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In-Trail Spacing Dynamics of Multiple CDTI-Equipped Aircraft Queues

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SUMMARY

One of the potential applications of a Cockpit Display of Traffic Information (CDTI) is self-spacing wherein a pilot can acquire and maintain a specified in-trail interval on a lead aircraft. An assumption behind this application is that pilots using CDTI should be able to achieve more consistent spacing performance than the present Air Traffic Control concept (which employs ground-controlled spacing techniques) and, hence, runway throughput could be increased. Along with this benefit, however, comes the question of whether dynamic oscillations would occur, similar to the "accordion" effect seen with a queue of automobiles in stop-and-go traffic.

In order to gain some insight into this potential problem, a brief experiment was conducted with the Transport Systems Research Vehicle (TSRV) ground-based simulator equipped with a CDTI which presented the position of other aircraft in the area. Three simulation sessions were conducted wherein queues of up to nine aircraft were built by recording successive approaches flown in the simulator and using this recording as the source for traffic data on each subsequent approach. Each aircraft was therefore equipped with a CDTI which the pilot used to self-space on the preceding aircraft. The aircraft crews were rotated to ensure that the pilots had no prior knowledge of the behavior of the lead aircraft they would be following. Two different spacing criteria were employed: a constant time predictor criterion and a constant time delay criterion. The experiment failed to uncover any dynamic oscillatory tendencies in queues of seven to nine aircraft.

INTRODUCTION

Cockpit Display of Traffic Information (CDTI) has been proposed for numerous applications (see, e.g., ref. 1), ranging from its use as a device to simply monitor the surrounding traffic situation to a display which would permit tactical-type operations to be performed, such as merging and spacing. One of the most obvious applications of CDTI is the in-trail following operation in which the CDTI-equipped aircraft follows a lead aircraft making an approach to landing. The projected benefits in runway throughput are based on the assumption that CDTI self-spacing will result in a lower interarrival-time dispersion at the runway threshold than can presently be achieved with ground-controlled spacing techniques. This, in turn, will permit a reduction in the mean spacing and, hence, an improvement in runway throughput (ref. 2).

The first series of studies directed toward obtaining quantitative data on in-trail, self-spacing performance was done at Massachusetts Institute of Technology between 1970 and 1975 (ref. 3). More recently, the National Aeronautics and Space Administration has conducted a series of experiments to explore the effect of various parameters on self-spacing performance. (See, e.g., refs. 4 through 9.) These studies typically involved one-on-one self-spacing; that is, the CDTI-equipped aircraft (ownship) was following a single lead aircraft.

A frequently asked question relative to this type of application is whether or not dynamic oscillations of the queue would occur (similar to the "accordion" effect seen with a queue of automobiles in stop-and-go traffic) if several CDTI-equipped aircraft were self-spacing on each other during in-trail maneuvers.

In order to explore this potential problem, it was necessary to create a queue (daisy chain) of CDTI-equipped aircraft, each performing in-trail self-spacing on the preceding aircraft. The queue was built with the Transport Systems Research Vehicle (TSRV) ground-based simulator in which the navigation display was converted to a CDTI by presenting the position of other aircraft. Position and velocity data on the other aircraft were obtained by recording successive approaches flown in the simulator and appending them to a common traffic tape. The first approach flown (aircraft 1) was a profile descent to runway 35R at Stapleton International Airport, Denver, Colorado, without any traffic. The next approach (aircraft 2) included self-spacing on aircraft 1 in addition to performing a profile descent. The third approach (aircraft 3) involved self-spacing on aircraft 2, and so on. Two crews of two pilots each were utilized in which the pilots alternated captain and first officer duties, and the crews flew alternate runs. Therefore, the pilots had no prior knowledge of the behavior of the lead aircraft they would be following. It is important to note, however, that as a result of the experiment design, all the aircraft in the queue had identical performance characteristics.

Two different self-spacing criteria were employed, a constant time predictor (CTP) criterion and a constant time delay (CTD) criterion. Three simulation sessions were conducted, two using the CTP criterion, and one with the CTD criterion.

