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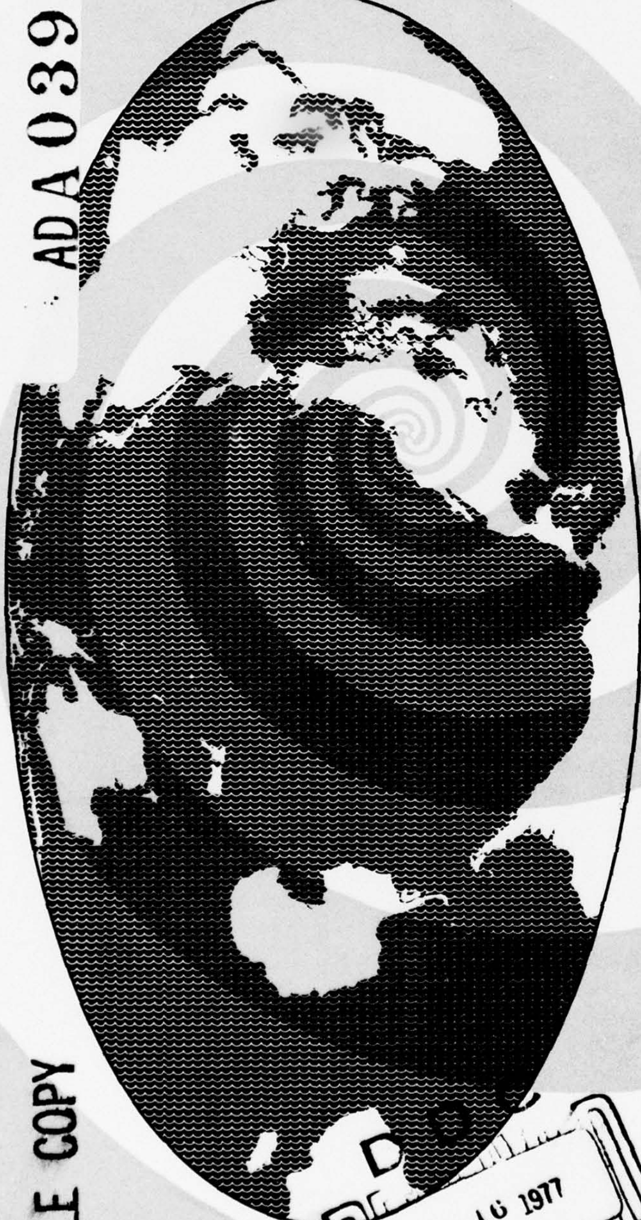

Technical Report No. 351

HOOD CANAL CONDITIONS
CALCULATIONS OF VESSEL ROLL ANGLE

by

L. H. Larsen

Naval Facilities Engineering Command
Contract N62477-76-M-3250

Reference M76-63
June 1976

seattle, washington 98195

UNIVERSITY OF WASHINGTON
DEPARTMENT OF OCEANOGRAPHY
SEATTLE, WASHINGTON 98195

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CALCULATIONS OF VESSEL ROLL ANGLE

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10 Lawrence H. Larsen
Principal Investigator

Francis A. Richards
Associate Chairman for Research

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ABSTRACT

The first part of the report contains a general parametric analysis of the heeling angle of a submarine exposed to currents. The current is assumed to have an arbitrary velocity distribution with respect to depth and to lay within a plane perpendicular to the length axis of the submarine.

In the second part, specific observed current conditions from Hood Canal, Washington are applied. Records from a total of ten current meters are evaluated and applied in computing cumulative histograms of the heeling angle. The "u" and "v" co-ordinate system for the velocity components is rotated (relative to the true North) by two angles (-10 and +50 degrees angular) to reflect actual location of the mooring piers. Also, the effect of both flooding and ebbing currents is evaluated by presenting the analysis for both positive and negative velocity components.

J.G. Dworski :

HEELING ANGLE OF SUBMARINE MOORED NORMAL TO CURRENT FLOW

Introduction

"Trident" class submarines will be moored at open piling piers in Hood Canal and will - therefore - be exposed to fairly strong currents. A project contractor's study proposes a procedure whereby the current velocity would be measured at three depths (5 m, 10 m, 15 m), a quadratic function fitted to these data, and the heeling moment computed considering the submarine hull as a vertical flat plate of same area as the vertical projected area of the actual hull.

Such procedure will overestimate the heeling moment because: as the actual cylindrical surface of the submarine's hull curves away from the vertical, there is - intuitively - less contribution by the "normal drag" and more contribution by the "skin friction" drag. The latter is, however, comparatively small.

This research note decomposes the drag forces into a component normal to the hull surface and a component tangential to it. Also, it uses some experimental data - curve fits - developed by the U.S. Naval Ordinance Test Station in China Lake, California, for drag on inclined surfaces, referred to experiments determining drag in normal flow incidence. The resulting heeling moment is then computed in general vectorial form and covers any placement of the restraining cleats, linking the submarine to the pier. Also, different levels of displacement (immersion) of the submarine are parametrically accounted for.

The main result is that the actual heeling angle will be only about 2/3 of that predicted by the "flat plate" approximation. A "Trident" class submarine will heel over about 5°-6° in 2 kt of current if restrained at cleats flush with the submarine's deck.

Analysis

Geometrical Constraints

Geometrical constraints are shown in Fig. 1.

$$d < 2R, \quad R(\theta) = R(-\sin\theta\,\vec{i} + \cos\,\vec{k}) \qquad (1)$$

$$z = d - R(1 - \cos\theta), \text{ within reach of submarine draft} \qquad (2)$$

$$\text{where } 0 \leq \theta \leq \pi - \alpha \qquad (3)$$

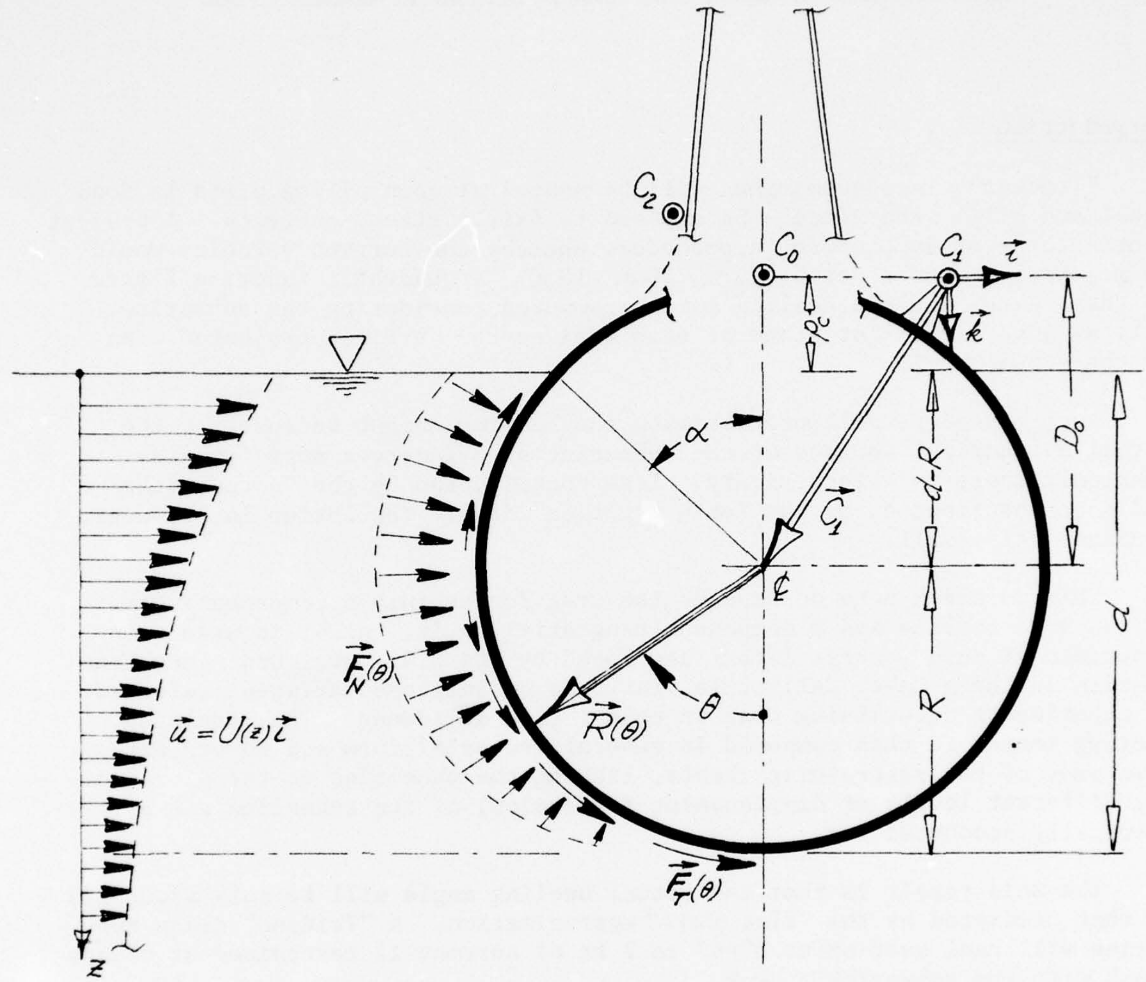


FIG. 1

$$\alpha = \cos^{-1}(d/R - 1) \tag{4}$$

Vector from cleat to ℄ hull, C_1 (or C_2, or C_0) is fixed vector, for example

$$\vec{C}_0 = (d + p_c - R)\vec{k} = D_0\vec{k} \tag{5}$$

because submarine heel angle is assumed to be small.

Normal and Tangential Forces for Decomposition Model

The following model has been developed in a study made for Honeywell Defense Laboratory, Seattle, by Dworski (1965). It is based on data collected by the U.S. Naval Ordinance Test Station, China Lake, California (1962) relating drag on inclined surfaces to wind tunnel and flume tests determining drag under normal (perpendicular) incidence of flow upon the surface. The empirical formula determined therefrom was modified in the above cited report to include certain compatibility relations that become important at large inclinations (where accurate description of tangential forces becomes mandatory). The appropriate schematic is shown in Fig. 2.

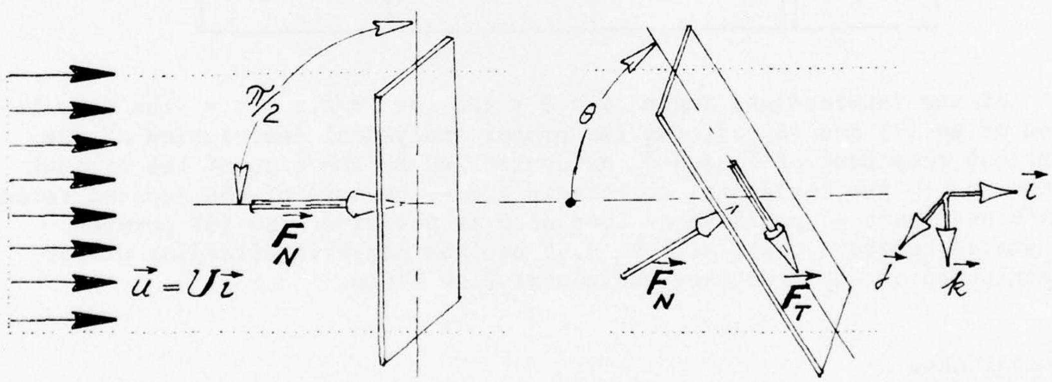


Figure 2

Let $G = C_D \frac{\rho}{2} U|U|$ (force per unit area) (6)

where C_D is the "normal" drag coefficient, ρ the density, and where $|U|$ is the absolute value of U which is to be used so that $U(z)$ may be defined negative for some z (i.e., the flow may reverse at some depth).

Dworski, J.G. (1965) "Mathematical Analysis of Tow Cable Configuration" Honeywell Defense Laboratory, Seattle
Project "Nixie" and Project "Lolita", Classified (above segment detached from Project report and declassified)

Then: $$\vec{F}_N = G\,|sin\,\theta|\,(sin^2\theta\,\vec{i} - sin\,\theta\,cos\,\theta\,\vec{k}) \quad (7)$$

(force per unit area) $$\vec{F}_T = nG|cos\,\theta|\,(cos^2\theta\,\vec{i} + sin\,\theta\,cos\,\theta\,\vec{k}) \quad (8)$$

where $n \simeq 0.02$ is the friction coefficient on a flat plate (a function of the Reynolds number and roughness) multiplied by C_D.

Note that, in Eq (7) and (8), the absolute values $|sin\,\theta|$, $|cos\,\theta|$ permit the angle of inclination θ to go beyond π/2.

Consider, for better visualization, the limiting cases:

from Eq (7) and (8): Table 1

θ	0	π/2	π
$\vec{F}_N$	0	$G\vec{i}$	0
$\vec{F}_T$	$nG\vec{i}$	0	$nG\vec{i}$

At any intermediate angle $0 < \theta < \pi/2$ or $\pi/2 < \theta < \pi$ the formulation of Eq (7) and (8) affords the proper analytical description of the vertical component of $\vec{F}_N$ and $\vec{F}_T$ as controlled by the sign of the product $sin\,\theta\,cos\,\theta$; the horizontal components are -- because of the squared terms $sin^2\theta$ and $cos^2\theta$ -- positive as long as U is positive. Eq (6) permits - as stated before - that, at some z, U becomes negative affording proper description of any arbitrary horizontal flow field.

General Case

Computation of the "heeling" moment (of flow forces on the submarine hull) relative to any fixed restraining point (cleat point) is facilitated by the vectorial decomposition shown in Figure 1, decomposing that moment into two integrals for each of the force subsets ($\vec{F}_N$ and $\vec{F}_T$):

(a) moment relative to the center of the cylindrical hull, which is zero for the normal forces $\vec{F}_N$.

(b) moment relative to the fixed point - related to the center of the hull:

Consider a unit width (Δy = 1 ft) strip of the submarine hull (the y axis, and the unit vector $\vec{j}$ associated with it, are positive out of the plane in Fig. 1; moments are positive when inducing a mathematically positive (counterclockwise) rotation about the fixed point)

Then the heeling moment relative to C_1 or C_2 (or C_o) is given by the vector (outer or cross) product integrals:

$$M_{C_i} = \int_0^{\pi-\alpha} [\vec{R}(\theta) \times \vec{F}_T(\theta,\vec{u})]\, R\, d\theta + \int_0^{\pi-\alpha} [\vec{C}_i \times \vec{F}_T(\theta,u)]\, R\, d\theta$$

$$i=0, \text{ or } 1, \text{ or } 2 \quad + \int_0^{\pi-\alpha} [\vec{R}(\theta) \times \underbrace{\vec{F}_N(\theta,\vec{u})}_{\equiv 0}]\, R\, d\theta + \int_0^{\pi-\alpha} [\vec{C}_i \times \vec{F}_N(\theta,\vec{u})]\, R\, d\theta \qquad (9)$$

Note that the current shear $\frac{dU}{dz}$ is reflected in description of $\vec{F}_N$ and $\vec{F}_T$ through Eq (6) in conjunction with Eq (2). For example: if the current profile were given as a quadratic function of depth:

$$U(z) = a_o + a_1 z + a_2 z^2 \qquad (10)$$

Then using Eq (2), within reach of the submarine draft:

$$U(\theta) = a_o + a_1 [d - R(1 - \cos\theta) + a_2[d - R(1 - \cos\theta)]^2 \qquad (11)$$

so that for $\theta = 0$, $U(\theta=0) = U(d) = a_o + a_1 d + a_2 d^2$ (12)

and for $\theta = \pi-\alpha$, $U(\theta=\pi-\alpha) = U(o) = a_o$ (13)

where Eq (13) follows from the fact that by Eq (4): $\cos(\pi-\alpha) = 1 - d/R$

In general, whenever the current has a z dependence, Eq (9) is best evaluated by a small computer program to avoid the messy algebra.

If the current were independent of z one can easily evaluate Eq (9) in analytic form, as shown in the following specialization.

Special Case, Analytical Solution

Assume current to be independent of depth and assume the cleat position to be at the center-plane of the submarine (i.e., at C_o). Evaluate the heeling moment M_{C_o} term-by-term, using $R(\theta)$ as defined by Eq (1):

$$\int_0^{\pi-\alpha} [\vec{R}(\theta) \times \vec{F}_T(\theta,U)]\, R\, d\theta = \vec{j}\, nGR^2 \int_0^{\pi-\alpha} |\cos\theta| \cos\theta \, d\theta$$

using symmetry:

$$= \vec{j}\, nGR^2 \int_0^{\alpha} \cos^2\theta \, d\theta$$

$$= \vec{j}\, nGR^2 \left(\frac{\pi}{2} + \frac{\sin 2\alpha}{4}\right) \quad (14)$$

(This is a moment per unit length of the submarine hull)

The next two contribution integrals (to Eq. 9) involve the fixed vector $\vec{C}_o$ which was defined by Eq (5):

$$\vec{C}_o = (d + p_c - R)\vec{k} = D_o\vec{k} \quad (15)$$

$$\int_0^{\pi-\alpha} [\vec{C}_o \times \vec{F}_T(\theta,U)]\, R\, d\theta = \vec{j}\, nGRD_o \int_0^{\pi-\alpha} |\cos\theta| \cos^2\theta \, d\theta$$

$$= \vec{j}\, nGRD_o\{2 \int_0^{\pi/2} \cos^3\theta \, d\theta - \int_0^{\alpha} \cos^3\theta \, d\theta\}$$

$$= \vec{j}\, nGRD_o \left(\frac{4}{3} - \sin\alpha + \frac{\sin^3\alpha}{3}\right) \quad (16)$$

$$\int_0^{\pi-\alpha} [\vec{C}_o \times \vec{F}_n(\theta,U)]\, R\, d\theta = \vec{j}\, GRD_o \int_0^{\pi-\alpha} |\sin\theta| \sin^2\theta \, d\theta$$

$$= \vec{j}\, GRD_o\{2 \int_0^{\pi/2} \sin^3\theta \, d\theta - \int_0^{\alpha} \sin^3\theta \, d\theta\}$$

$$= \vec{j}\, GRD_o \left(\frac{2}{3} + \cos\alpha - \frac{\cos^3\alpha}{3}\right) \quad (17)$$

The results of Eq (16) and (17) represent - as was the case of Eq (14) - contributing moments per unit length of the submarine hull.

Comparison of Complete Analysis to an Engineering Approximation

For a submarine of the "Trident" class, one of the project contractors intends to use a heeling moment computation that:

(a) Takes into account possible vertical shear of the current impinging upon the hull by means of a quadratic function described in our Eq (10).

(b) Computes the heeling moment of the submarine by a formula that effectively models the submarine hull as a flat plate (perpendicular to the current), of area equal to the projected area of the actual submarine hull.

It was item (b) that motivated the subject research note, with the intuitive notion that the above approximation (flat plate) is overly conservative in the sense that it would predict too large a heeling moment. The question remained: by how much? In absence of current shear, this question can be answered by a simple parametric analysis, as follows:

Assumptions: Both analyses use the same C_D (drag coefficient) for a plate element under normal incidence of flow.

The heeling angle is (for small angles) linearly proportional to the heeling moment and the ratio of the two computed moments (per unit length of submarine hull) will be the ratio of the resulting angles.

Under this assumption both analyses are performed with the same function G, defined by Eq (6). Using terminology of Fig. 1:

"Flat Plate" Analysis

$$M_{C_o} = \vec{j} \int_0^d (z + p_c)\, G\, dz$$

$$= \vec{j}\, Gd \left(\frac{1}{2} d + p_c\right) \tag{18}$$

Eq (18) can be compared to the sum of Eq (14), (16) and (17) using the following geometrical relations (from Fig. 1):

$$d = R(1 + \cos\alpha) \tag{19}$$

$$D_o = R\cos\alpha + p_c \tag{20}$$

$$R/D_o = \frac{1}{\cos\theta + \frac{p_c}{R}} \tag{21}$$

Then, the "flat plate" analysis yields:

$$|M_{C_O}|_{F.P.} = GRD_O \cdot (1 + \cos\alpha) \cdot [1 + \frac{1}{2}\frac{R}{D_O}(1 - \cos\alpha) \tag{22}$$

When the same relations are applied to Eq (14) thru (17), the complete analysis yields:

"complete analysis"

$$|M_{C_O}| = GRD_O \cdot \left\{\left(\frac{2}{3} + \cos\alpha - \frac{\cos^3\alpha}{3}\right) + n\left(\frac{4}{3} - \sin\alpha + \frac{\sin^3\alpha}{3}\right) + n\frac{R}{D_O}\left(\frac{\alpha}{2} + \frac{\sin 2\alpha}{4}\right)\right\} \tag{23}$$

It is easy to see that for small α (refer to Fig. 1); i.e., for a fully loaded submarine, the ratio of Eq (23) to (22) is

$$\frac{M_{C_O}}{M_{C_O\,F.P.}} = \left(\frac{1 + \cos\alpha}{\frac{2}{3} + \cos\alpha - \frac{\cos^3\alpha}{3}}\right)^{-1} = \left(\frac{2}{3}\right) \quad \text{for } \alpha \to 0 \tag{24}$$

with $n \simeq 0.02$, and $R/D_O \simeq 1$

Thus, indeed, the approximate engineering analysis is conservative, in fact, possibly too conservative because it seems that for dockside operations on the "Trident" type submarines even small heeling angles would be only reluctantly tolerated.

Illustrative Quantification

The analysis refered to on p. (the "flat plate" approximation) ends with an estimate of the heeling angle:

$$\Theta_{F.P.} = \tan^{-1}\left(\frac{\overline{R_{es}} \times (p_r + p_c)}{\Delta(2240)\ \overline{GM}}\right) \tag{25}$$

where $\overline{R_{es}}$ is the force resultant on the submarine hull, and $(p_r + p_c)$ its moment arm relative to C_O. Δ is the submarine's displacement in "longtons", $\overline{GM}$ is the metacentric height in (feet) and 2240 converts tons into pounds.

Actually, in our terminology, with L the length of the submarine:

$$\Theta_{F.P.} = \tan^{-1}\left[\frac{M_{C_O F.P.} \times L}{\Delta(2240)\overline{GM}}\right]$$

$$= \tan^{-1}\frac{GR^2\frac{D_O}{R}(1+\cos\alpha)[1+\frac{1}{2}\frac{R}{D_O}(1-\cos\alpha)] \times L}{\gamma \times R^2(\pi-\alpha+\sin\alpha\cdot\cos\alpha) \times L \times \overline{GM}}$$

$$= \tan^{-1}\frac{G\frac{D_O}{R}(1+\cos\alpha)[1+\frac{1}{2}\frac{R}{D_O}(1-\cos\alpha)]}{\gamma \times (\pi-\alpha+\sin\alpha\cdot\cos\alpha) \times \overline{GM}} \tag{26}$$

where γ is the "specific weight", $\gamma = \rho g$, of the water and the simplification cancelling L and R is possible considering the submarine hull as partially submerged cylinder. Going even further, using Eq (6) and assuming α to be small:

$$\Theta_{F.P.} \simeq \tan^{-1}\left[\frac{C_D U^2 \frac{D_O}{R}}{\pi g \overline{GM}}\right] \tag{27}$$

with $C_D \simeq 1.2$, $U = 2$ kt $= 3.37$ ft/s, $D_O/R \simeq 1.1$ and $\overline{GM} \simeq 1$ ft, we get

$\underline{\Theta_{F.P.} \simeq 8.4°}$ while a better estimate, using results of our

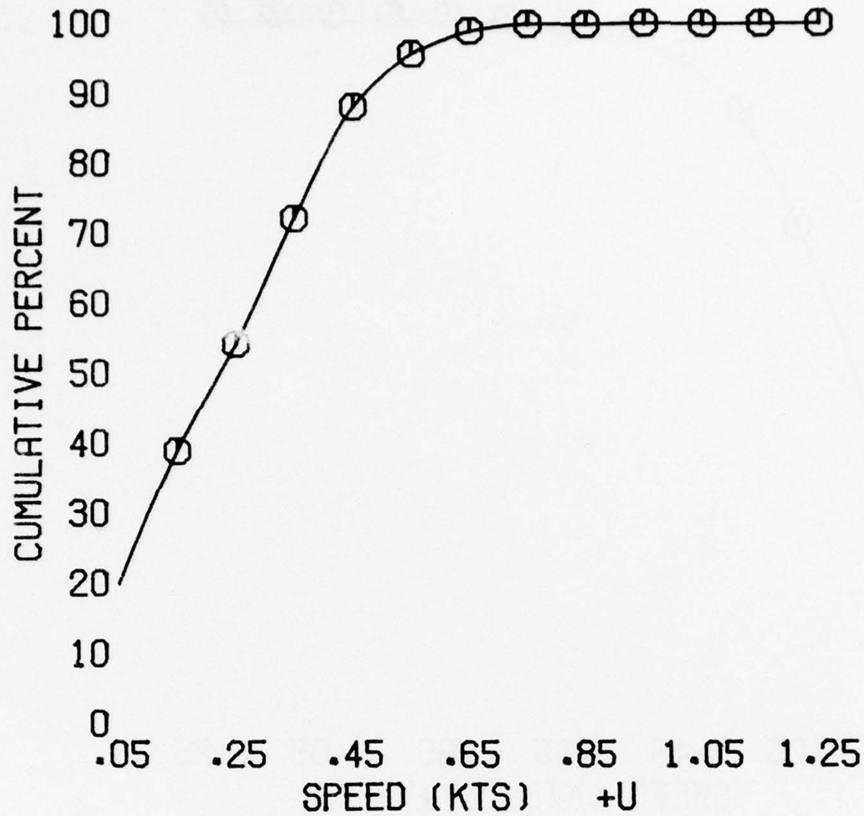
Eq (24) is $\underline{\underline{\Theta \simeq 5.6°}}$

This completes the analysis by J. G. Dworski. Some results, computed from actual currents in Hood Canal, by L. H. Larsen follow and are shown in the figures hereafter.

FIGURES

In the following we show the results of applying EQ (27) to the observations. The parameters are as listed below EQ (27). Half-hour averaged data was used. Because the half-hourly average data underestimates peak currents the results tend to underestimate the instantaneous roll as given by (27). Also, note that the angle is almost linear with respect to the argument in (27). Thus, for example, if we halve $\overline{GM}$ the angles are doubled.

The cumulative plots are labeled with the current meter number and the start time for the deployment of the instrument. In all cases the valid data from the entire deployment is used.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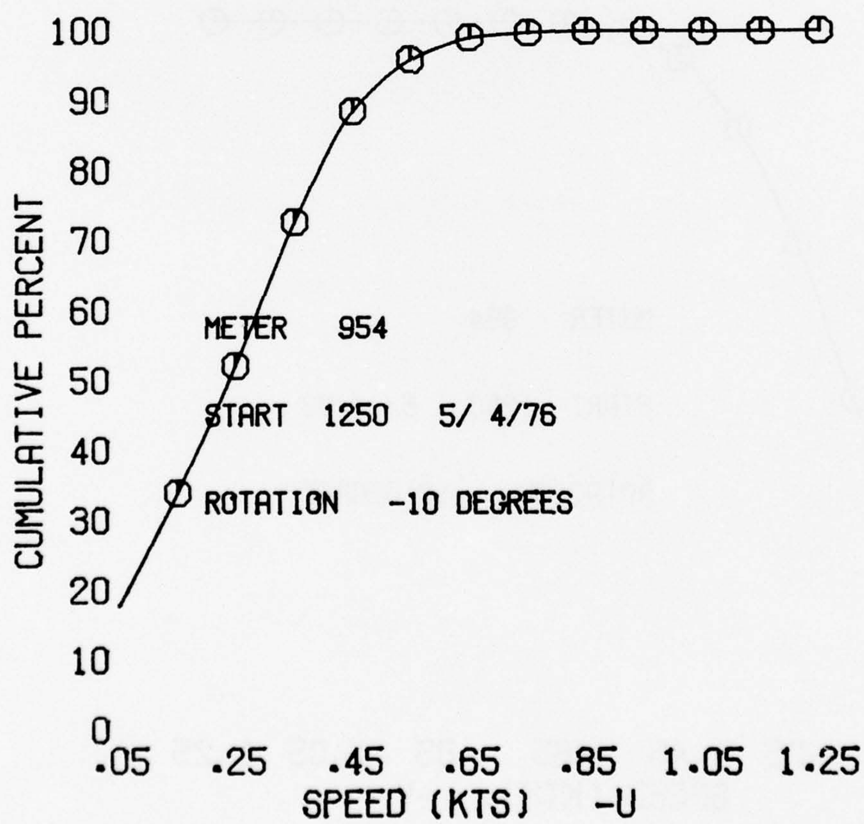
SPEED (KTS) +U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CUMULATIVE PERCENT
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START 1250 5/ 4/76
ROTATION -10 DEGREES
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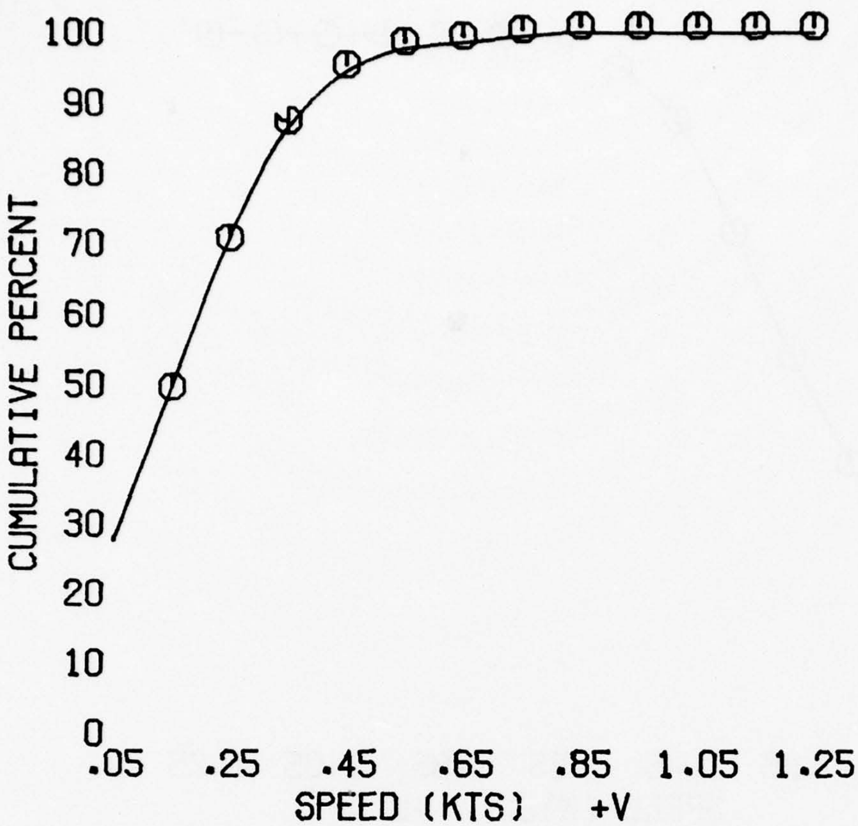
SPEED (KTS) -U

FIG. 1A. AND 1B.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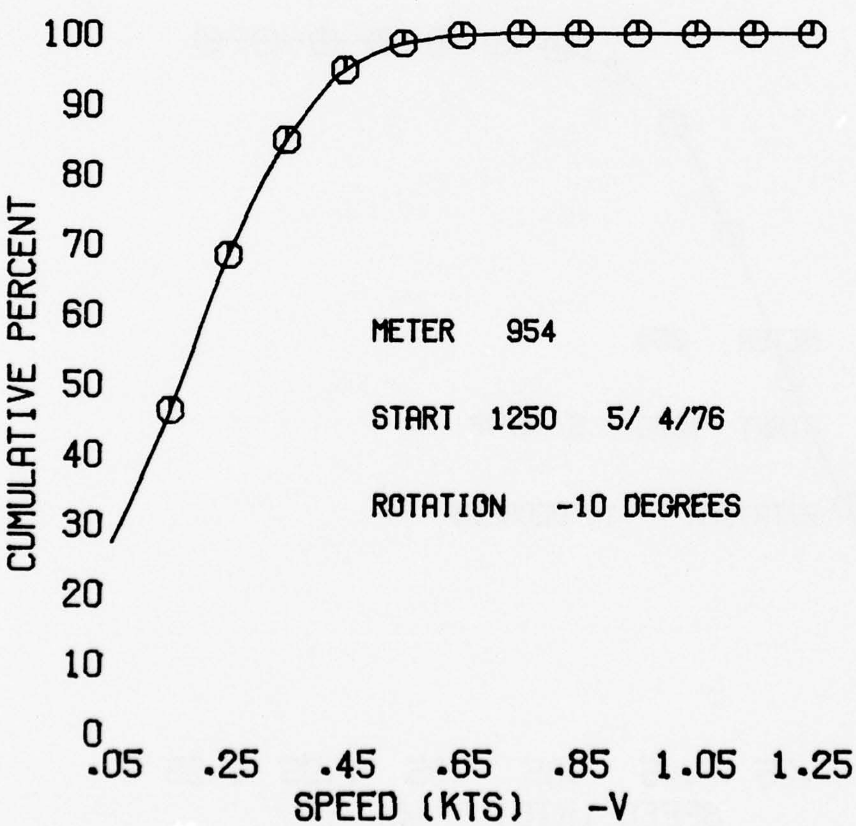
SPEED (KTS) +V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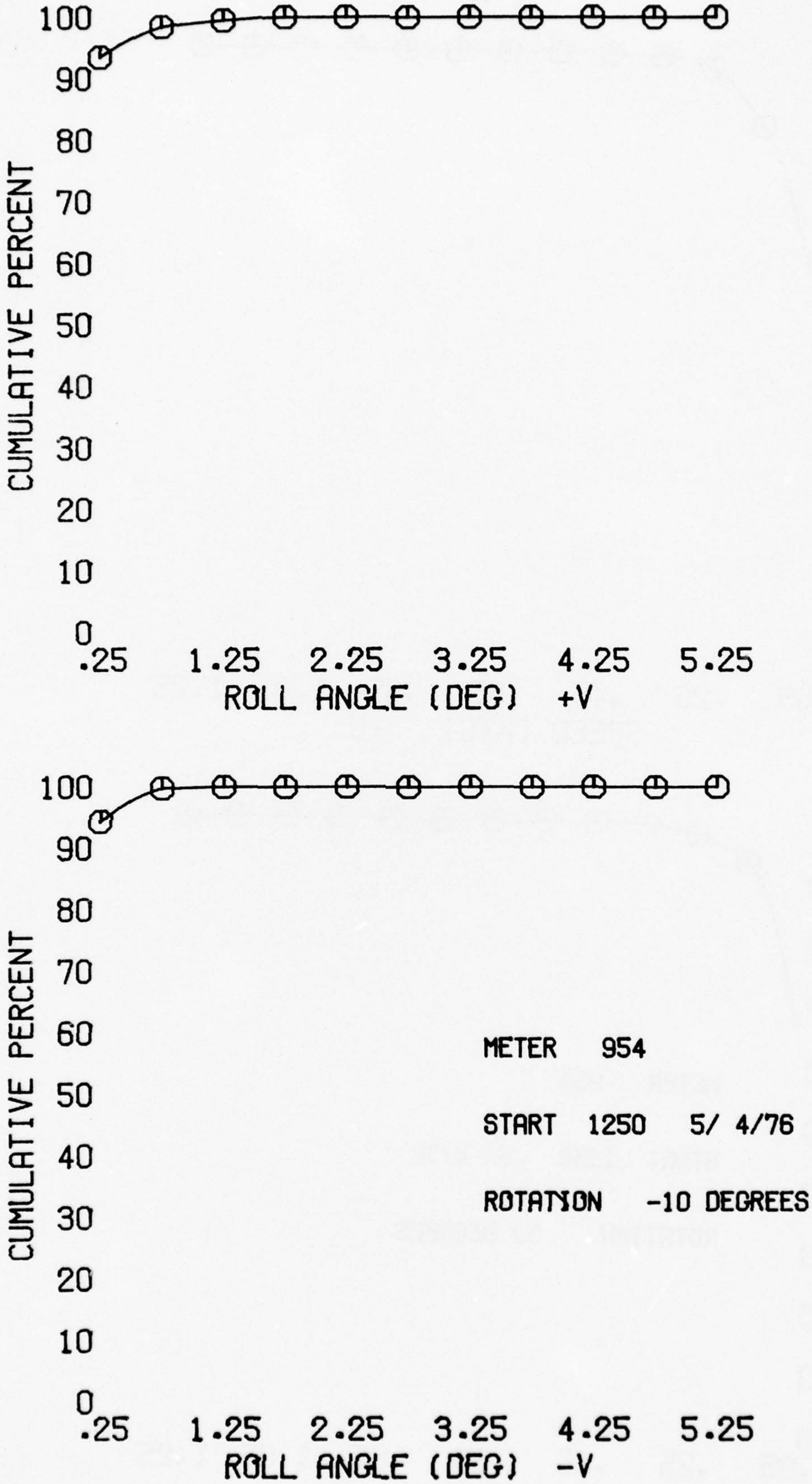
SPEED (KTS) -V

