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INVESTIGATION OF VTOL APPROACH METHODS BY USE OF GROUND-CONTROLLED-APPROACH PROCEDURES

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SUMMARY

In anticipation of the instrument-approach problems that would be likely to occur in the instrument operation of convertible VTOL aircraft, a flight-test program has been conducted by using a small helicopter and ground-controlled-approach equipment. Methods of approach utilizing a minimum amount of airspace were studied in simulated instrument flight. Transition to visual flight at ceilings as low as 50 feet at the lower glide-slope angles terminated the approaches. The approaches were made at glide-slope angles from 3° to 27° at a rate of descent of about 500 ft/min and at airspeeds of 65, 45, and 25 mph under various wind conditions from initial altitudes of 1,000, 800, and 500 feet.

Without head winds, the maximum steepness of approach was limited to about 13° (to about a 150-foot ceiling), whereas with head-wind components of 10 knots approaches of 24° could be made although not to as low a ceiling. Since the steepest approaches could be made only with head winds of 10 knots or more, pattern letdowns were investigated for use under other wind conditions. Both circular and rectangular patterns were attempted. In circular patterns, a point was usually reached where a very rapid and large heading change was necessitated by the effect of the wind. The use of rectangular patterns allowed time for the pilot-controller team to converge on a desired heading in the legs with a resulting improvement in precision.

INTRODUCTION

In anticipation of the introduction of operational high-speed VTOL aircraft, research into various instrument-approach methods is needed to determine procedures which will permit the development of maximum potential utility of VTOL aircraft. Flight operations with multiengine military helicopters under Instrument Flight Rules conditions in high-density traffic have been conducted by the Federal Aviation Agency, and certification of multiengine helicopters for commercial operation under instrument-flight conditions is now underway.

The principal characteristics of the VTOL aircraft which make new methods appear desirable are its ability to operate at low speeds and to make steep approaches to landing. Such ability is useful when the aircraft is operating in limited airspace. The requirement of making the instrument approach with utilization of a small amount of airspace in the terminal area appears to be important both from traffic and obstacle-clearance considerations. For example, the operation of helicopters in civil terminal areas has indicated some desirability of separating the approach facilities for VTOL aircraft from those for conventional aircraft so that traffic would not be slowed by the intermixing of helicopters with conventional traffic. If separate approach ways were used, the airspace for the VTOL facility would be severely limited by conventional approach ways. Terminal airspace may be also limited by buildings and other obstacles surrounding VTOL landing areas.

The performance of steep-gradient instrument approaches poses special problems arising from the lack of visual cues in the approach, the various operating boundaries of the VTOL's, the operation limitations imposed by the necessity of transition to visual flight at low altitude (breakout ceiling), and wind effects. More specific factors affecting the choice of the method of approach using a limited airspace are: (1) the surface-wind velocity and direction, (2) the vertical gradient of the wind velocity and direction, (3) performance limitations of the aircraft, (4) aircraft stability and control characteristics at low speeds, (5) pilot ability and workload, and (6) approach-aid characteristics. In order to examine the interrelation of such factors to determine how present approach methods may be modified and what research requirements, equipment improvements, and piloting techniques may be needed to implement the improved methods, the flight investigation reported herein using a small helicopter and ground-controlled-approach (GCA) radar equipment was undertaken. Because of a prior lack of guidance equipment with steep-gradient capabilities, these problems have been studied only with a visual simulation of GCA as in the investigation of reference 1. The present investigation was undertaken to study other methods of approach such as circular and rectangular letdowns, in addition to the steep straight-in approaches, with the more realistic conditions and better tracking capabilities as provided by the GCA equipment.

SYMBOLS

r	radius of turn, ft
X, Y, Z	three-dimensional Cartesian axis system with origin located at desired touchdown point on runway. X-axis lies along runway center line and is positive toward target; Y-axis is in horizontal plane and perpendicular to runway center line and is positive on pilot's right as he approaches touchdown; Z-axis is vertical and positive up
x, y, z	coordinates of target (aircraft) relative to X-, Y-, and Z-axes, ft
dz/dt	rate of descent, ft/min
ϕ	bank angle, deg
ω	rate of turn, deg/sec
$d\omega/d\phi$	sensitivity of rate of turn to bank angle, 1/sec

VTOL SIMULATION

In order to make a study of steep instrument approaches that might be applicable in the operation of both helicopters and convertible-type VTOL's, it was decided to use a small helicopter. In the slow-speed regime many of the characteristics of helicopters, significant in the task of instrument approach, are similar to those of the convertibles. Some characteristics of helicopters which reflect on the applicability of the results to the convertible-type VTOL are outlined as follows: (These characteristics are illustrated in fig. 1 by using as an example, where necessary, the characteristics of the test helicopter.)

(a) Below the speed for minimum power required, the helicopter must fly on the so-called back side of the power-required curve. (See fig. 1 (a).) It is well known (see ref. 2) that flying with constraint to a glide slope on the back side of the power-required curve introduces different and often more difficult control procedures than otherwise. This, in general, is characteristic of all types of aircraft in this low-speed regime including the convertible-type VTOL.

(b) Simple calculations show that for all aircraft at low speed the variation of the rate of turn with bank angle is inversely proportional to speed. (See fig. 1(b).) Therefore, the large changes in rates of turn accompanying small changes in bank angle at low speed require increased pilot attention to the task of maintaining the on-course line.

(c) In the single-rotor helicopter, an increase in vertical force necessitates an increase in rotor torque with the result that a correction is required to maintain a heading. Unless torque changes are automatically compensated for, such correction is required every time a power or speed change is made. This is particularly significant when flying on the back side of the power-required curve.

(d) The very light disk loading of small helicopters results in low down-wash velocities. Therefore, the region of roughness associated with the vortex-ring state (fig. 1(c)) is encountered, for example, at rates of descent as low as 400 ft/min below 10 mph (roughness region from aircraft handbook). In this example, the no-wind flight-path angle at this speed is limited to about 27°.

(e) Maximum rates of descent in a helicopter are generally considered limited for instrument flight by the autorotation boundary (airspeed and rate of descent combinations at which the rotor requires no engine power to maintain a given operating rpm). (See fig. 1(c).)

EQUIPMENT

Test Helicopter

The helicopter used in the tests is shown in figure 2. This helicopter had a power-control system with a feel system in the cylic control having a stick-force gradient of about one-half pound per inch and press-to-release type of trim control. It had satisfactory speed stability (variation of stick position with speed) and satisfactory maneuvering stability as defined in reference 3. A blind-flying instrument panel (fig. 3) was installed for the subject investigation.

Ground-Controlled-Approach Radar Set

The approach aid used in the test was a ground-controlled-approach (GCA) radar set. Basically, the set has two modes of operation: search (plan-position-indicator (PPI) display) and precision. (The upper half of the precision display shows the elevation plane and the lower half shows the azimuth plane.) The scan interval was about 4 seconds in the search mode and averaged about 2 seconds in the precision mode. Typical scope displays are shown in figure 4. The horizontal scale in the precision display represents slant range, and the vertical scales represent elevation angle and azimuth angle from the antenna location reading from top to bottom, respectively, rather than vertical and lateral distance. Curved lines called cursors represent the glide path and the on-course path which extend to touchdown.

A K-24 camera was modified in order to record the data for conversion to Cartesian coordinates and analysis of flight-path deviations.

TESTS

General

Two basic types of approaches were examined in this investigation. They were: (1) the straight-in approach, conventional except for the steepness of the glide slope, and (2) the descent-pattern approach. The descent-pattern approaches found most useful were those which terminated in a straight-in approach. The approach flight paths investigated are shown in figure 5.

In order to expedite the tests a safety pilot would usually fly the helicopter to a position some distance beyond the point of interception of the glide slope with the initial altitude, or a predetermined fix and make the turn onto the base leg. From this point the instrument pilot would attempt to fly the prescribed course with the aid of instructions from the GCA controller until a ceiling of 100 to 50 feet was reached. The instrument approach was discontinued when the intended ceiling of 50 to 100 feet was reached or when the deviation became so large as to make continued instrument flight impractical.

Steep Straight-In Approaches

Tests were made at glide-slope angles of approximately 3°, 6°, 9°, 13°, 24°, and 27° from an initial altitude of 500 feet and also from altitudes between 800 to 1,000 feet. The lower approach angles (9° and below) were flown at airspeeds of 65 and 45 mph. These speeds roughly correspond to the speed for a maximum lift-drag ratio and the speed for minimum power, respectively. (See fig. 1(a).) At a glide-slope angle of 13° the airspeed was limited to a maximum of about 25 mph without head winds, and glide-slope angles of 24° and 27° could be flown at 25 mph only with head winds. These limits are imposed by a requirement (discussed subsequently) that the rate of descent not exceed 500 ft/min.

Descent-Pattern Approaches

Circular- and rectangular-descent-pattern approaches were attempted in order to reduce the airspace required under wind conditions which would be unfavorable for the steep straight-in approaches.