ABBREVIATIONS

AGCS	Advanced Guidance and Control System
CAS ENG	calibrated airspeed engage
CDTI	Cockpit Display of Traffic Information
CRT	cathode-ray tube
CTD	constant time delay
CTP	constant time predictor
GS	ground speed
IXX	unaided inertial-navigation mode
RAD	radius
SEL/CAS	calibrated airspeed mode selected
STAR	standard terminal arrival route
TCV	Terminal Configured Vehicle
TSRV	Transport Systems Research Vehicle
VCWS	velocity control wheel steering

SIMULATION FACILITY

Cockpit

The tests were conducted with the Transport Systems Research Vehicle (TSRV) ground-based simulator. This facility is configured to support the NASA TSRV (formerly TCV) Boeing 737 research aircraft described in reference 10. The simulator cockpit shown in figure 1 is a replica of the aft flight deck installed on the research aircraft. The cockpit is equipped with panel-mounted controllers that take the place of the conventional wheel and column and provide an unobstructed view of the CRT displays mounted on the pilot's and copilot's panels. Conventional rudder pedals are installed, but they are not used with the advanced control modes.

Controls for the landing gear, flaps, and speed brakes are provided, along with status indicators for the landing gear and flaps. The speed-brake position is derived from the position of the speed-brake handle.

The cockpit is connected to a digital-computer complex programmed to provide a full range of control and display options similar to those available on the aircraft. The computer program is a six-degree-of-freedom simulation which includes nonlinear aerodynamic data, engine dynamics, and a flight-control-system model. This control-system model incorporates nonlinear actuators, hysteresis, dead bands, and so forth. The tests were conducted under simulated calm atmospheric conditions (i.e., no wind and no turbulence). Density altitude effects were included in the simulation.

Control Modes

All tests were conducted with the velocity control wheel steering (VCWS) mode which provides track-angle and flight-path-angle hold in nonmaneuvering flight. The pilot can change his flight-path angle or track angle by pitch and roll inputs, respectively, through the panel-mounted controllers. A detailed description of the VCWS mode is given in references 11 and 12 for the lateral and the longitudinal degrees of freedom, respectively.

The two speed-control options available to the pilot were manual throttles and an autothrottle called the calibrated airspeed engage (CAS ENG) mode. The manual-throttle is a standard, nonautomatic mode. The CAS ENG is an automatic mode which drives the throttles to capture and maintain a reference airspeed. This reference airspeed is selected with a knob on the Advanced Guidance and Control System (AGCS) control-mode panel shown in figure 2.

Displays

The pilot's and copilot's instrument panels each contained three CRT's, as shown in figure 1. The upper CRT on each side presented vertical situation and predictive information, using the "improved" format reported in reference 12. The middle CRT on each side, the CDTI, presented horizontal situation and predictive information and proximate aircraft on a 7 1/2 in. (high) by 5 1/2 in. (wide) display. The lower CRT was not used during this experiment. Airspeed, altitude, vertical speed, and engine status were displayed on conventional dial-type instruments.

CDTI DESCRIPTION

Symbology

The CDTI-display format used for this investigation is shown in figure 3. This format retains the basic features of the original TSRV navigation display (ref. 10). It is a track-up display with both a digital readout and a moving-tape indication of the current magnetic track angle (225° in fig. 3). A fixed-reference mark is provided for the moving tape.

The nominal flight path is displayed by a dashed line and star-shaped waypoint symbols. Tags can be selected by the pilot from a control-mode panel mounted on the center console forward of the throttles. These tags (fig. 4) give the waypoint identification, the desired crossing airspeed in knots, and the minimum crossing altitude in feet.

Six different map scales, 1, 2, 4, 8, 16, and 32 n.mi./in., can be selected by the pilot. The map scale in use is indicated by an alphanumeric tag in the lower left corner of the display. Other readouts include the control mode (SEL/CAS for the calibrated airspeed engage mode), ownship ground speed (GS) in knots, the navigation mode (IXX indicates an unaided, inertial-navigation mode), and a readout showing the range (RAD for radius) of a reference mark displayed in front of ownship (2 n.mi. for these tests).

Ownship is represented by a fixed chevron-shaped symbol located in the center of the screen horizontally, and 5 inches from the top of the screen vertically (which is two-thirds of the total display height). The reference point for the ownship symbol is the apex of the chevron. Directly below the chevron are digital displays of ownship ground speed (in knots) and altitude (in feet).

A time-based predictor vector, composed of three segments, indicates where ownship is projected to be in 30, 60, and 90 sec. The gaps between the segments are 6 sec in length and the curve of the vector is a function of the aircraft turning radius (fig. 5). Only the 30- and 60-sec segments are displayed on the 1 n.mi./in. map scale (fig. 4); all three segments are displayed on the remaining map scales.

A reference mark is displayed perpendicular to the time vector 2 n.mi. ahead of ownship. When ownship is turning so the trend vector is curved, the 2-n.mi. reference mark translates with the curved vector and, consequently represents the path length (circular arc distance) as opposed to a radial distance ahead of ownship.