FIG. 2A AND 2B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ROLL ANGLE (DEG) +V
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CUMULATIVE PERCENT
METER 954
START 1250 5/ 4/76
ROTATION -10 DEGREES
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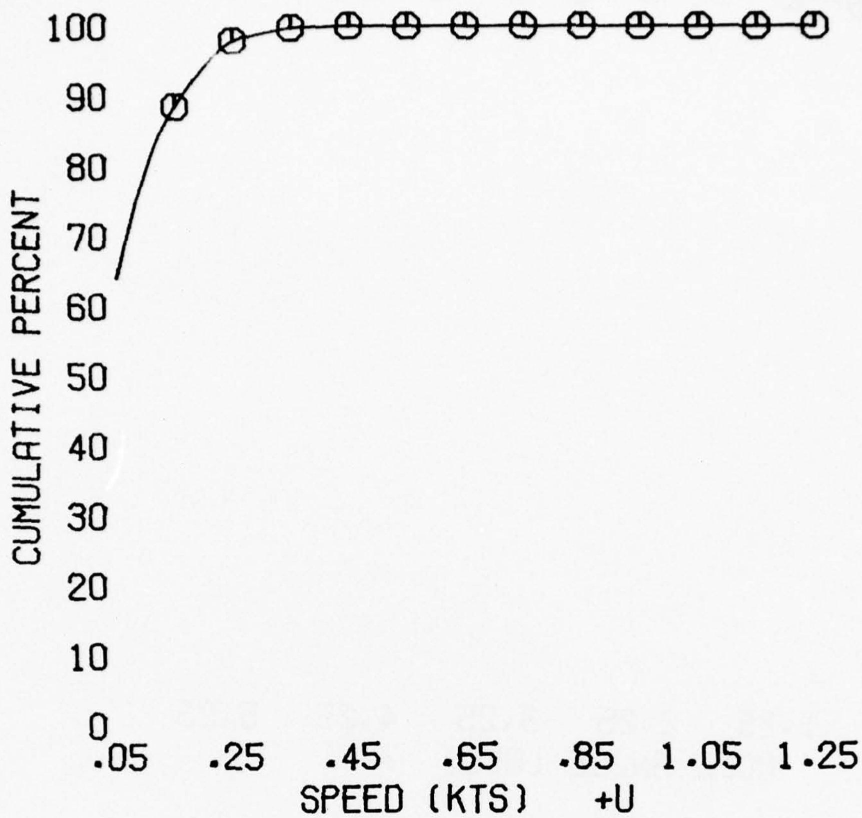
ROLL ANGLE (DEG) -V

FIG. 3A AND 3B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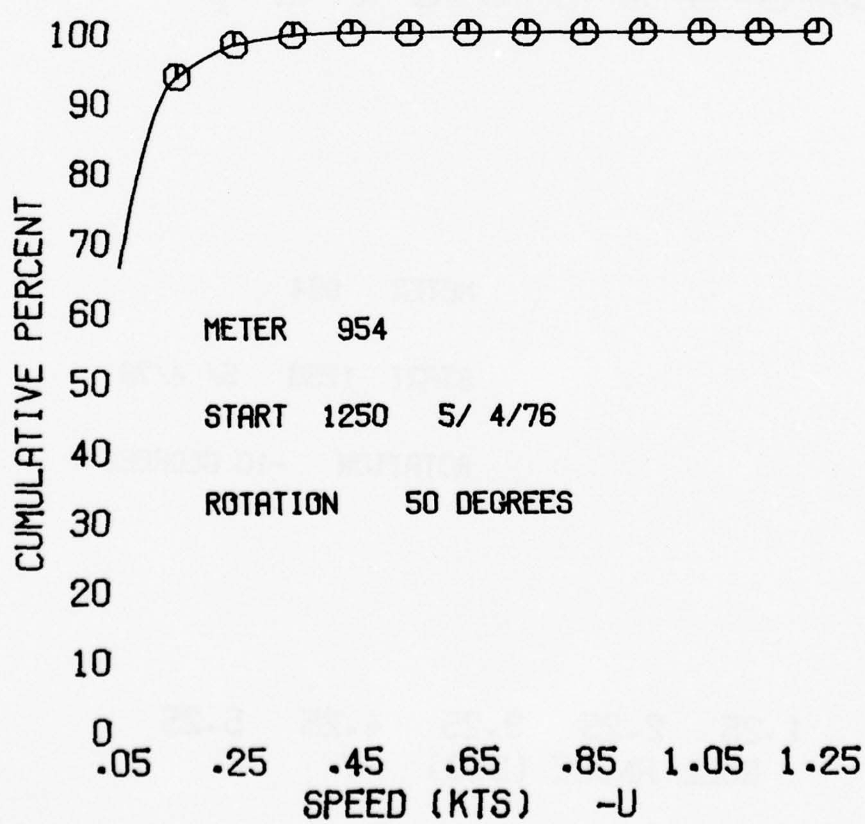
SPEED (KTS) +U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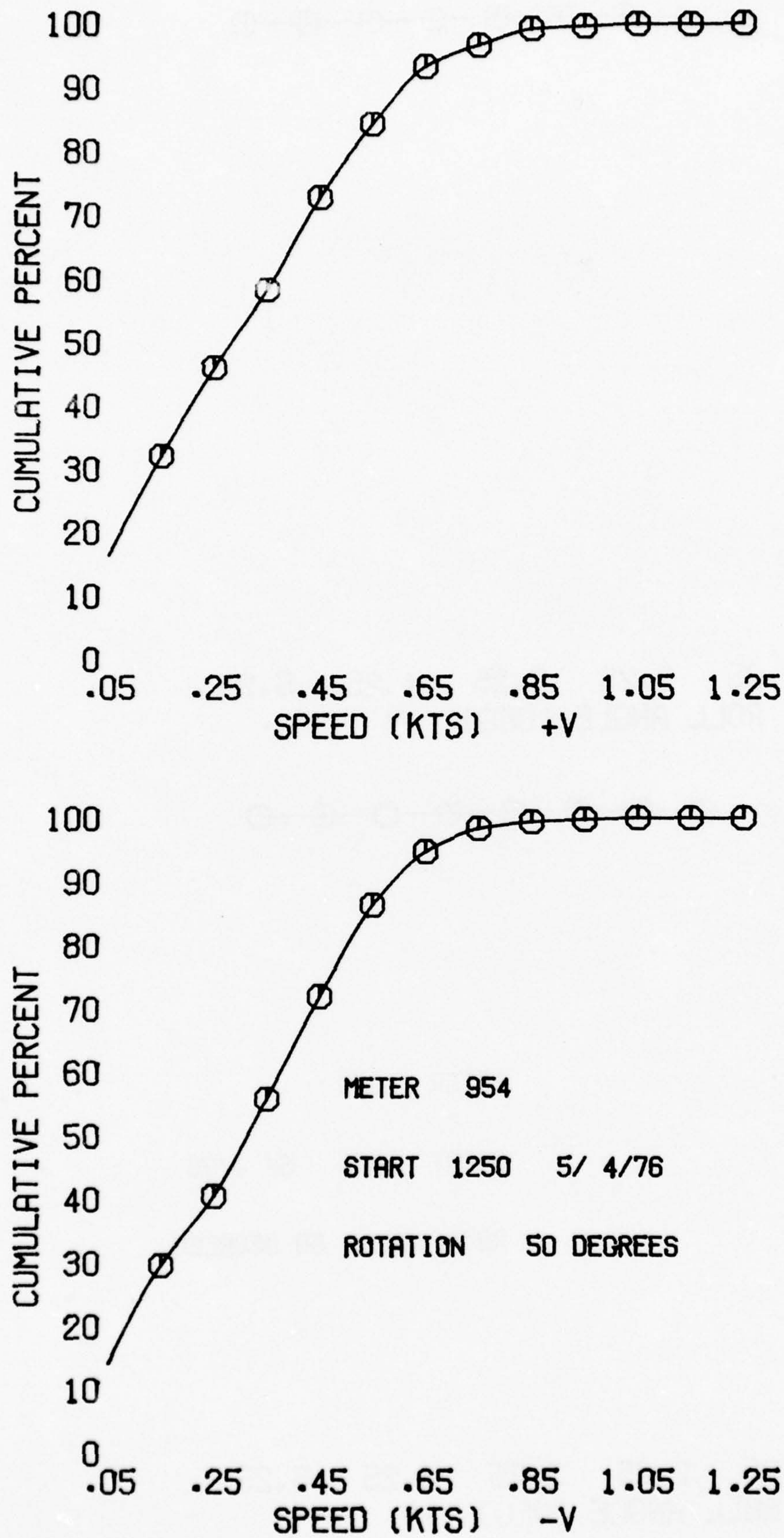
SPEED (KTS) -U

FIG. 4A AND 4B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SPEED (KTS) +V
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CUMULATIVE PERCENT
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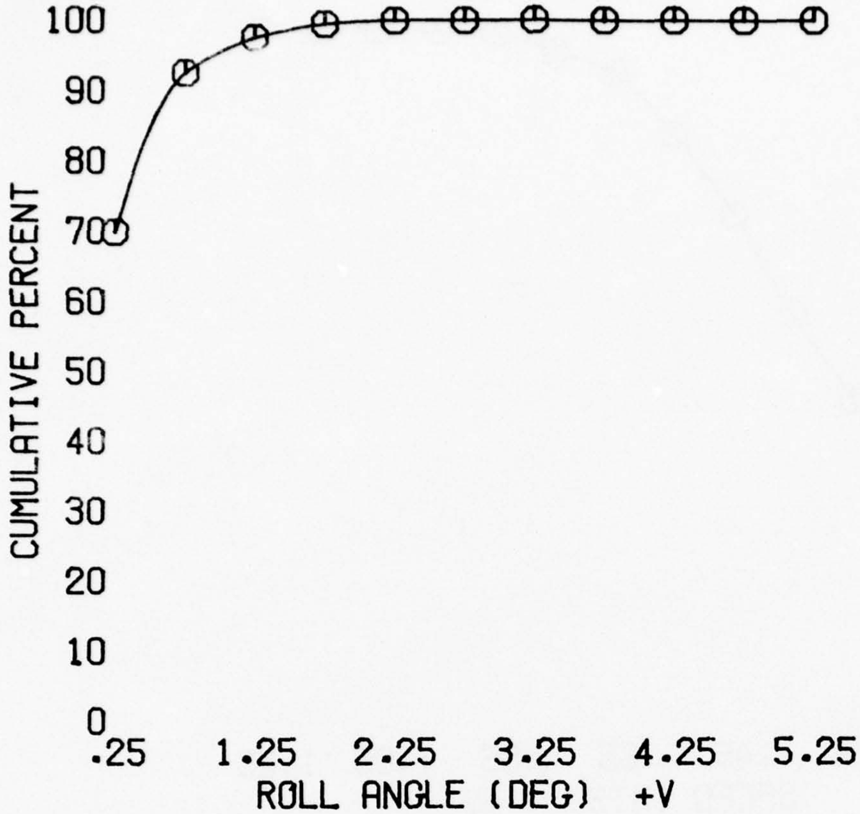
SPEED (KTS) -V

FIG. 5A AND 5B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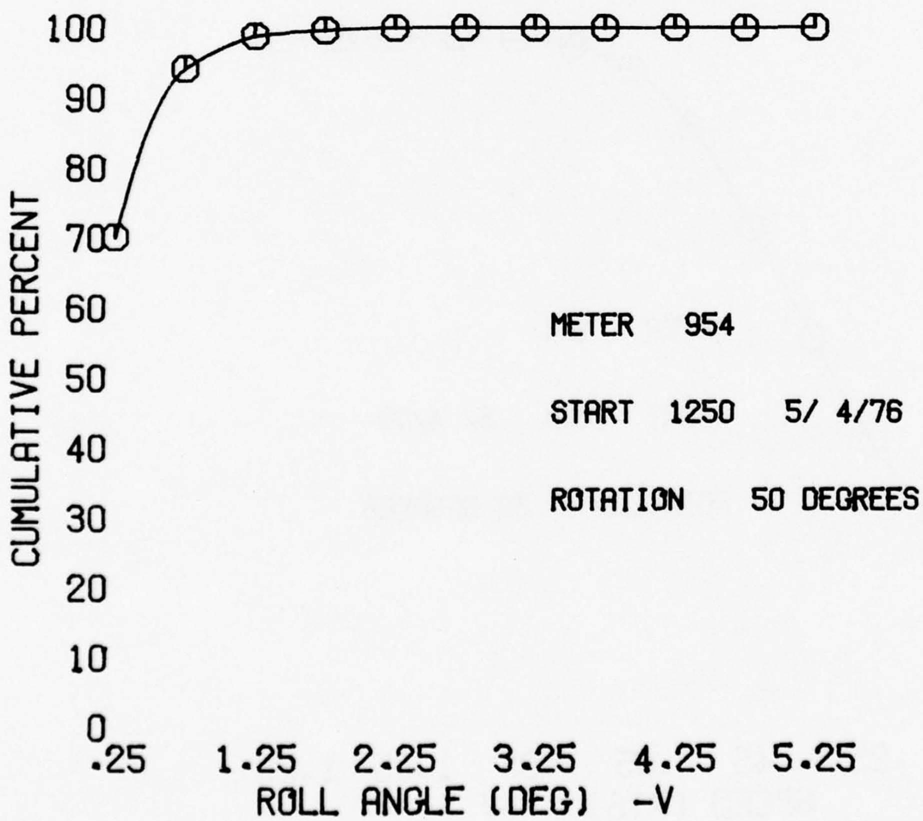
ROLL ANGLE (DEG) +V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ROTATION 50 DEGREES
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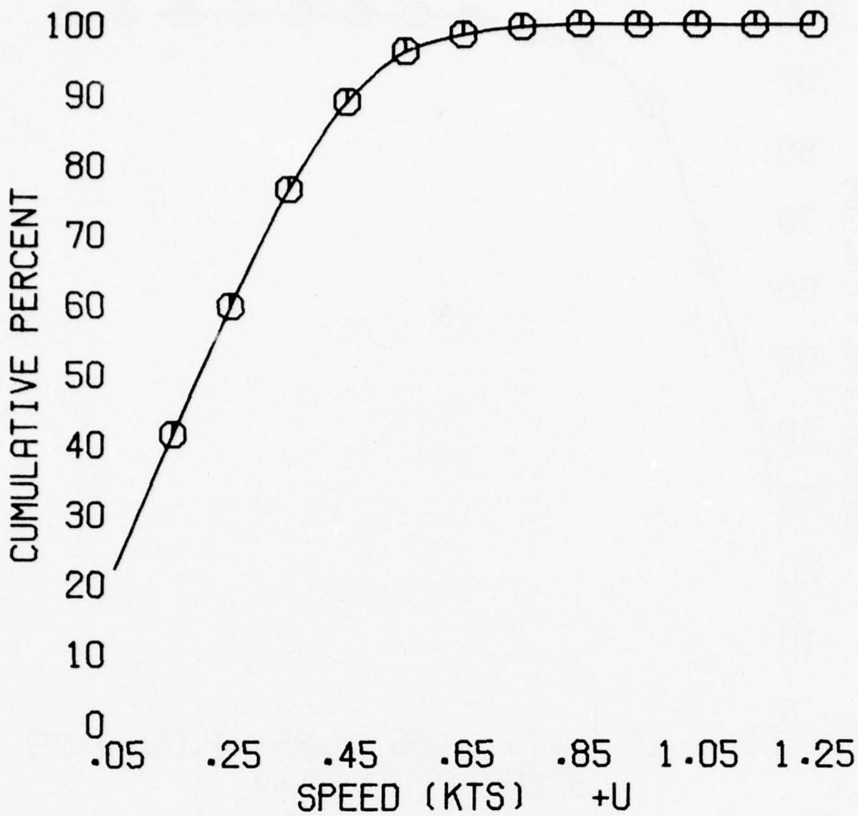
ROLL ANGLE (DEG) -V

FIG. 6A AND 6B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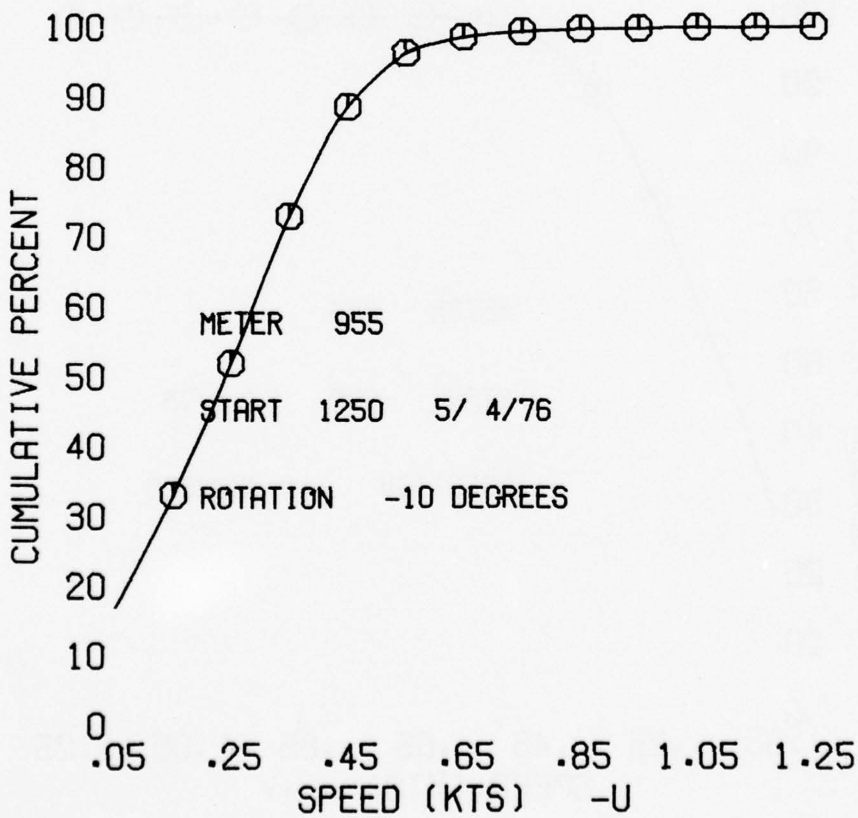
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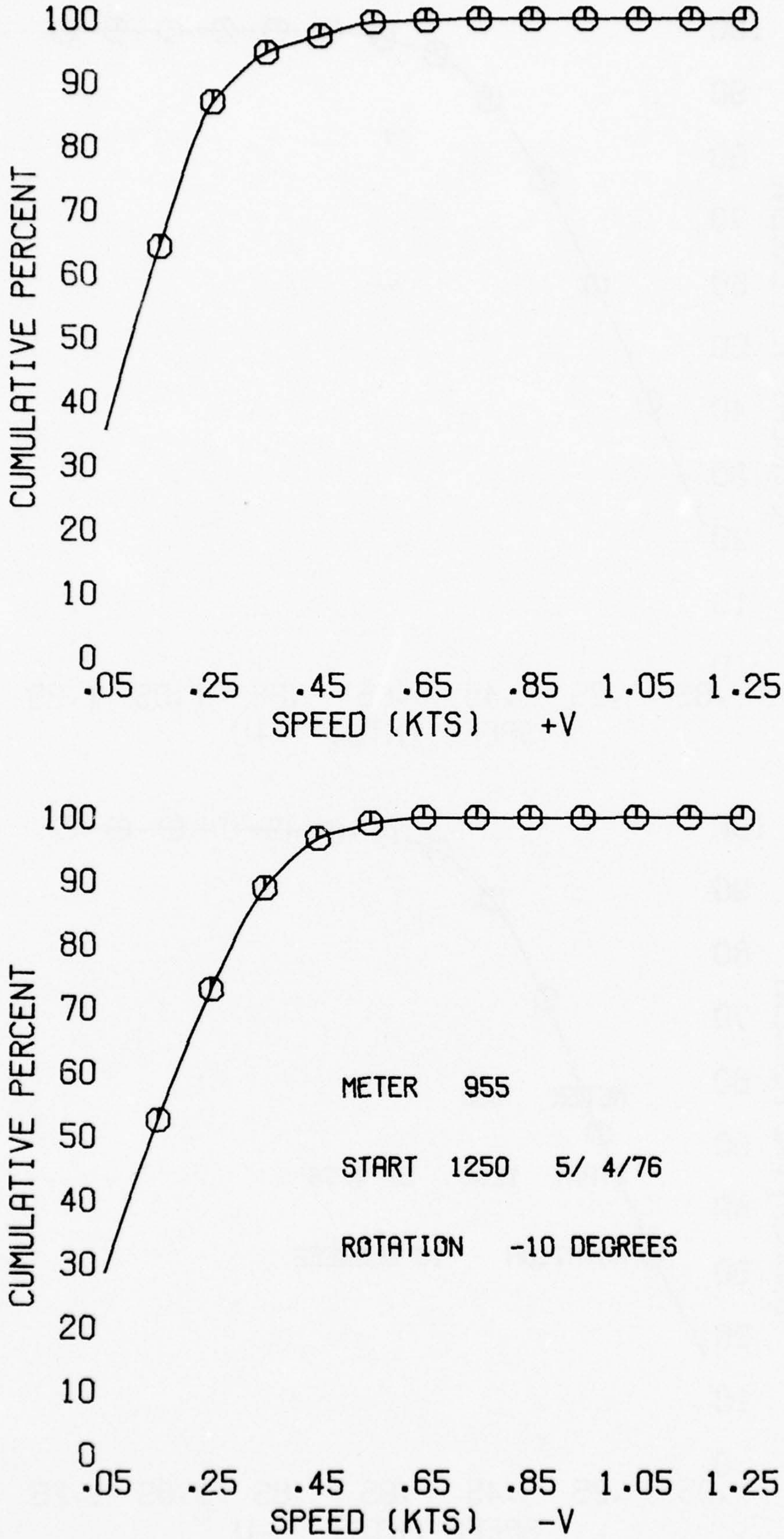
METER 955
START 1250 5/ 4/76
ROTATION -10 DEGREES

FIG. 7A AND 7B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METER 955
START 1250 5/ 4/76
ROTATION -10 DEGREES
.05 .25 .45 .65 .85 1.05 1.25
SPEED (KTS) -V

FIG. 8A AND 8B

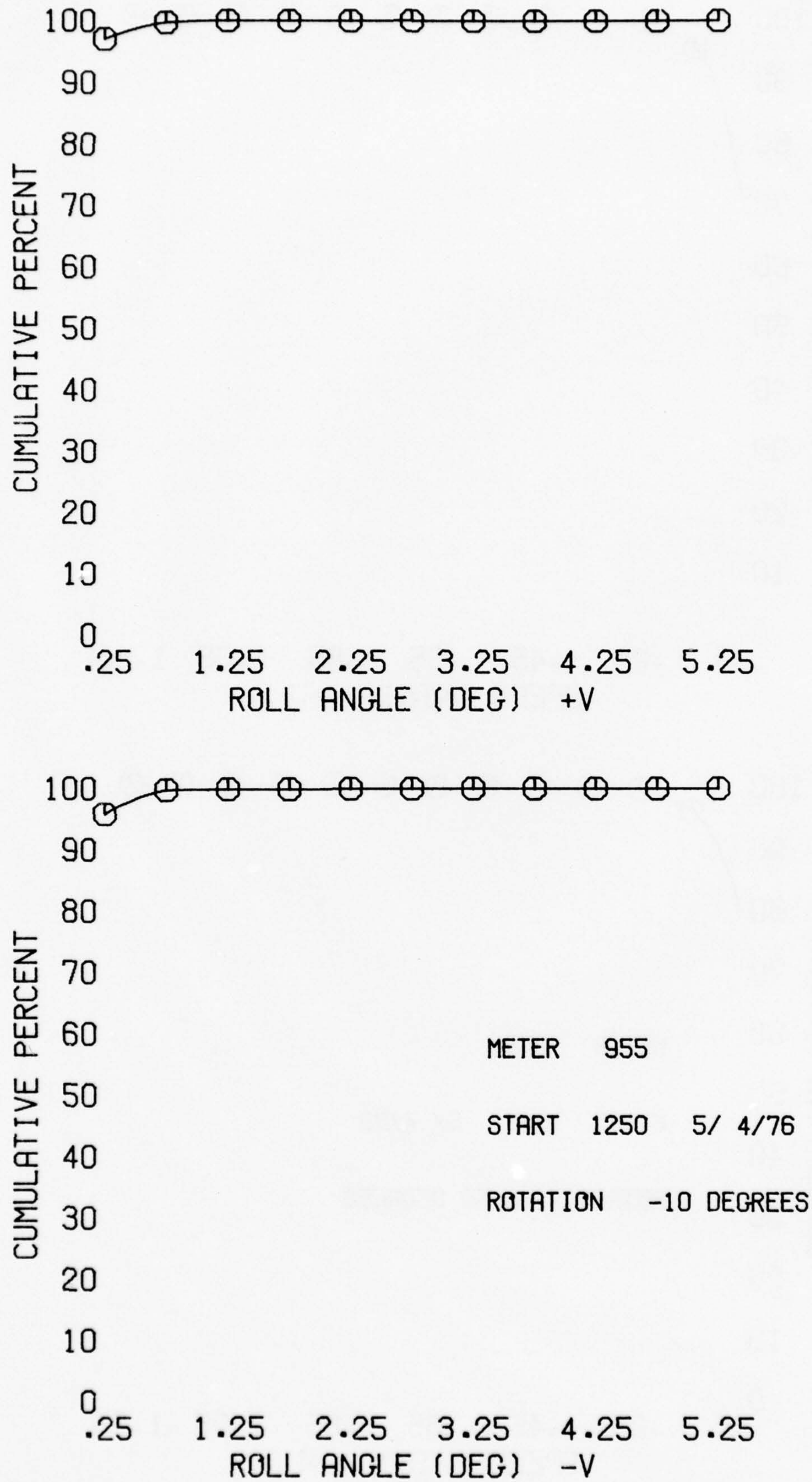
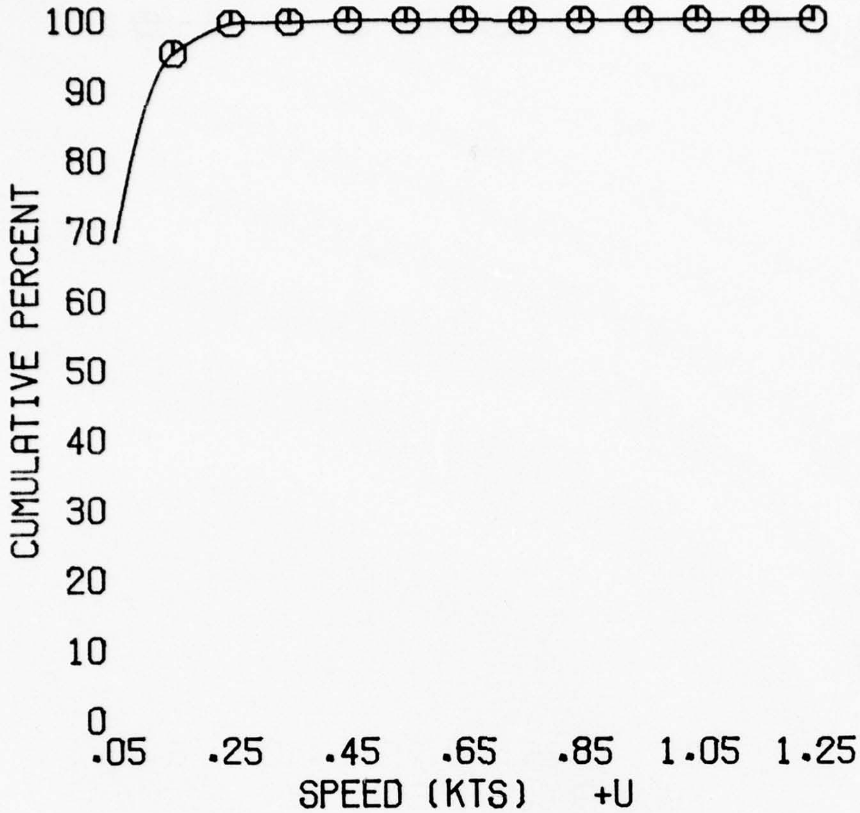

100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE PERCENT
.25 1.25 2.25 3.25 4.25 5.25
ROLL ANGLE (DEG) +V
100
90
80
70
60
50
40
30
20
10
0
CUMULATIVE PERCENT
METER 955
START 1250 5/ 4/76
ROTATION -10 DEGREES
.25 1.25 2.25 3.25 4.25 5.25
ROLL ANGLE (DEG) -V

Fig. 9a and 9b



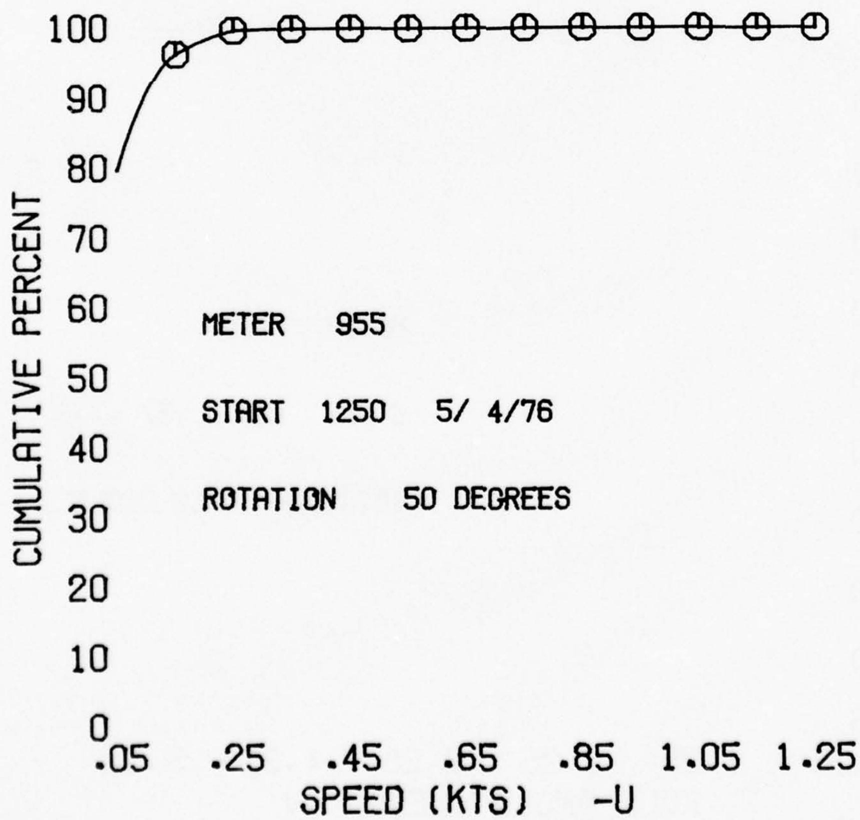
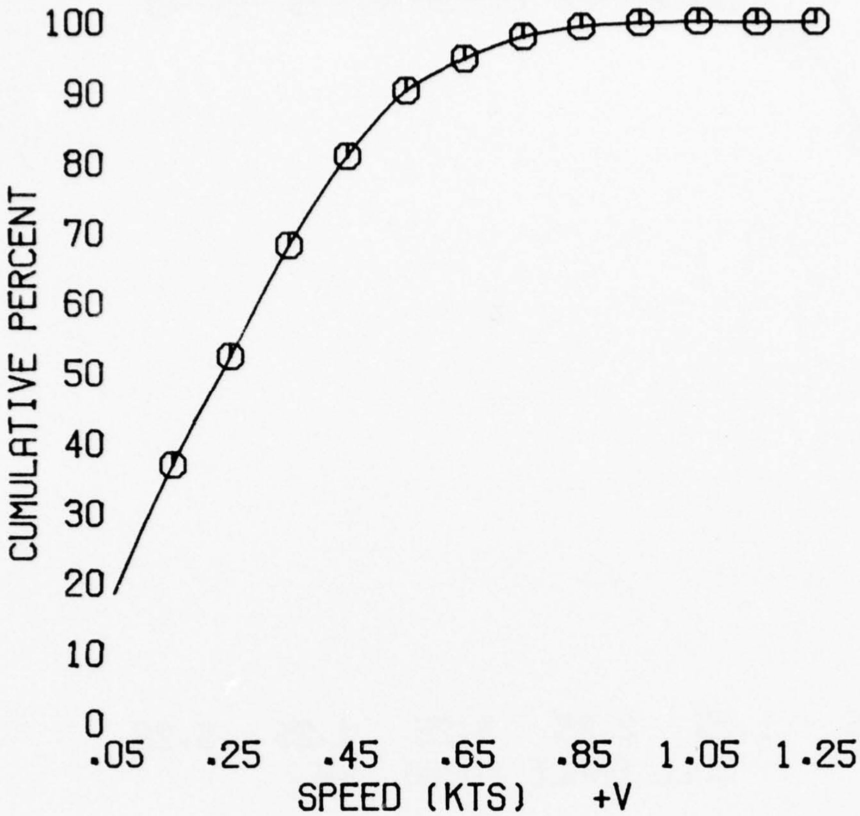