For the descent-pattern approaches the controller directed the helicopter to a fix on the runway center line (extended) either over the touchdown point, or at the point of interception of the glide slope with the initial altitude, or some distance beyond the glide-slope interception point. From this fix the controller would direct the pilot to fly a predetermined descent pattern. (See figs. 5(b) and 5(c).) These patterns were initiated at an altitude of approximately 1,000 feet. The rate of descent in the pattern was gaged so that approximately 500 feet in altitude were lost in one circuit. For the test condition in which only one 360° circuit was to be made, an interception with a steep glide slope followed the turn and a straight 9° approach was continued to breakout altitude; when two 360° turns were made, the circular flight path was terminated at touchdown. In some later descent patterns a shallow (3°) glide slope was intercepted after one circuit in which approximately 800 feet of altitude were lost. The patterns were laid out for a no-wind airspeed of 25 and 45 mph. Two types of patterns were used, circular and rectangular.

The circular patterns were superimposed by means of an overlay (scaled to the 1-nautical-mile range) on the precision azimuth display where they appeared oval shaped with the long axis perpendicular to the on-course line. The radius of the circle corresponded to turns of approximately 3° per second (standard rate) or 6° per second at the desired airspeed. (See figs. 5(b) and 6.)

The rectangular patterns were drawn on the PPI display (also 1-nautical-mile range) for either 30- or 15-second legs at the desired airspeed with the corners rounded for turns at 9° per second. The rectangular patterns (fig. 5(c)) terminated in a straight approach after intercepting a 9° glide slope (3° for one case). The radar set was switched from the search mode to the precision mode at the termination of the pattern in order to have a vertical display to aid in acquisition of the glide slope.

RESULTS AND DISCUSSION

Current Instrument-Approach Techniques

Before discussing the results of the approaches, the instrument-approach techniques in current use will be discussed briefly as a matter of background.

In instrument approaches under minimum weather conditions, the present approach system, ILS (for instrument landing system), has proved to be both safe and practical and is in worldwide use today. One of the main factors in this system's favor is that under "perfect-approach" conditions all the cockpit indications are steady except for the altimeter. Ideally, the ILS is flown at a constant heading, with wings level, and at a constant airspeed and rate of descent. This gives the pilot a chance in his scan pattern to note any deviations from that desired, and corrections can be made to one variable without the others suddenly becoming unmanageable.

The GCA technique is identical to the ILS except for the means of presenting the error signal to the pilot. For ILS the cross-pointer indicator is used; for GCA radio voice corrections are used. Normal GCA procedures require the controller to give height above or below glide slope and correction in heading from successive target positions with respect to the on-course line until the pilot and controller cause the aircraft to converge on the correct flight path. Even with these systems, constant practice is necessary to insure any sort of safe operation when approaches are carried down to allowable minimums.

Steep Straight-In Approaches

Although many approaches were made at 3°, 6°, and 9° down to ceilings of 100 to 50 feet, only typical flight paths of the steeper (13° and 24°) straight-in approaches are shown in figure 7. Although the maximum deviations from the desired flight path in the last 1,000 feet of horizontal distance x before breakout for such steep approaches were large, it is believed that approaches with such errors would be satisfactory for VTOL aircraft where, at breakout, the pilot could arrest the descent and determine his position visually before bringing the aircraft to a landing at the desired point. However, because of the large deviations at the termination of the 13° and 24° approaches, the approaches were continued to altitudes no lower than 150 feet for the 13° and 200 feet for the 24°, indicating roughly the breakout ceilings attainable.

As would be expected, the difficulty in flying the approaches increased with increase in glide-slope angle. Figure 1(c) shows that with a 6° glide slope at 65 mph and a 9° glide slope at 45 mph the rate of descent is about 600 ft/min. Approaches made at these rates of descent from initial altitudes of about 500 feet allowed the pilot less than a minute to acquire and stabilize on the glide slope. Pilots commented that this is not enough time to become established "comfortably" on the glide slope. If this rate of descent is maintained when a breakout altitude of 50 feet is reached, less than 5 seconds safety margin is available in which to initiate flare and deceleration. According to the pilots associated with this investigation, rates of descent higher than about 500 to

600 ft/min down to an altitude of 50 feet are unsatisfactory. The pilots' comments were further supported by some of the flight-path data (not shown) obtained during the tests. The deviations from the desired glide slope during the last 1,000 feet (along X-axis) for the glide slopes of 6° and 9° where the rate of descent was about 600 ft/min were greater than for the 3° glide slope, where the rate of descent was about 300 ft/min.

Wind effects.- Limiting the rates of descent to allow time for flaring and deceleration limits the glide-slope angle for a given airspeed under no-wind conditions. Thus, limiting the rate of descent to the comfortable value of 500 ft/min at the lowest airspeed at which the helicopter appeared to be controllable in instrument flight, 25 mph, results in a glide-slope angle under no-wind conditions of about 13° (see fig. 1(c)) which is, therefore, a maximum flyable no-wind glide-slope angle with the test equipment. Using head-wind components to reduce the ground speed while maintaining a controllable airspeed of 25 mph makes it possible to approach at steeper glide-slope angles. Figure 8 shows the glide-slope angles calculated for a 10-knot wind from any direction, a rate of descent of 500 ft/min, and airspeeds of 25, 45, and 65 mph. The effect of a 180° change in direction of a 10-knot wind can vary the glide-slope angle by a factor of $2\frac{2}{3}$ at an approach speed of 25 mph and a rate of descent of 500 ft/min.

The results of figure 7(b) show that approaches can be made at approximately 24° with a 10-knot head wind and airspeed of 25 mph but the pilots indicated considerable difficulty in making such approaches. When the glide-slope angles were increased further with the same airspeed and head wind, the difficulty in acquisition became more evident until at 27° the glide slope could not be accurately acquired even in three attempts. If the glide-slope interception point was overshot the rate of descent had to be increased and/or speed decreased to acquire the glide slope. At the steeper angles and low speeds the rates of descent approached those for autorotation.

Another problem involved in attempts to use head winds for steeper approaches is that of the variation of wind velocity and direction with altitude. Some wind measurements made at the time of the tests (see fig. 7) showed a large variation in velocity and direction which is commonly the case at the low altitudes. Examples of extreme wind gradients (velocity change of 45 knots in an altitude difference of less than 1,000 feet) are contained in reference 4.

Wind gradients and turbulence introduce a need for changes in airspeed, in addition to those necessary to converge on the glide-slope line. As the turbulence changes from isotropic in the region of the initial altitude to horizontal near the ground, the correction required for forward speed should increase relative to those for rate of descent. However, when flying on the back side of the power curve altitude changes following speed corrections at constant power are opposite to those necessary for stabilizing on a glide slope with the result that corrections in speed result in the need for correction of rate of descent by power changes. Corrections in heading necessitated by power change and horizontal turbulence are complicated by increased sensitivity to bank angle of aircraft at low speed. (See fig. 1(b).)

When approaches are made with the large head-wind velocity gradient (with the low wind near the ground) the approach should be made no steeper than the surface velocity would permit. This procedure requires that higher airspeeds must be used to make sufficient ground-speed headway at the initial altitude. It also requires that the airspeed be continuously reduced as the descent is made.

Pilot workload.- The many additional corrections necessary in the steeper approaches imposed such a workload on the pilot that he was near the saturation point in meeting the demand of the tasks. Pilots reported that an occasional lapse of continuity occurred as a result of the high workload combined with inadequate position information. When this occurred at low speed the resulting displacement errors were small compared to displacement errors should they have occurred in the same lapsed time at higher speeds. Obviously, such operations could not be permitted under real IFR conditions. Improvement in low-speed flying qualities and information quality should tend to reduce the pilot's workload and eliminate any lapses of continuity.

Descent-Pattern Approaches

Because of the problems associated with steep straight-in approaches and in order to provide a means of conserving airspace during the letdown when surface head winds are unfavorable for straight-in approaches, various descent patterns were tried. These patterns have previously been described in the section entitled "Tests."

Circular-pattern approaches.- Low-speed spiraling descents all the way to touchdown have been suggested in reference 1 as a possible means of making approaches with VTOL's utilizing only a small amount of airspace. Since, in concept, no specific flight path need be followed, the aircraft would be released from the z-x (altitude-horizontal distance) constraint, and therefore difficulties arising from flying on the back side of the power-required curve with such a constraint would be alleviated and high rates of descent could be avoided. Although no specific navigational aids were suggested for circular-pattern approaches in reference 1, it became obvious after a few attempted approaches using GCA that some aid with which the pilot could readily visualize his position and track relative to his intended path and/or touchdown point would certainly be preferable to GCA for such circular approaches. For, in actuality, although the z-x constraint was no longer required in the circular approaches, the use of GCA required that a circular flight path (pattern) be prescribed in the horizontal plane for reference of the GCA controller. This prescribed circular pattern, if adhered to properly, would in itself, be a constraint; if not adhered to properly, large corrections, unacceptable for instrument operation, would be required at the end of the approach, in order to arrive at the touchdown point. Maintaining a circular ground track in a steady wind requires a variation in rate of turn and consequently bank angle, a variation of two more quantities which would not be varied for this reason in the usual GCA. Actually, of course, variations in wind usually exist with both time and altitude. Continual variation of the primary instrument indications to the pilot makes higher scan rates necessary, more frequent corrections, and hence a higher workload on the pilot at a critical time. At the time of the investigation of the circling approaches to touchdown it was thought necessary to monitor the flight path in the vertical plane throughout the entire approach, thus use of the precision mode was required. Because of the limited azimuth coverage in the precision mode and the relative positions of the GCA touchdown point and the antenna, outer portions of the circles (which were tangent to the normal on-course at the touchdown point) were off-scale or nearly off-scale so that the target was occasionally lost for a short time. The resulting lack of guidance during a small portion of these approaches appeared to have greatly influenced the results so they were not further evaluated in this investigation. However, circling approach patterns designed tangent to the on-course line at some distance out from the touchdown point to allow interception of a relatively low-angle glide slope (3° to 9°) were geometrically compatible with the precision mode such that all the patterns were on-scale and are therefore evaluated. Figure 9 shows the results of three attempts to descend from initial altitudes of 800 to 900 feet at 45 mph and intercept a 9° glide slope after one circuit of an approximately circular pattern (shown by the solid line) at a turn rate of about 6° per second. The complete flight paths in the turns are not shown in the elevation plane because they are off the scope display. The large deviations from the on-course line at roll-out from the circular-pattern descent in figure 9 are believed to result primarily from the inability of the pilot and controller to cope with the wind at that altitude. The large errors in the intermediate stages of these approaches were not considered satisfactory for instrument approaches, even though the approaches terminated satisfactorily.