The "traffic" is represented by triangular-shaped symbols, wherein each apex is the position reference point for the aircraft. The angular orientation of the triangles indicates the current track angle of each aircraft. A tag is displayed adjacent to the lead aircraft that is immediately in front of ownship; it gives the ground speed of that aircraft in knots. The tag maintains an upright orientation when the triangle rotates and changes in 10-knot increments.

Operational Aspects

The trend vector of ownship, the track-angle displays, the map translation, and the map rotation were updated 16 times/sec, which appears continuous from the viewpoint of the pilot. All the proximate aircraft positions and headings, the ground speed tag of the lead aircraft, and the alphanumeric data of ownship (other than the track-angle readouts) were only updated once every 4 sec. As such, the traffic moved in a leapfrog fashion, changing positions and headings at the 4-sec update, and then remained fixed relative to the ground between updates.

Spacing Criteria

Two different spacing criteria were employed in the experiment: the constant time predictor (CTP) criterion and the constant time delay (CTD) criterion. These criteria have been used in several previous studies and are explained in detail in references 6 and 8. Basically, both spacing criteria are designed to keep successive aircraft separated by a fixed time interval. In this study, the time interval chosen was 1 min (60 sec), which meant that ownship should cross a given point on the path 1 min after the preceding aircraft crossed it. As explained in references 6 and 8, however, the CTP criterion had an inherent slow-down characteristic which resulted in ownship crossing a given point in slightly more than 1 min. In addition, the CTP criterion had an inherent damping effect which should tend to suppress any oscillatory tendencies in spacing (ref. 9).

The CTP criterion is satisfied by using the TSRV time-based predictor vector as a "yardstick" to maintain an in-trail "position" on the preceding aircraft. The pilot's instructions (table 1) were to maintain 1-min spacing to touchdown. The pilot's task therefore, was to control his spacing such that the 60-sec predictor segment was superimposed on the apex of the lead aircraft symbol at the 4-sec update. (Although it may not be apparent in figs. 3 through 5, the 60-sec segment of the predictor vector was highlighted (drawn brighter than the other segments) for this experiment.)

The other criterion used in this study was the constant time delay (CTD) criterion. The spacing cue was a phantom aircraft symbol which showed where the preceding aircraft was 1 min earlier. (The criterion, of course, is applicable to any previous time interval.) The CTD symbology is illustrated in figure 6. The phantom aircraft symbol was updated at discrete 4-sec intervals, the same as the other traffic symbols. The pilot's task was to fly ownship so that the apex of ownship chevron symbol passed over the apex of the phantom aircraft symbol at the time the update occurred.

TEST DESCRIPTION

Test Subjects

Four NASA test pilots were used as subjects for this experiment. All four were familiar with the TSRV configuration and operating characteristics. In addition, three of the four pilots had participated in a previous CDTI study conducted in the TSRV simulator (ref. 4). All four test subjects had also participated in another CDTI study (ref. 5), which used a conventional cockpit aircraft simulator. Since all the pilots were familiar with the CDTI concept and the TSRV simulator, familiarization runs as such were not conducted.

The tests assumed a two-man crew operation wherein the second crewman (the first officer) would handle radio communications, monitor aircraft systems, and actuate the landing gear and flap controls on command from the captain. It was also assumed that the first officer would monitor his CDTI for traffic and, hence, the captain could independently select a map scale for his CDTI predicated solely on the self-spacing task.

Standard Terminal Arrival Route

The scenario used in this experiment employed a hypothetical profile descent to runway 35R at Stapleton International Airport, Denver, Colorado. The profile descent was defined by the standard terminal arrival route (STAR), as shown in figure 7. The segment from KEANN intersection to FLOTS intersection was based on published, profile-descent procedures for Denver. The segments from FLOTS to GANDR (the outer marker) were based on vectoring practices by Denver approach controllers. The STAR terminated with an instrument landing system approach to runway 35R.

The speeds shown adjacent to the waypoints are indicated airspeeds in knots. They represent the desired nominal speeds at the waypoints. The altitudes, on the other hand, represent the minimum allowable crossing altitude, in feet, at the waypoint.

Task

The pilot's primary task was to maintain the specified in-trail separation (CTP or CTD) from the preceding aircraft while executing a profile descent to runway 35R at Denver. The captain could utilize landing gear, flaps, and/or speed brakes at his discretion to assist in maintaining the desired in-trail position. Path deviations were to be used only to prevent getting closer than 2 n.mi. from the other aircraft. The complete set of pilot instructions given to the crews is shown in table 1.

