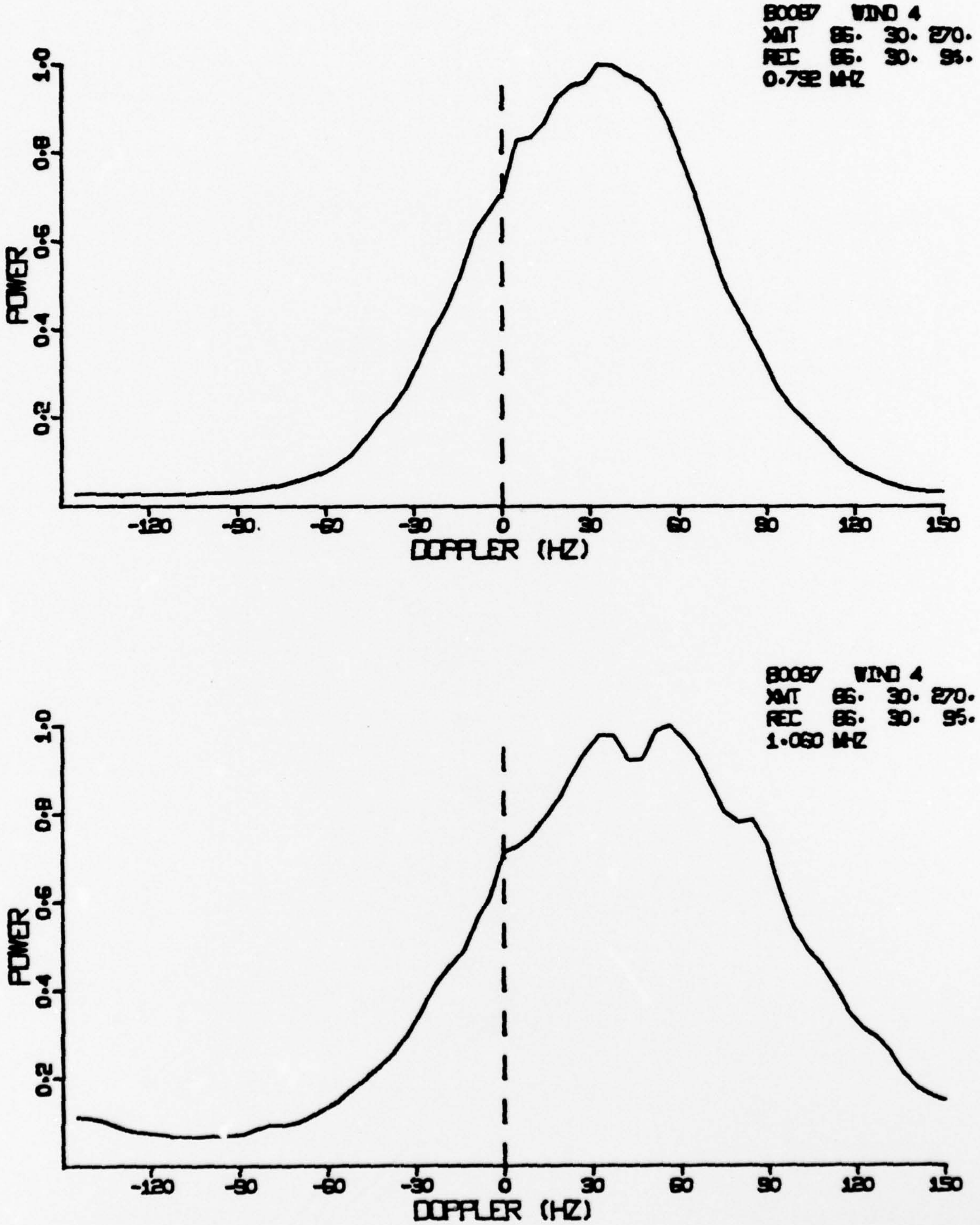

FIG. 6b. Frequency spread at 30 degree grazing, 8.3 m/s wind, crosswind, receiver rotated 5 deg. clockwise in azimuth