Past experience with GCA has demonstrated that, for conventional low-angle approaches, the quality of the information is satisfactory. In circular descents, however, the information requirements seem to be more severe. For a turn of 6° per second, about eight target positions are presented to the controller within a turn of 90°. This data rate does not appear sufficiently high to allow the controller to estimate adequately the closure rate of the target to the circular flight path. The time necessary for the controller to estimate the target situation and the correction necessary plus the time for the voice transmission resulted in an appreciable lag. With heading constantly changing and with wind effects causing differences between heading and flight-path direction, the controller was unable to estimate corrections in heading, but gave corrections in relative position and in some cases informed the pilot of trends toward or away from the desired flight path. Transformation of the circle into an oval for the precision-mode presentation made it difficult for the controller to realize whether the target path was nearly circular or not.

Navigation systems which present a horizontal-situation display to the pilot might make circling approaches feasible as the information lag would be eliminated.

Rectangular-pattern approaches.- The rectangular patterns were planned so that the pilot would have to vary, essentially, only one quantity at a time, either the heading in the high-rate-of-turn corners or the altitude in the legs. Straight legs were also employed so that the pilot-controller team could attempt to converge on a heading. Although the radar scan rate was half that for the precision mode, improvement in information quality was gained by the presentation of the patterns in true shape through use of the PPI mode for that portion of the approach. The results as illustrated by the flight paths of figure 10 indicated that the approach pattern could be flown satisfactorily with 30-second legs at

25 mph. As can be seen, the roll-out from the pattern onto the on-course was accomplished with good accuracy. Enough altitude was lost in the rectangular-pattern descent to put the target well below the 9° glide slope so that the on-course could be acquired before it was necessary to acquire the glide slope. The fact that the pilot could direct his attention to acquiring one coordinate of the flight path at a time further simplified his task. Deviations in the one case where a 3° glide slope was used indicated that simultaneous acquisition of the on-course and the 3° glide slope was possible but more difficult. Since all three rectangular-pattern descents shown resulted in good terminal conditions this method is considered satisfactory.

Attempts to further reduce the airspace required by use of 15-second legs resulted in larger deviations from the pattern in the first of two attempts. Roll-out to the on-course and on-course acquisition were accomplished accurately in both cases and the glide slope was accurately acquired in the second attempt but not in the first. Thus, it appears that 15-second legs may be too short for satisfactory routine operation.

No doubt, the improvement in the information presented to the controller when the PPI mode was used greatly simplified his task and contributed to the success of the rectangular descent method in spite of the lower scan rate.

Airspace, Time, and Traffic-Control Considerations

Figure 11 shows the size of the rectangular descent patterns used in this investigation compared with the normal GCA landing patterns used for fixed-wind-type aircraft. Considerable airspace can evidently be saved by using the techniques discussed previously. It is apparent (fig. 5(a)) that diminishing amounts of airspace with relation to approach angles are saved as the approach angles are steepened.

The use of procedures such as the rectangular-pattern descents is believed to be compatible with many traffic-control requirements. For example, any leg of a rectangular pattern may be entered if a reasonable rate of descent from the entry point would bring the aircraft to the final on-course fix at the proper altitude. Also, the descent patterns appear to be compatible with holding and letdown procedures. Figure 5 shows the airspace required for the various planned patterns tested. From the results of the study, a safety zone of about 500 feet on either side of the desired path seems adequate to provide for deviations to be expected in operations. Applying this safety-zone dimension to the 25-mph, 30-second-leg rectangular pattern requires airspace 2,500 feet wide and 4,000 feet long.

At 25 mph and with no wind it would take about 2 minutes to use the 13° glide slope for descent from 1,000 feet. With 30-second legs and turns in the corners of 9° per second it should take 2 minutes and 40 seconds to circumnavigate the rectangular patterns and slightly less than 2 minutes to complete the approach from the pattern. Thus the total time to descend would be about $4\frac{1}{2}$ minutes for the complete rectangular-pattern approach compared to about 2 minutes for the straight-in descent from roughly the same location from the touchdown.

From 1,000 feet both the 13° straight-in approaches and the pattern approaches can be made within three-fourths of a nautical mile from touchdown. As a head-wind component would be necessary to make the approaches steeper than 13°, an omnidirectional facility would be desirable for use with the steep straight-in letdowns. The airspace required for such an omnidirectional terminal would, consequently, be about $1\frac{1}{2}$ nautical miles in diameter.

When omnidirectional facilities are not available or such approaches are not practical, pattern approaches will allow operation even with tail winds and would actually require less airspace; for example, the 25-mph rectangular approaches would require airspace about three-fourths of a nautical mile by one-half of a nautical mile.

It should be recognized that for some sites two-directional (opposite) steep straight-in approaches might be satisfactory in which case the airspace length would be about twice that for the rectangular approaches whereas the width may be less than half.

Effect of Low-Speed Characteristics

From the discussion in the previous section concerning the desirability of steep approaches to conserve airspace, it is evidently desirable to approach at low speeds. The section entitled "VTOL Simulation" which describes the characteristics of helicopters at low speeds emphasizes, however, that several factors inherent in the design and flight of service VTOL aircraft tend to make these aircraft difficult to handle at low speeds.

Several means are now under consideration to alleviate some of these conditions. By providing adequate torque compensation such as required for single-rotor helicopters the necessity for pilot adjustment of heading upon changing power may be eliminated. By providing improved damping in all axes of rotation the pilot control of attitude and therefore speed, rate of descent, bank angle, rate of turn, and heading should be improved. One way to achieve this is by stability augmentation.

The use of higher disk loadings would increase rate-of-descent boundaries of the vortex-ring state. These boundaries would not limit steep approaches for most convertible VTOL aircraft since they have high disk loadings compared to the test helicopter. According to reference 5 the vortex-ring state occurs when the rate of descent is equal to the downwash velocity at the rotor disk.

CONCLUSIONS

The following conclusions are drawn from results of an investigation of VTOL approach methods using a small helicopter and a GCA radar set:

1. Two methods of approach under Instrument Flight Rules conditions with small airspace requirements have been demonstrated to be feasible. These two

methods are the rectangular-descent-pattern approach and the steep straight-in approach.

2. On the basis of total airspace required for any wind direction, the rectangular-pattern approaches are advantageous since they can be made even with moderate tail winds, whereas the steep straight-in approaches to be omnidirectional would require a circular airspace of diameter twice the length of a single approach.

3. When compared on the basis of time in the approach, the steep straight-in approaches appear advantageous since the minimum time is limited only by the maximum rate of descent tolerated by the pilots, whereas in the rectangular-pattern approaches a relatively large amount of time was consumed in the timed legs of the pattern and the final approach.

4. Existing wind fields assumed major importance in the execution of slow-speed approaches. A 180° change in direction of a 10-knot wind can vary the glide-slope angle by a factor of $2\frac{2}{3}$ at an approach speed of 25 mph and a rate of descent of 500 ft/min. Without head winds, the maximum steepness of approach was limited to about 13° (to about a 150-foot ceiling) whereas with head-wind components of 10 knots approaches of 24° could be made although not to as low a ceiling.

5. Lag and low rate of information to the pilot inherent in ground-controlled approach combined with large heading and flight-path-angle changes resulting from changing winds at low airspeeds appeared to be principal factors affecting the accuracy of position at the breakout ceiling.

6. The pilot workload increased as the glide slope increased, resulting in decreased accuracy of breakout with steepness.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 24, 1962.