FIG. 10A AND 10B



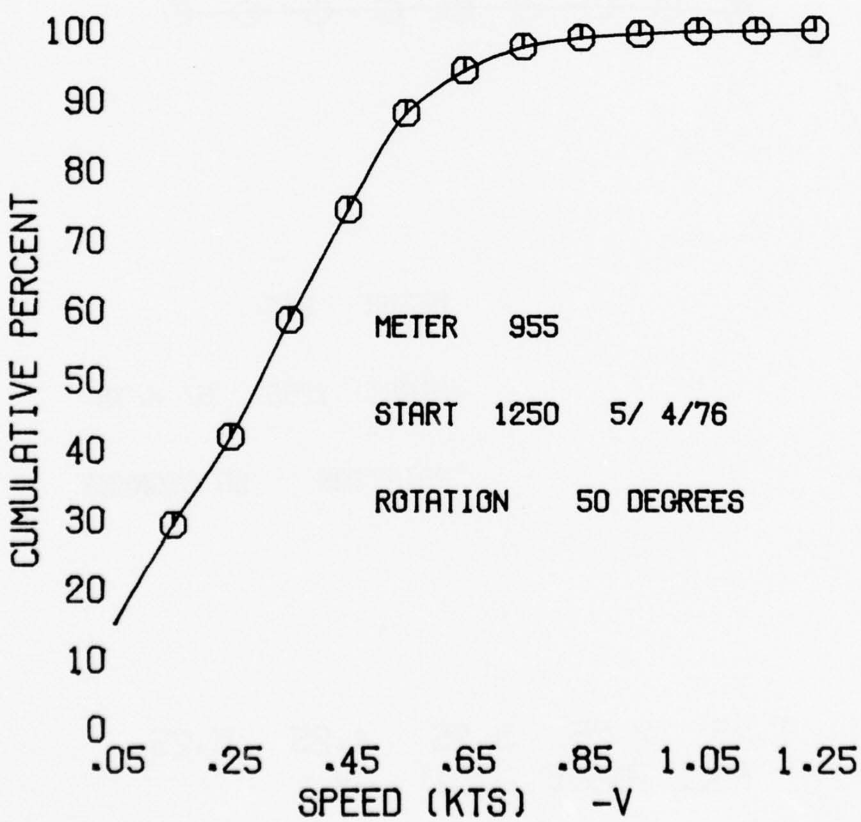
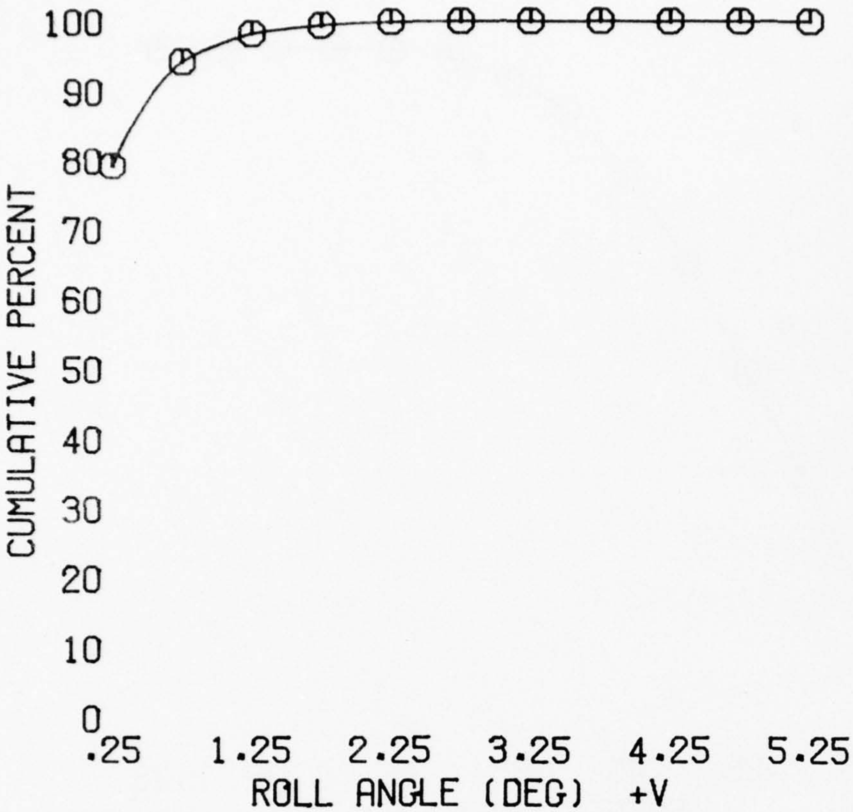


FIG. 11A AND 11B



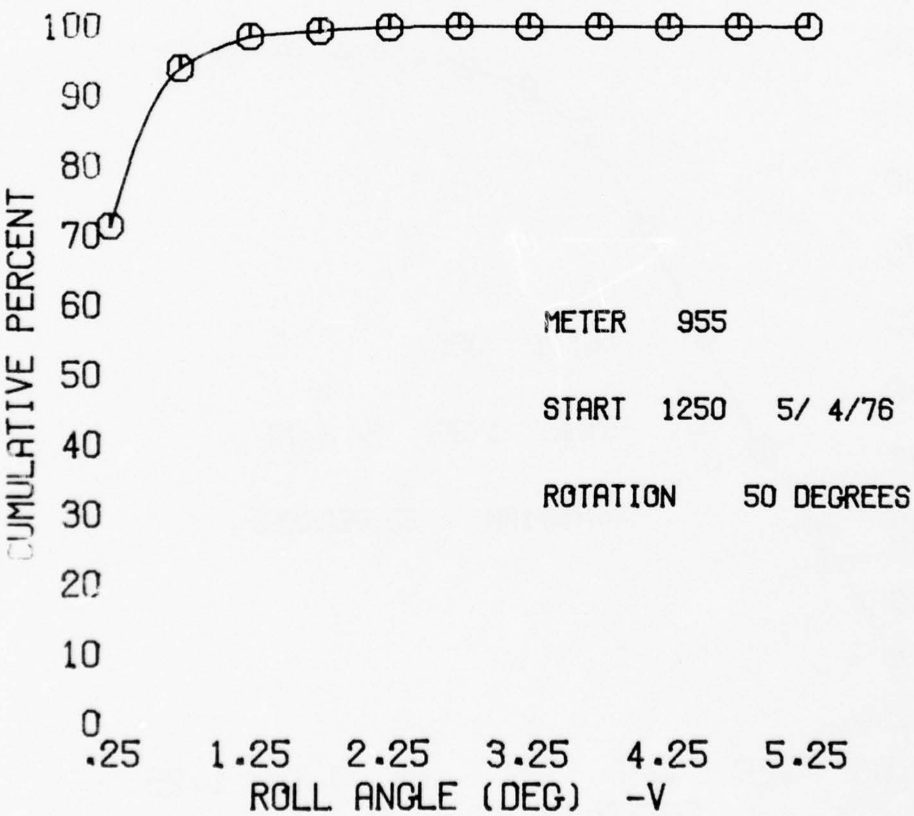
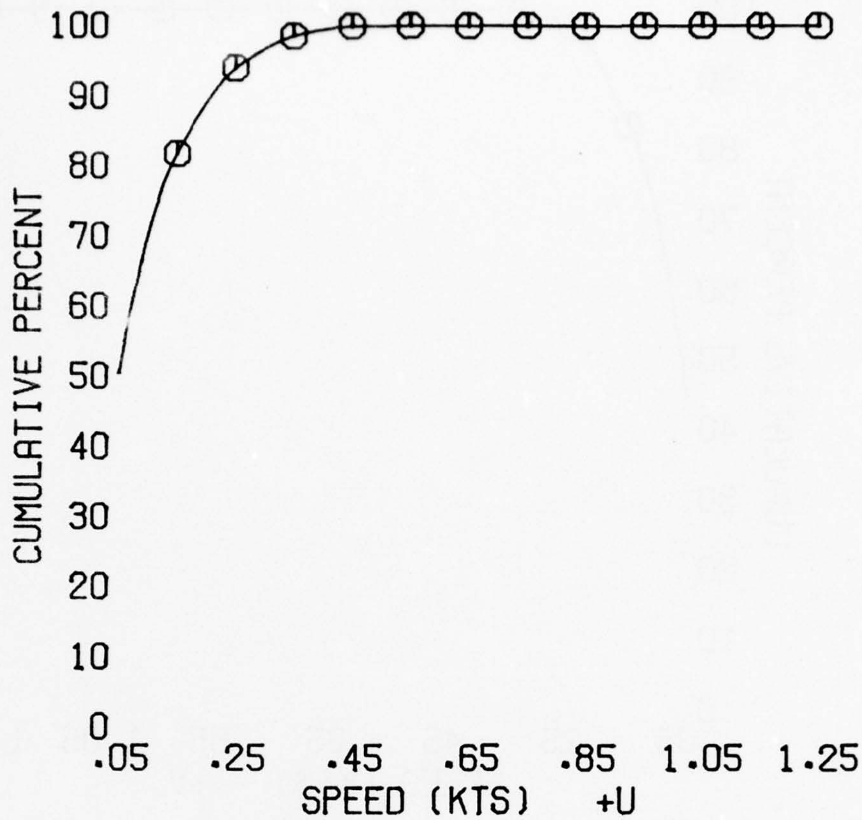


FIG. 12A AND 12B



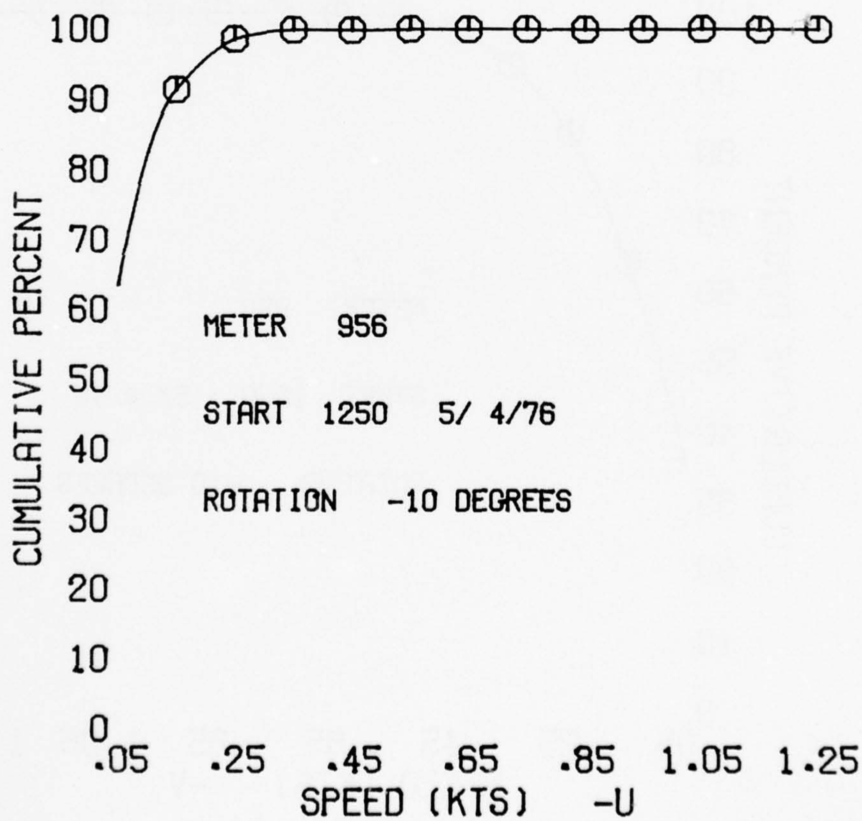
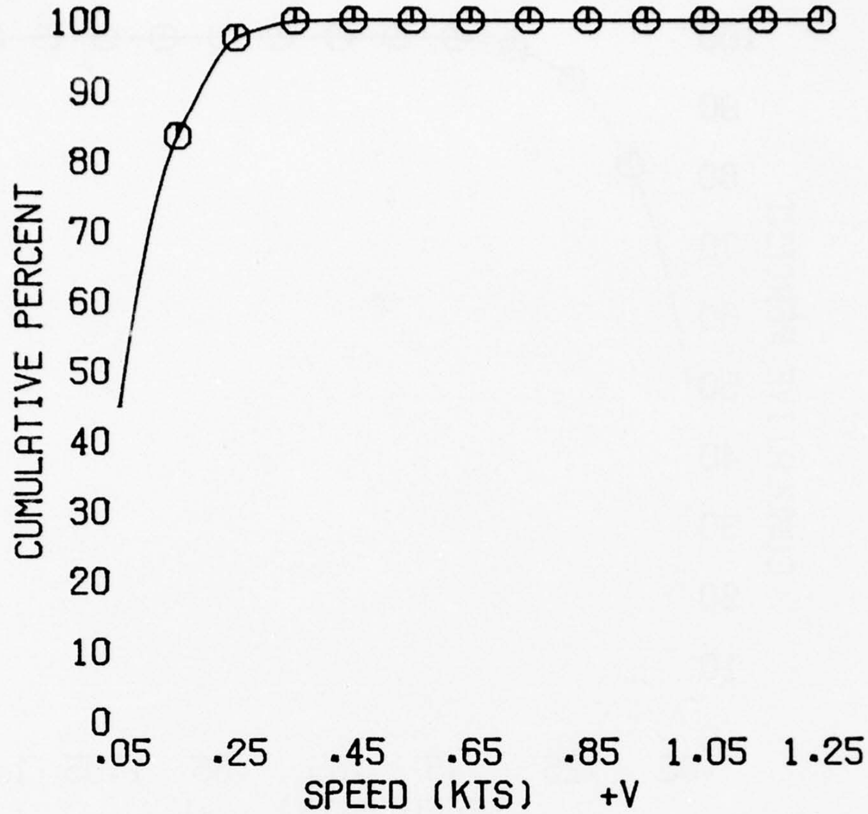


FIG. 13A AND 13B



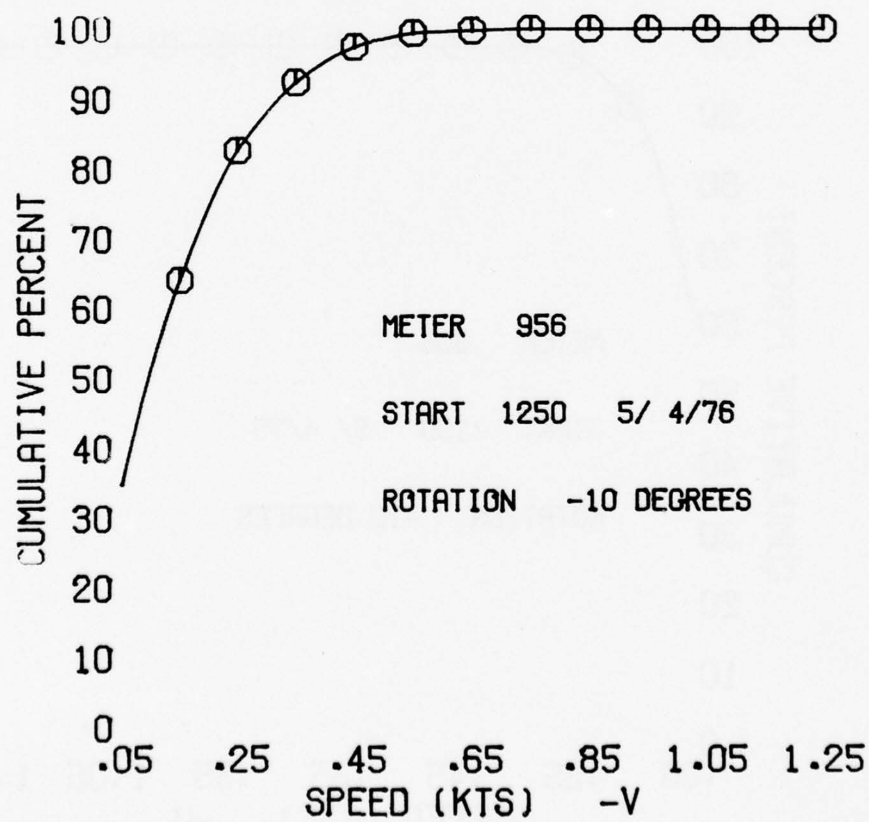
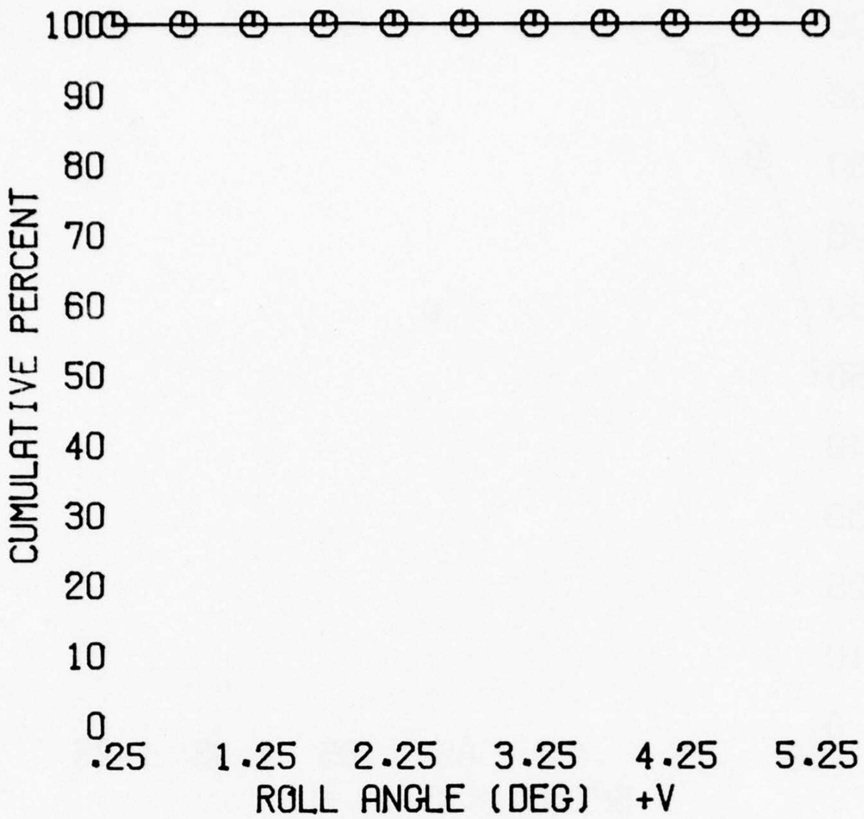


FIG. 14A AND 14B



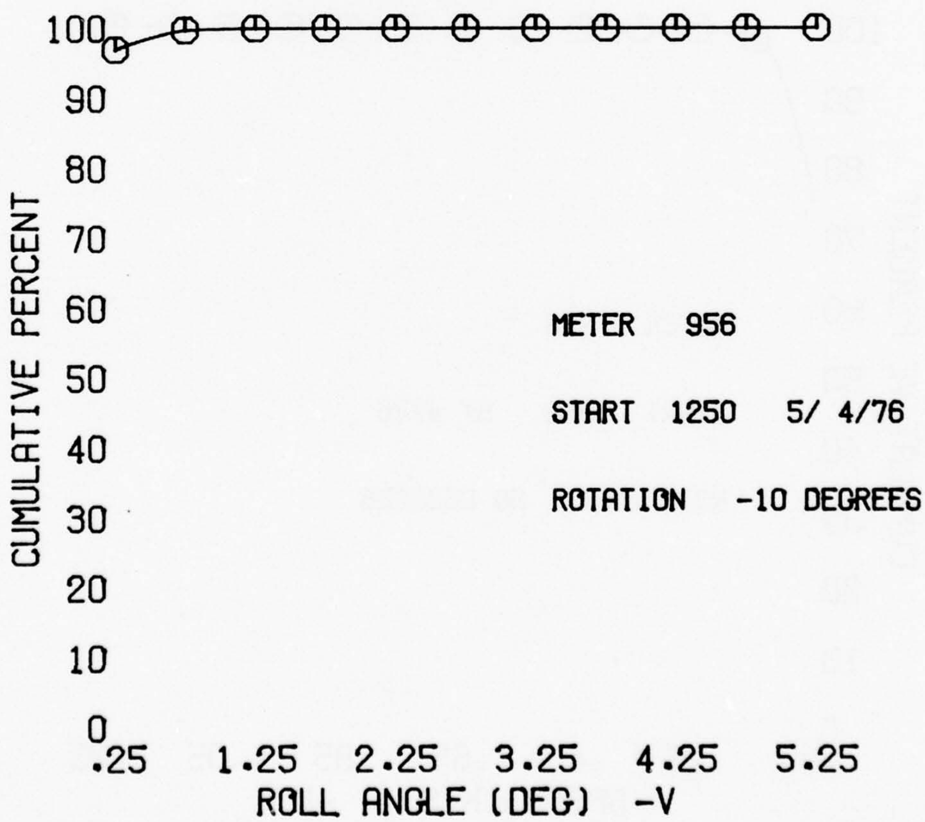


FIG. 15A AND 15B

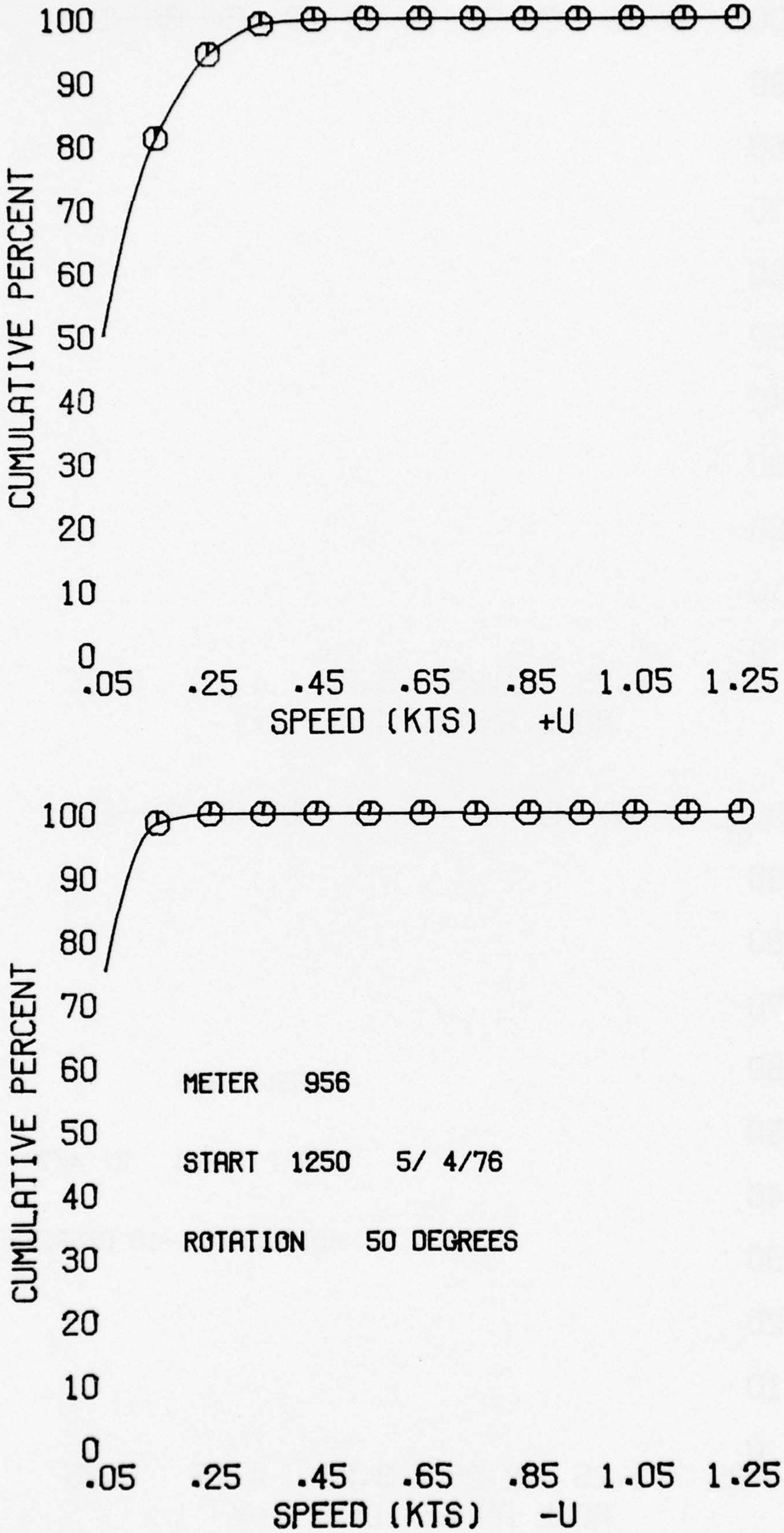


FIG. 16A AND 16B

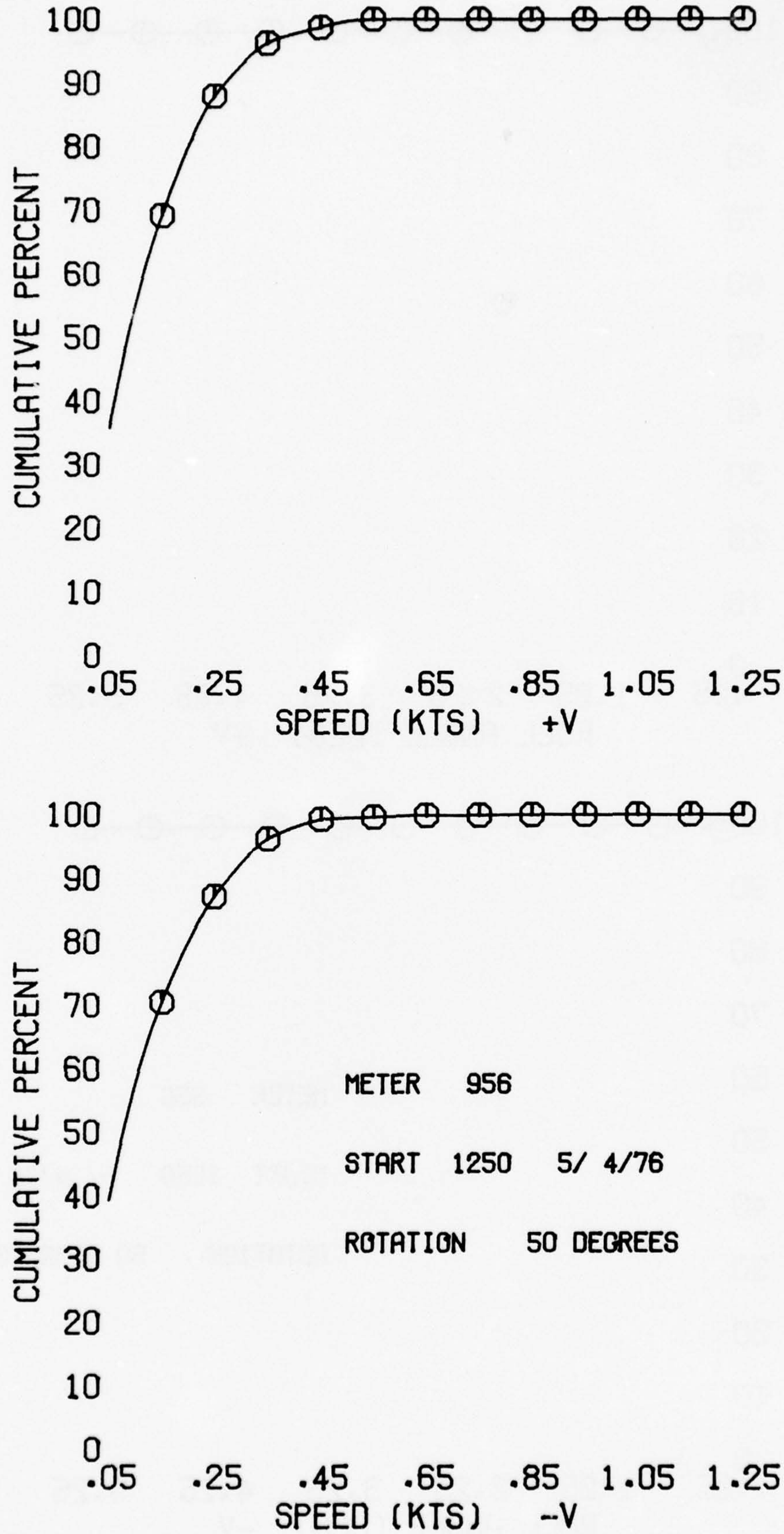
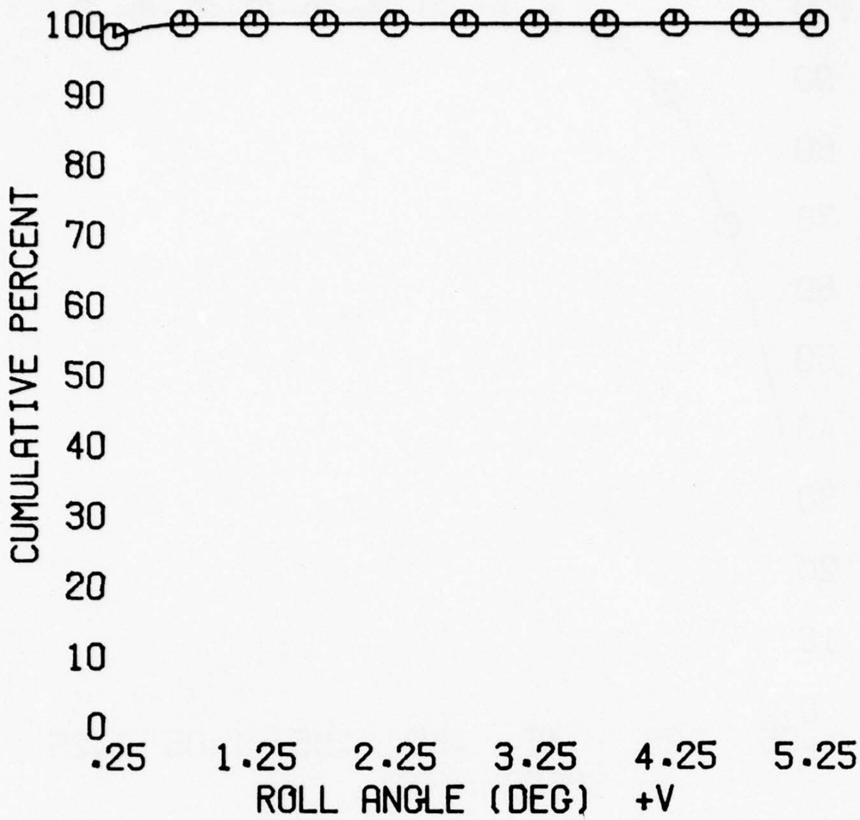