Test Procedures

The four test subjects previously described were divided into two crews. The first crew flew an approach (according to the STAR) without any other traffic in the area. This approach was not observed by the other crew. The position and velocity of the aircraft were recorded during this approach and served as data for the lead aircraft used by the second crew.

The second crew flew the next approach, only this time they were required to self-space on the lead aircraft. At this time, the CDTI showed only two aircraft, ownship and the lead aircraft from the preceding run by the first crew. This time the first crew was not allowed to observe the approach being flown. The position and velocity data from the second approach were appended to the data from the first approach to create a traffic tape which then contained two aircraft.

The third approach was flown by the first crew but with the pilots exchanging captain and first officer positions. The queue continued to be built up in this manner until the simulation session ended. During the sessions reported herein, queues of 7 and 9 aircraft were built as illustrated in figure 8. (It should be noted that all the aircraft had identical performance characteristics.)

During the test, the crews and crew positions were alternated, and the crews were not allowed to observe one another. This way the captains would have no prior knowledge of the behavior of the lead aircraft they would be following.

RESULTS AND DISCUSSIONS

General

The main purpose of this brief experiment was to determine if a queue of CDTI-equipped aircraft would tend to oscillate while performing in-trail, self-spaced approaches and landings. None of the test results indicated any oscillatory behavior of the queue, much less a tendency toward any dynamic instability. Although neither the constant time predictor (CTP) nor the constant time delay (CTD) spacing criteria exhibited oscillatory tendencies, there was a distinct difference in the performance associated with each of them, as discussed in the following sections.

Constant Time Predictor

The performance obtained with the CTP criterion during the two simulation sessions conducted in the study is illustrated in figures 9 and 10. Part (a) of each figure shows ground speed as a function of path distance to go for all approaches, whereas part (b) shows the cross range plotted against the range ground tracks.

The slow-down characteristic encountered with the CTP spacing criterion is illustrated by figures 9 and 10. This characteristic is inherent in the CTP cue and occurs because the lead aircraft is decelerating and, hence, ownship must also decelerate to keep from overtaking the lead. Since the time prediction is based on ownship holding constant ground speed (and ownship has to slow down) the interval will take longer to fly than predicted.

A clear indication of the slow-down characteristic is illustrated by a plot of time for the approach as a function of sequence number as shown in figure 11. During both test sessions, the ninth aircraft took more than a minute longer to fly the approach than the first follower. The data also indicated that, in general, each successive aircraft in the queue put the landing gear and flaps down earlier than their respective lead aircraft.

In summary, although there were no dynamic instabilities associated with using the CTP criterion for in-trail spacing of multiple CDTI-equipped aircraft queues, the slow-down characteristic associated with this criterion makes it undesirable for this application. Additional information on the operational aspects of the CTP spacing criterion can be found in references 6, 8, and 9.

Constant Time Delay

The results of the constant time delay (CTD) simulation session are shown in figure 12. In this case, a seven-aircraft queue was built up during the test period. As noted in references 6 and 8, the CTD criterion provides cues directing each follower to fly the exact same speed profile as its respective leader. Therefore, if each aircraft in the queue achieved perfect separation, all ground-speed profiles would overlay one another. The extent to which the speed profiles differ is an indication of the variability of self-spacing performance with the CTD criterion.

It is obvious from the ground-speed tracks shown in figure 12(a) that the CTD criterion does not have any oscillatory tendencies neither does it exhibit the slow-down characteristic of the CTP criterion. A plot of the approach time versus sequence number (fig. 13) confirms the absence of the slow-down characteristic. It is interesting to note, however, that each successive approach with the CTD criterion took from 1 to 5 sec longer to fly than the preceding approach. In addition, the time differences tended to become smaller with each successive approach.

An examination of the landing gear, speed brake, and flap schedules, with plots such as the one shown in figure 14, indicated that the follower tended to use schedules similar to the lead aircraft. This is probably because all the aircraft had identical performance characteristics, all the pilots received the same standardization training, and the speed profile of each follower was similar to its respective lead aircraft. Since the flaps, and to some extent the landing-gear schedules, are tied to the speed profile, similar speed profiles would result in similar gear and flap schedules.