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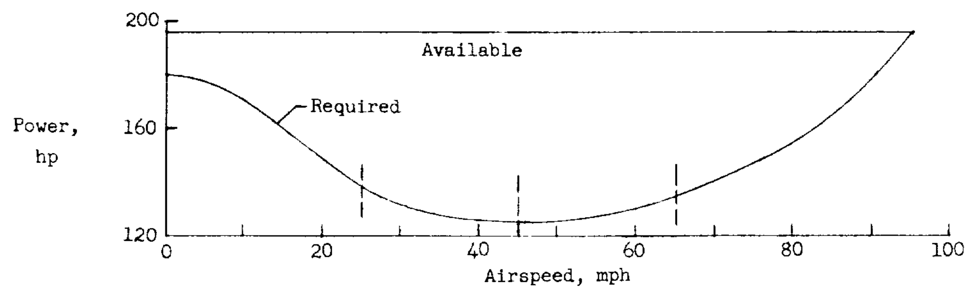
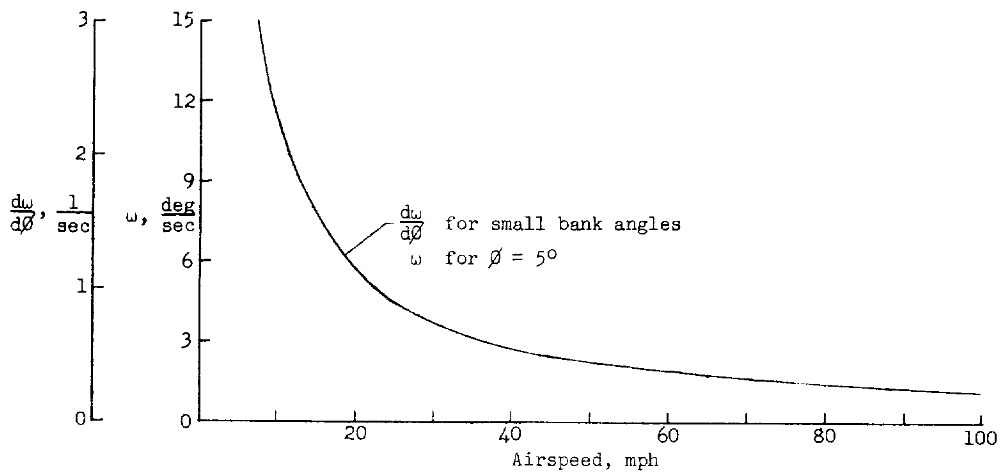
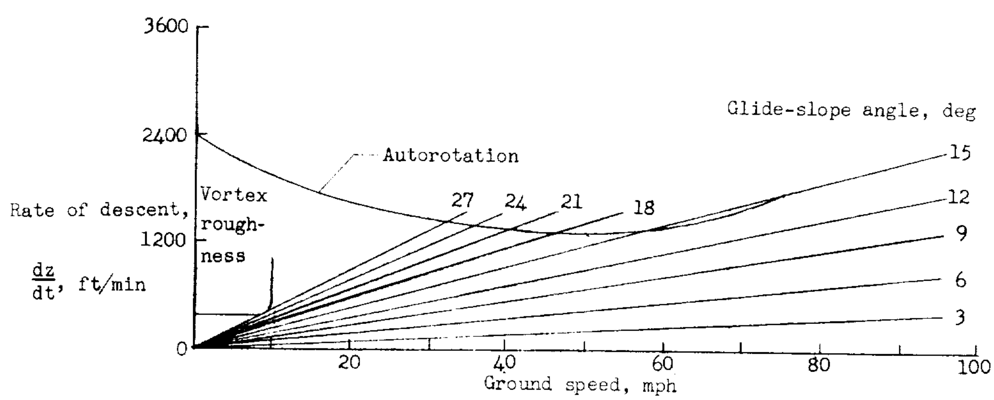


(a) Horsepower required for level flight and horsepower available as a function of airspeed for test helicopter at an altitude of 500 feet and at 3,100 rpm. Weight of helicopter = 2,790 pounds. (Test airspeeds of 25, 45, and 65 mph indicated by dashed lines.)



(b) Sensitivity of rate of turn to bank angle as a function of airspeed. No-wind conditions.



(c) Rate of descent as a function of ground speed at various glide-slope angles. Limitations of rates of descent at autorotation and region of roughness associated with the vortex-ring state are also shown for the no-wind conditions.

Figure 1.- Operational limitations of test helicopter and general characteristics of aircraft pertinent to approaches at low speeds.