FIG. 17A AND 17B



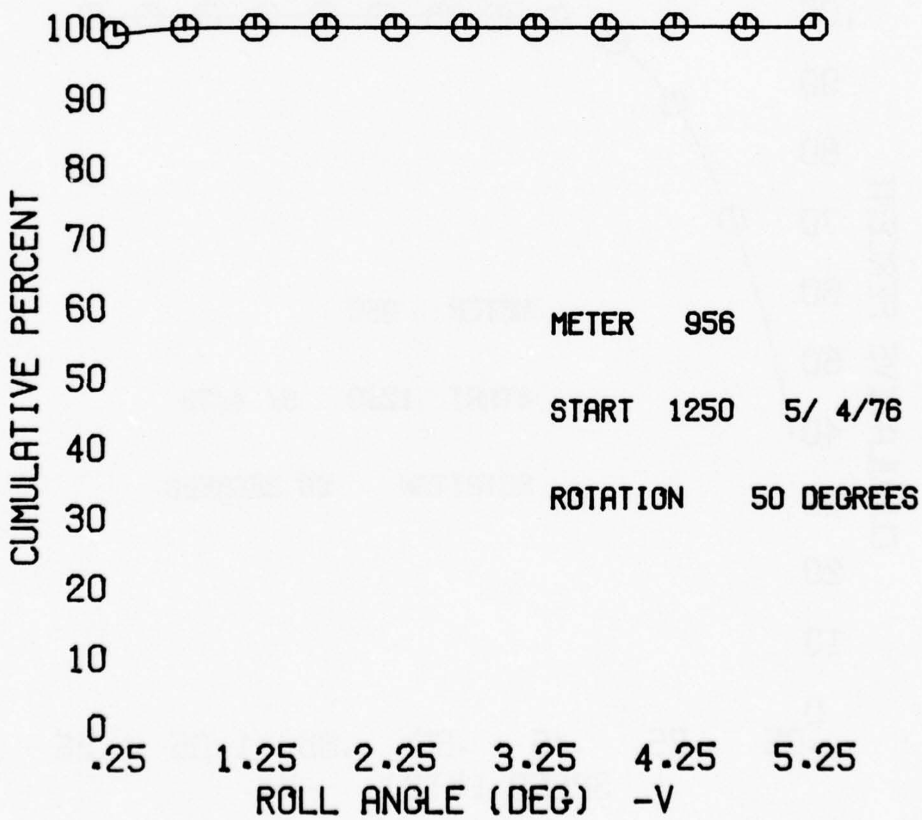


FIG. 18A AND 18B

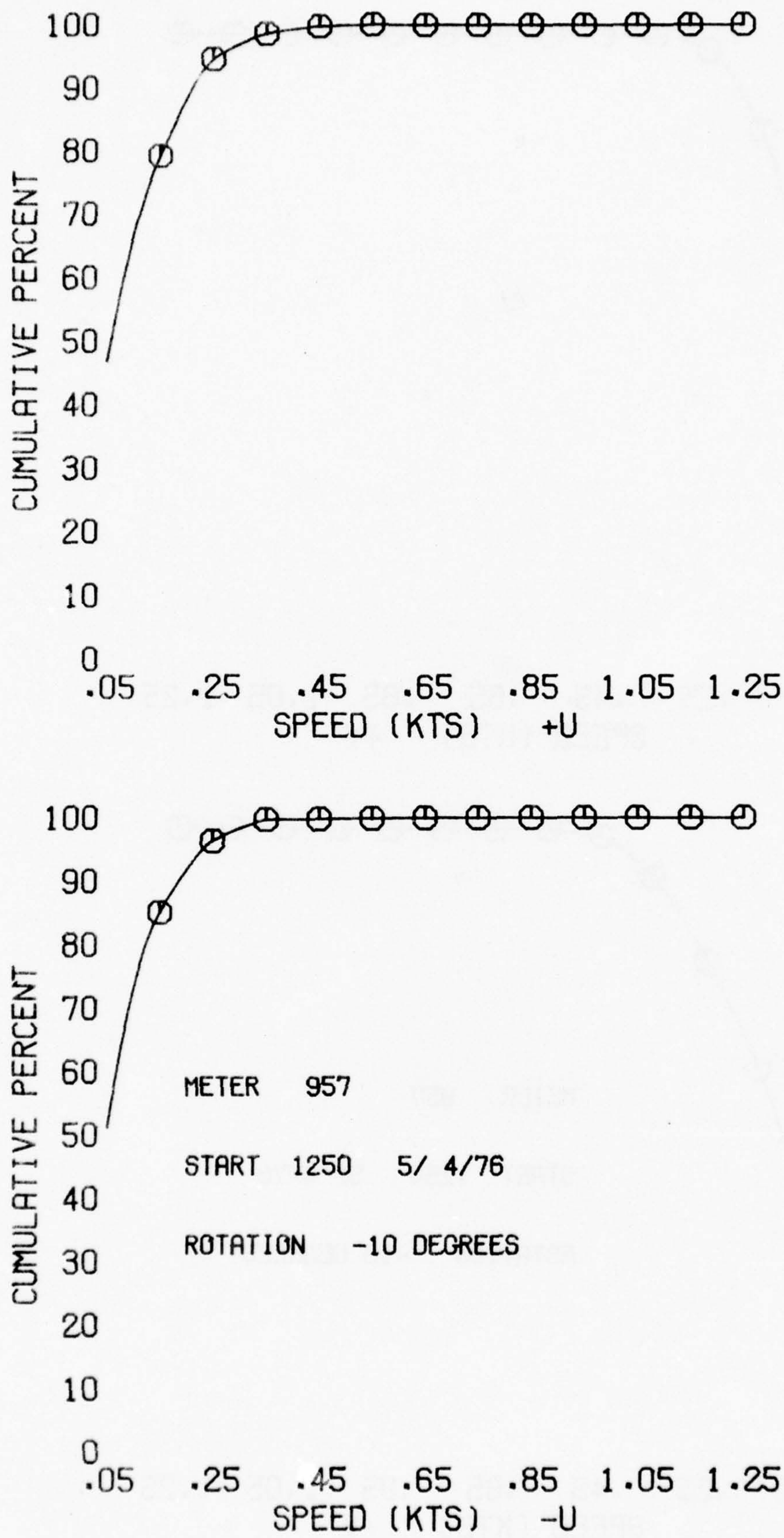


FIG. 19A AND 19B

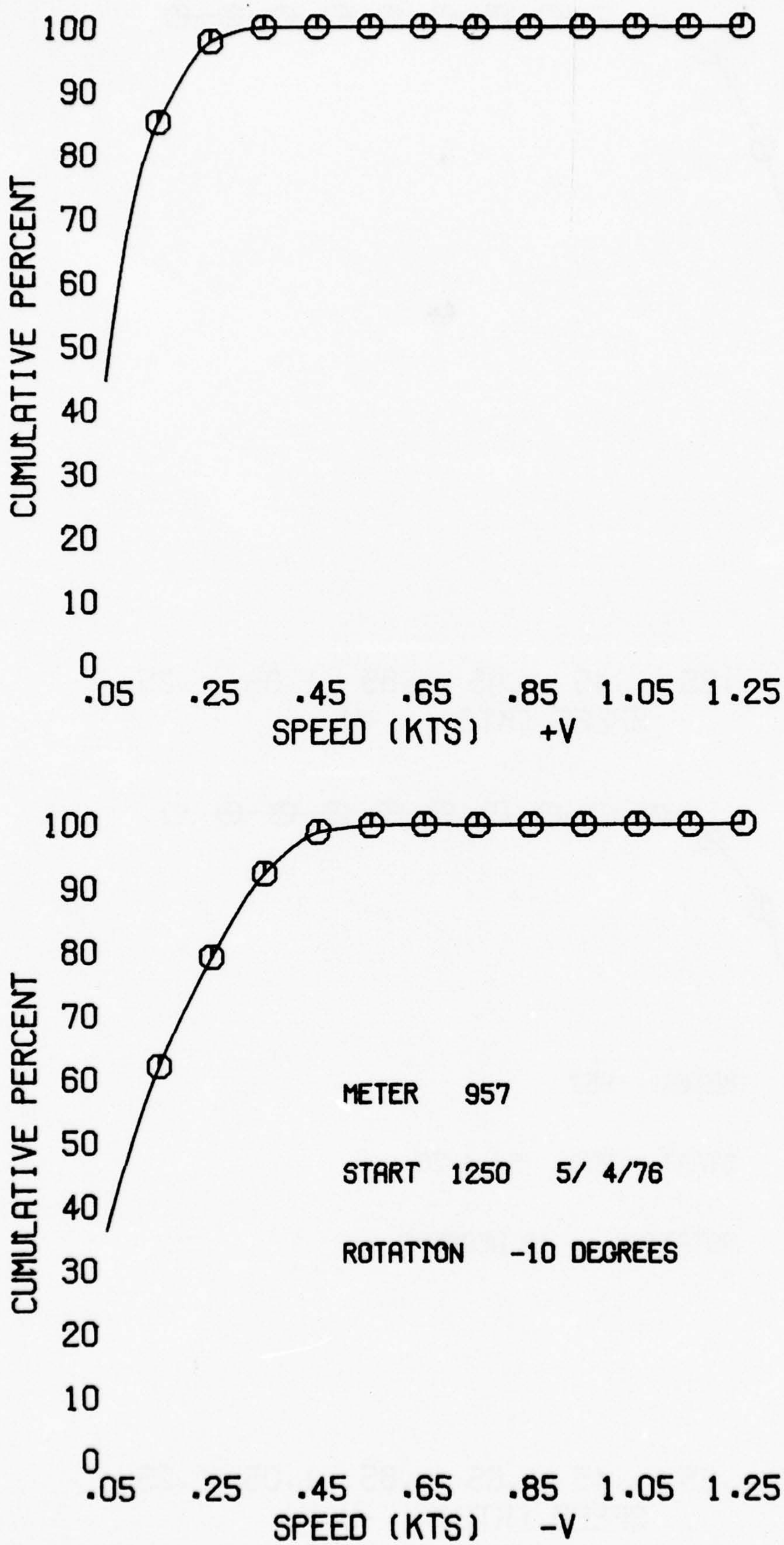


FIG. 20A AND 20B

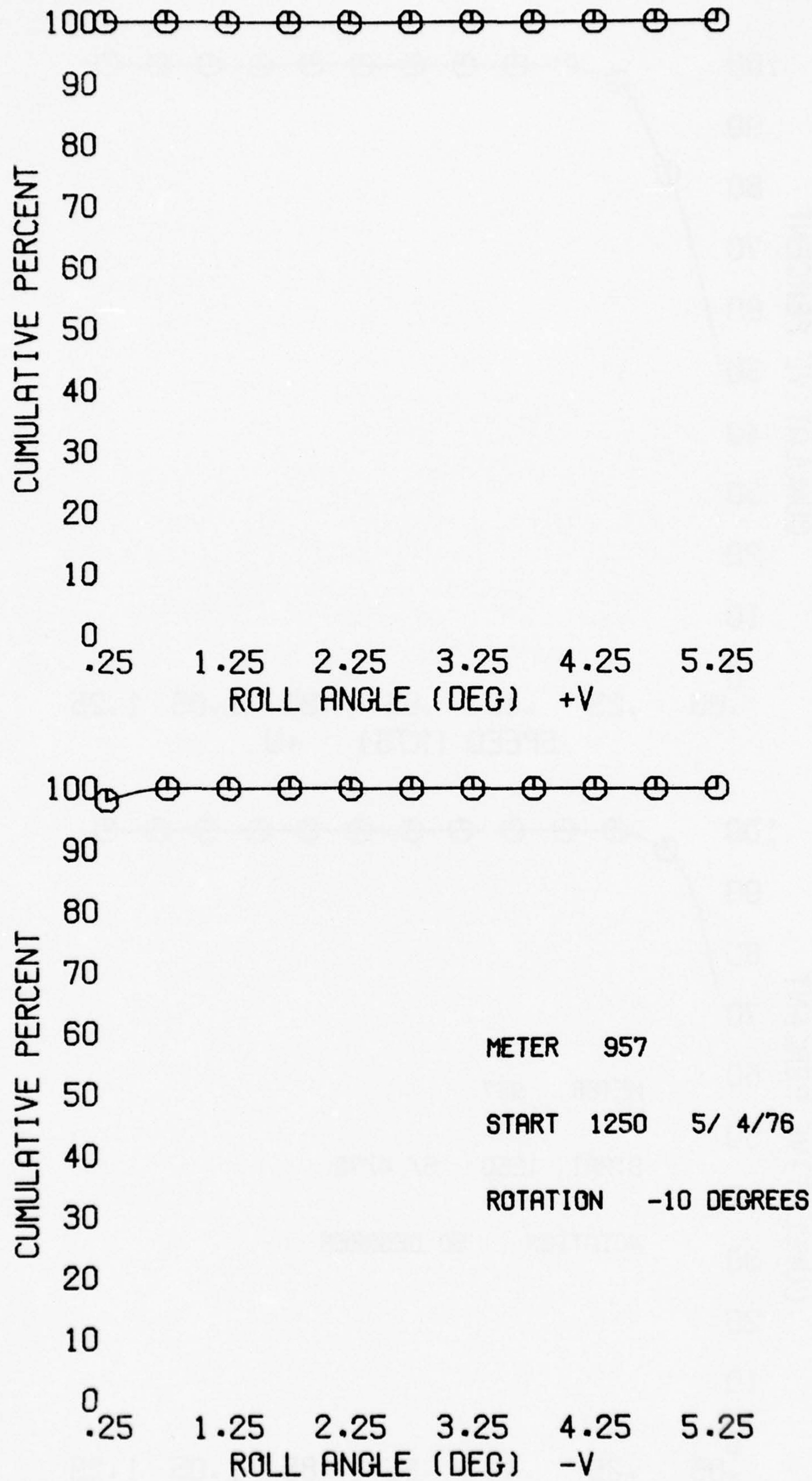
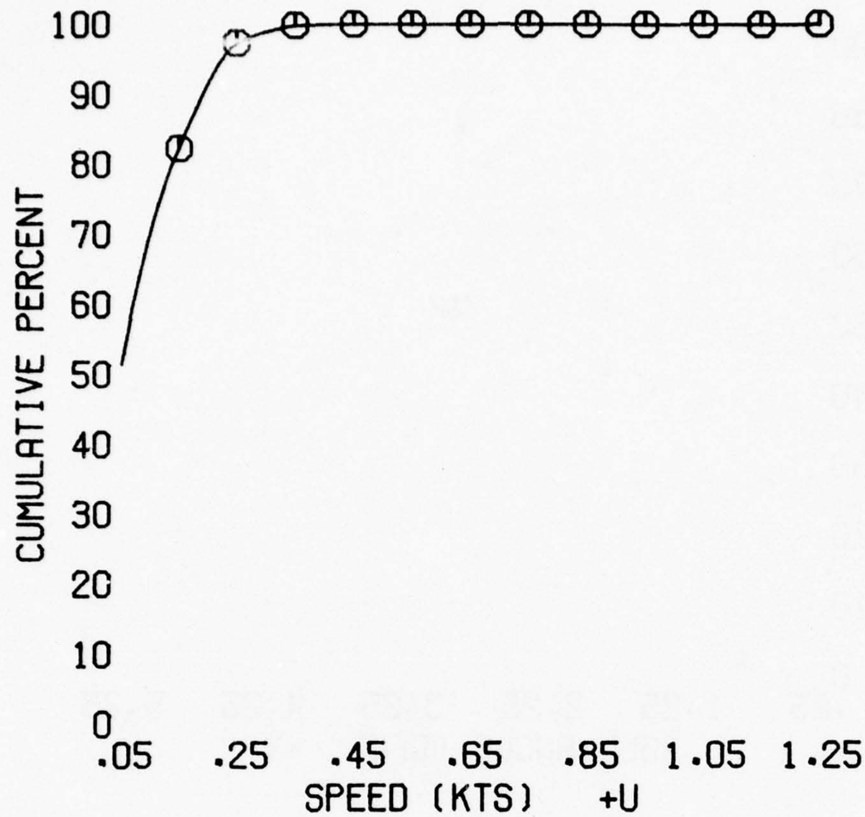


FIG. 21A AND 21B



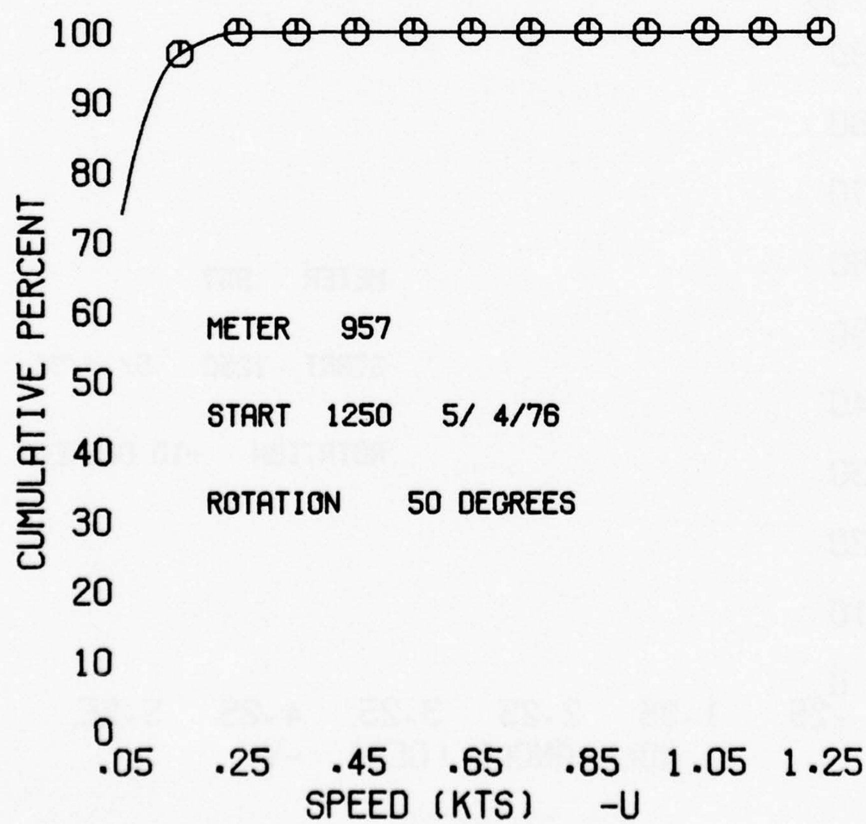


FIG. 22A AND 22B

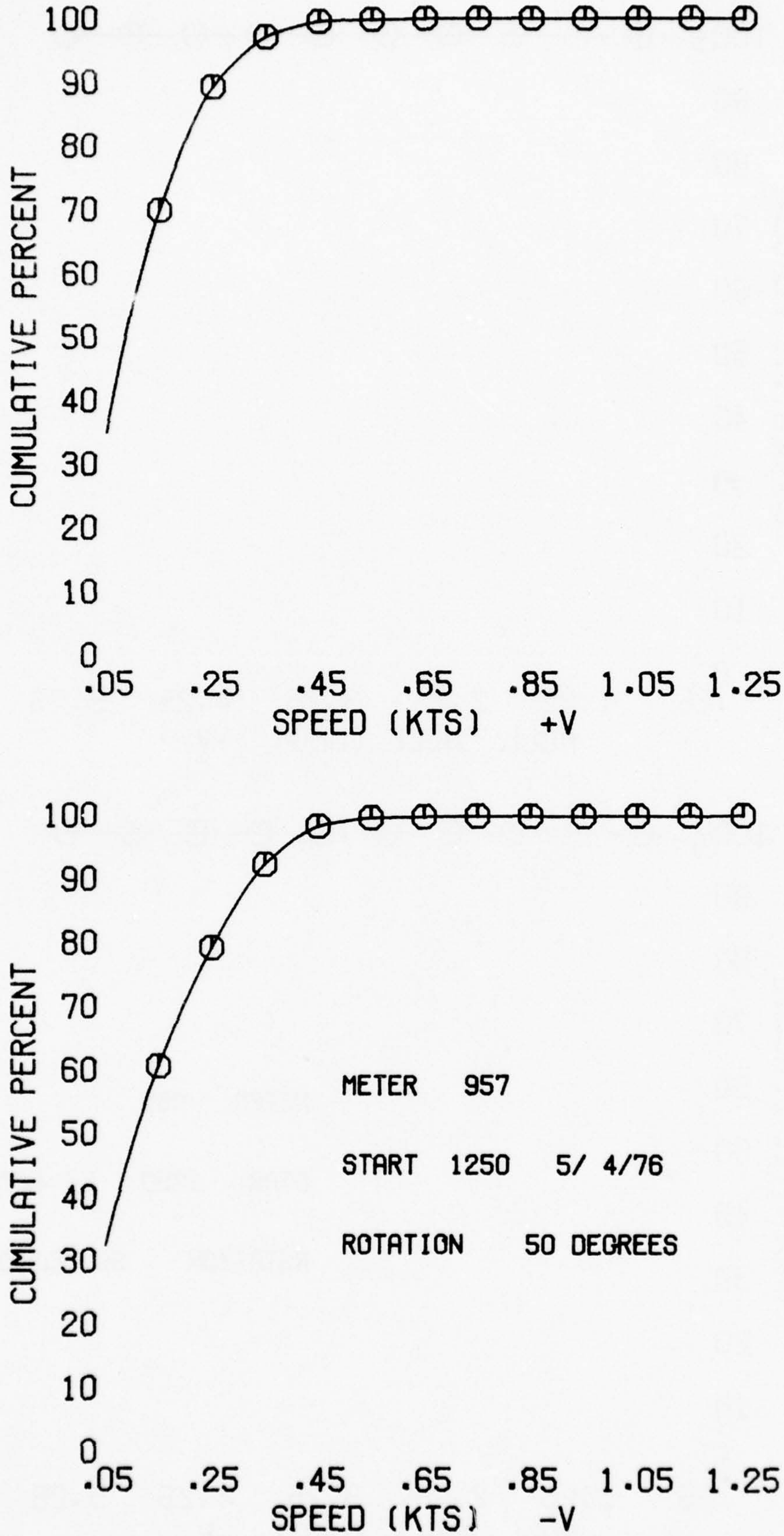
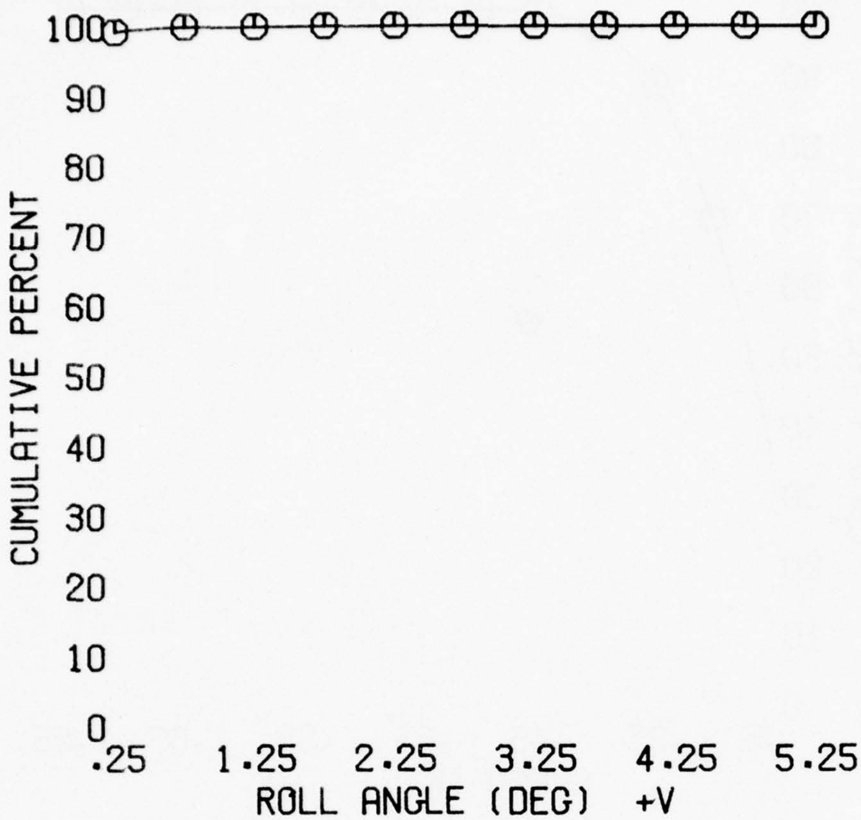


FIG. 23A AND 23B



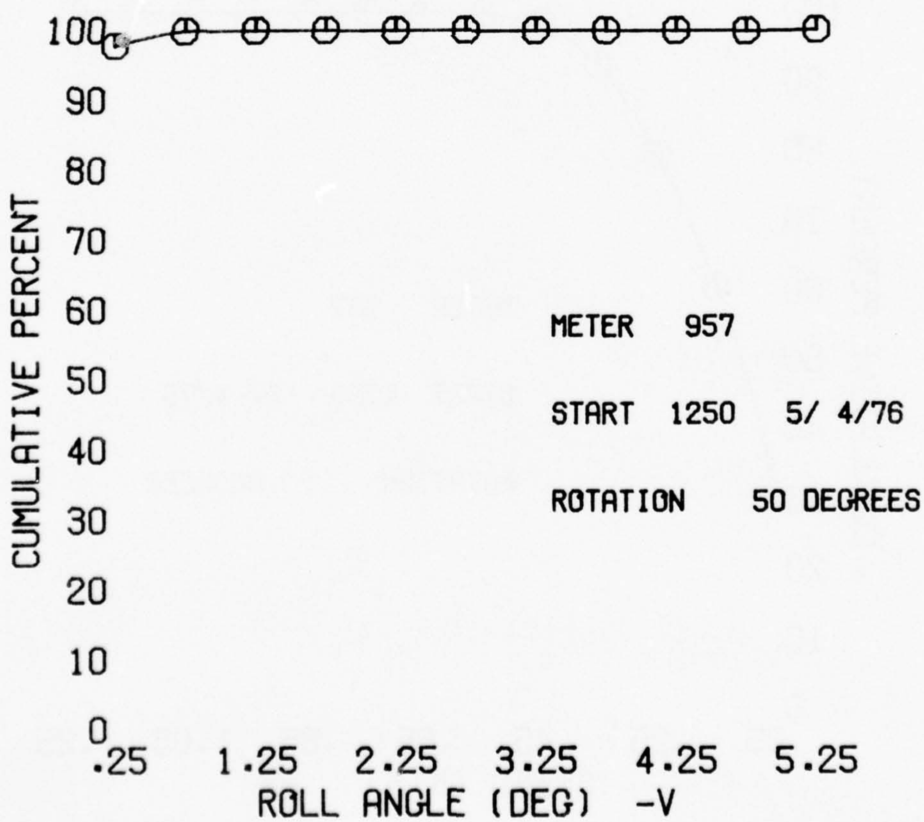


FIG. 24A AND 24B

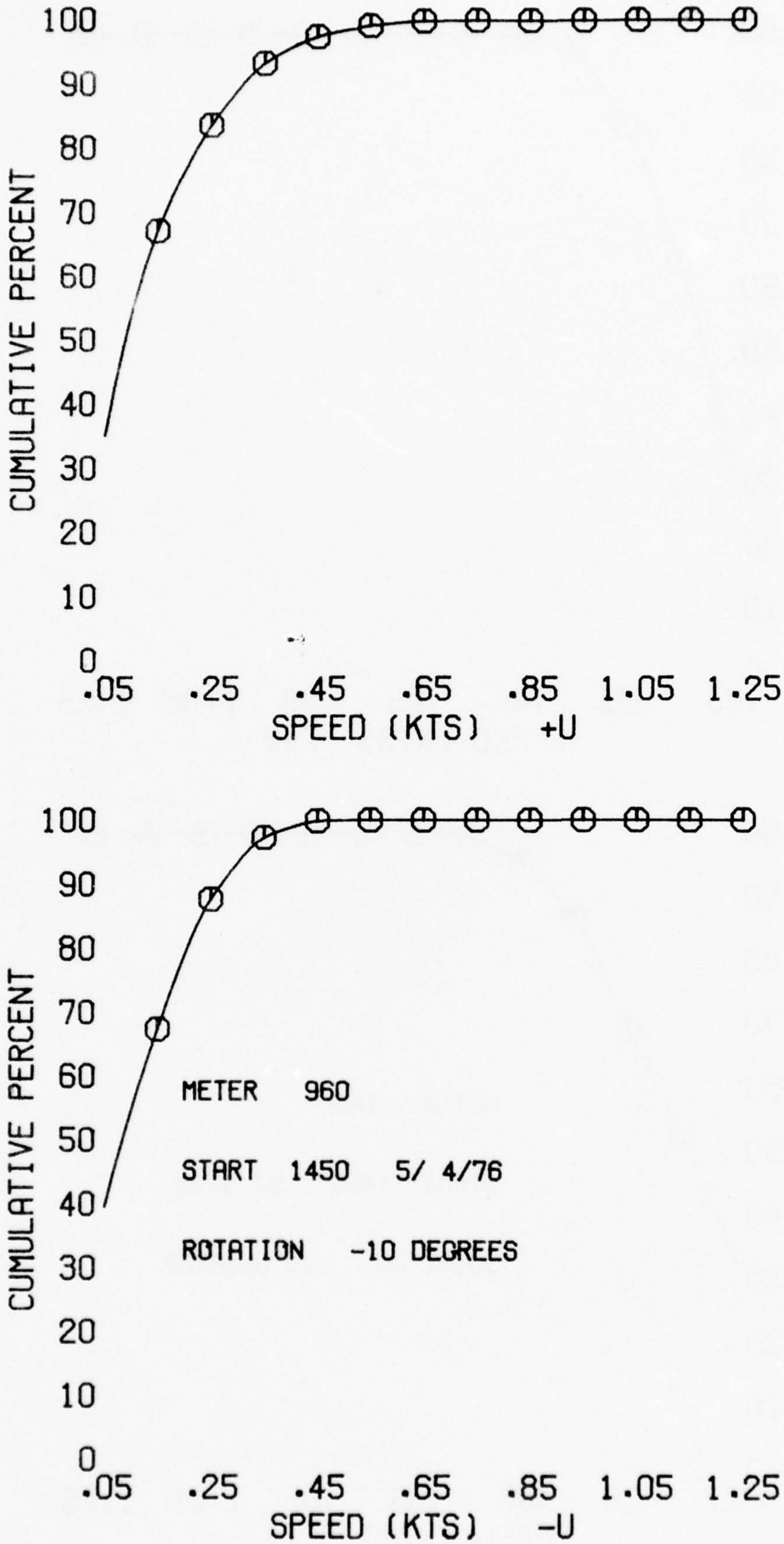


FIG. 25A AND 25B

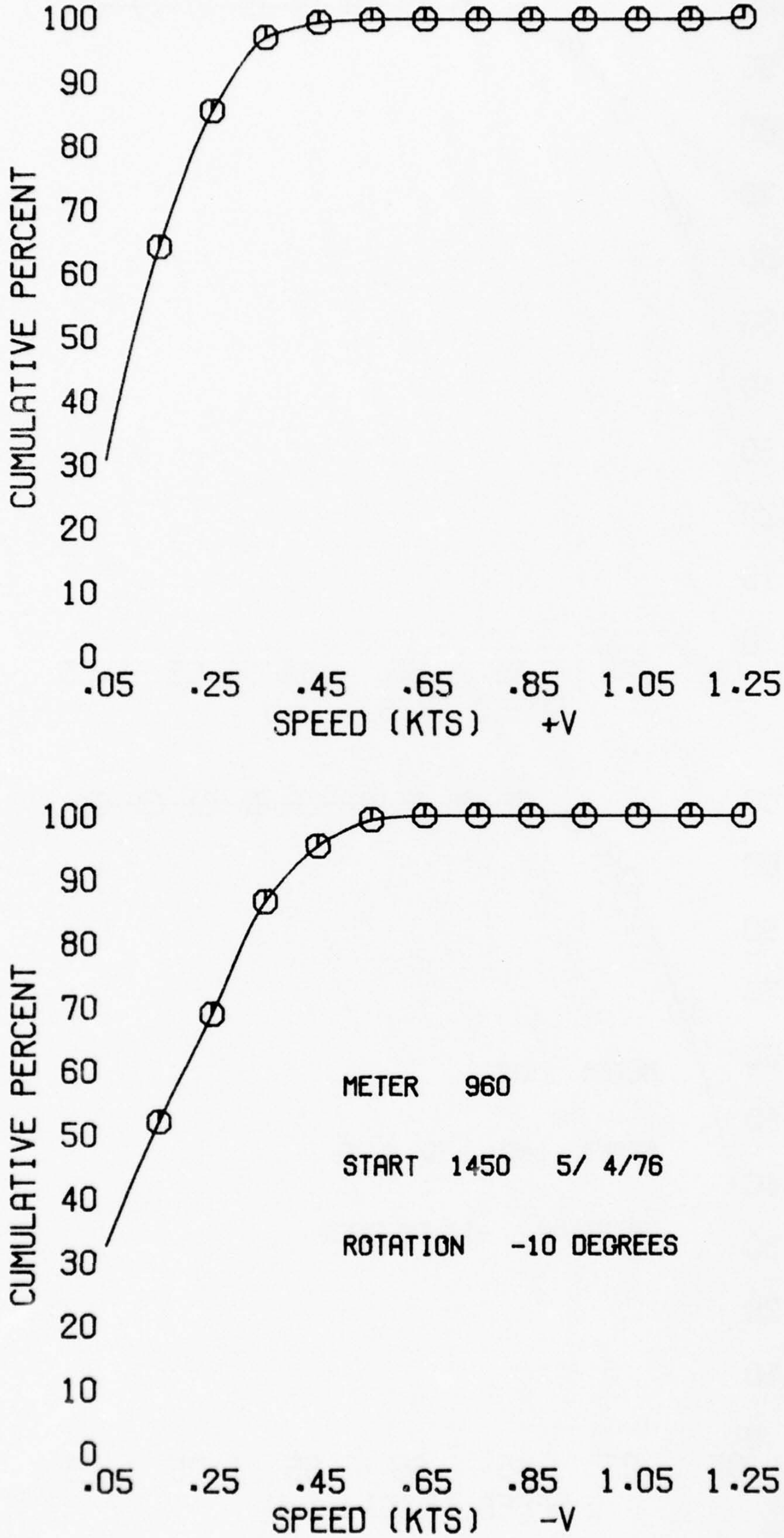


FIG. 26A AND 26B

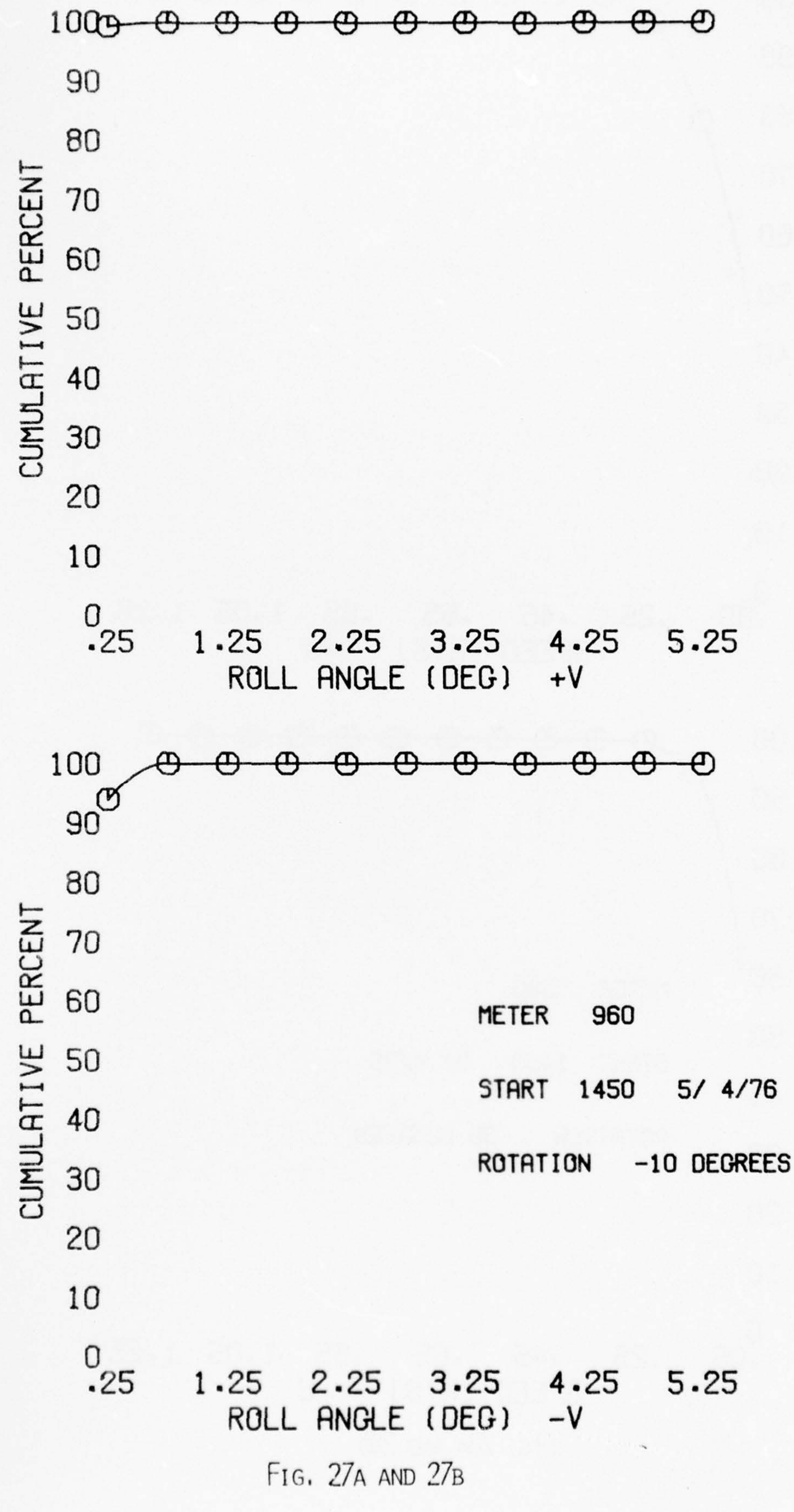


FIG. 27A AND 27B

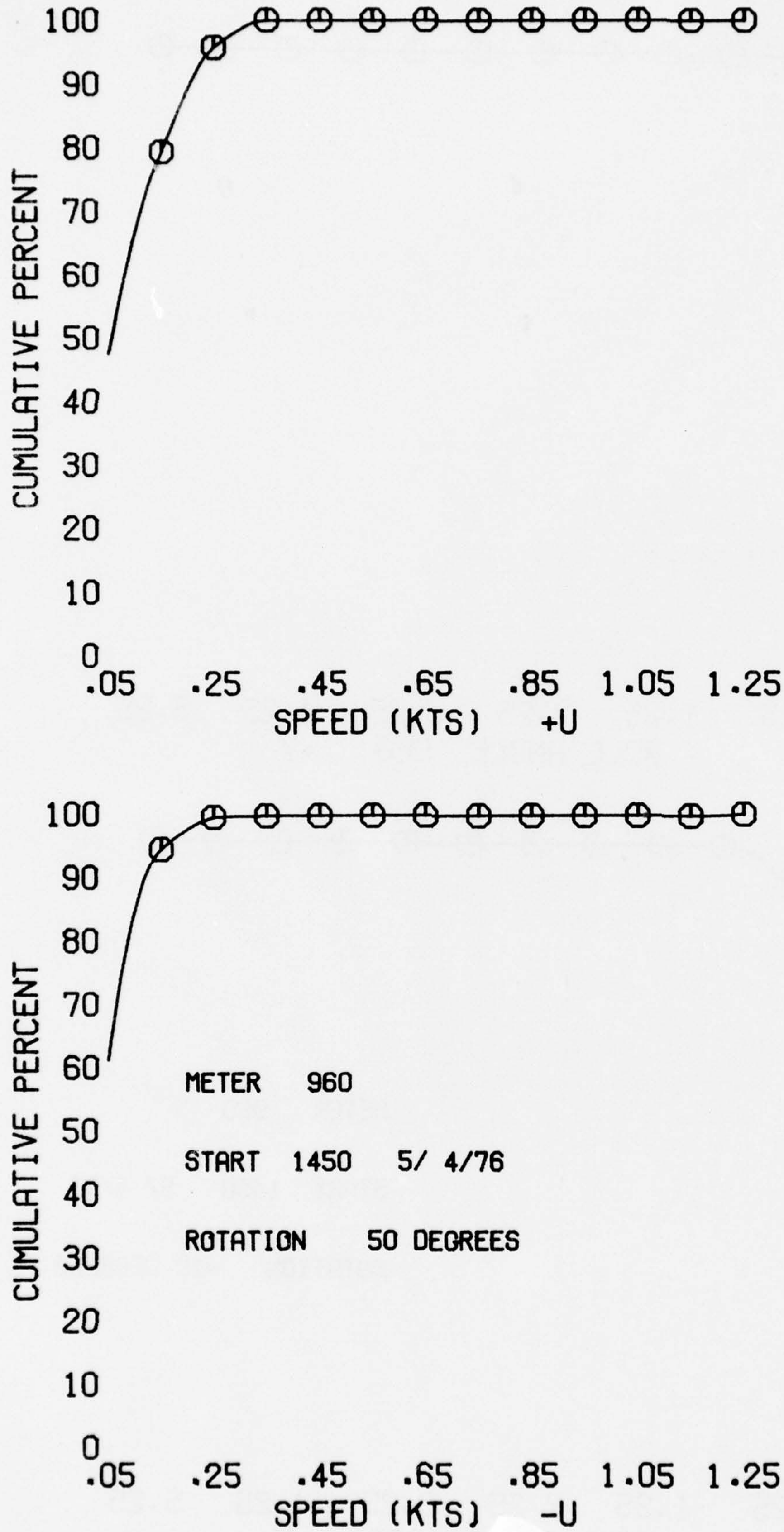
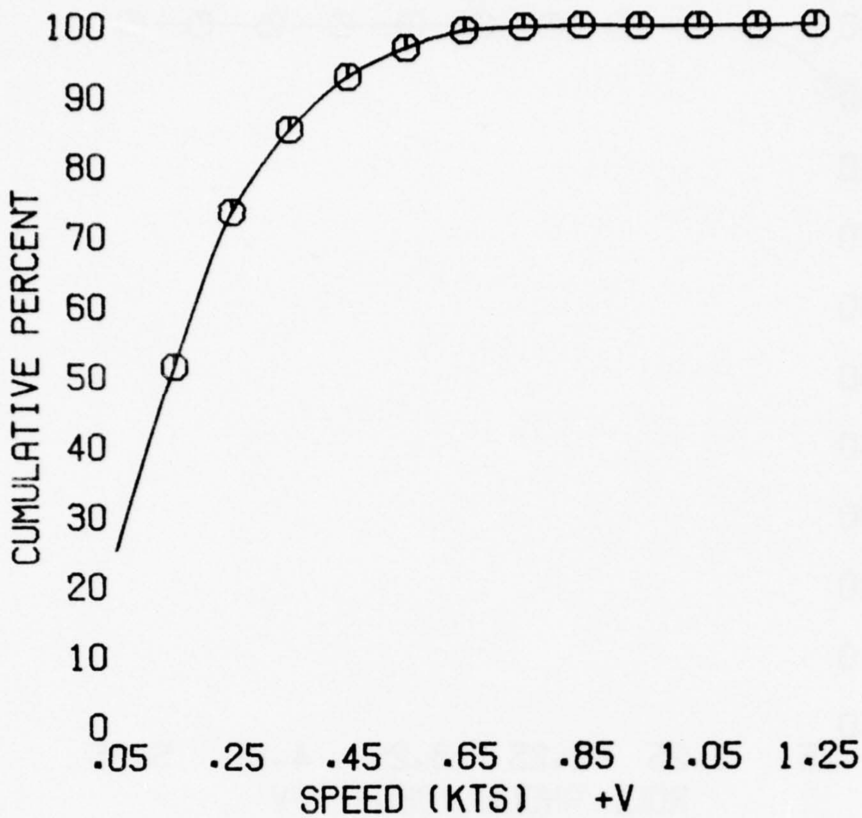