CONCLUDING REMARKS

The experiment described in this report failed to uncover any dynamic oscillatory tendencies in queues of seven to nine CDTI-equipped aircraft performing in-trail self-spaced approaches with either a constant time predictor (CTP) or constant time delay (CTD) spacing criterion. Unlike automobiles wherein an accordion effect is observed in stop-and-go traffic, the aircraft queues were primarily decelerating (slowing down) all the way to touchdown. This monotonic behavior is one possible explanation for the absence of an oscillatory behavior.

Another possibility is that the self-spacing loop closure has such a long period that the oscillatory behavior is masked by the speed perturbations associated with a normal approach. During in-trail following, the pilots generally observed several updates (at one every 4 sec) to verify a rate of change in separation before making a configuration change, such as adding speed brakes. It took several more update observations to detect the consequence of their action and establish the need, if any, for further action. The result, therefore, amounted to a very low frequency loop closure.

Although the test results did not indicate any oscillatory behavior of the queue, they did provide clear documentation of the slow-down characteristic inherent in the CTP spacing criterion. This characteristic had been encountered in previous studies with single lead-follower pairs, but the cumulative effect for multiple aircraft queues had not been considered. These test results indicate that the CTP spacing criterion is undesirable for in-trail spacing of multiple CDTI-equipped aircraft queues.

The CTD spacing criterion appeared to provide a suitable spacing criterion for the multiple aircraft, in-trail approach case examined during these tests. Caution should be exercised in extrapolating this result to the real world, however, since the effects of different types of aircraft and dissimilar piloting procedures were not examined.

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December 5, 1983

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TABLE 1.- PILOT INSTRUCTIONS FOR DAISY-CHAIN TEST

1. Maintain 1-min spacing to touchdown.
2. Path deviations are to be used _only_ to prevent getting closer than 2 n.mi. from the target.
3. VCWS should be used in pitch and roll.
4. Throttle control mode is optional (CAS ENG or MANUAL).
5. Gear, flaps, and speed brakes can be used at the pilot's discretion.
6. The spacing task takes _precedence over_ the profile descent airspeeds.
7. Waypoints should be crossed _at or above_ the specified waypoint altitude.
8. The altitude-range arc may be used for altitude control.
9. S-turns on final are prohibited.
10. Complete approaches to touchdown.