Figure 2.- Photograph of test helicopter. L-96950

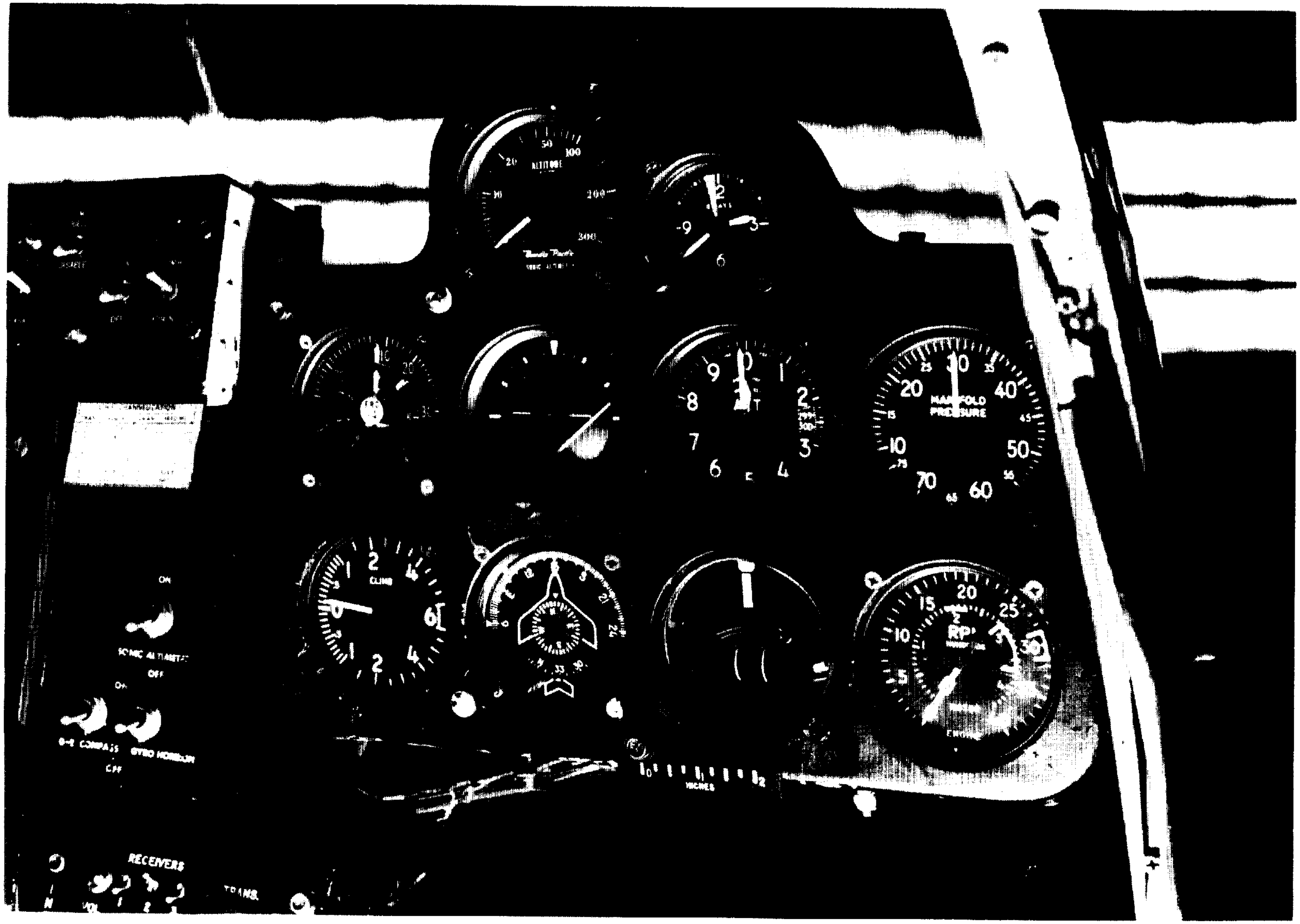
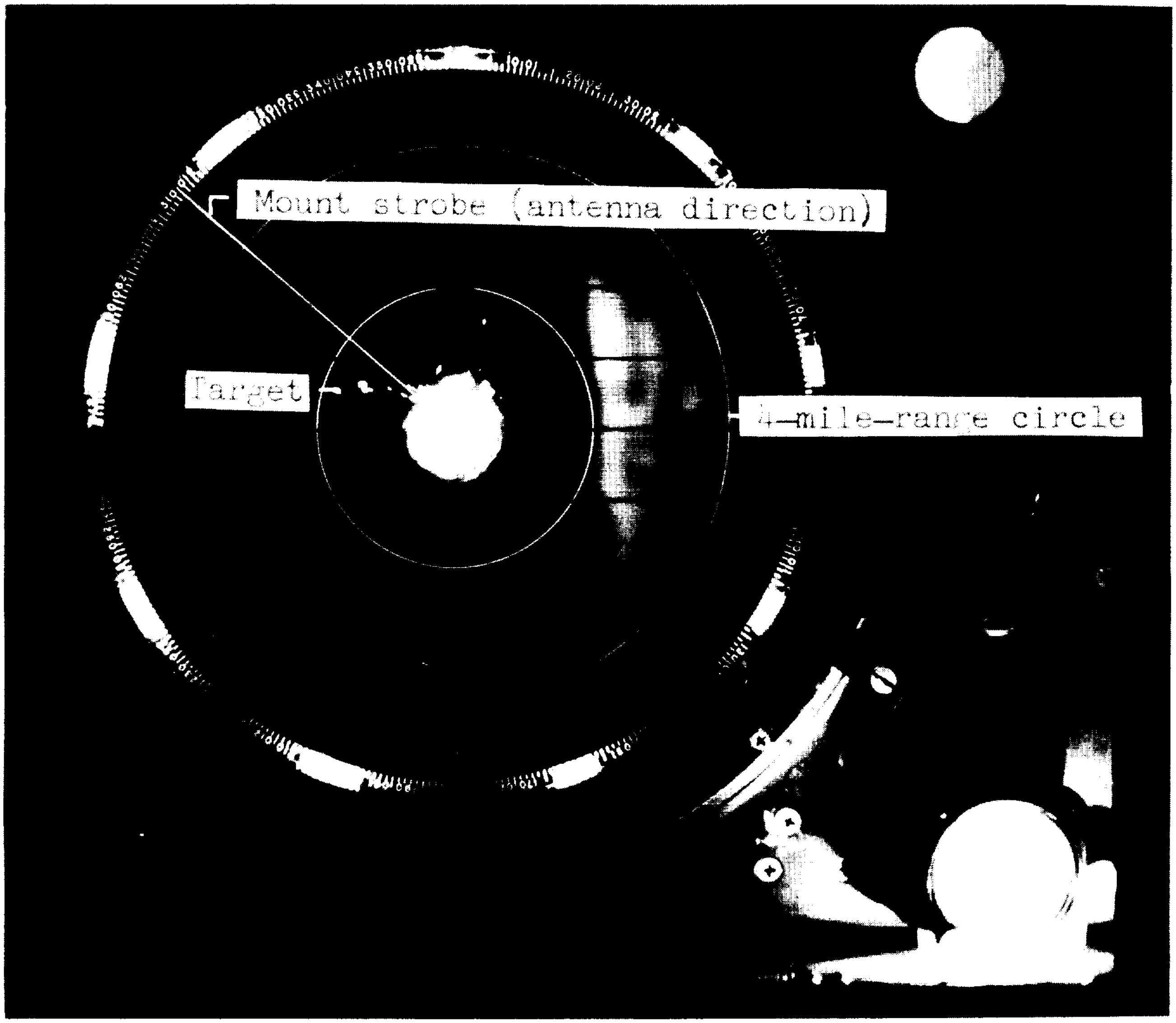
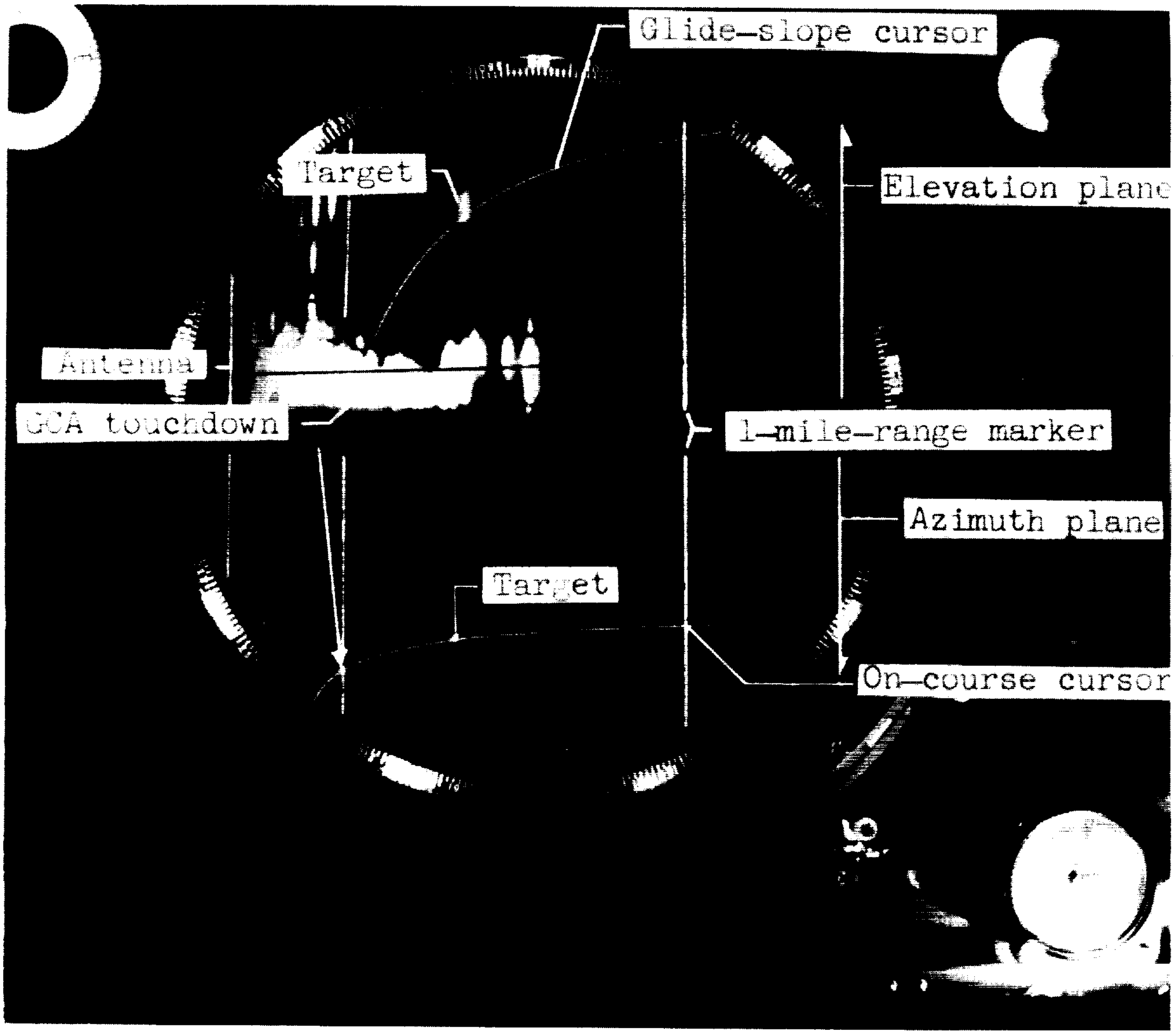


Figure 3.- Photograph of blind-flight instrument panel. L-61-1390



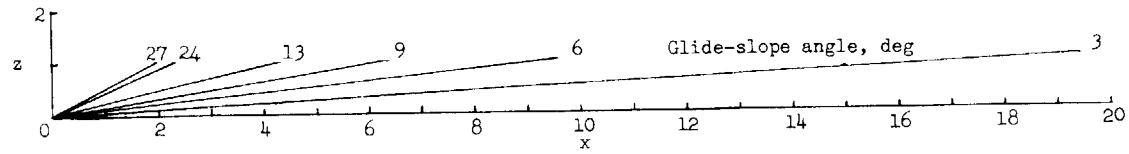
(a) Search mode (plan-position-indicator display). L-62-1025

Figure 4.- Photographs from the data camera of the GCA scope showing two principal modes of operation.

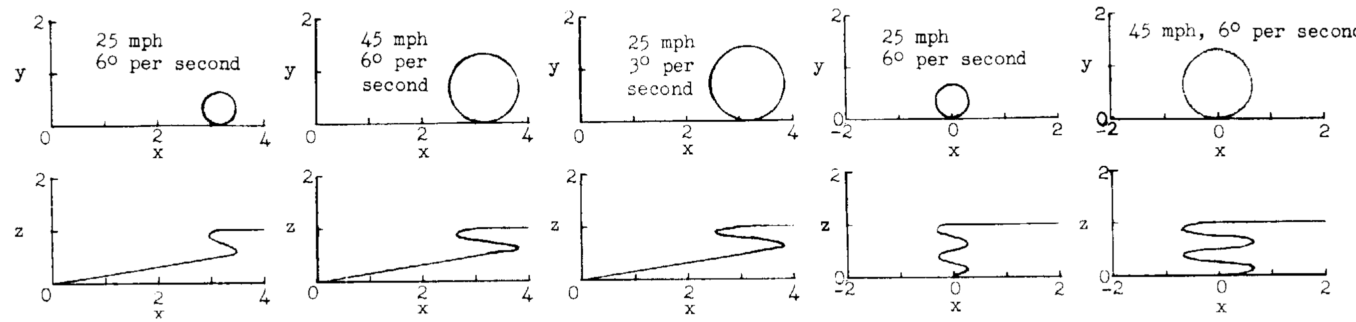


(b) Precision mode. L-62-1026

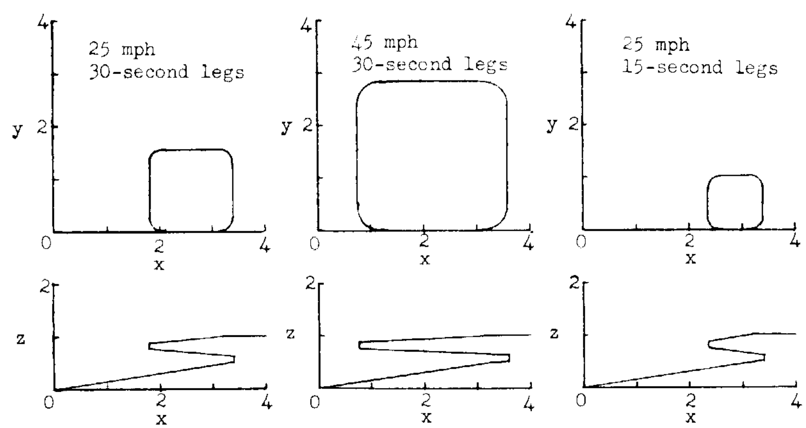
Figure 4.- Concluded.