FIG. 28A AND 28B



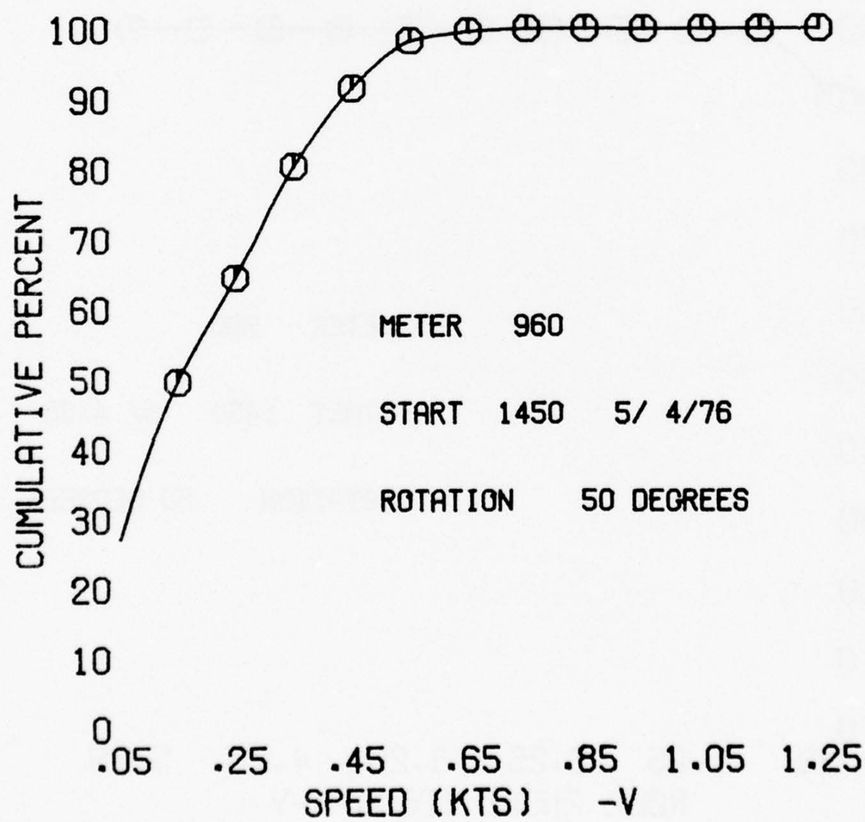
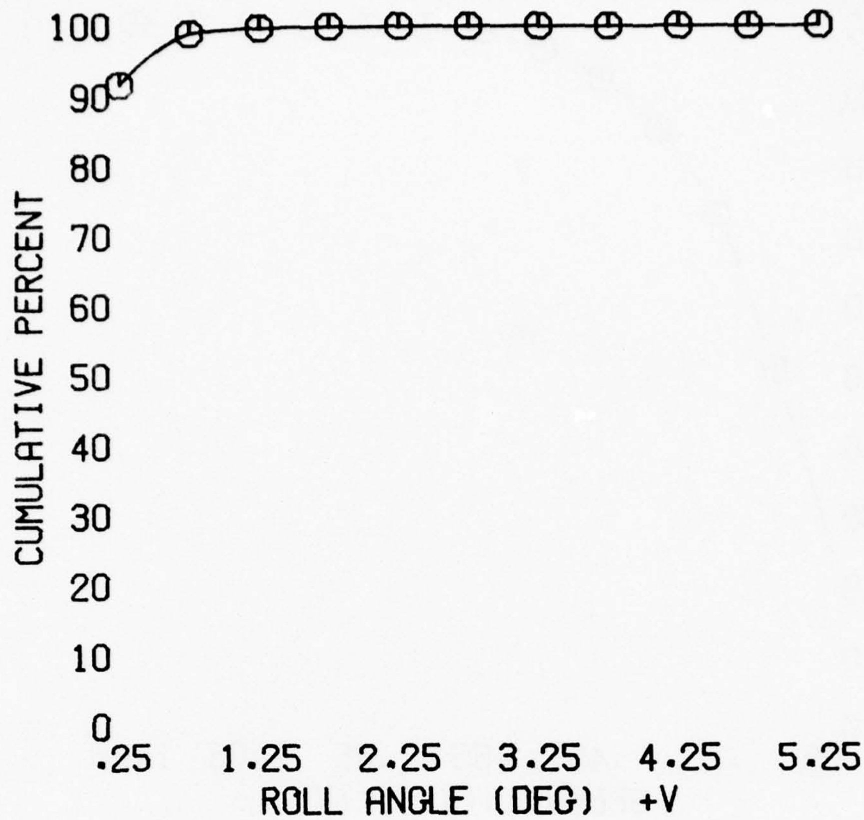


FIG. 29A AND 29B



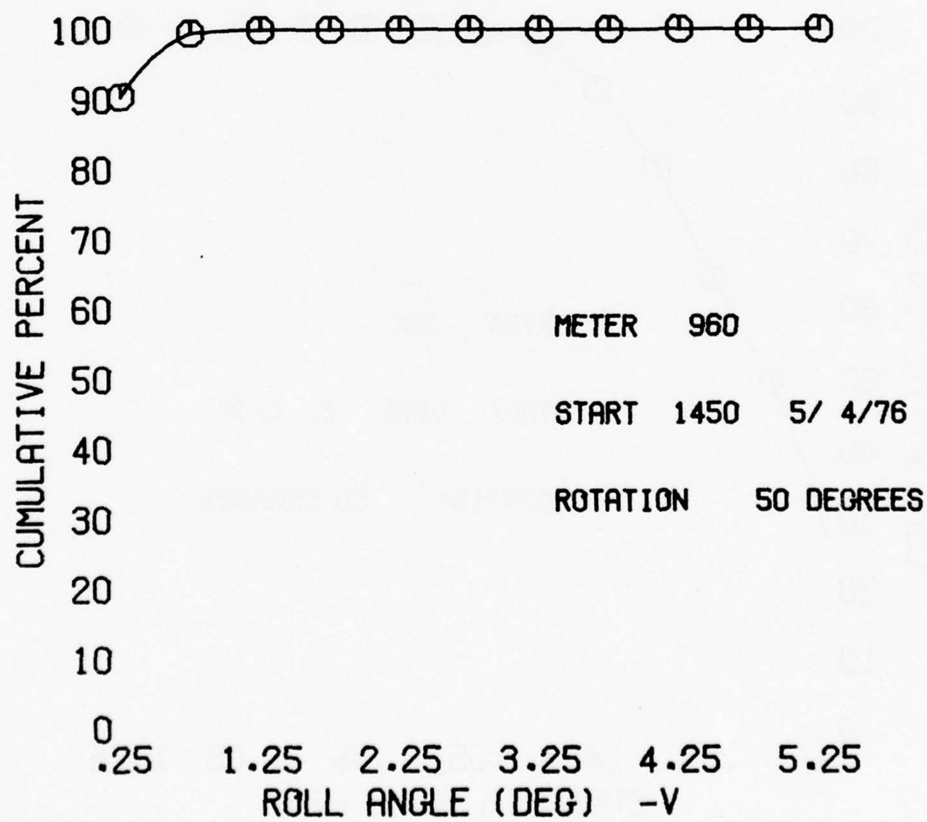


FIG. 30A AND 30B

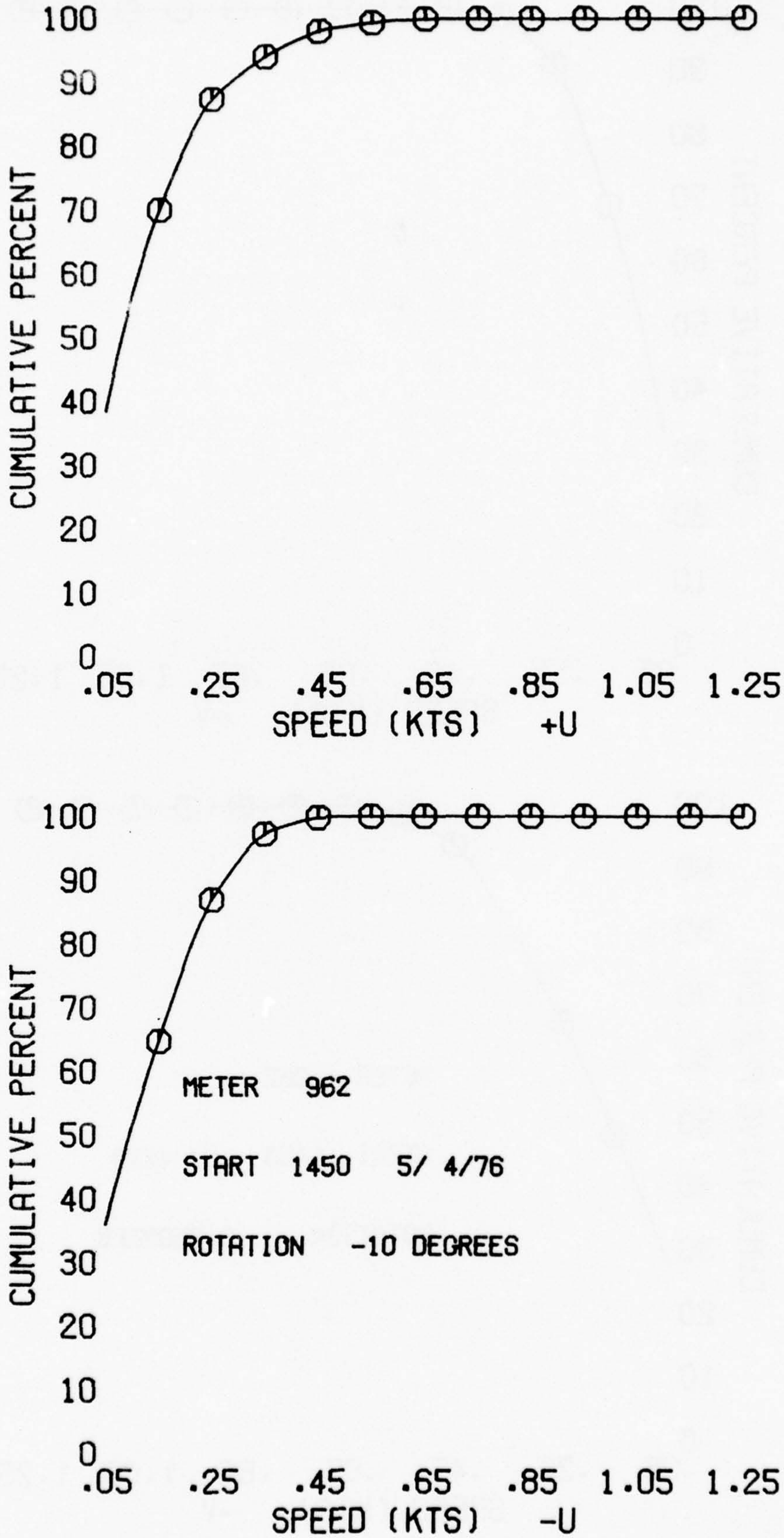
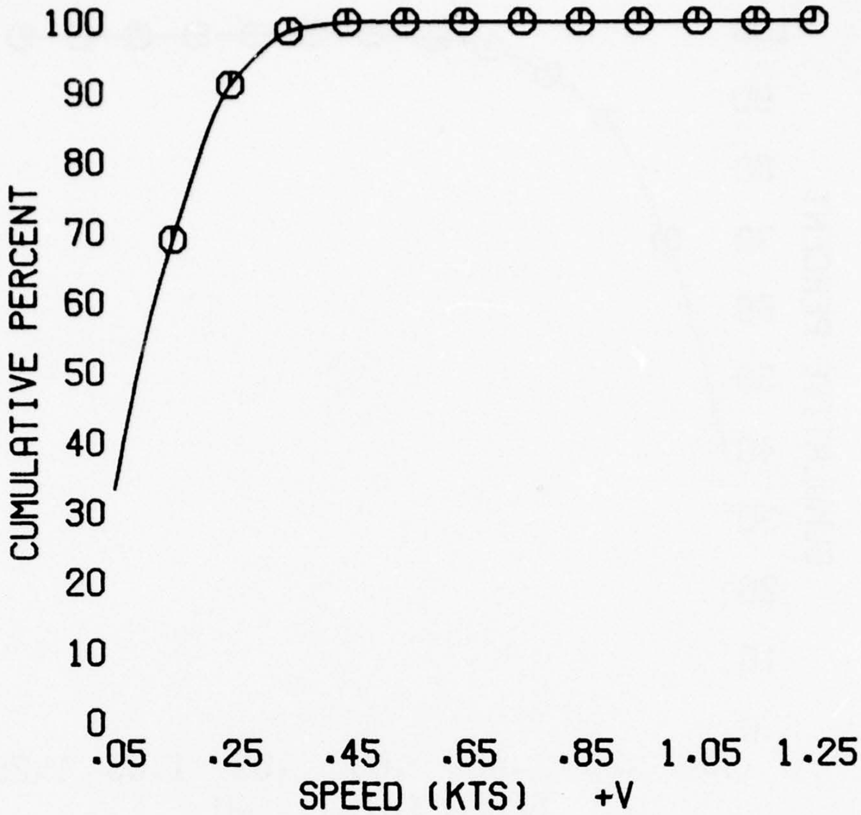


FIG. 31A AND 31B



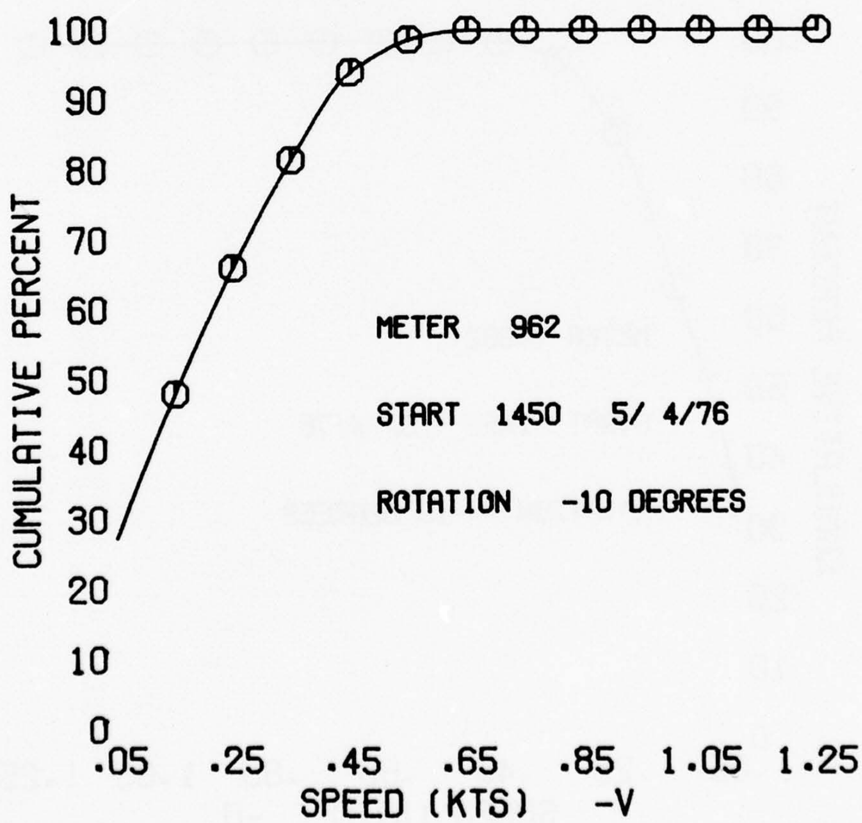


FIG. 32A AND 32B

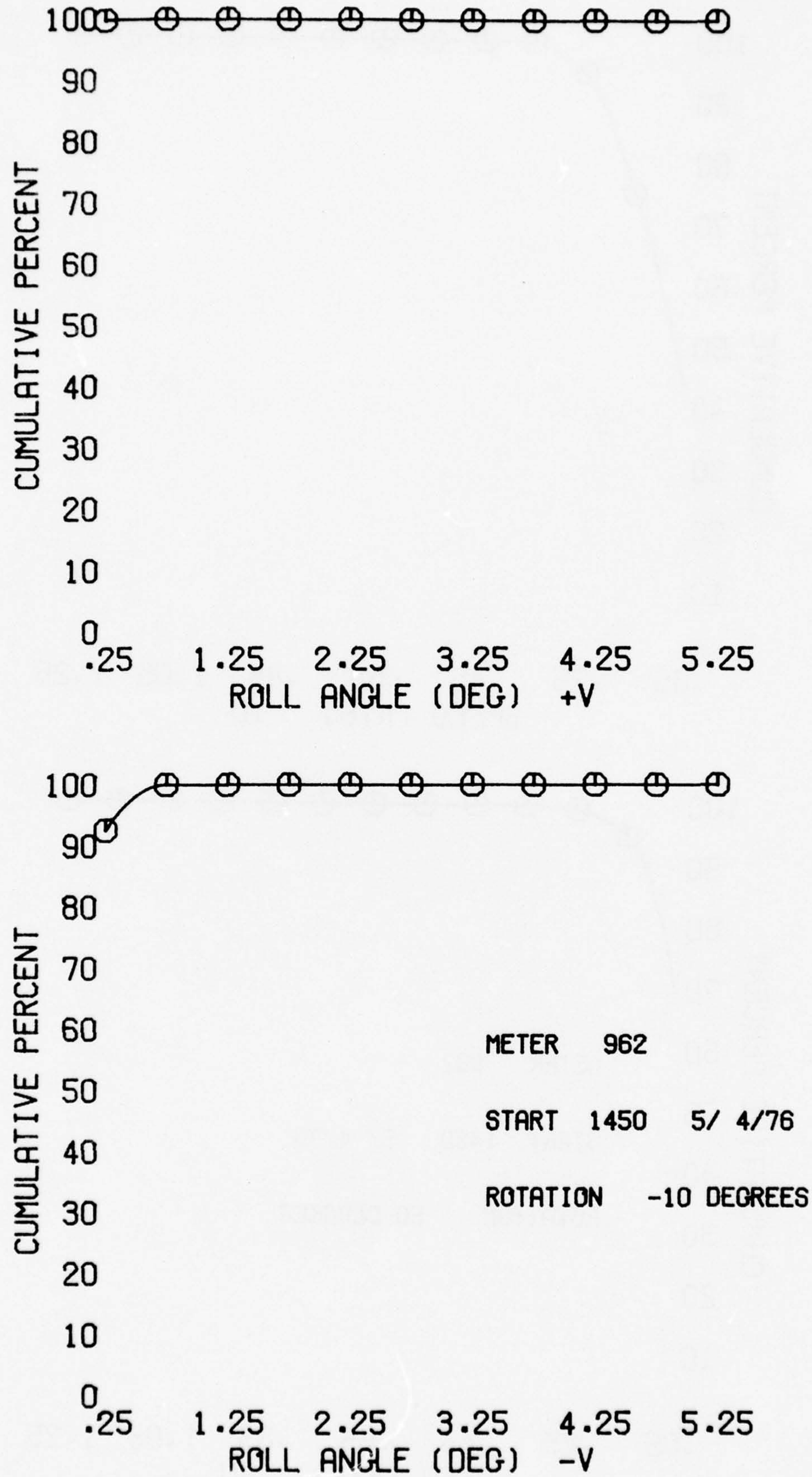


FIG. 33A AND 33B

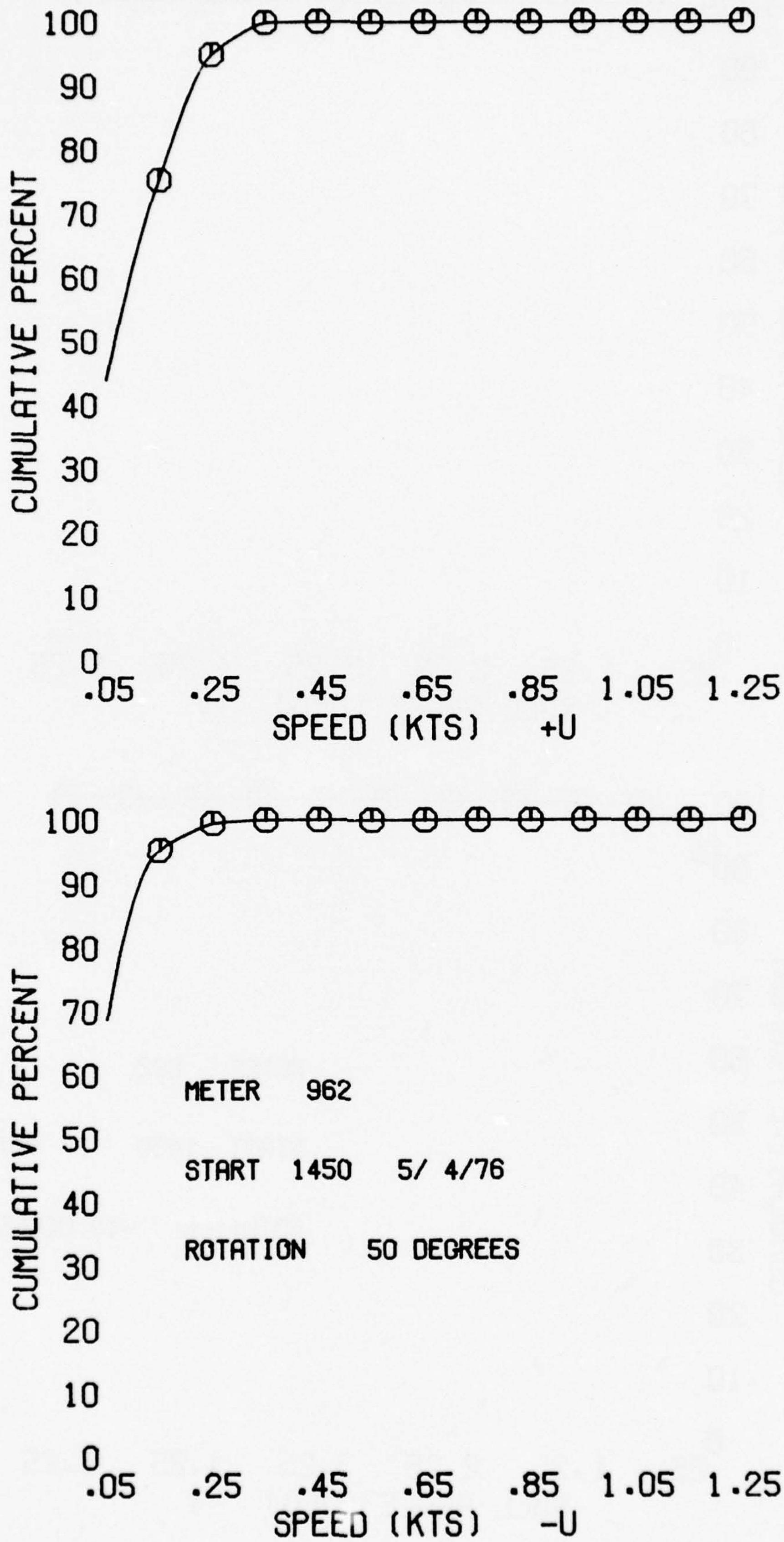
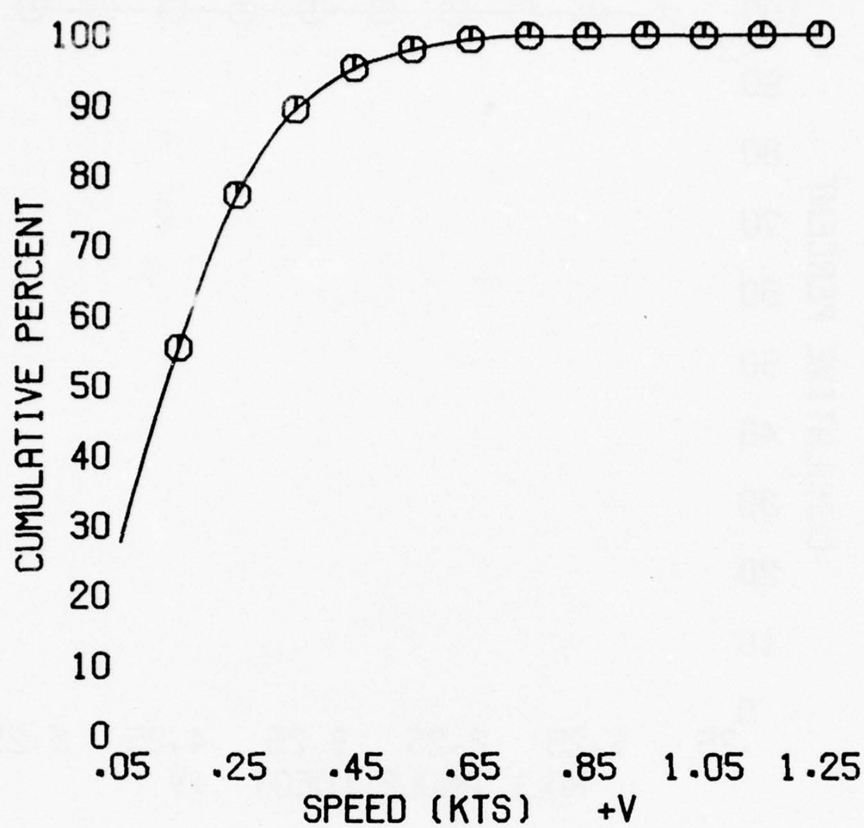