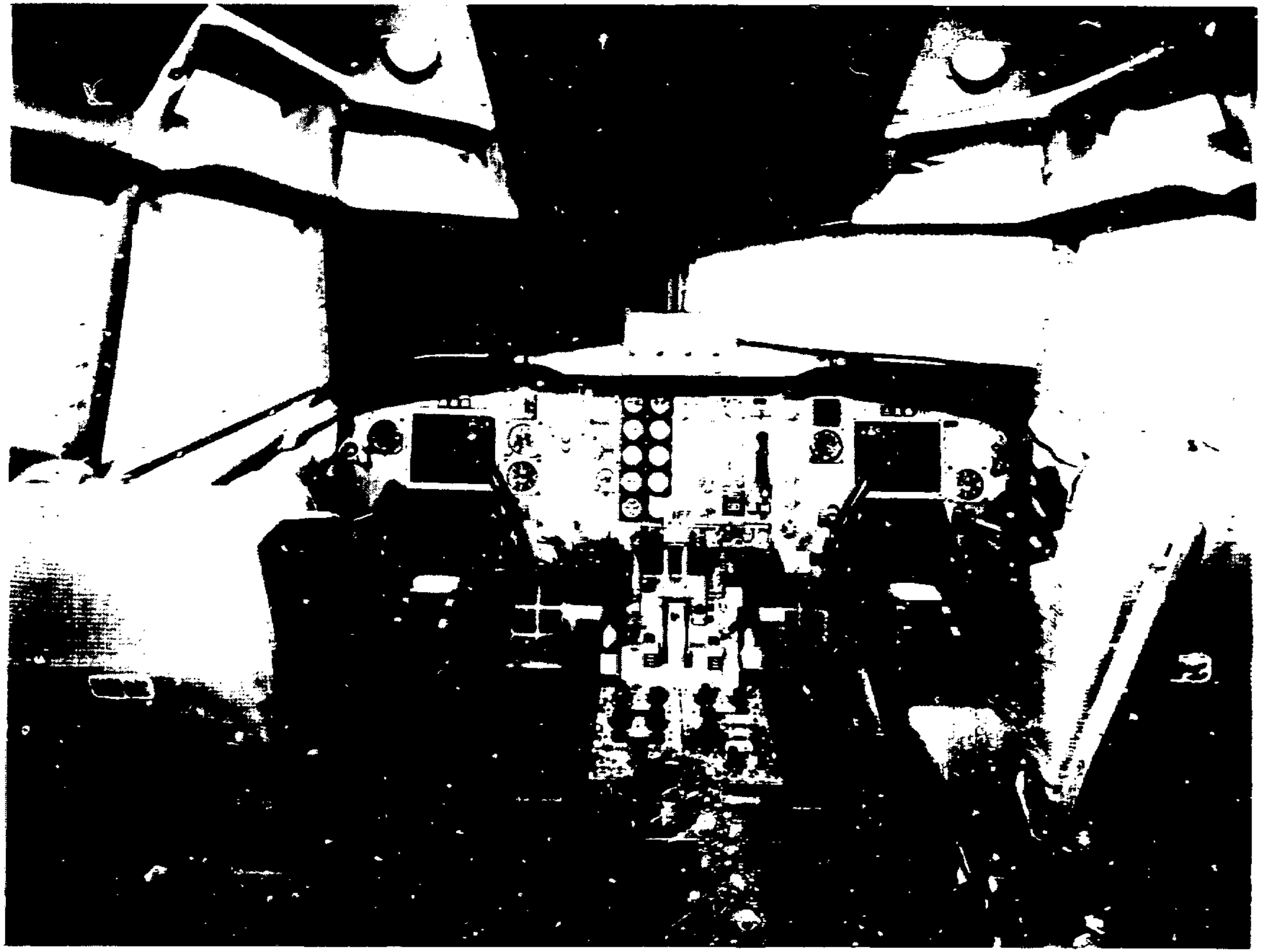

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Figure 1.- Ground-based simulator.