(a) Glide slopes for straight-in approaches.



(b) Circular approach patterns.



(c) Rectangular approach patterns.

Figure 5.- Planned flight paths for the approach methods investigated. All dimensions in 1,000 feet.

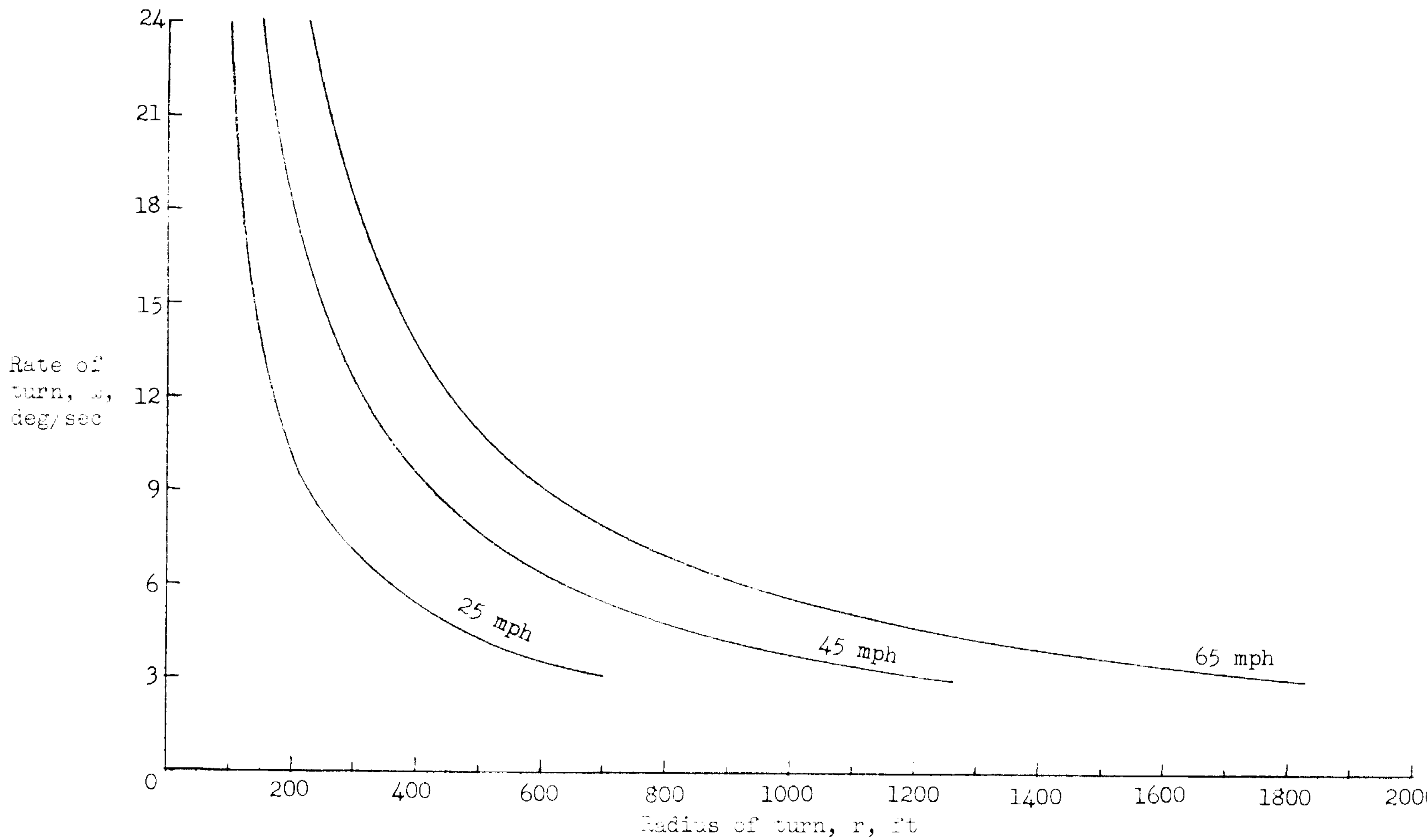
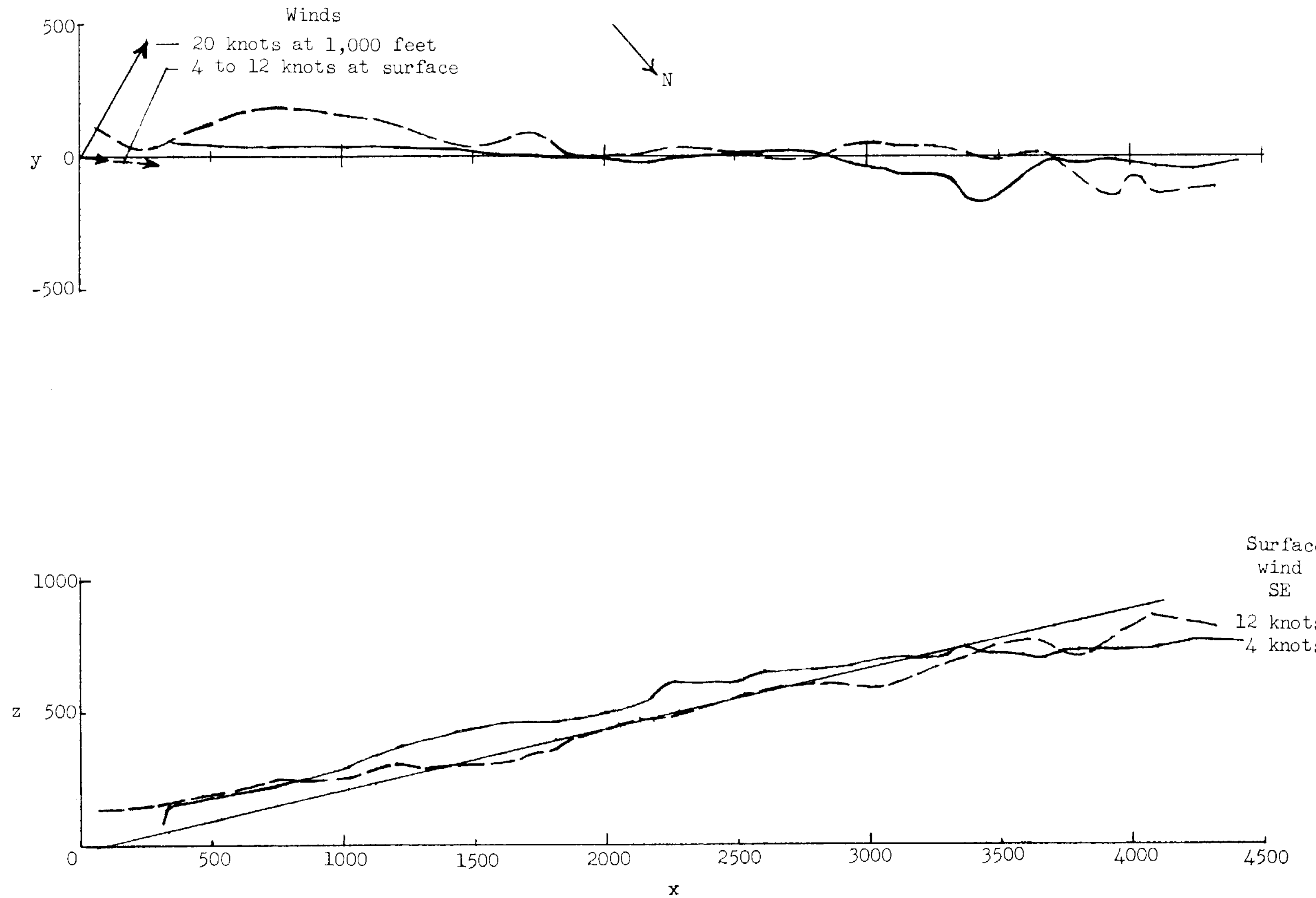
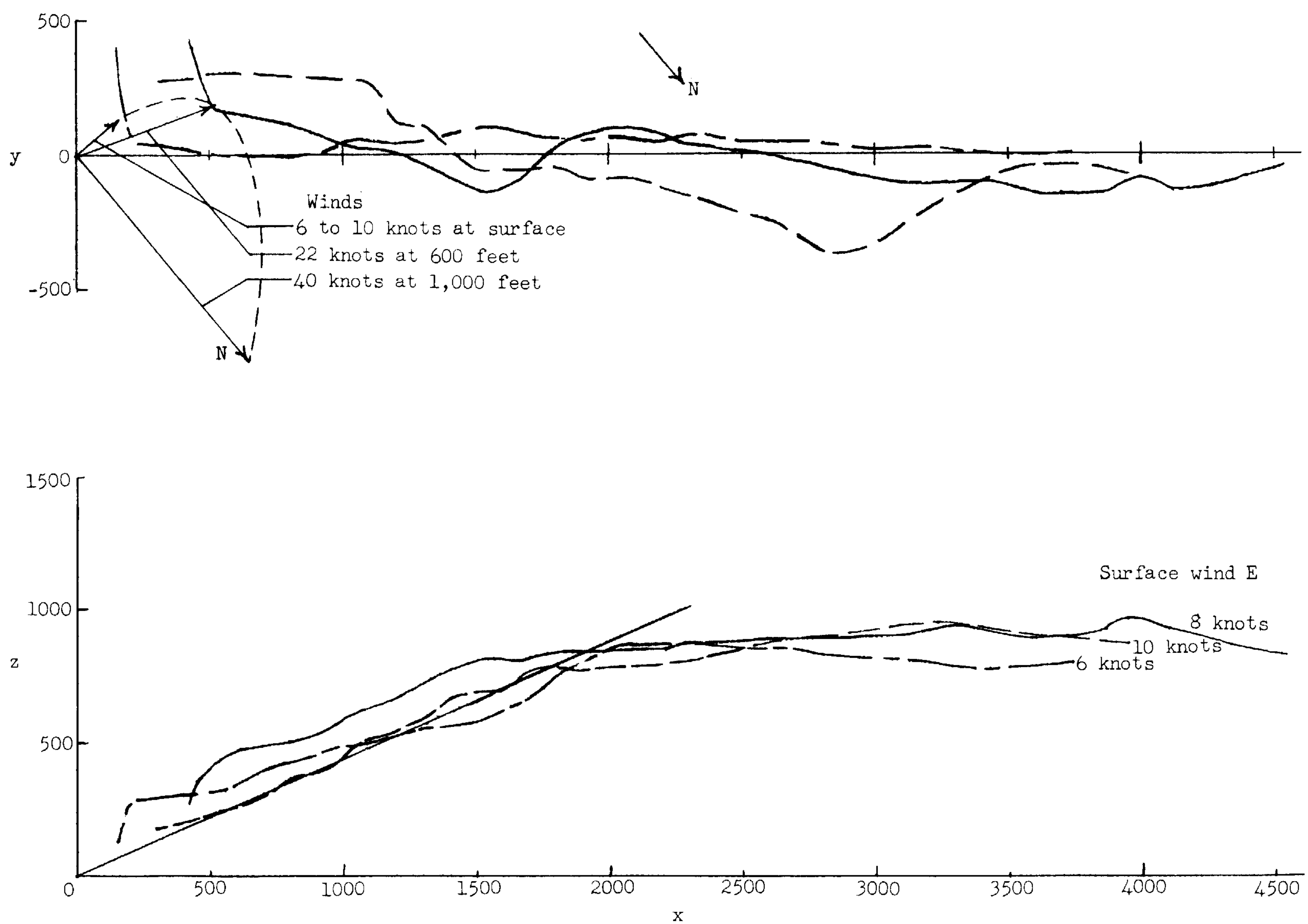