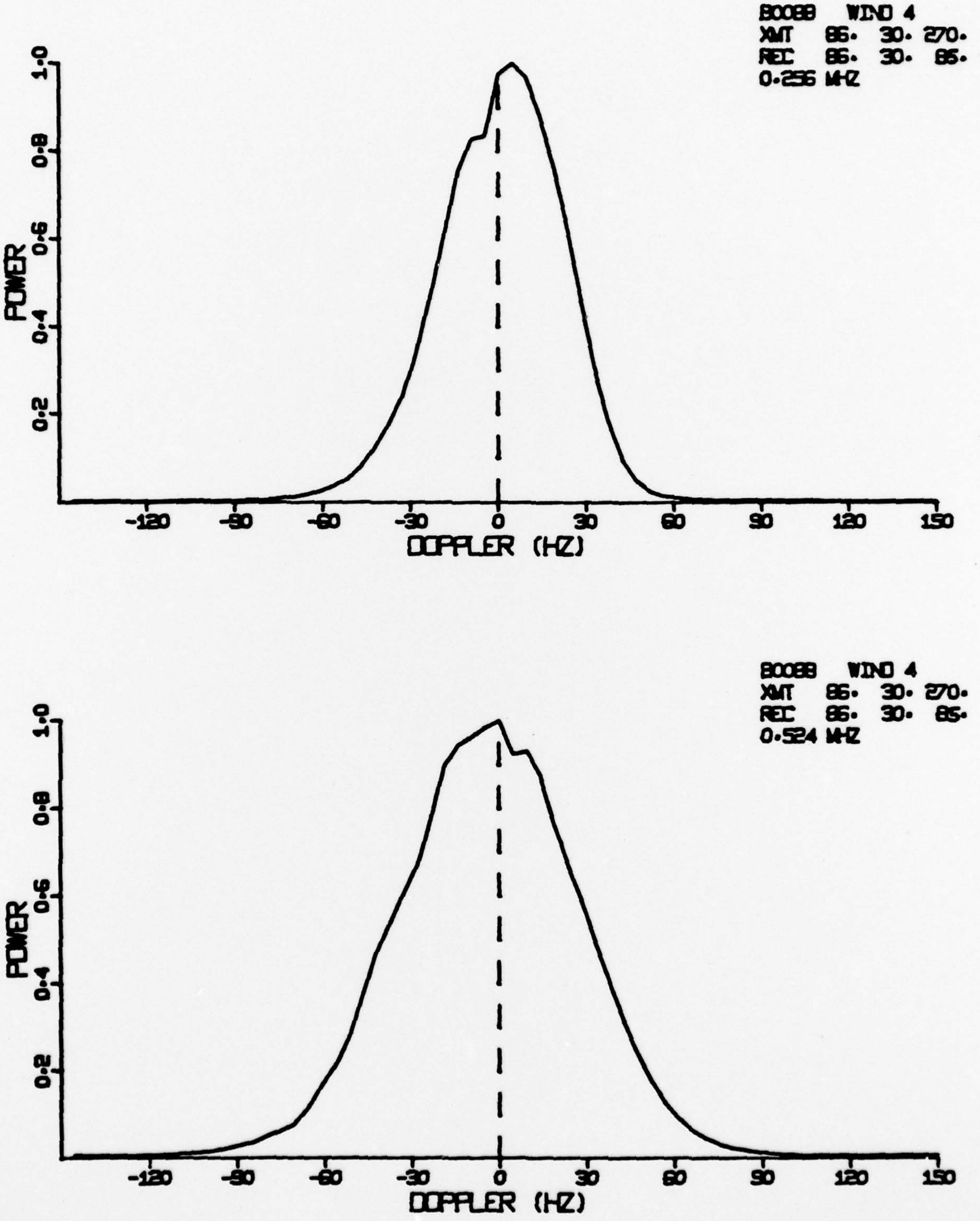

FIG. 7a. Frequency spread at 30 degree grazing, 8.3 m/s wind, crosswind, receiver rotated 5 deg. counterclockwise in azimuth

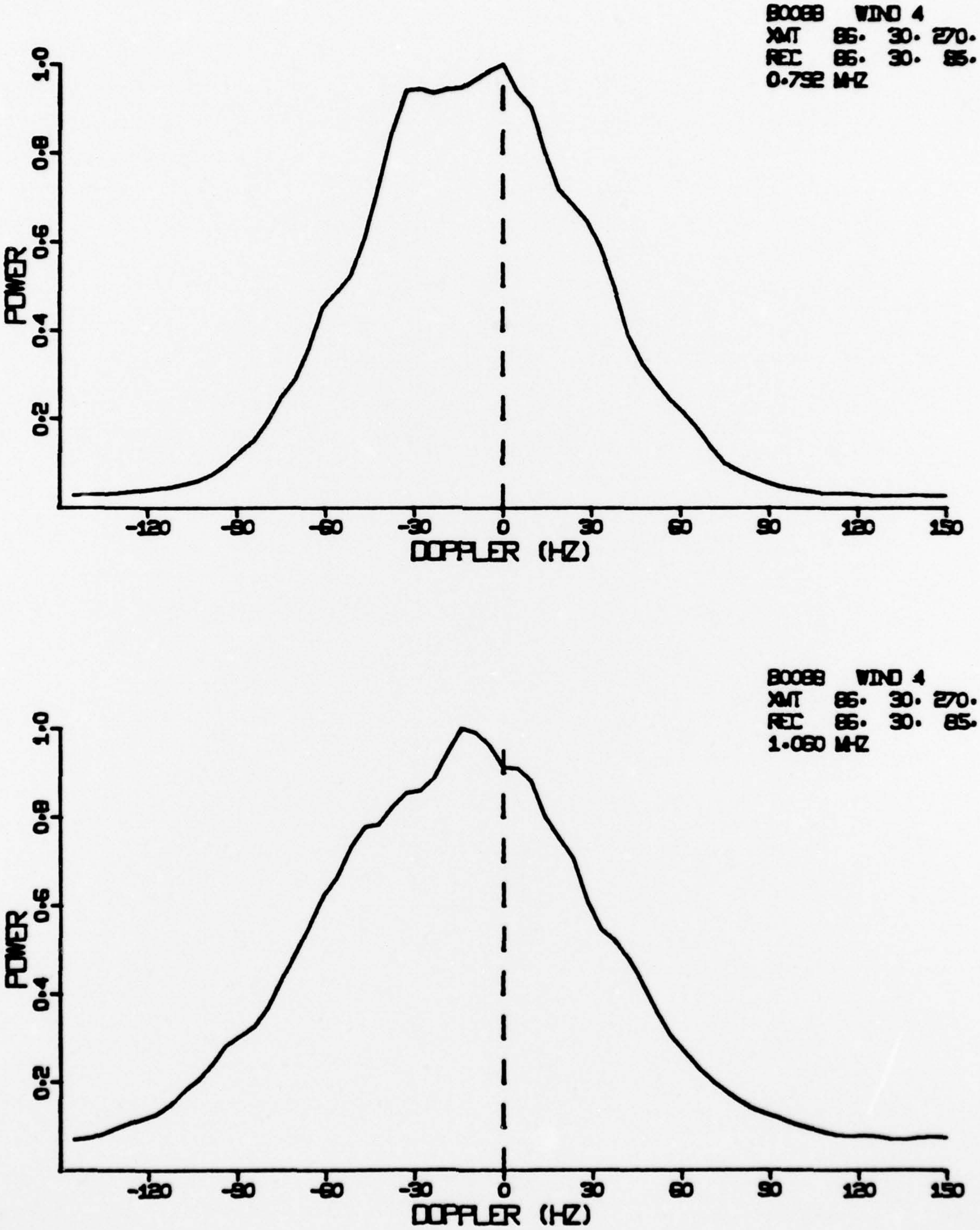

FIG. 7b. Frequency spread at 30 degree grazing, 8.3 m/s wind, crosswind, receiver rotated 5 deg. counterclockwise in azimuth