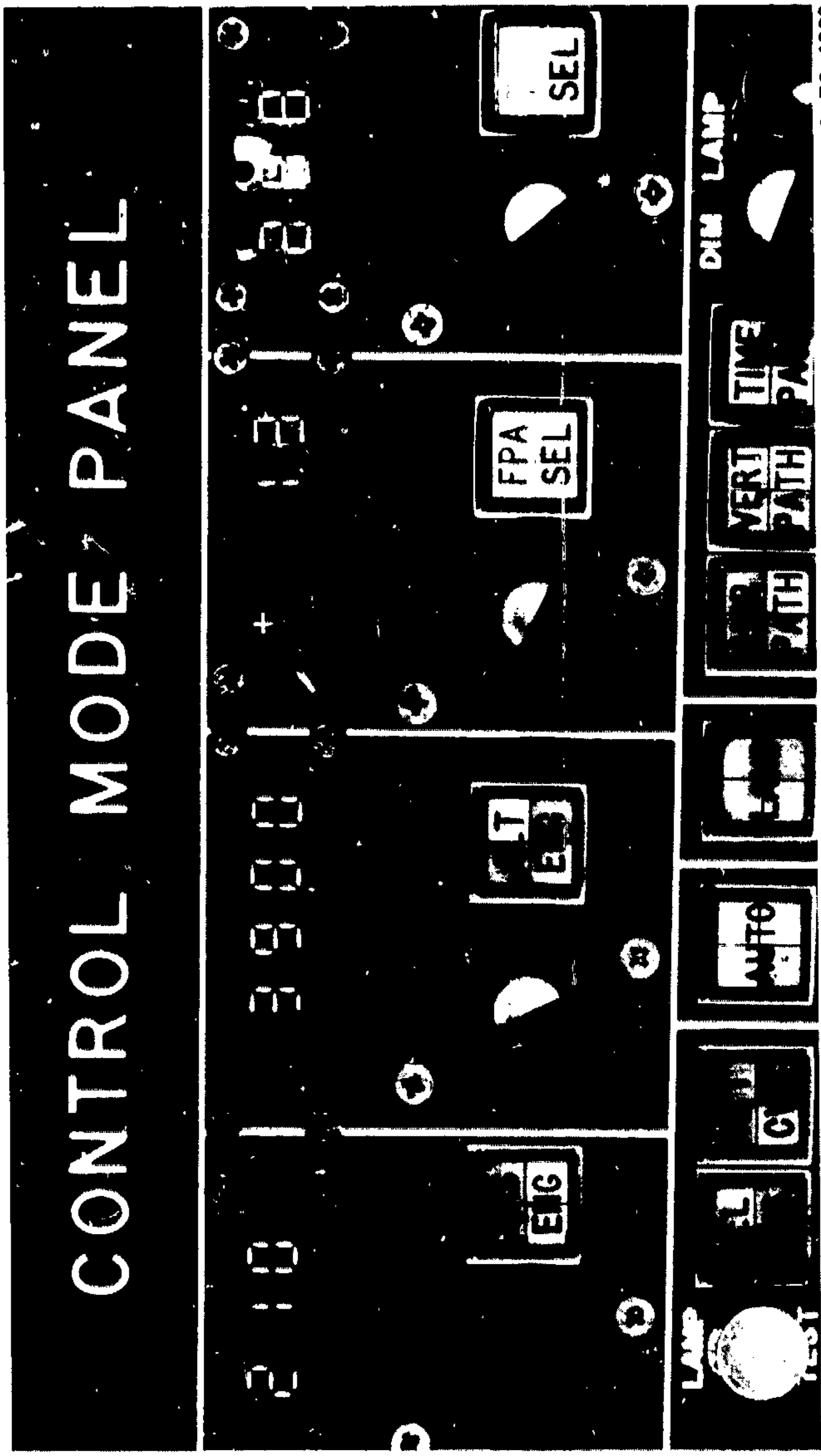

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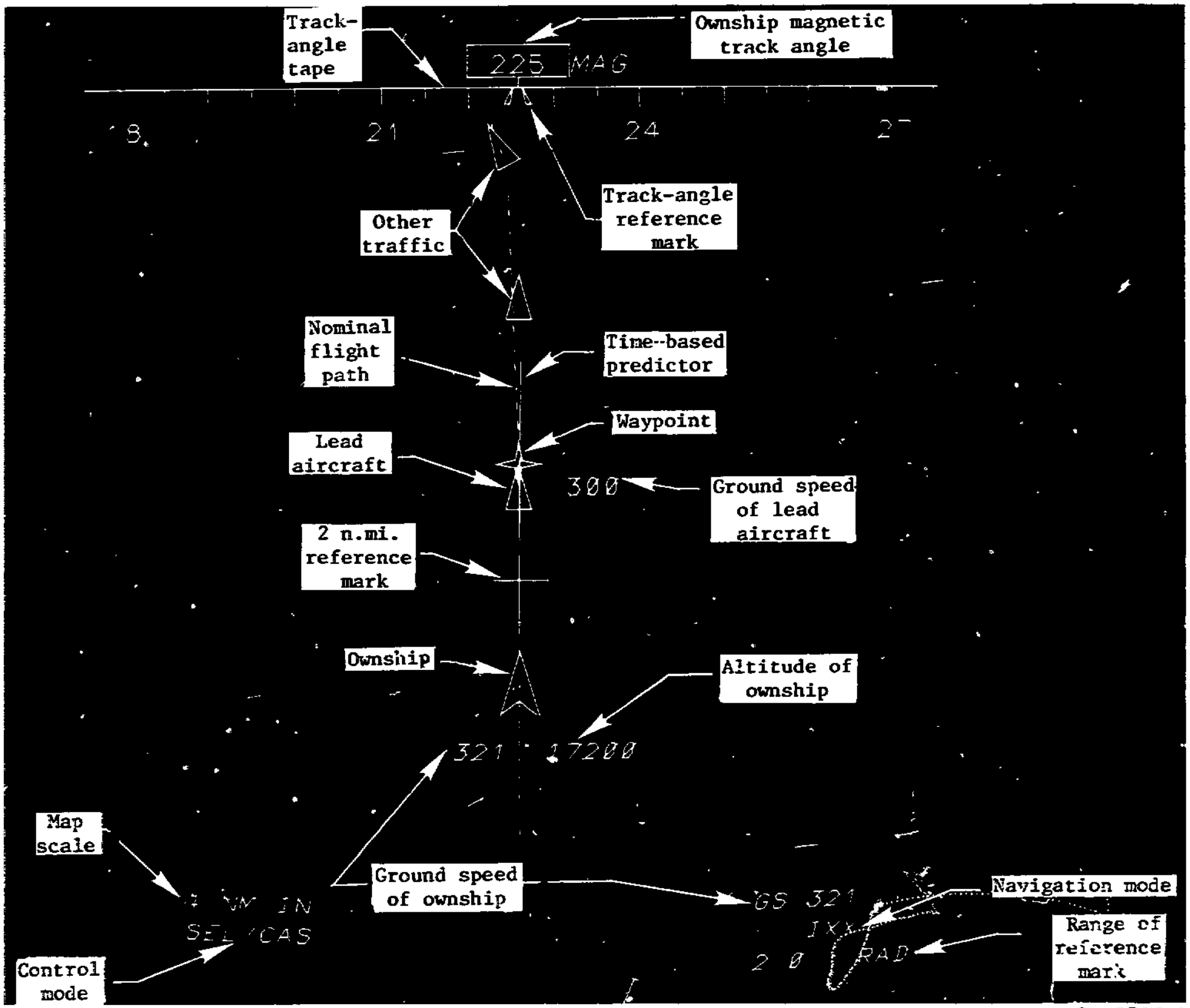
Figure 2.- AGCS control-mode panel.