Figure 6.- Variation of rate of turn with radius of turn.



(a) Glide-slope angle, 13°.

Figure 7.- Steep straight-in approaches.



(b) Glide-slope angle, 24°.

Figure 7.- Concluded.

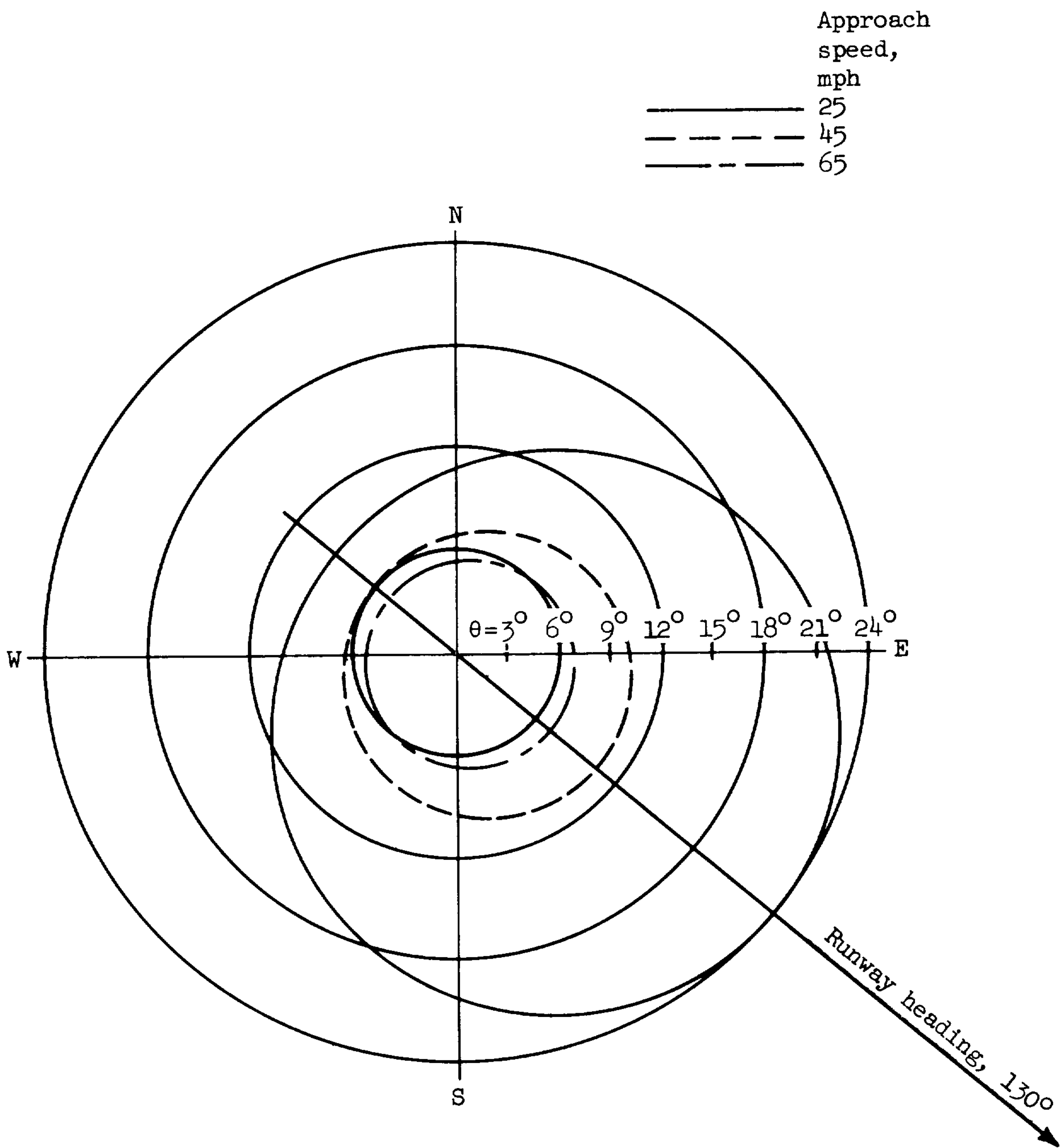


Figure 8.- Polar diagram showing effect of variation of wind direction on steepness of approach glide-slope angle θ. The polar angle represents the wind direction with wind vector toward origin; radial distance indicates glide-slope angle. Rate of descent, 500 ft/min; 10-knot wind.