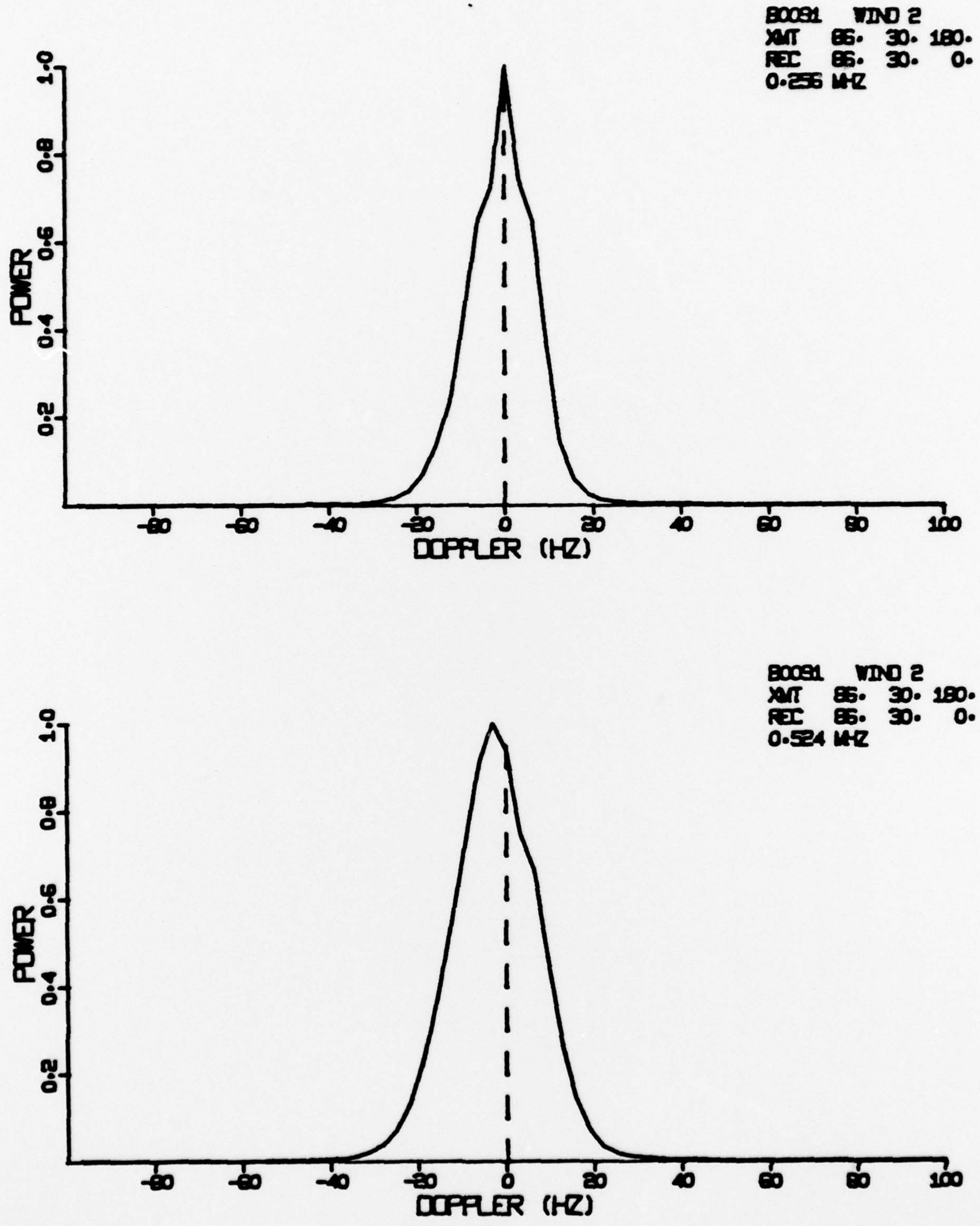

FIG. 8a. Frequency spread at 30 degree grazing, 5.4 m/s wind, upwind

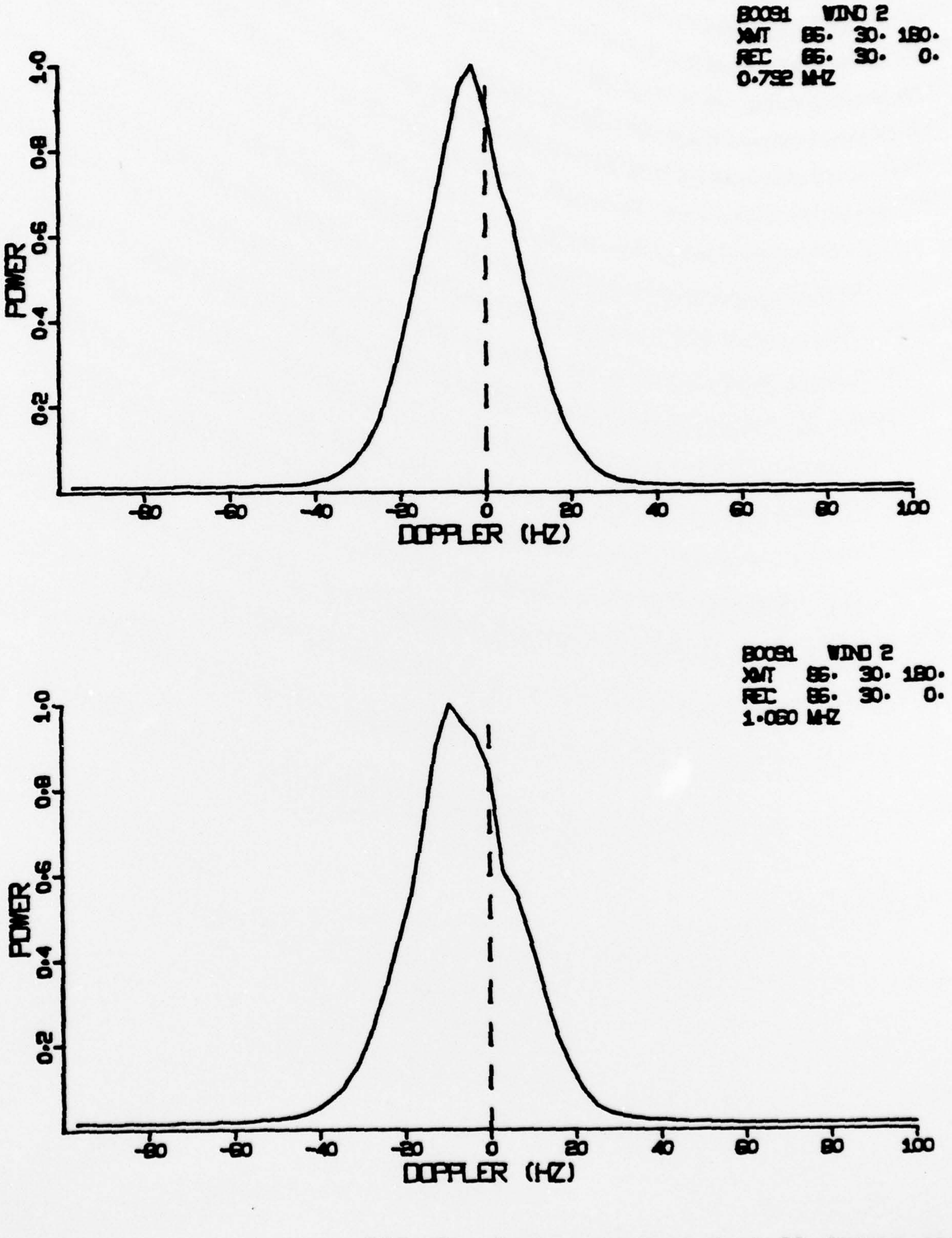

FIG. 8b. Frequency spread at 30 degree grazing, 5.4 m/s wind, upwind

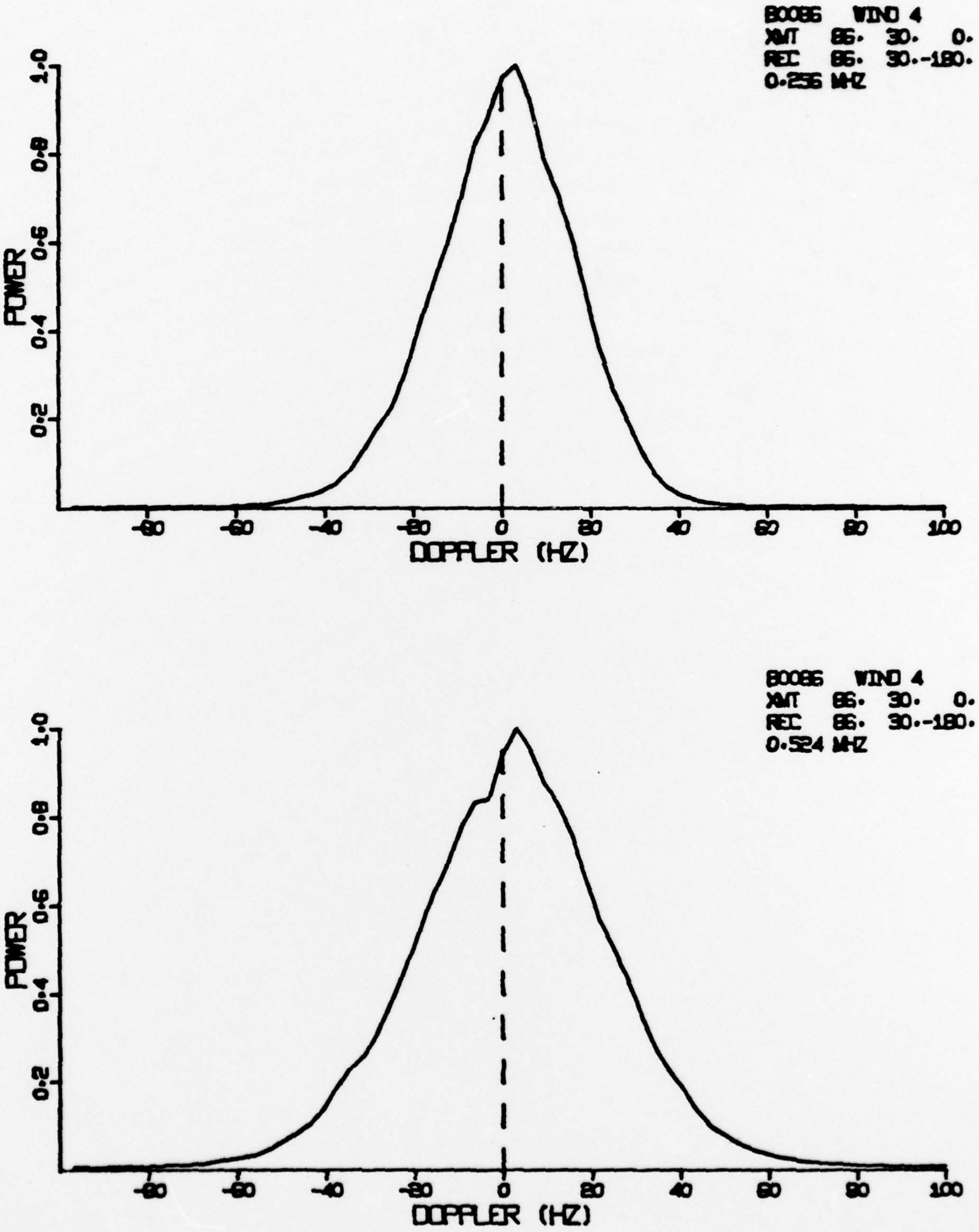

FIG. 9a. Frequency spread at 30 degree grazing, 8.3 m/s wind, downwind

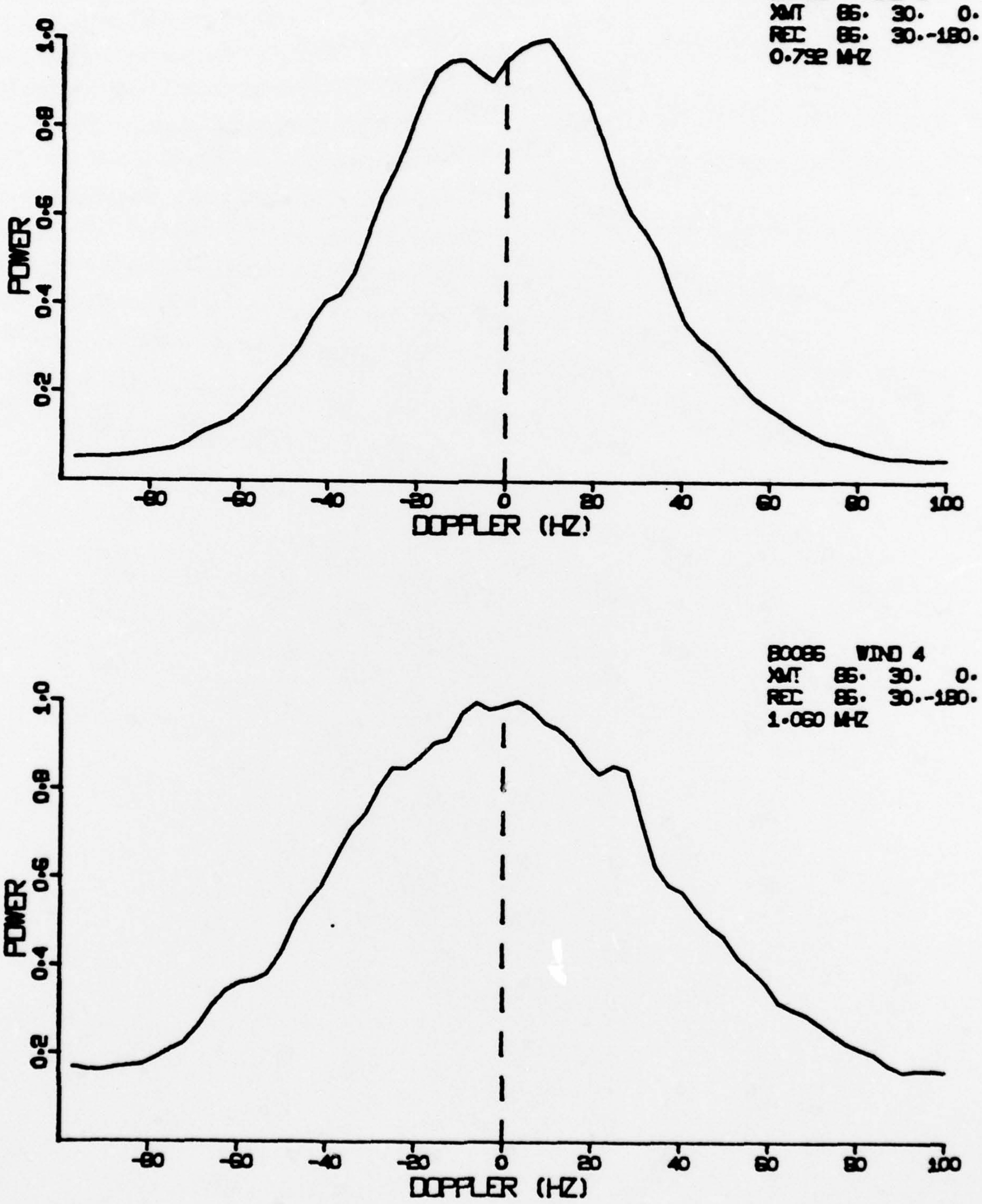

FIG. 9b. Frequency spread at 30 degree grazing, 8.3 m/s wind, downwind

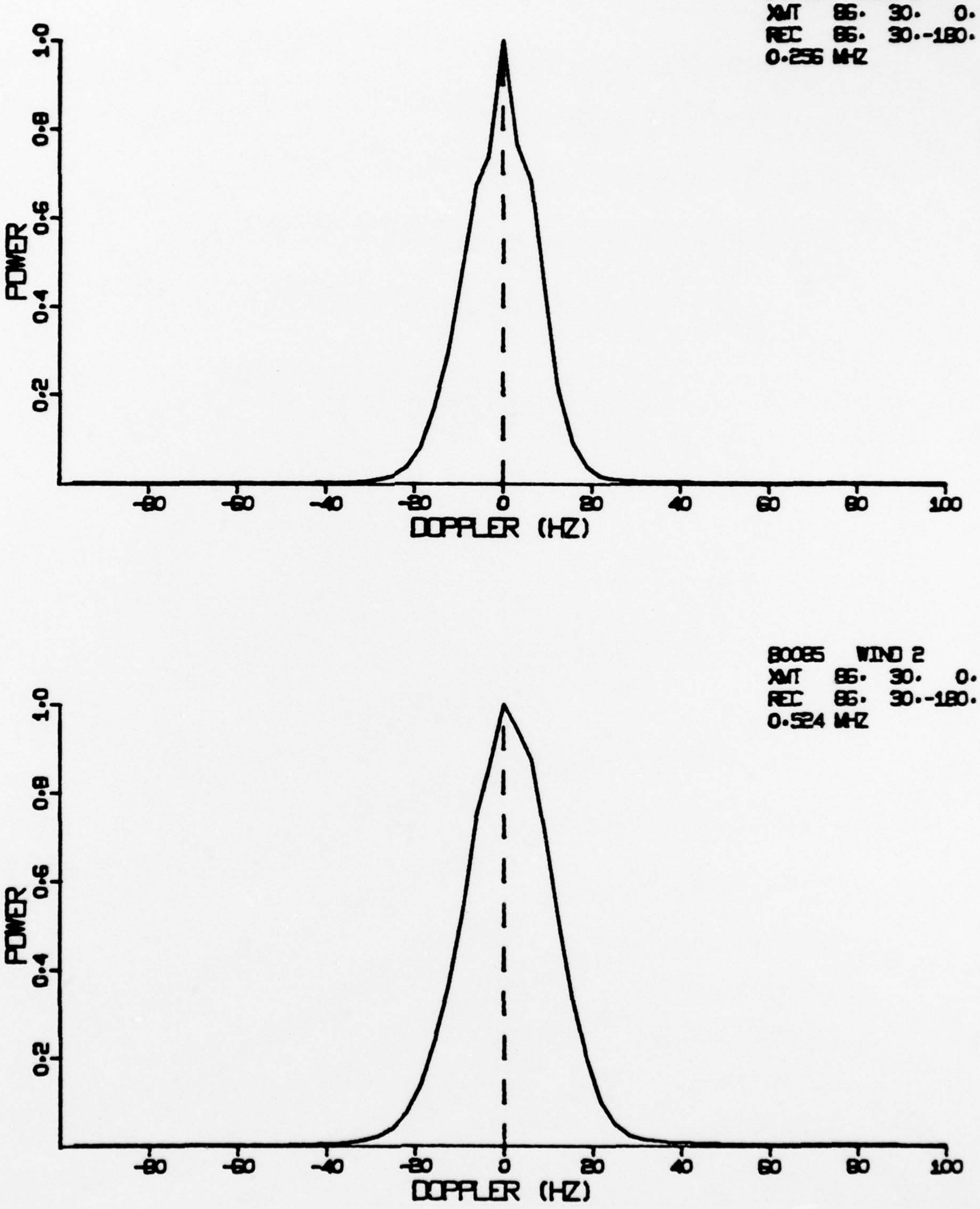

FIG. 10a. Frequency spread at 30 degree grazing
5.4 m/s wind, downwind

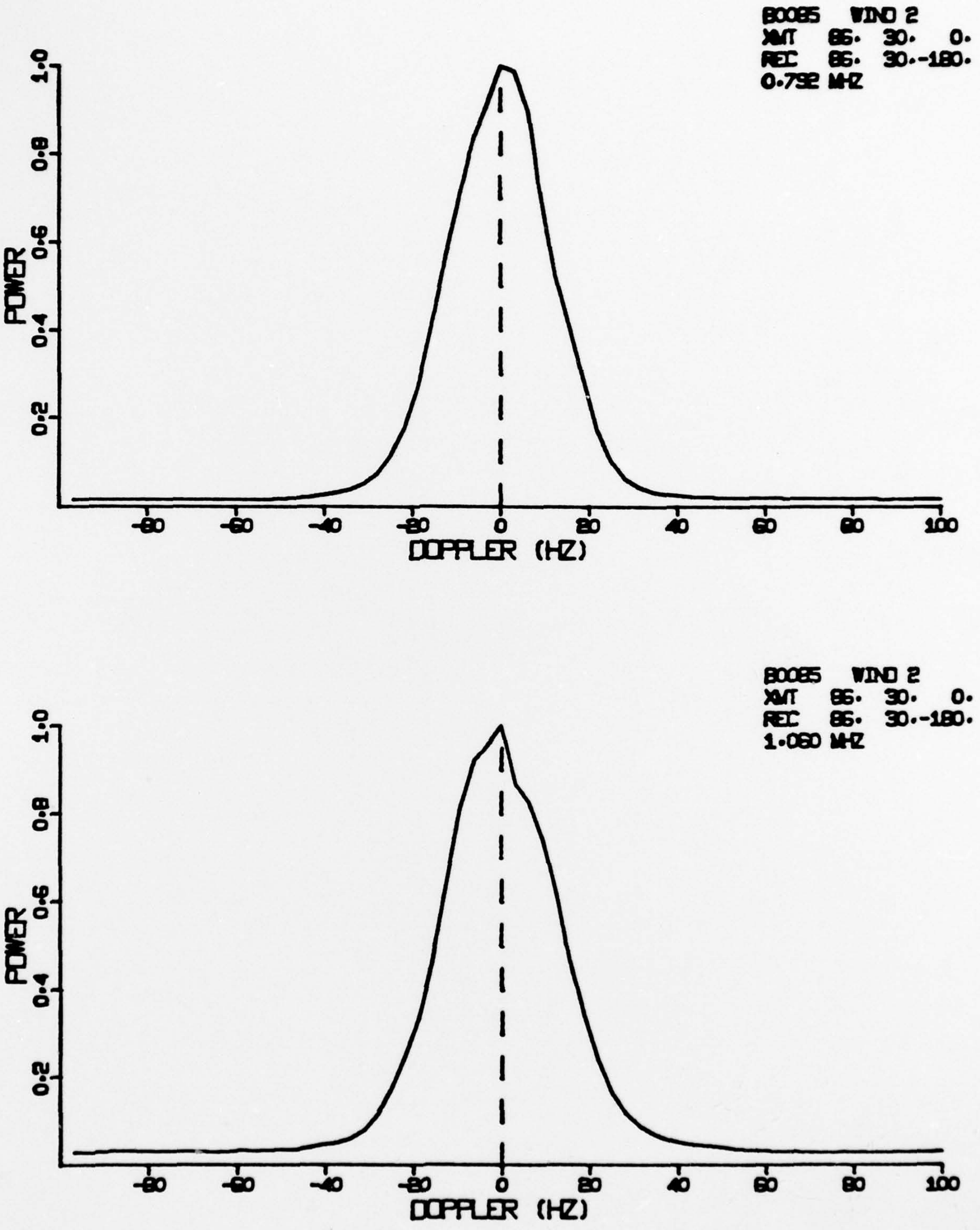