FIG. 34A AND 34B



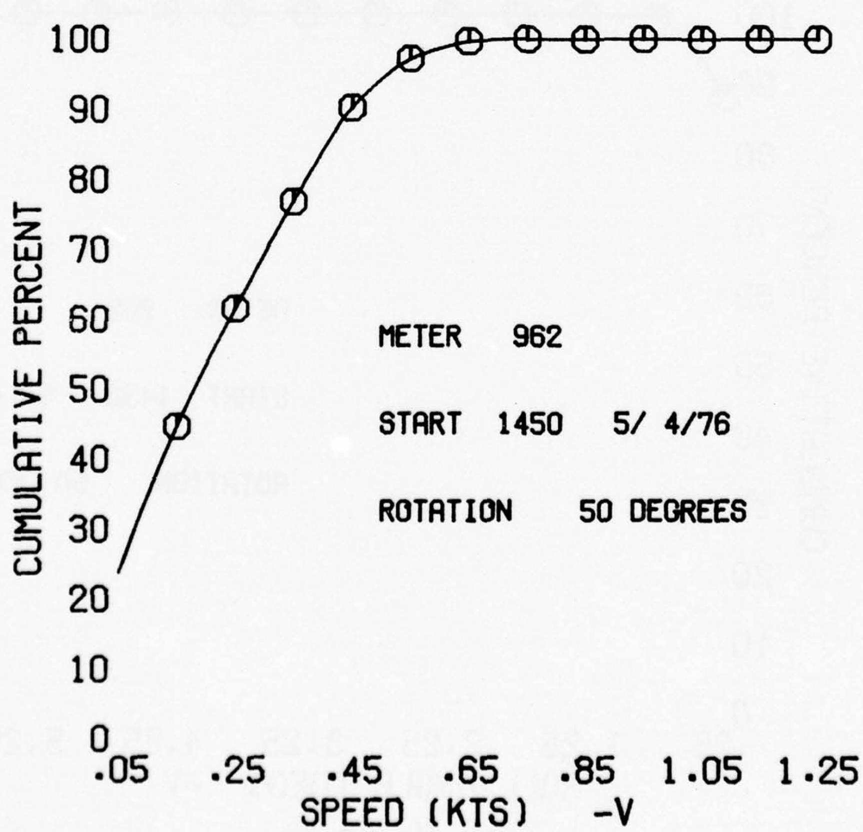


FIG. 35A AND 35B

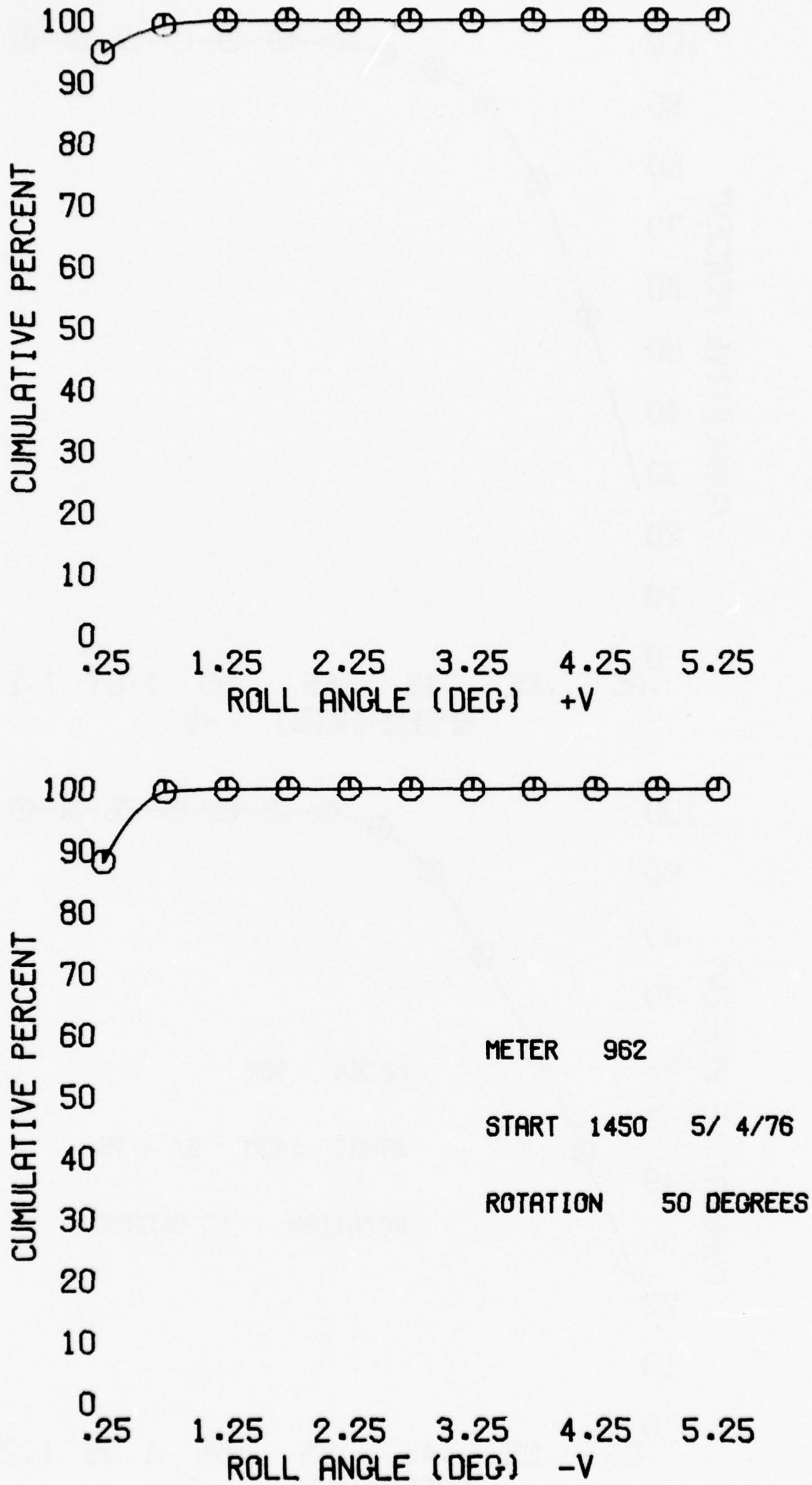


FIG. 36A AND 36B

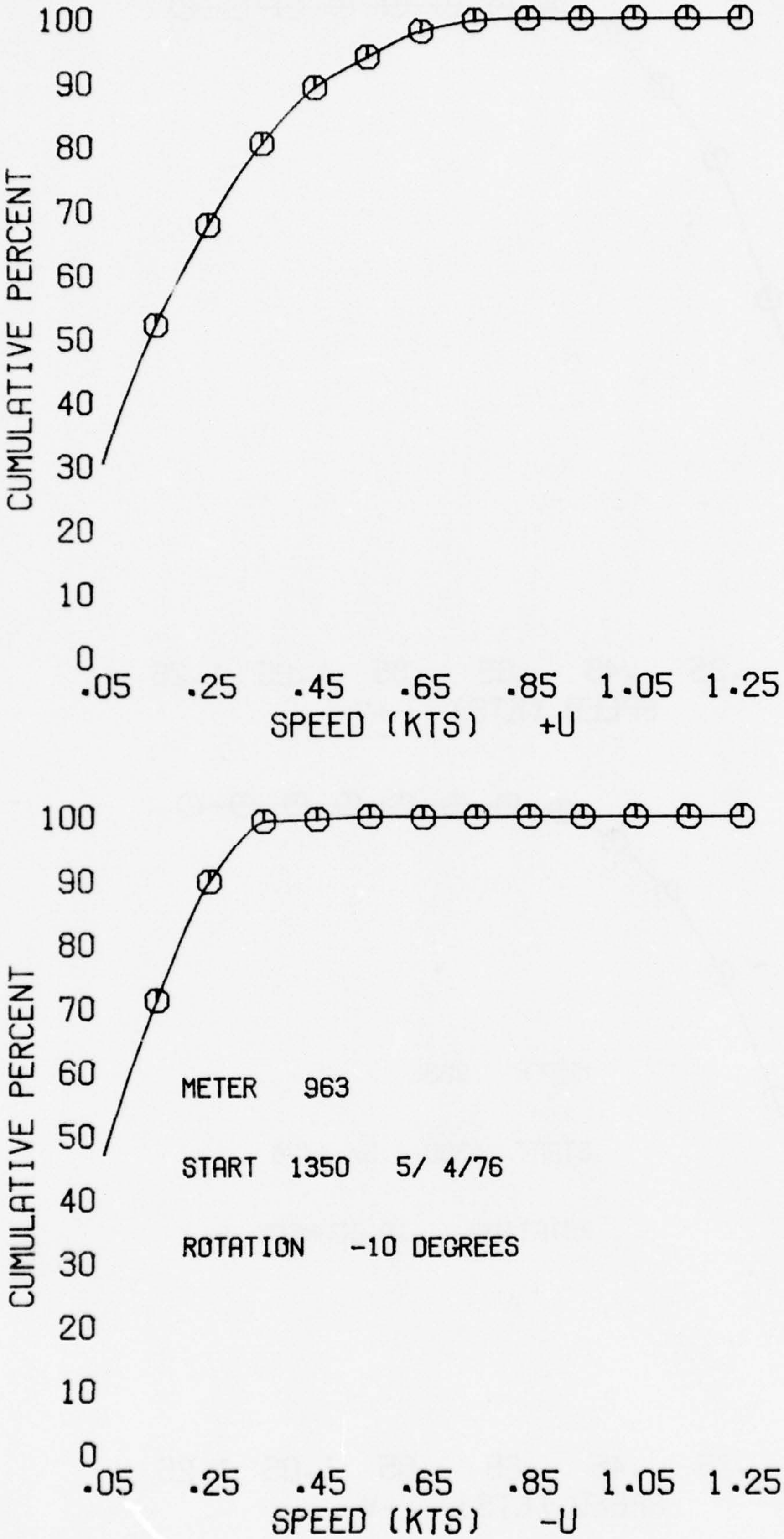


FIG. 37A AND 37B

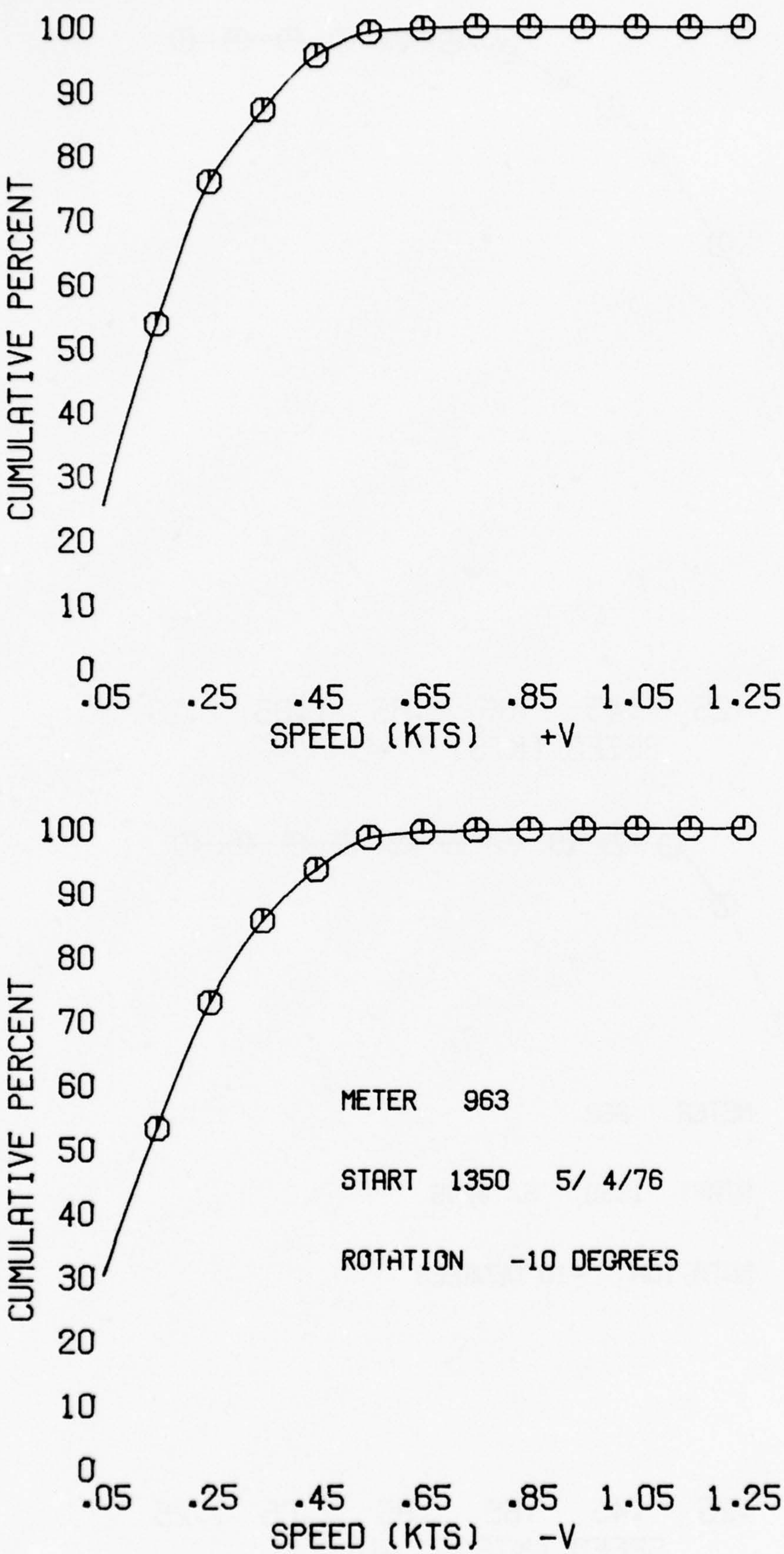
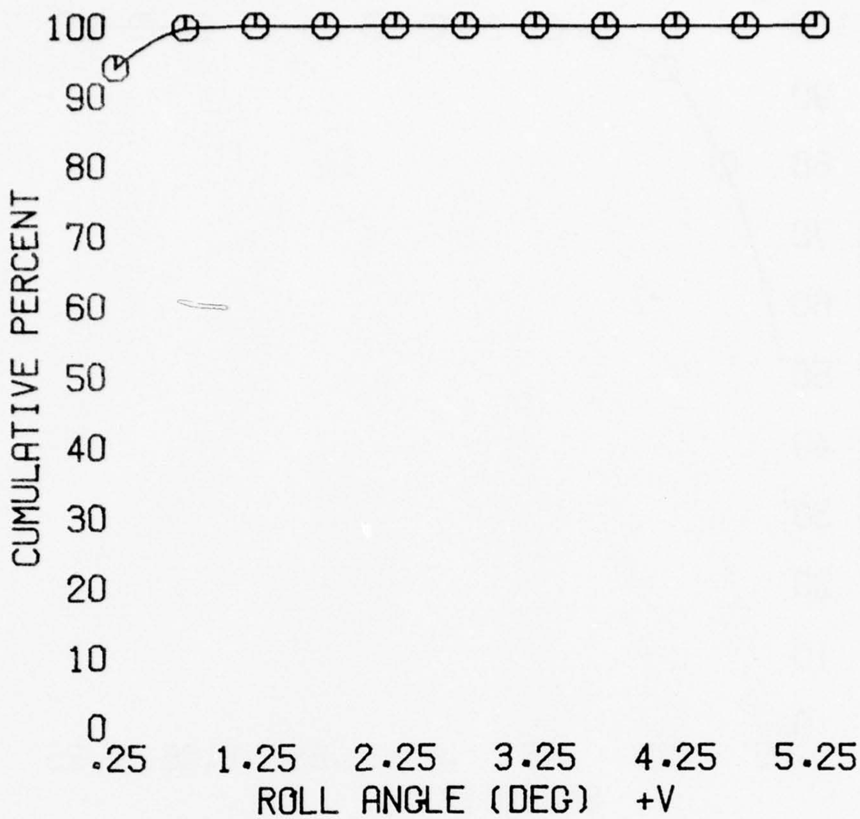


FIG. 38A AND 38B



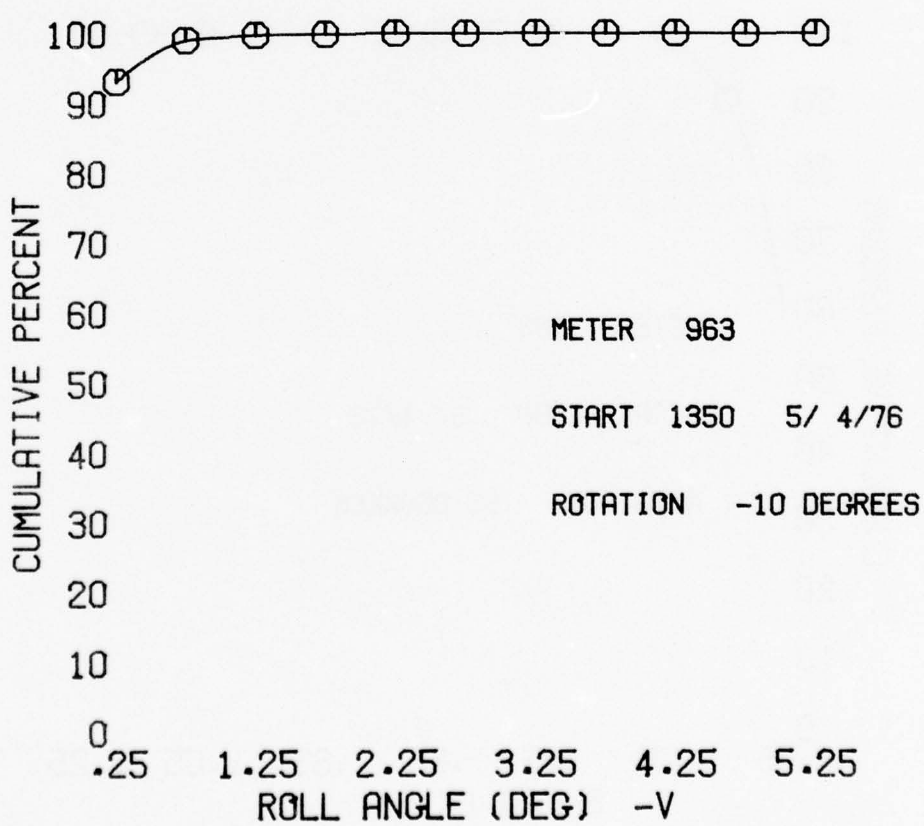
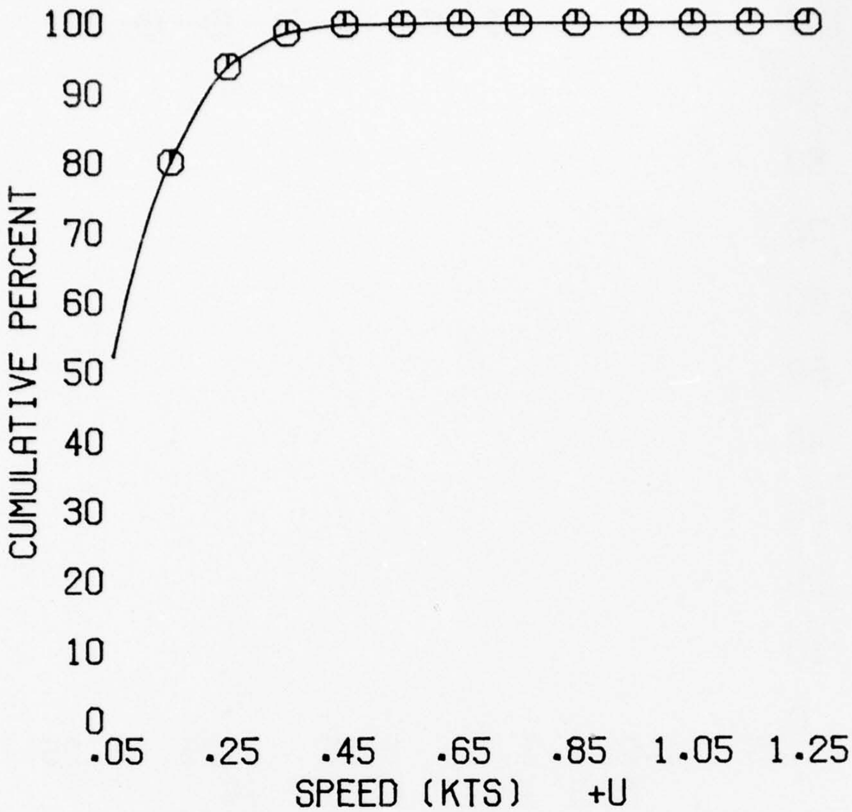


FIG. 39A AND 39B



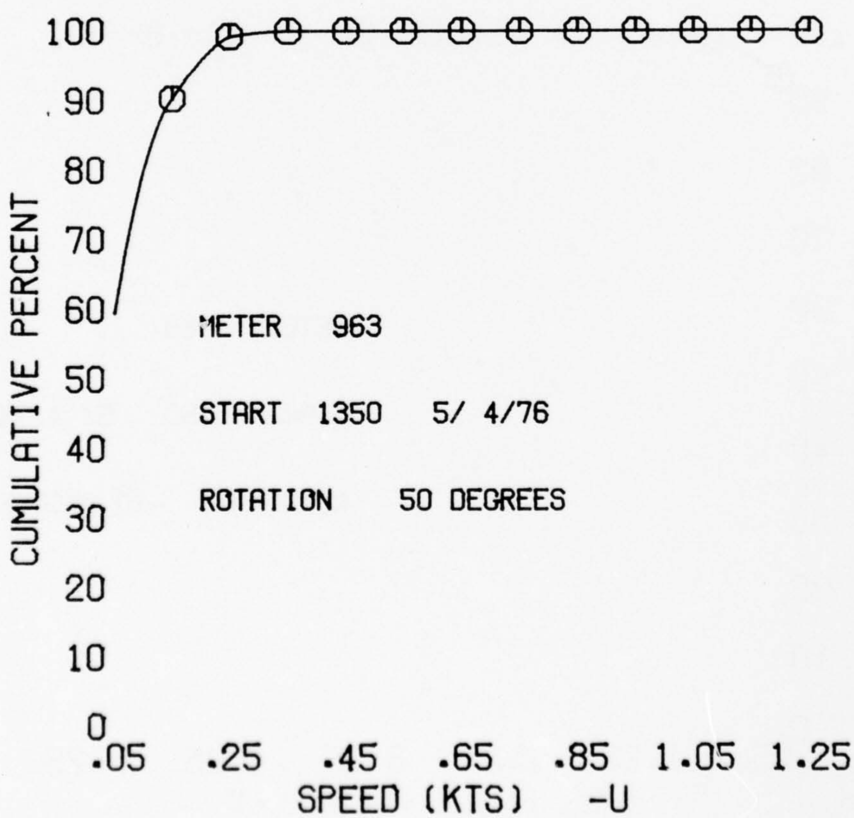
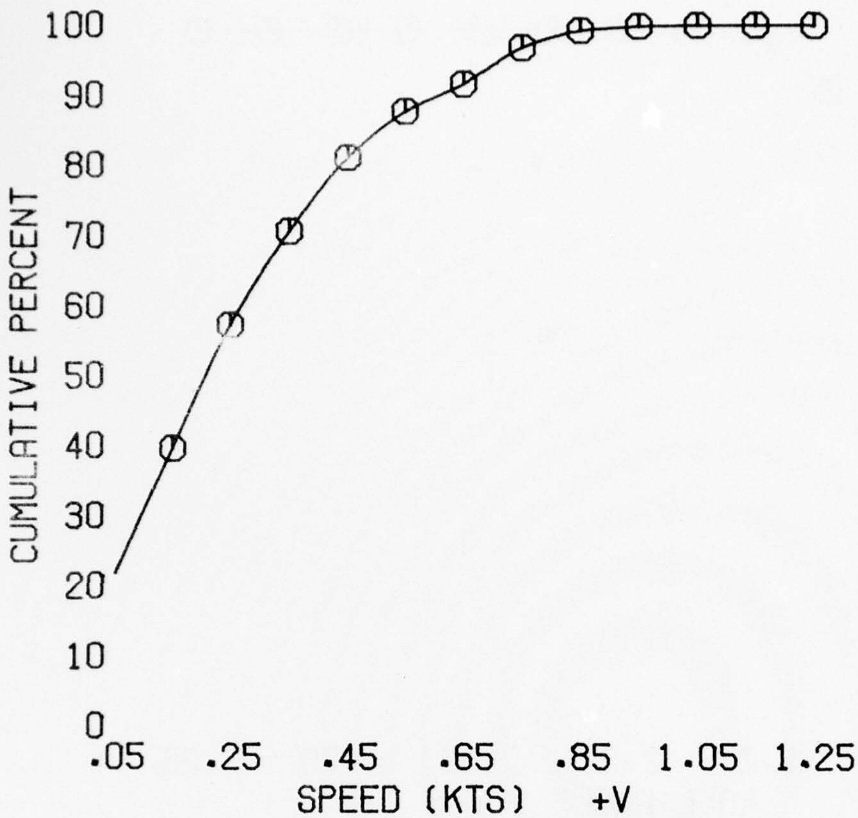


FIG. 40A AND 40B



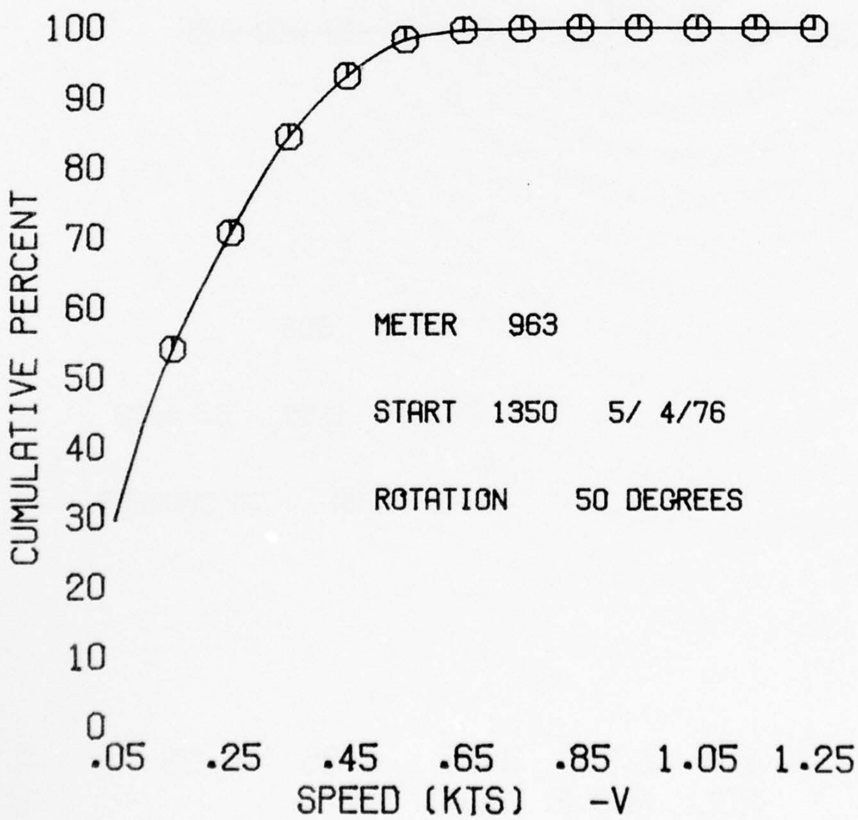
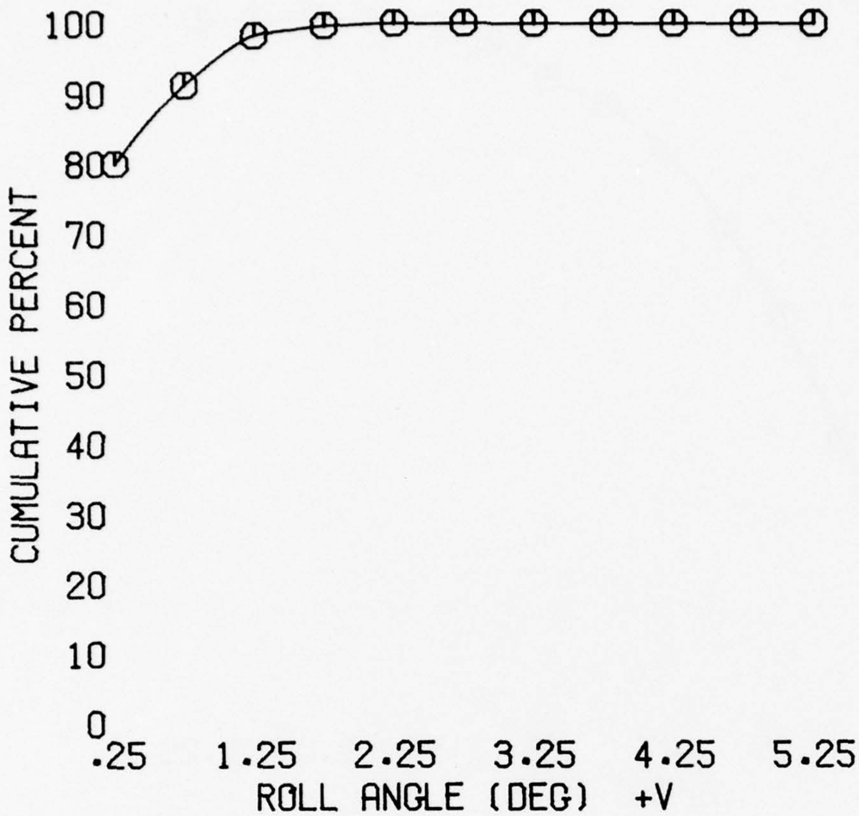


FIG. 41A AND 41B



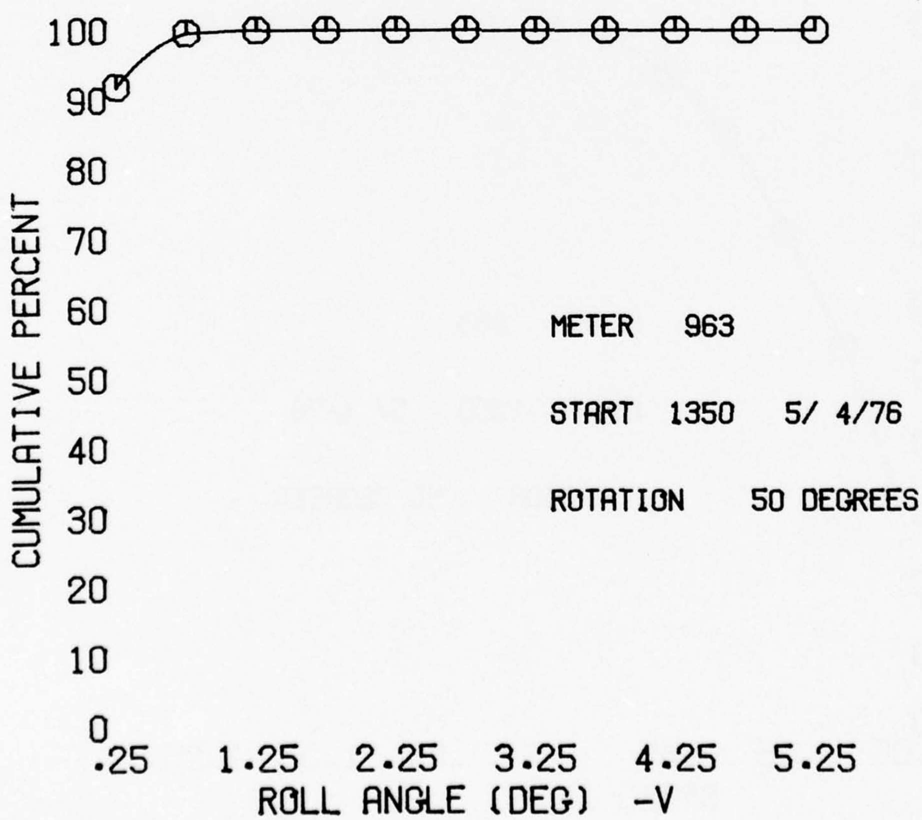
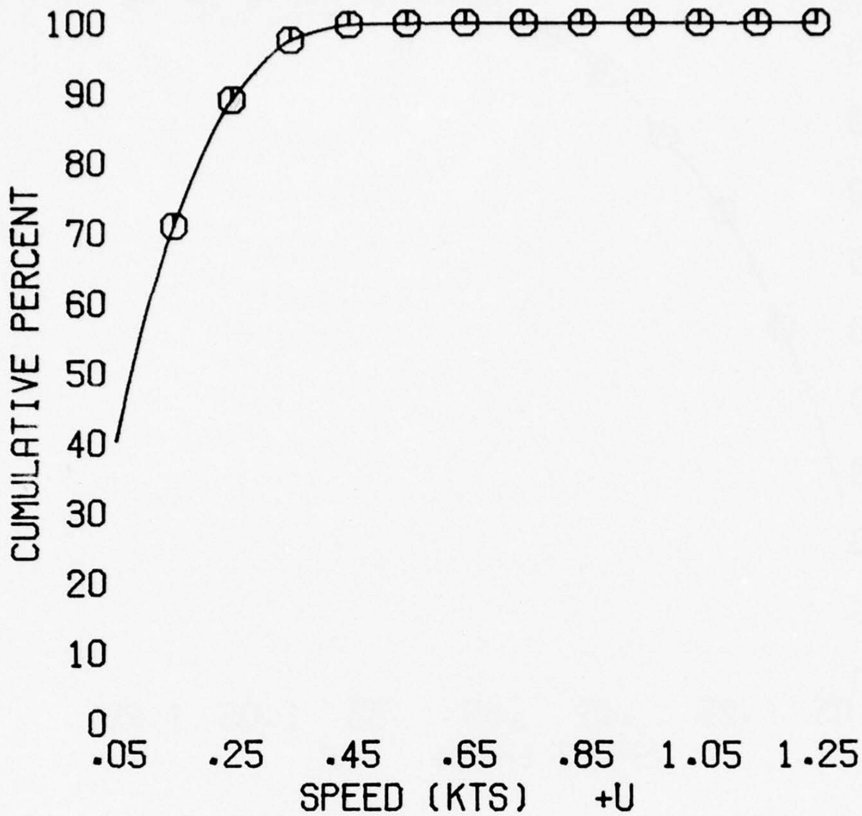


FIG. 42A AND 42B



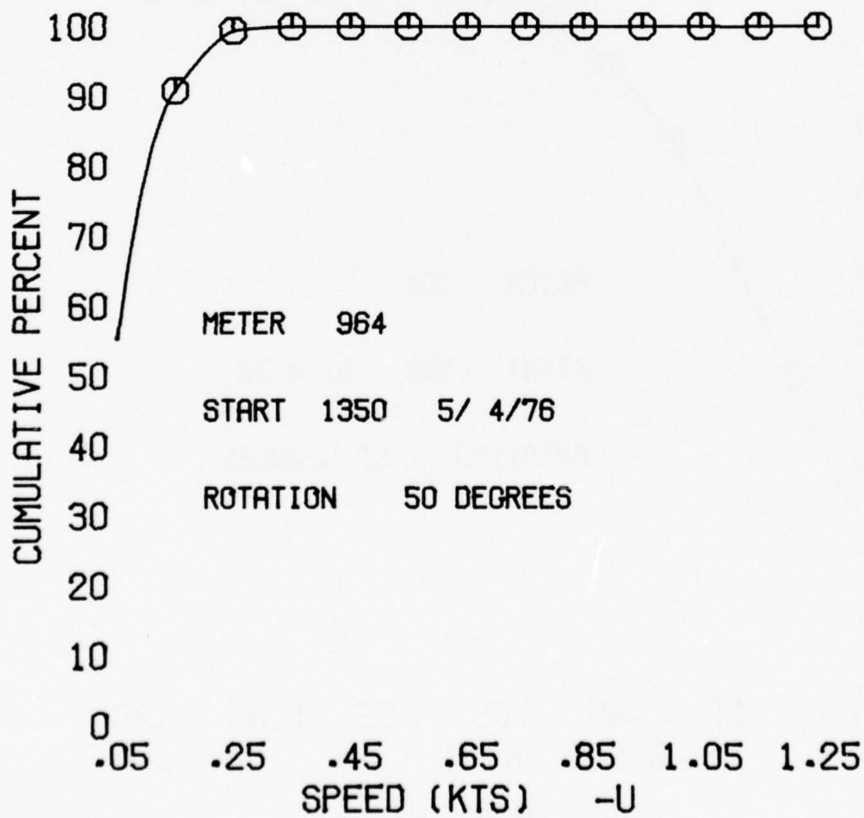


FIG. 43A AND 43B

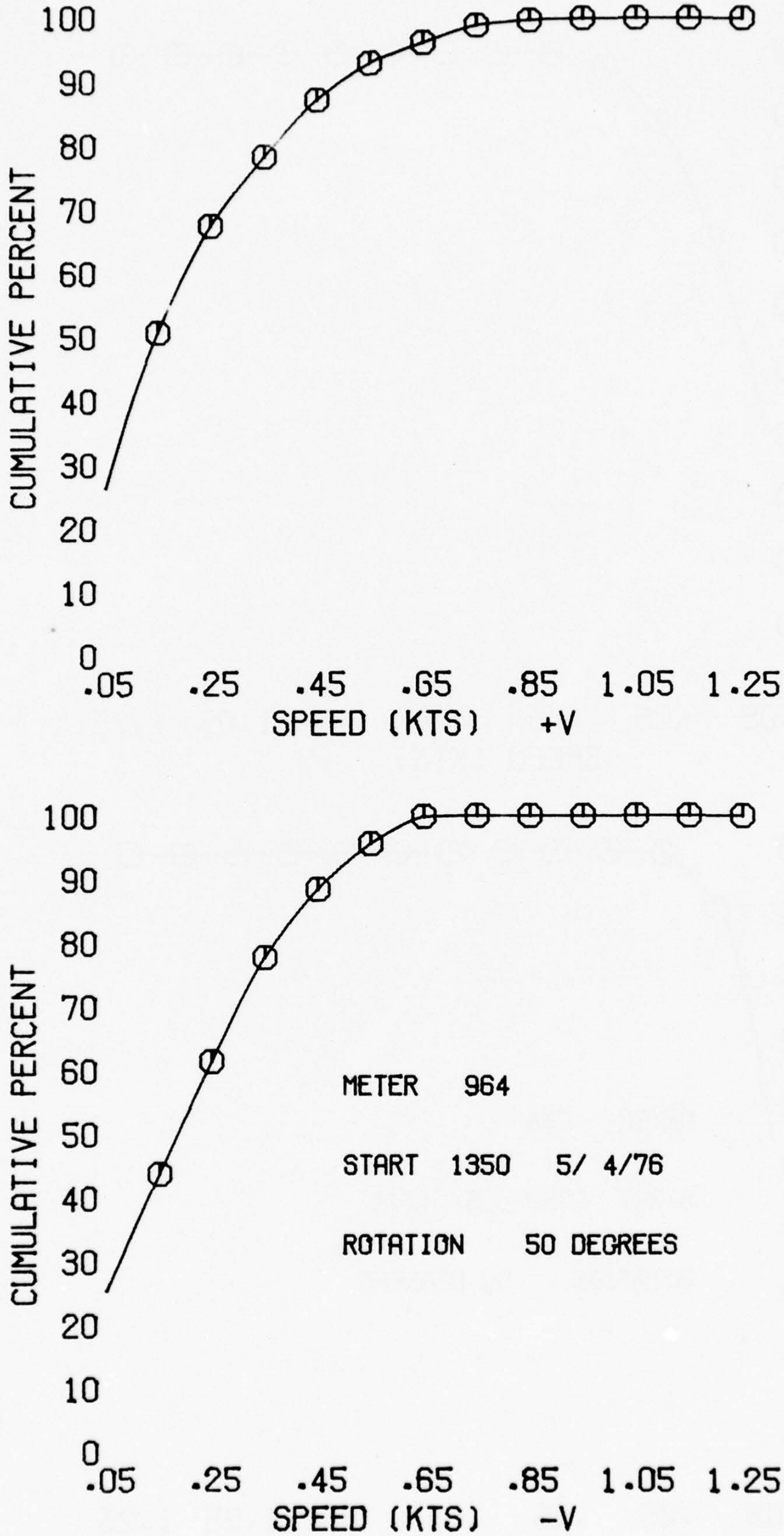


FIG. 41A AND 41B

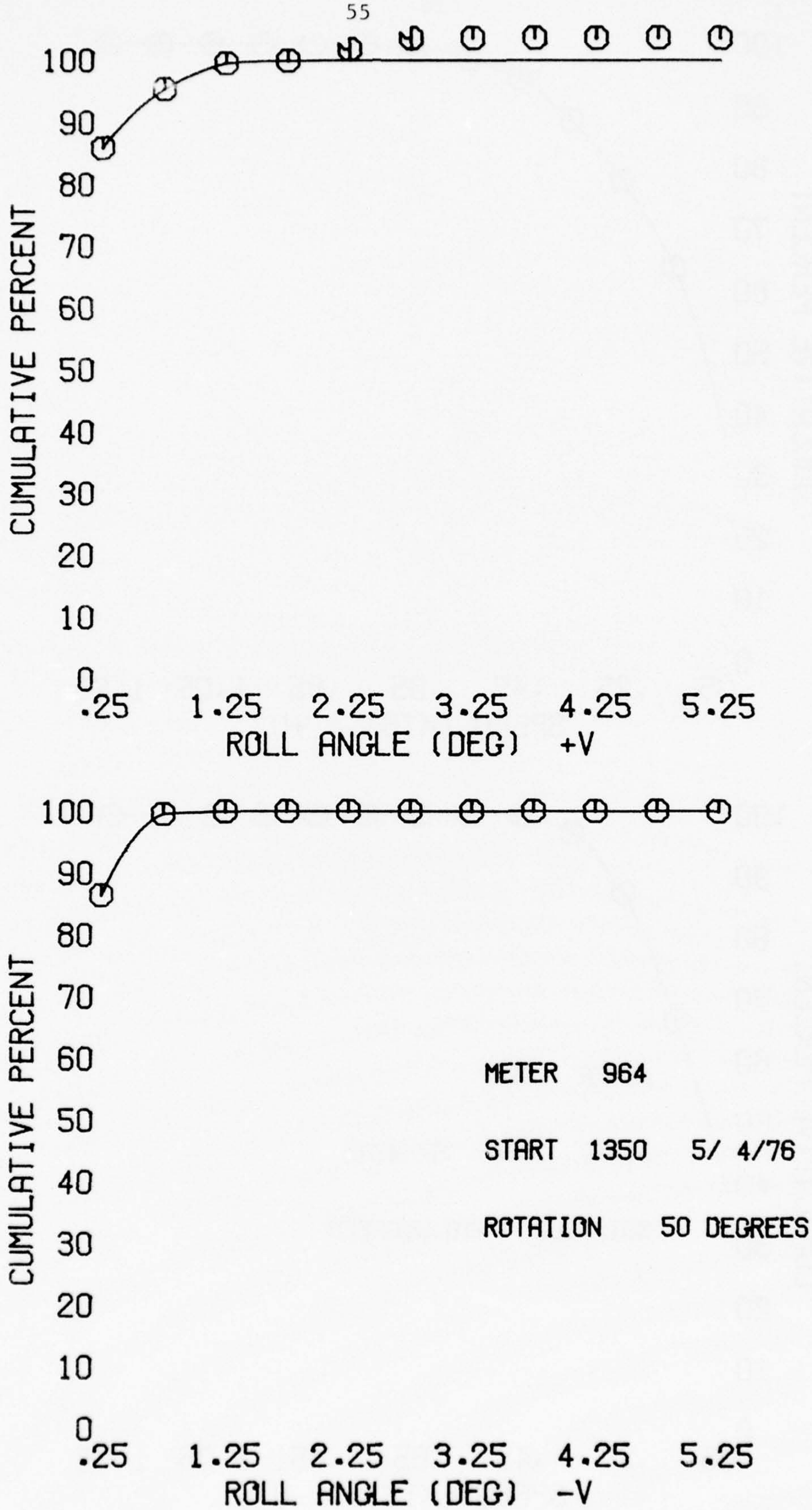
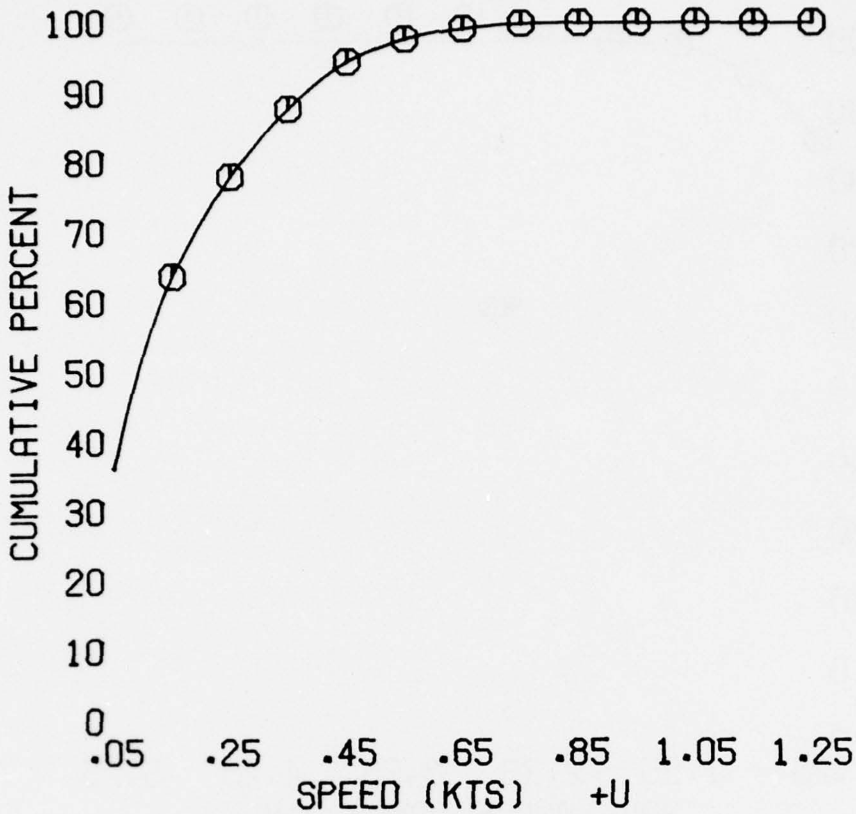