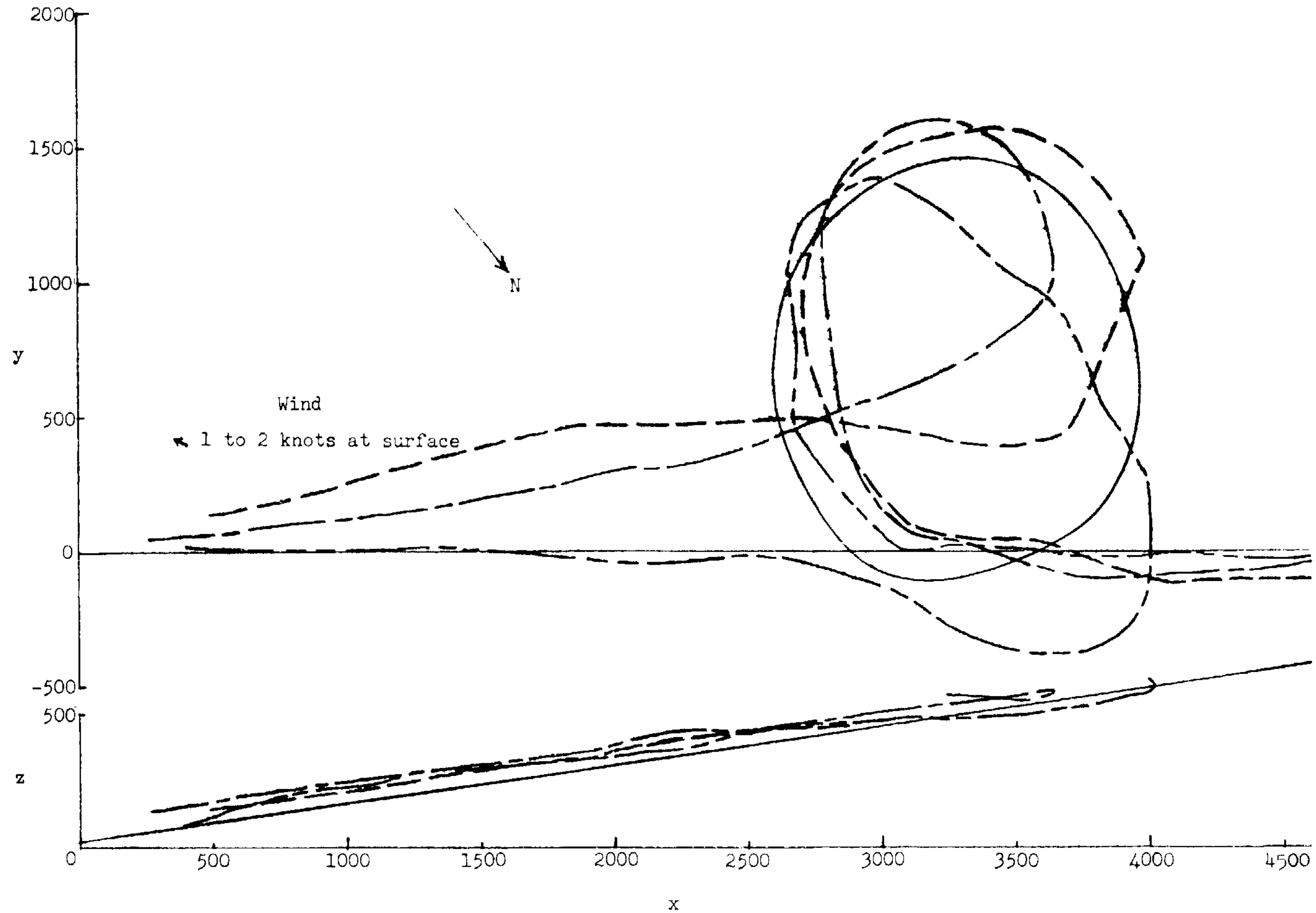


Figure 9.- Approaches in circular descent pattern to a 9° glide slope. Airspeed = 45 mph; rate of turn ≈ 6° per second; surface wind NNW 1 to 2 knots.

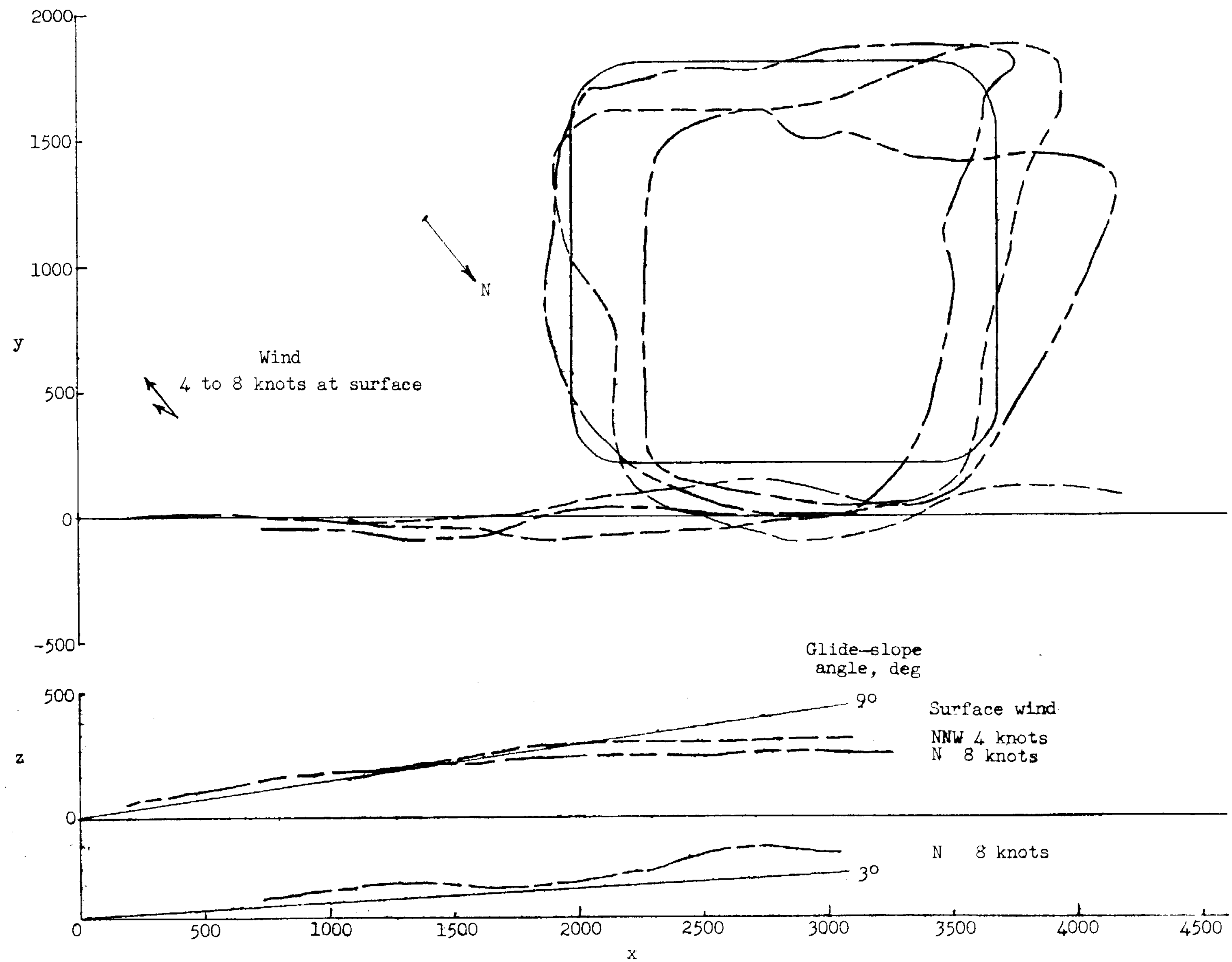


Figure 10.- Approaches in rectangular descent pattern to the designated glide slope. Airspeed = 25 mph; 30-second legs; rate of turn in corners = 9° per second.

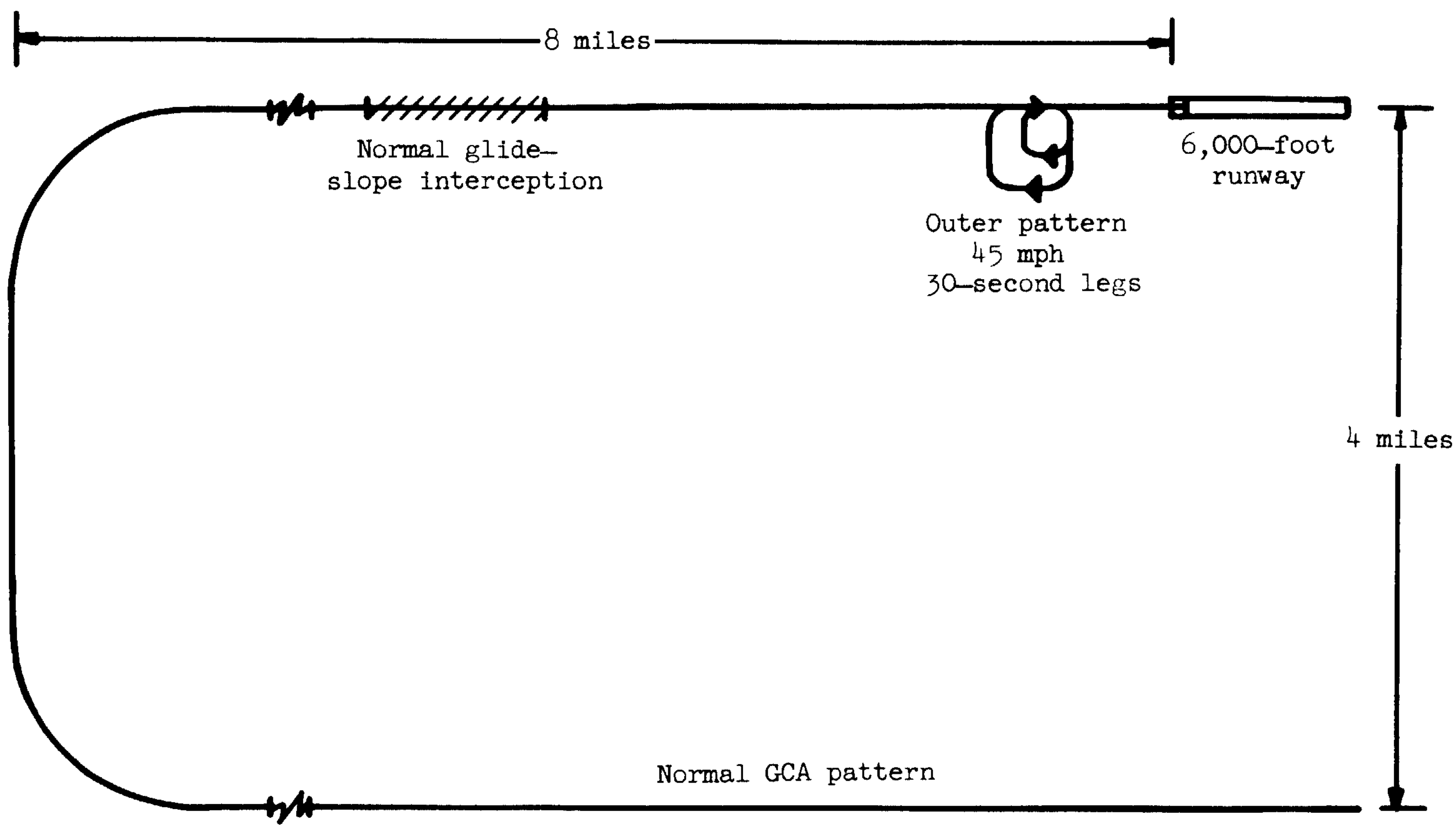


Figure 11.- Comparison of VTOL descent pattern and conventional aircraft landing pattern.

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