FIG. 10b. Frequency spread at 30 degree grazing, 5.4 m/s wind, downwind

shift can be detected. The reasons for this are probably complex and have to do with the two mechanisms for frequency spreading discussed in (2). However, further study will be required before any conclusions can be drawn from these observations.

The supplemental measurements have been only briefly annotated in this report. It is the authors' intention to continue to study the phenomenon of frequency spreading both theoretically and empirically before drawing any further extensive conclusions. The data thus far taken are included here principally in order to give an indication of the state of progress at the present time.

IV. Surface Slope Measurements

As was mentioned in Section I the measurements of scattering strength at short wavelength have not been adequately explained in terms of an analytical model. One possible reason for this is the failure of current theory to characterize correctly the statistics of the wind driven water surface. Mathematical models used to date have in general relied on assumptions of Gaussian distribution for modelling waveheight and slope. The scattering data, however, indicated that these assumptions might not be accurate enough to permit prediction of scattering strength at low grazing angles. A study of the literature revealed some evidence that the probability density of slopes in wind driven surfaces was in many cases grossly non-Gaussian. It was therefore decided to extend the techniques being used at this facility for waveheight measurement to the measurement of slope statistics. This study is still underway. However, some preliminary measurements have been obtained which indicate significant non-Gaussian slope distribution in both downwind and crosswind directions (Fig. 11-12). It had been