FIG. 45A AND 45B



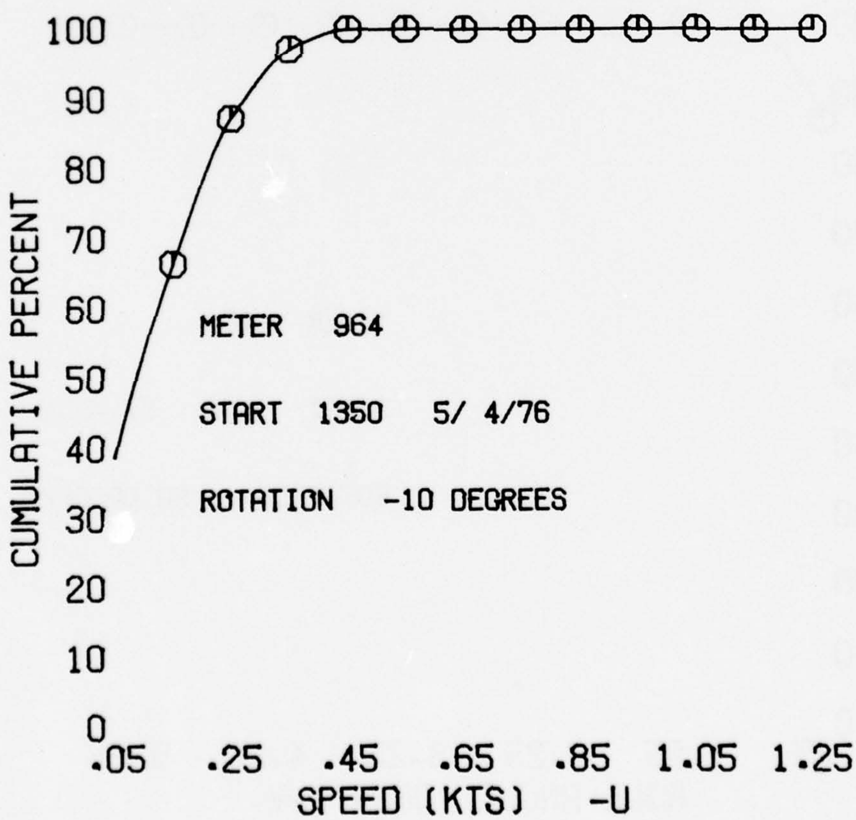
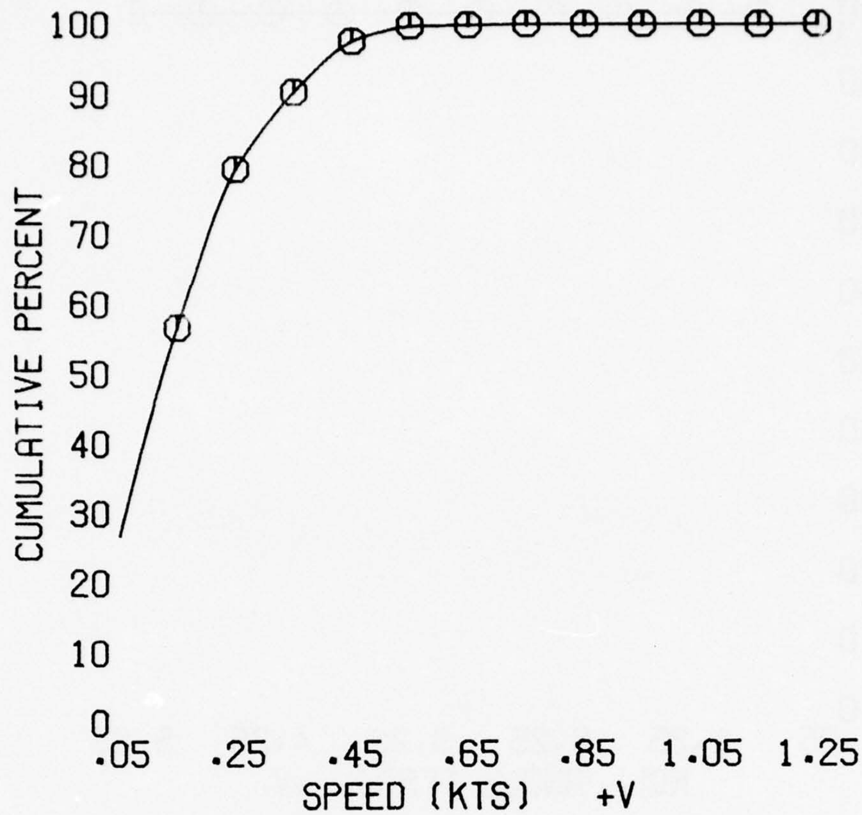


FIG. 46A AND 46B



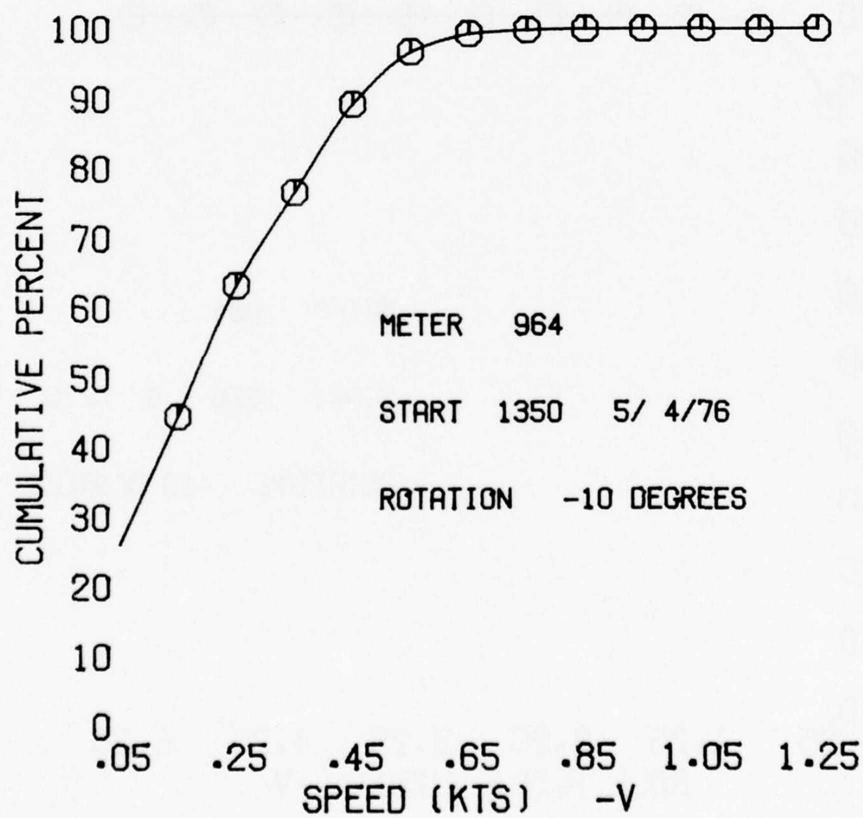


FIG. 47A AND 47B

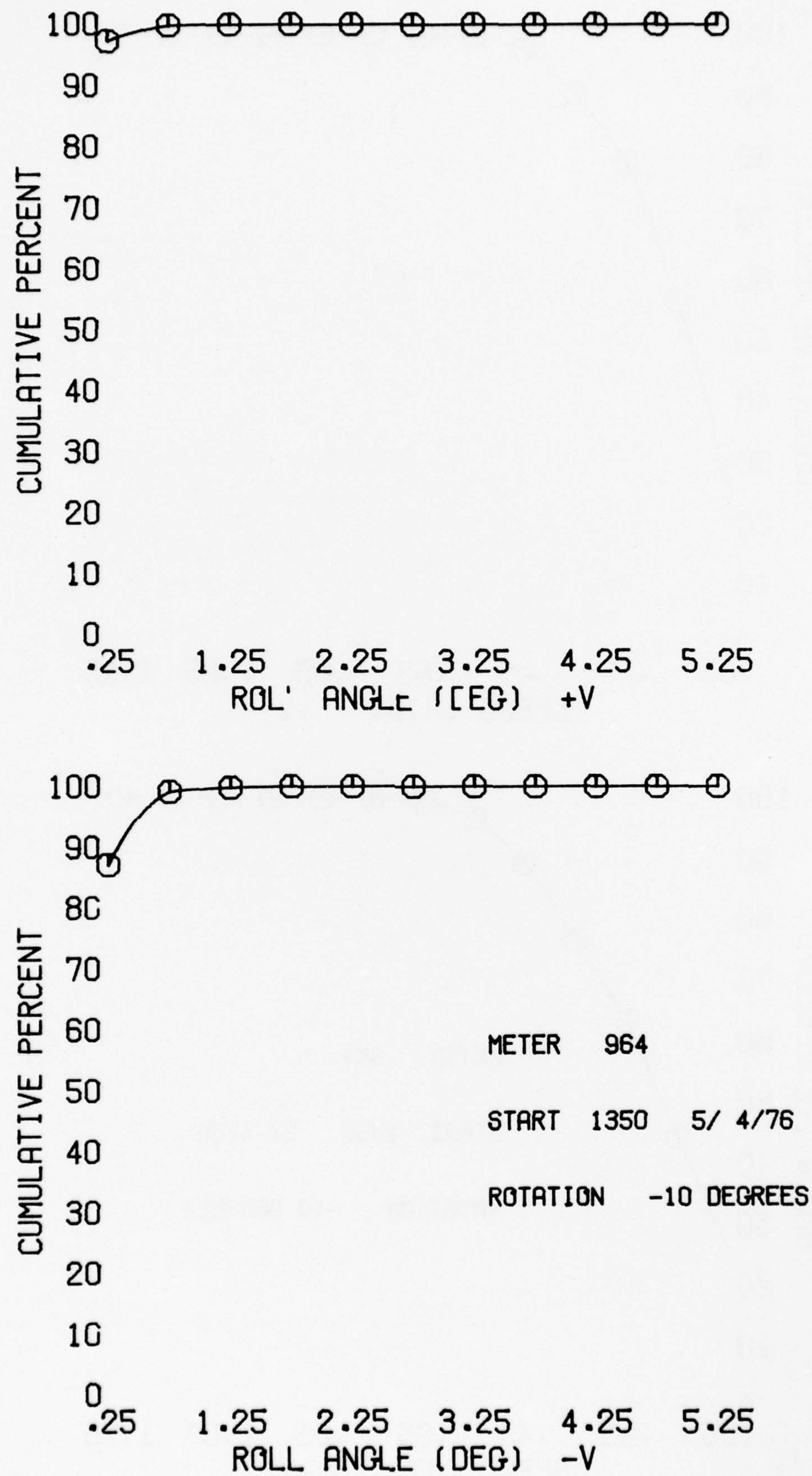
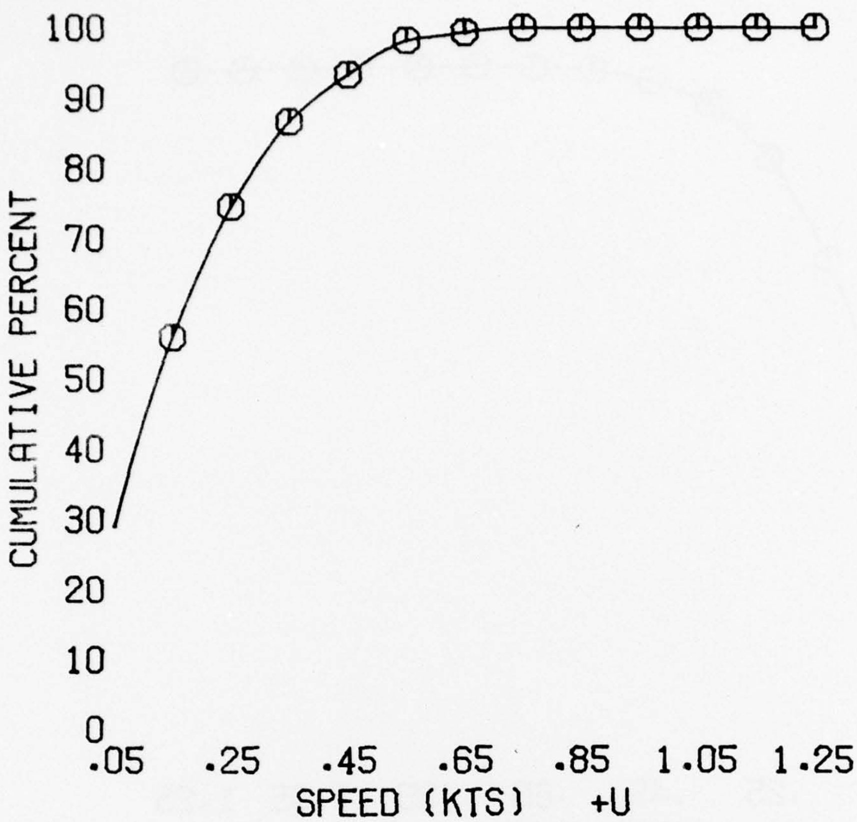


FIG. 48A AND 43B



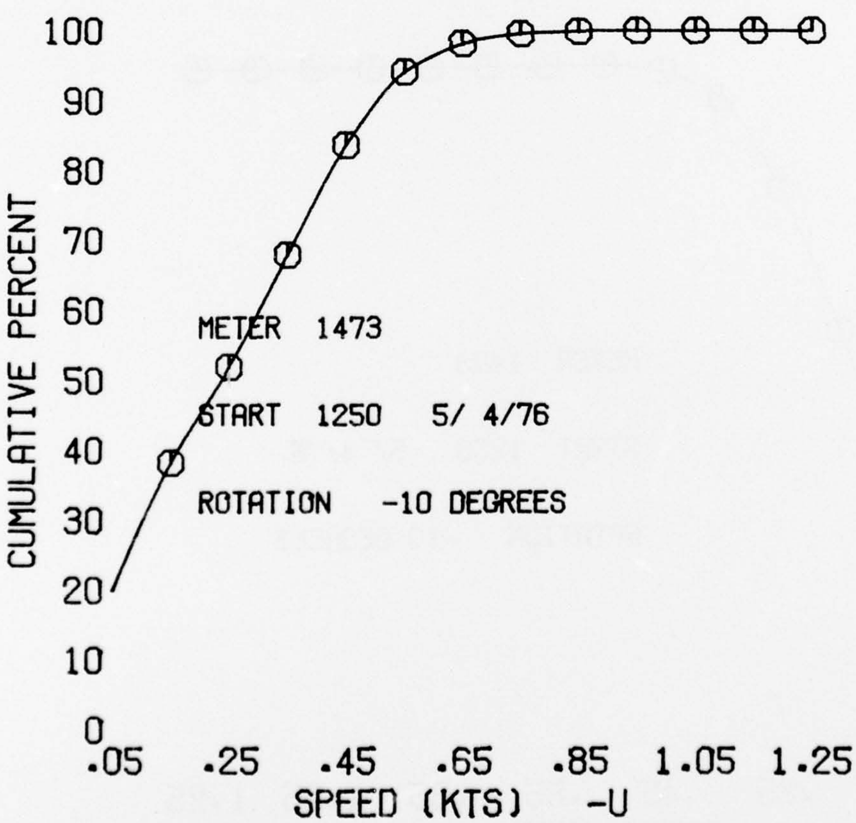
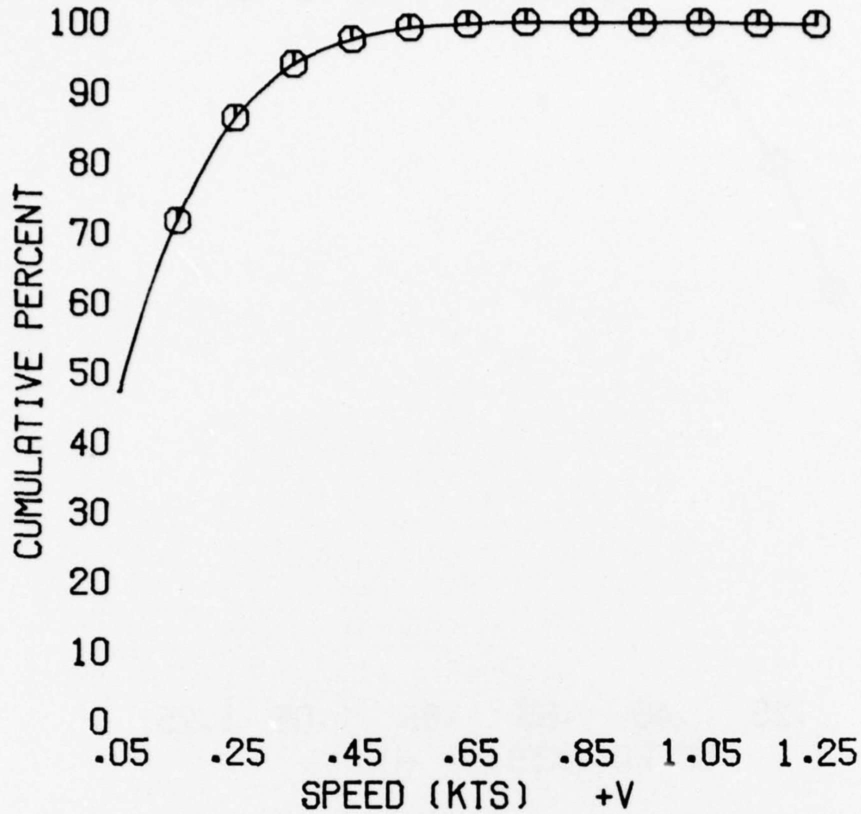


FIG. 49A AND 49B



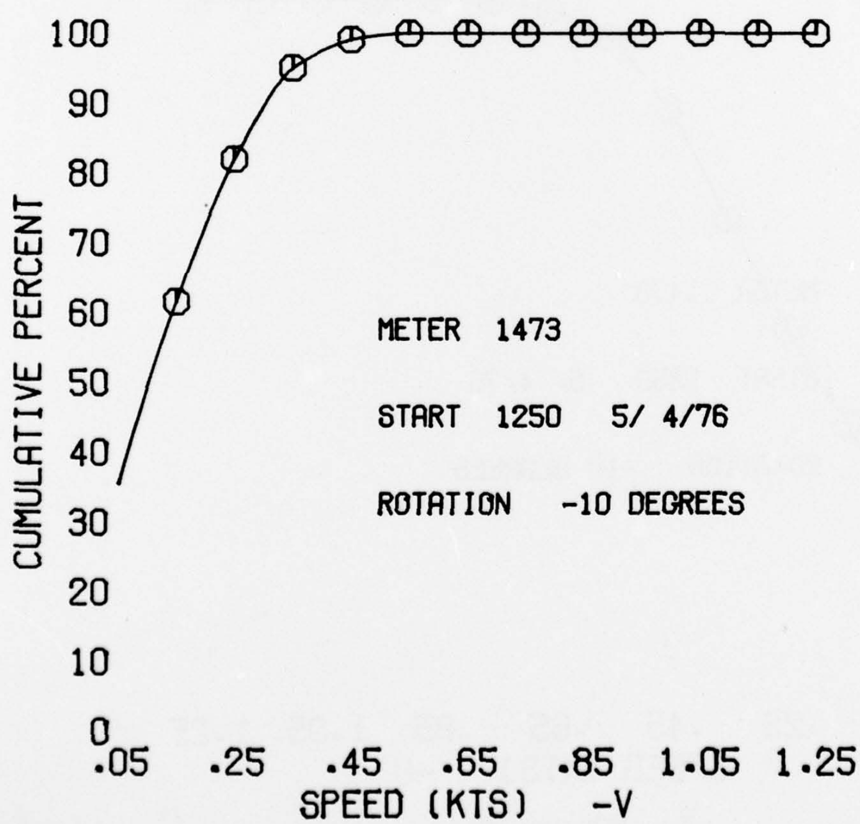
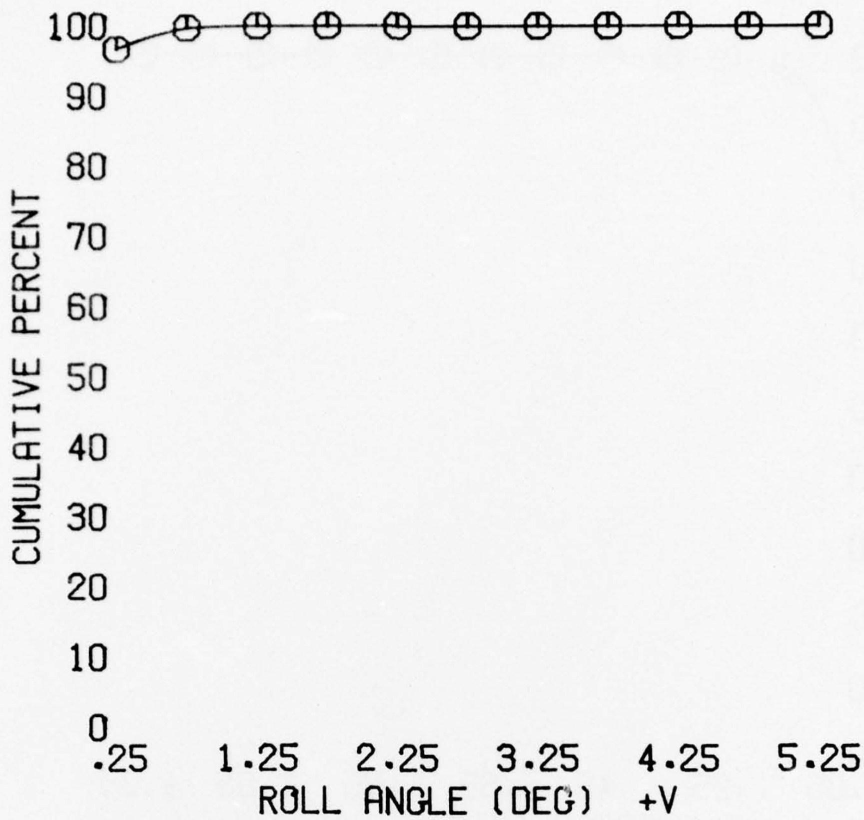


Fig. 50a and 50b



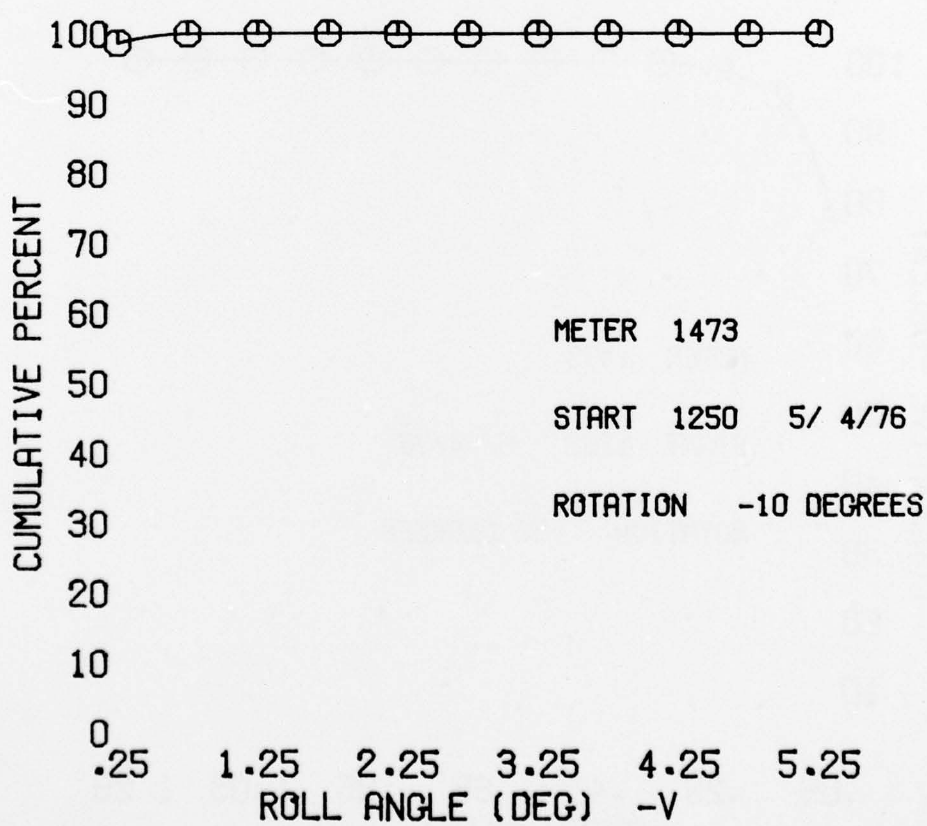
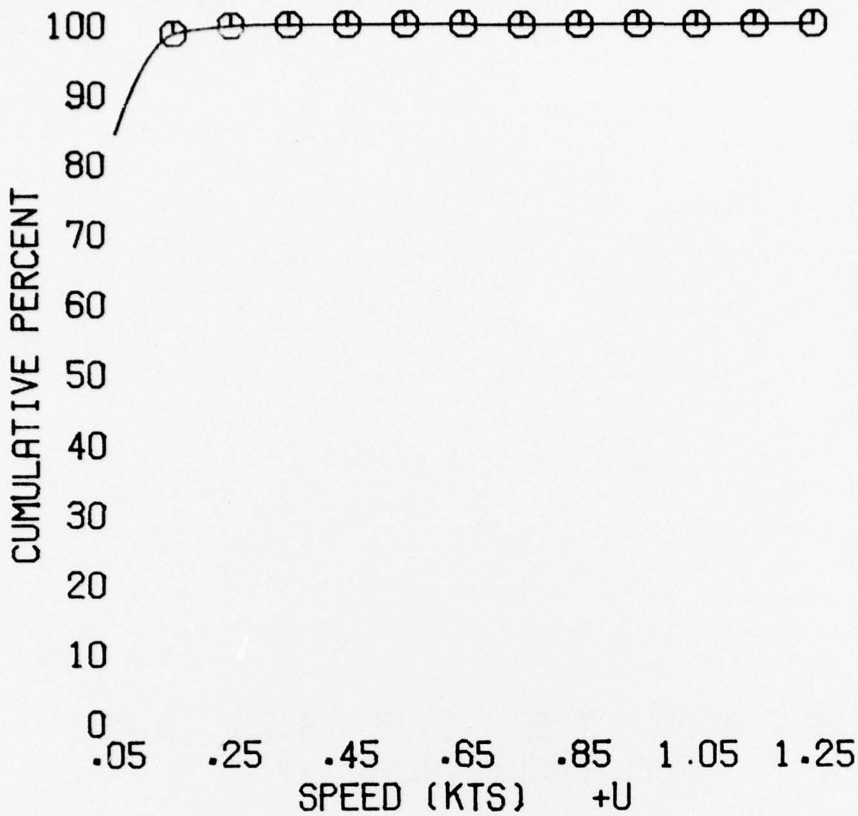


FIG. 51A AND 51B



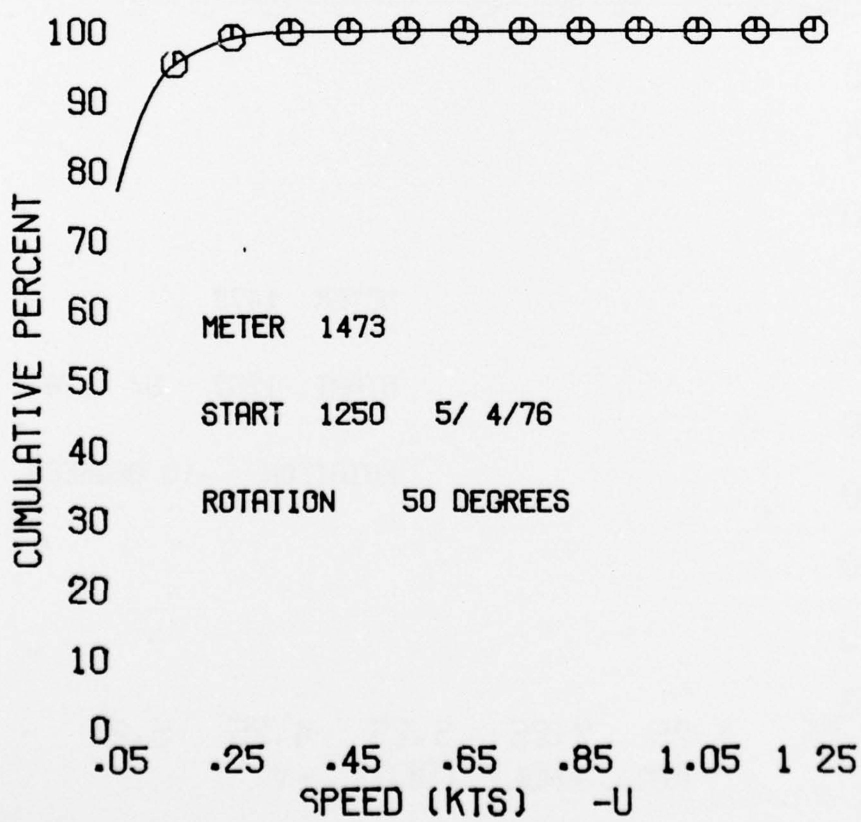
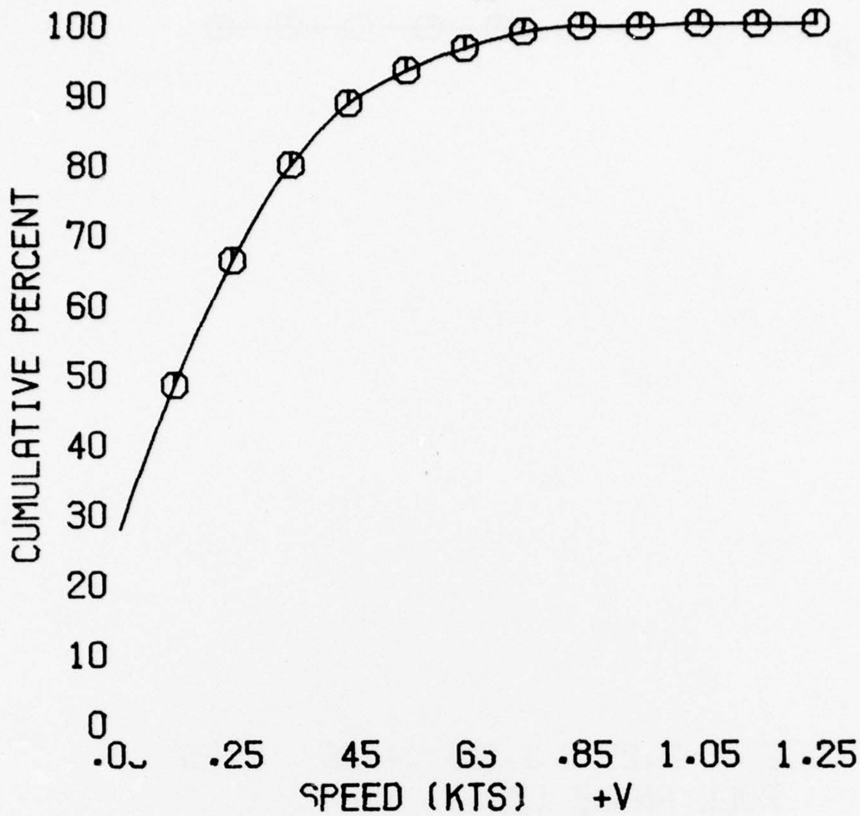