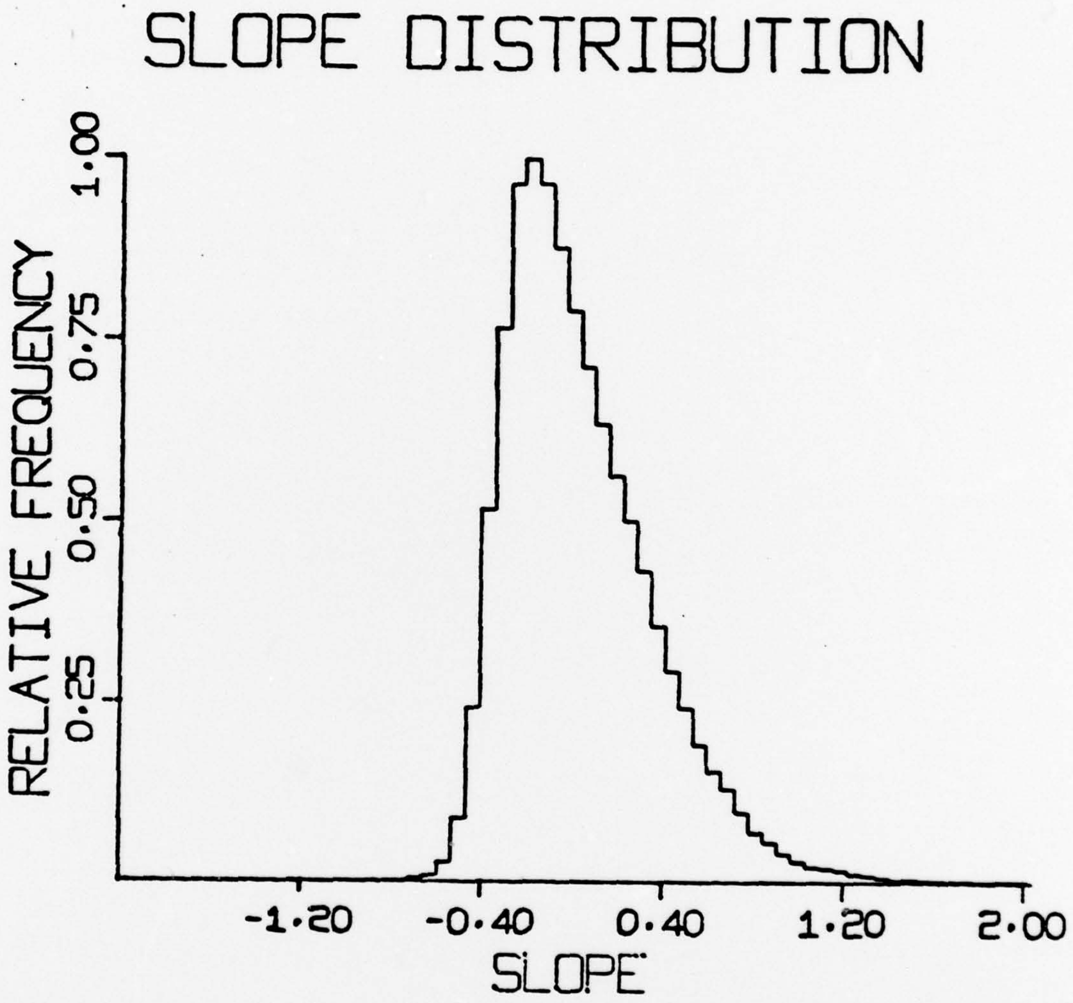

FIG. 11. Measured histogram of wave slopes taken with 1 mm. probe spacing in the up/downwind orientation at Wind 4 (8.3 m/s)

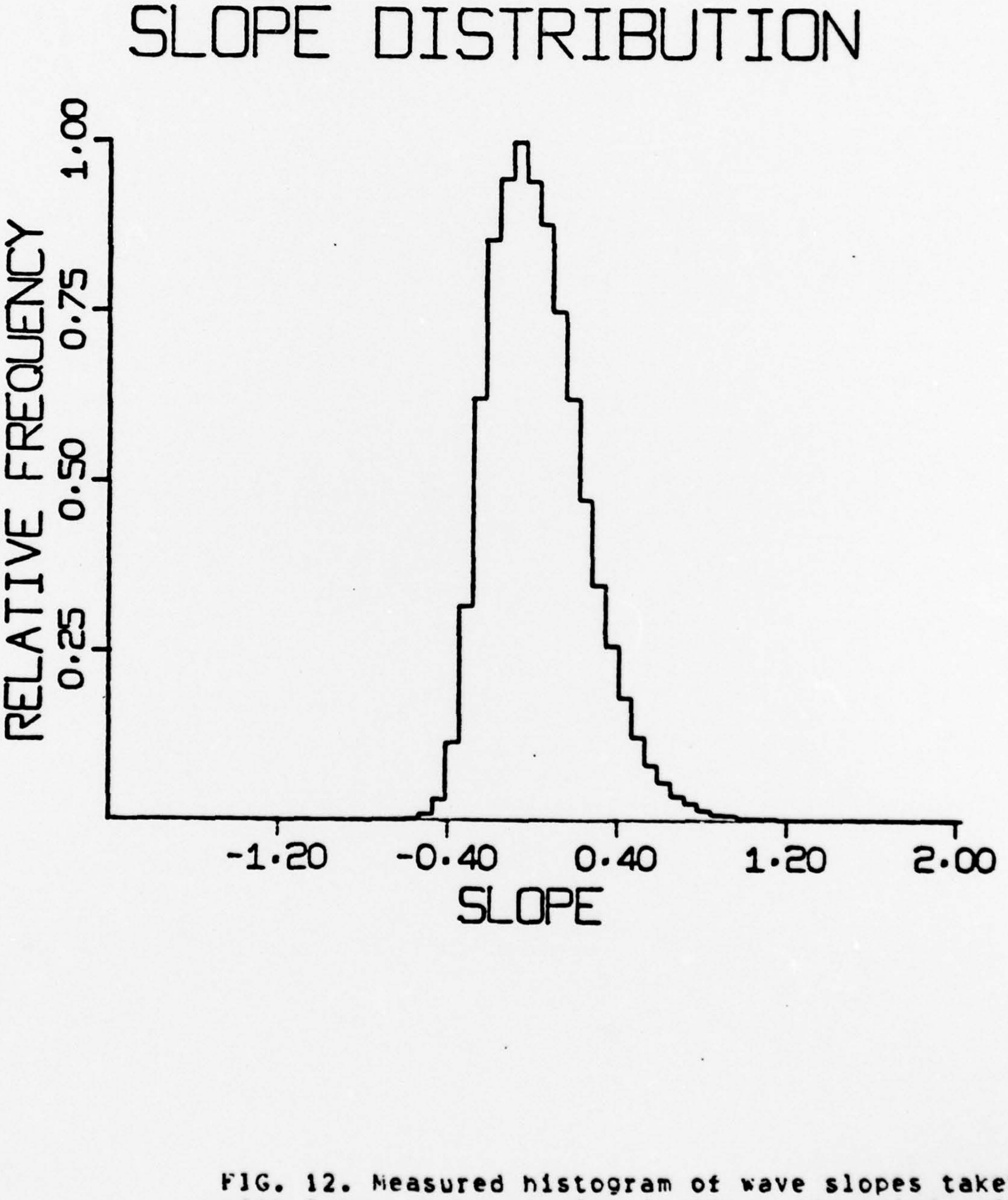

FIG. 12. Measured histogram of wave slopes taken with 1 mm. probe spacing in the up/downwind orientation at wind 2 (5.4 m/s)

hoped that these measurements would yield evidence of surface slopes sufficient to accomodate a facet mechanism of scattering at short wavelengths. This would require evidence of slopes as high as 3.5 for the scattering strength data collected so far. As can be seen no slopes of this magnitude have been detected as yet. In fact no evidence seems to exist in the literature of slopes this high in limited fetch facilities. It should be pointed out, however, that the relative frequency of such slopes required for consistency with measured scattering strengths is extremely small and failure to observe them thus far should not be regarded as a refutation of the facet model. It is our intention to continue to pursue this study and to publish its results. At present, though, there remain substantial obstacles to effective analytical prediction of bistatic scattering strength.

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