FIG. 52A AND 52B



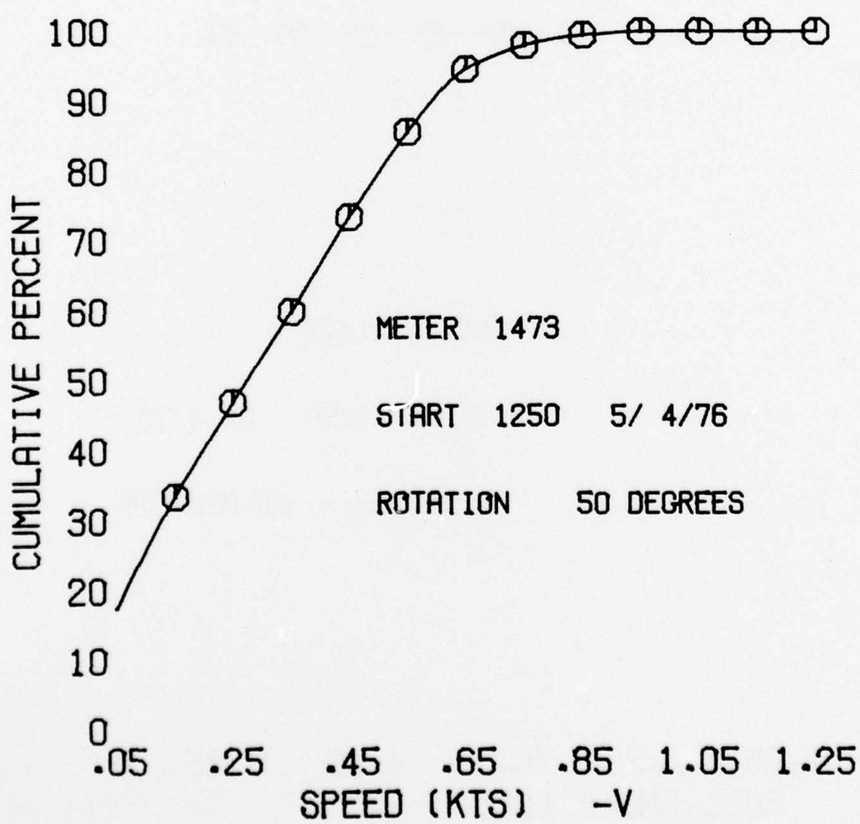
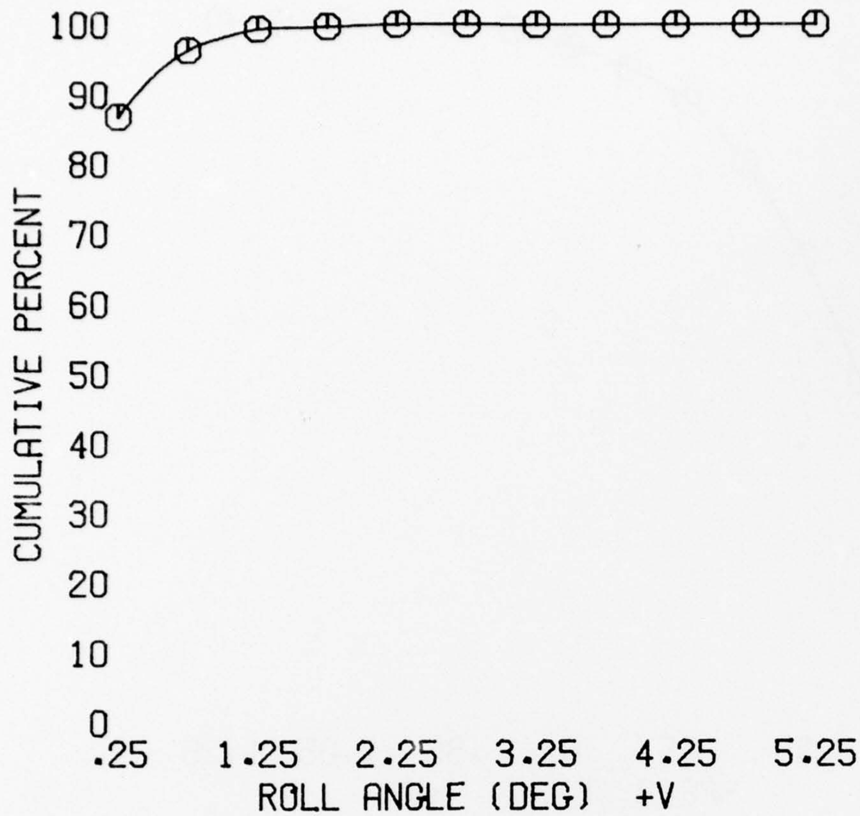


FIG. 53A AND 53B



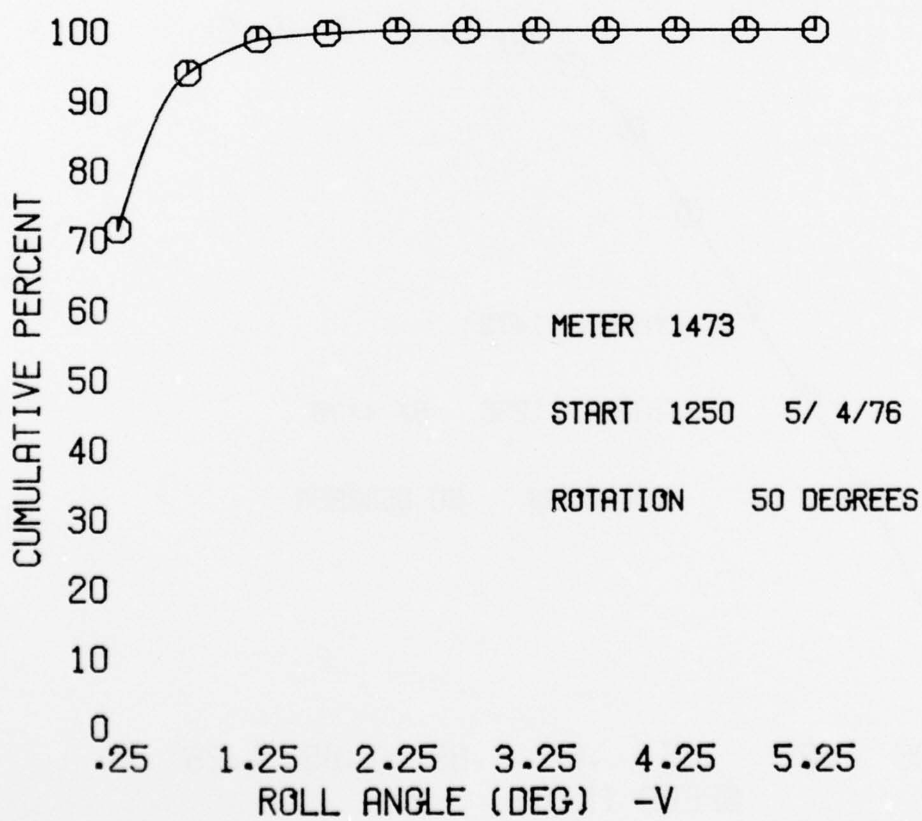
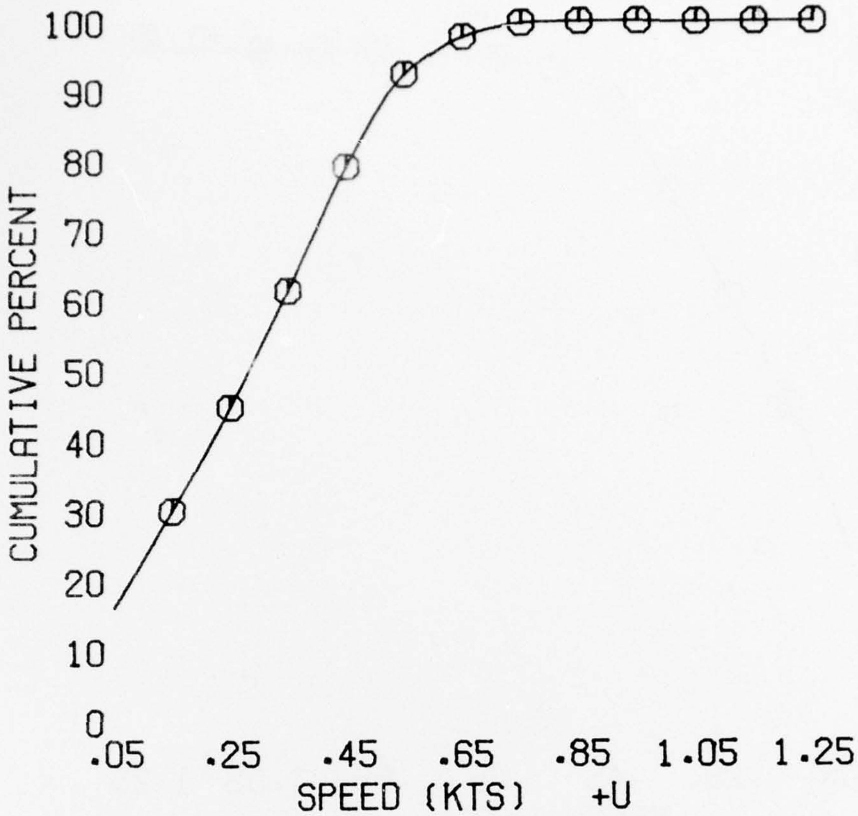


FIG. 54A AND 54B



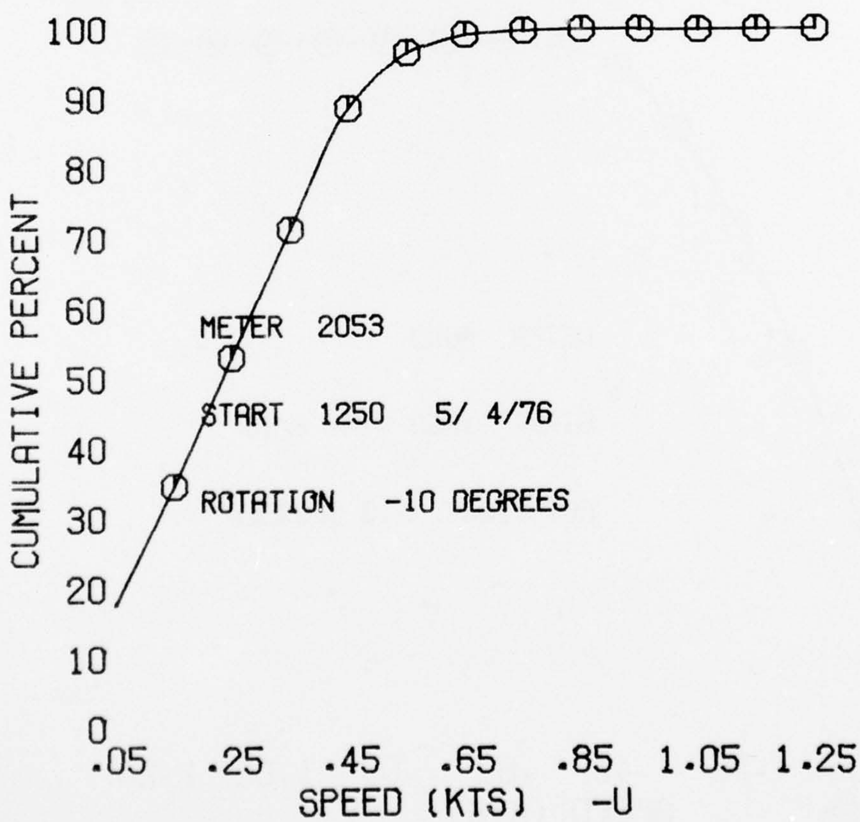
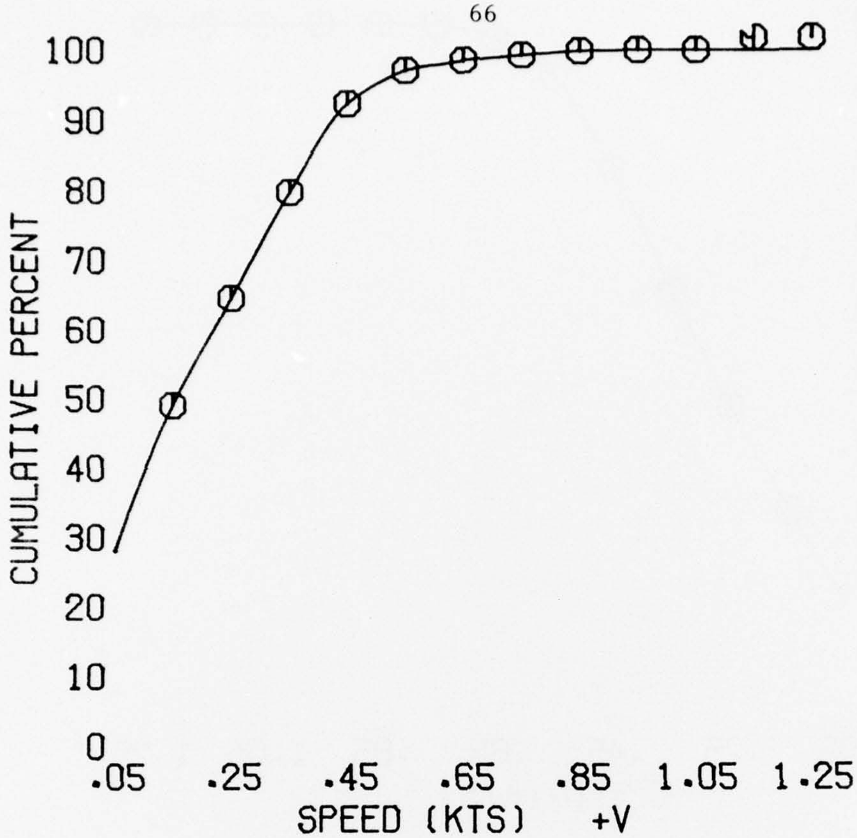


FIG. 55A AND 55B



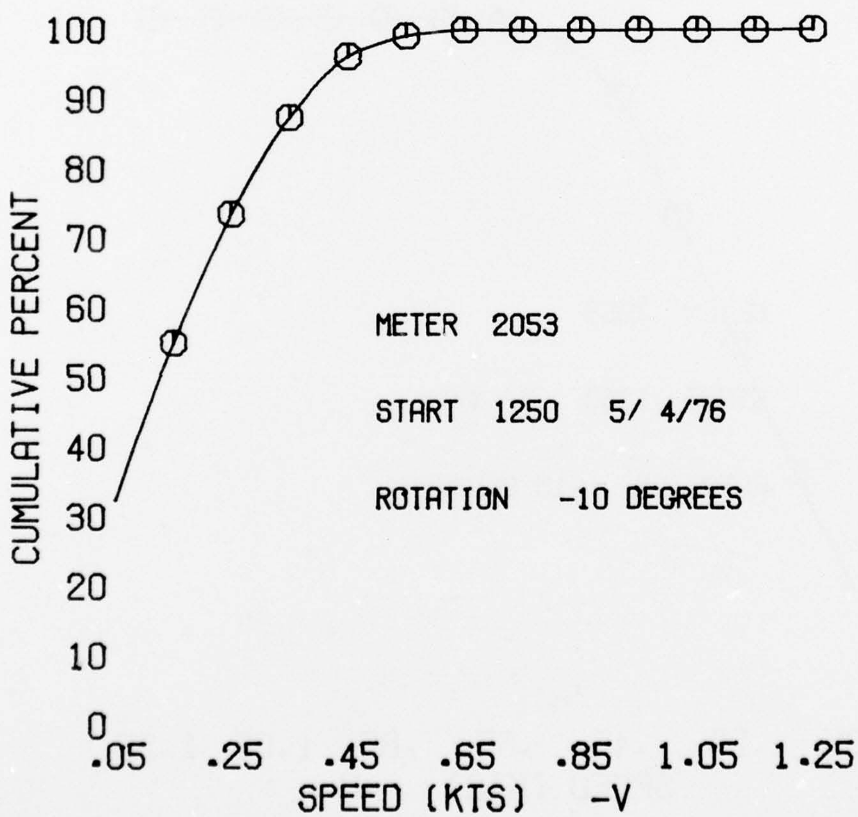


FIG. 56A AND 56B

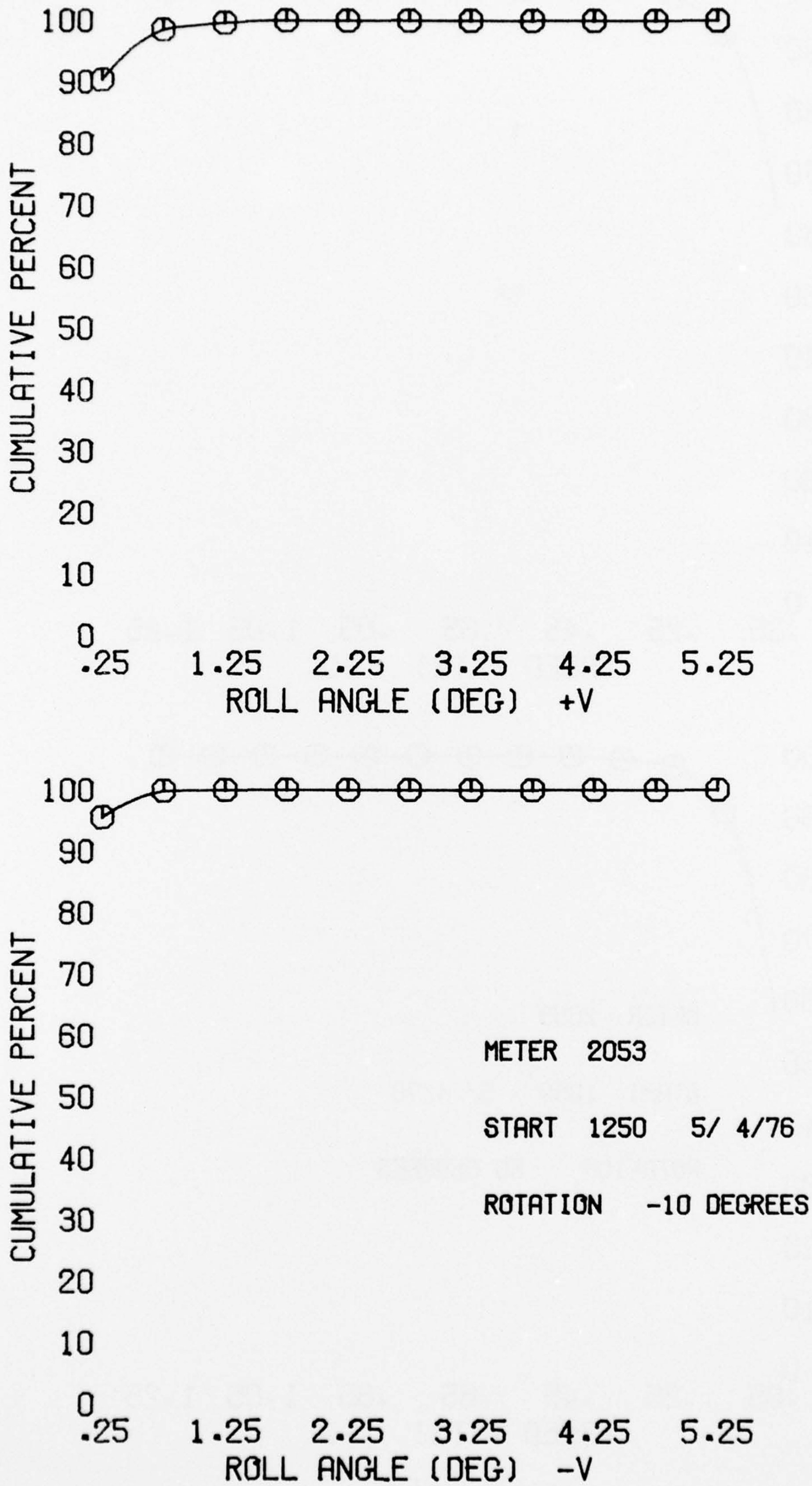
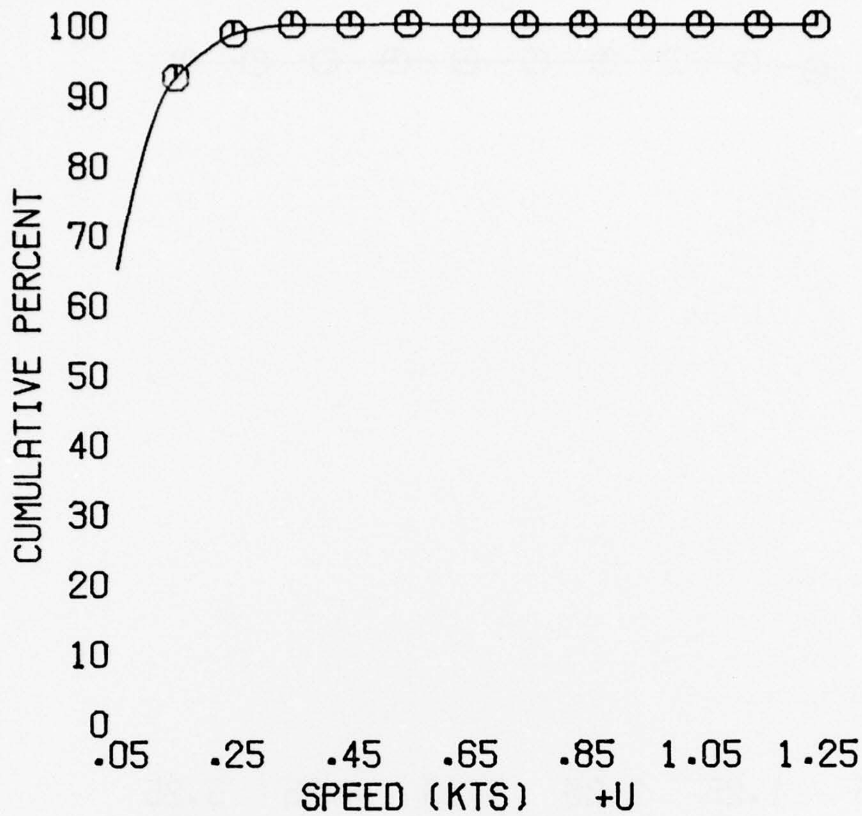


FIG. 57A AND 57B



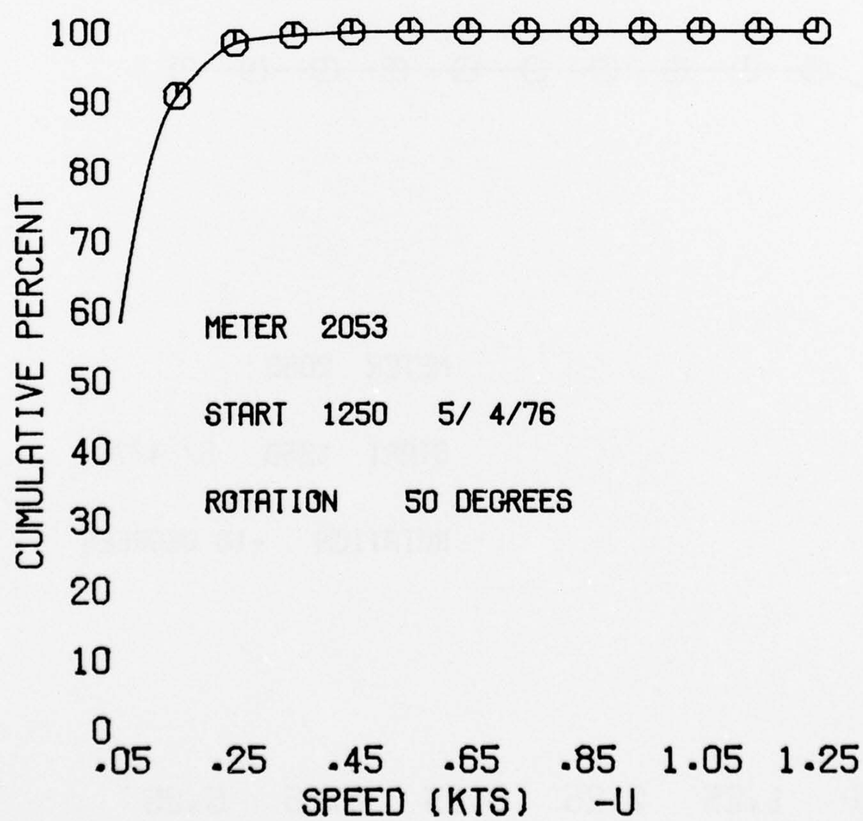
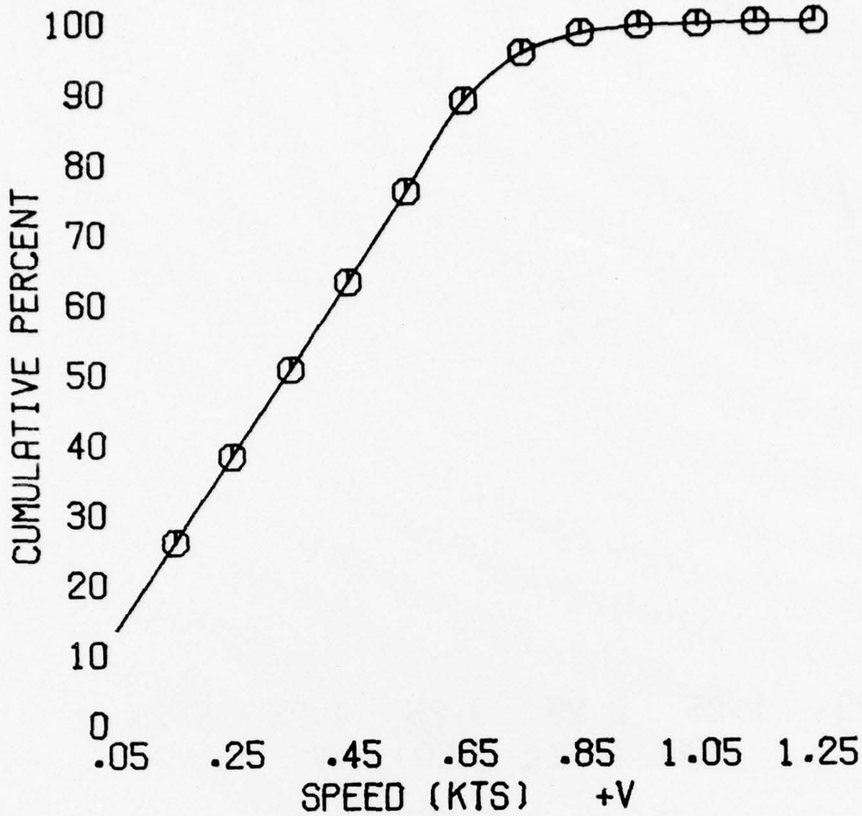


FIG. 58A AND 58B



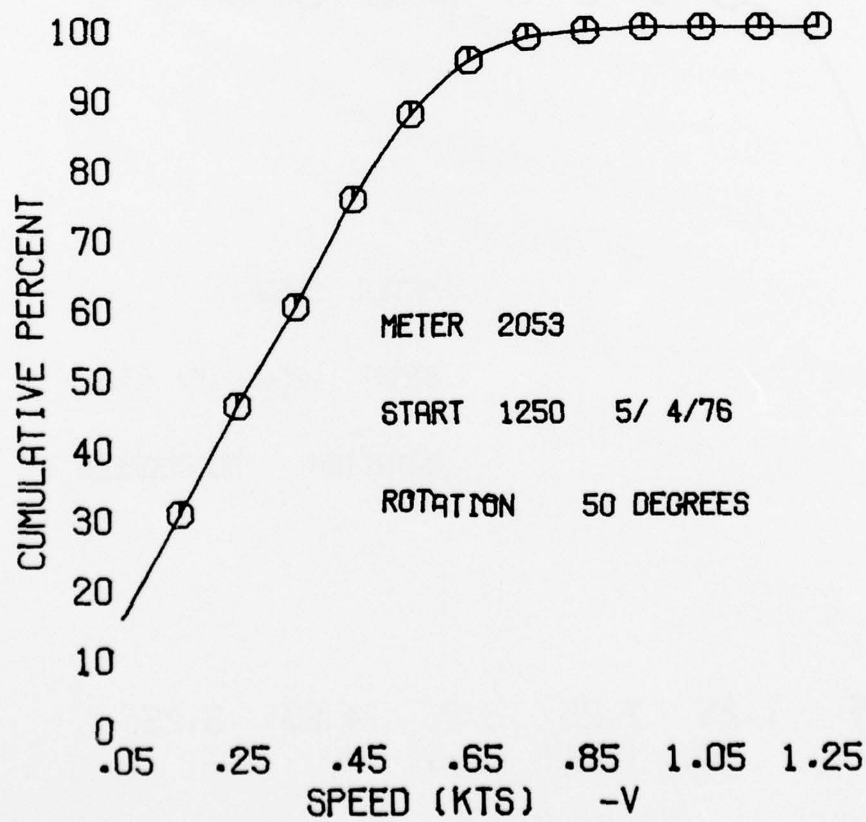
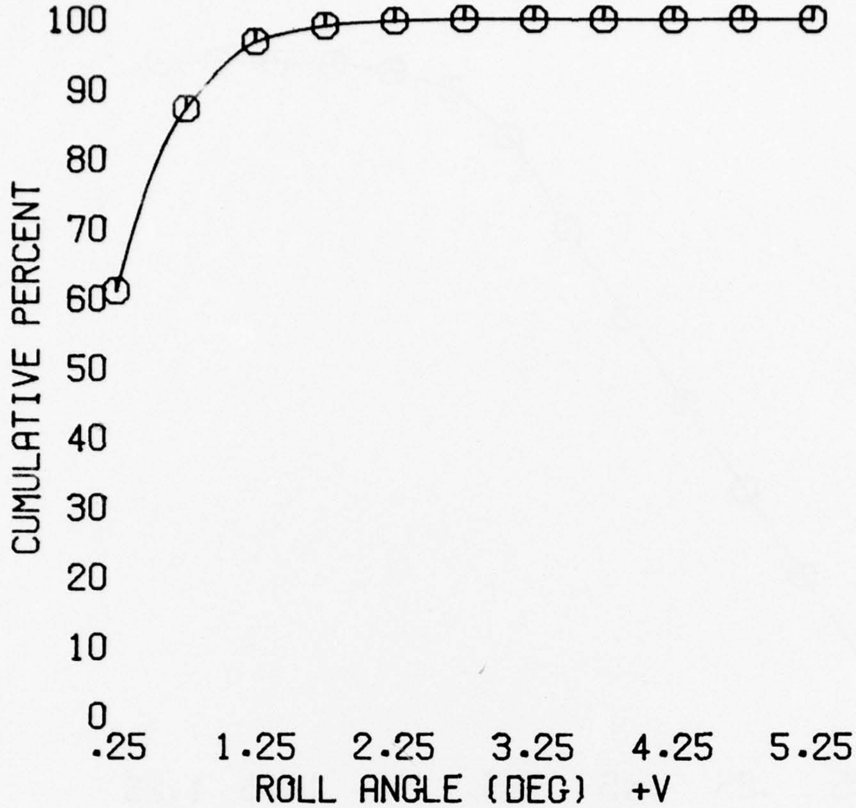


FIG. 59A AND 59B



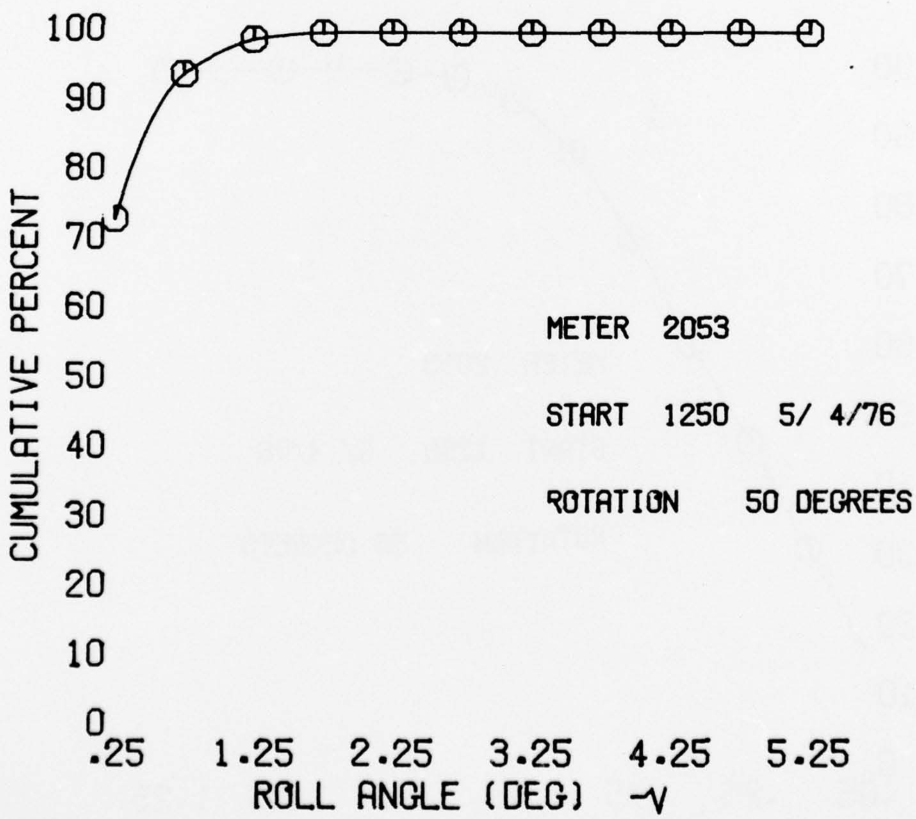


FIG. 60A AND 60B

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The first part of the report contains a general parametric analysis of the heeling angle of a submarine exposed to currents. The current is assumed to have an arbitrary velocity of distribution with respect to depth and to lay within a plane perpendicular to the length axis of the submarine. In the second part, specific observed current conditions from Hood Canal, Wash., are applied. Records from a total of 10 current meters are evaluated and applied in computing cumulative histograms of the heeling angle.

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