(a) Labeled.

Figure 3.- CDTI format with CTP cue.

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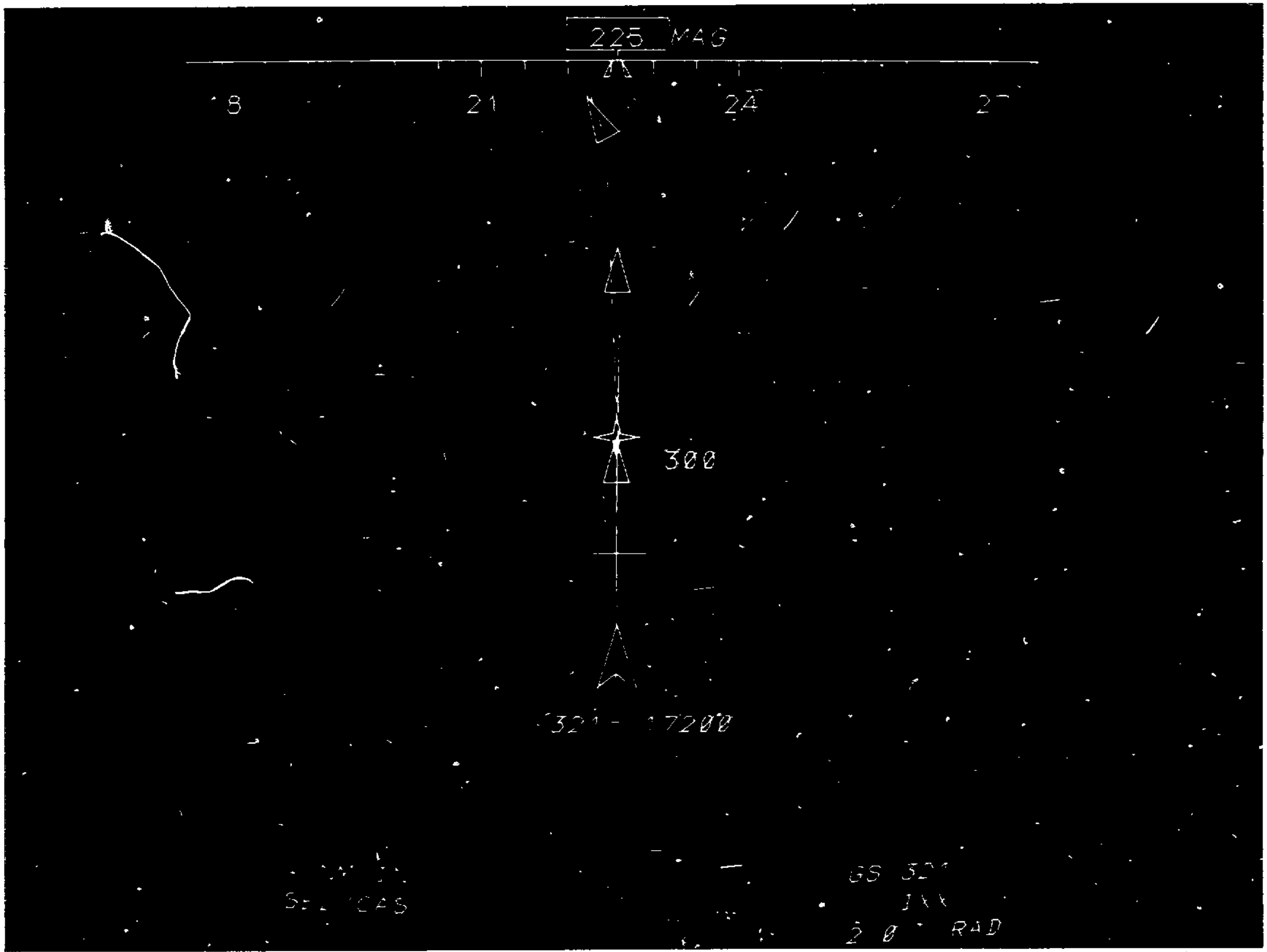

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(b) Unlabeled.

Figure 3.- Concluded.

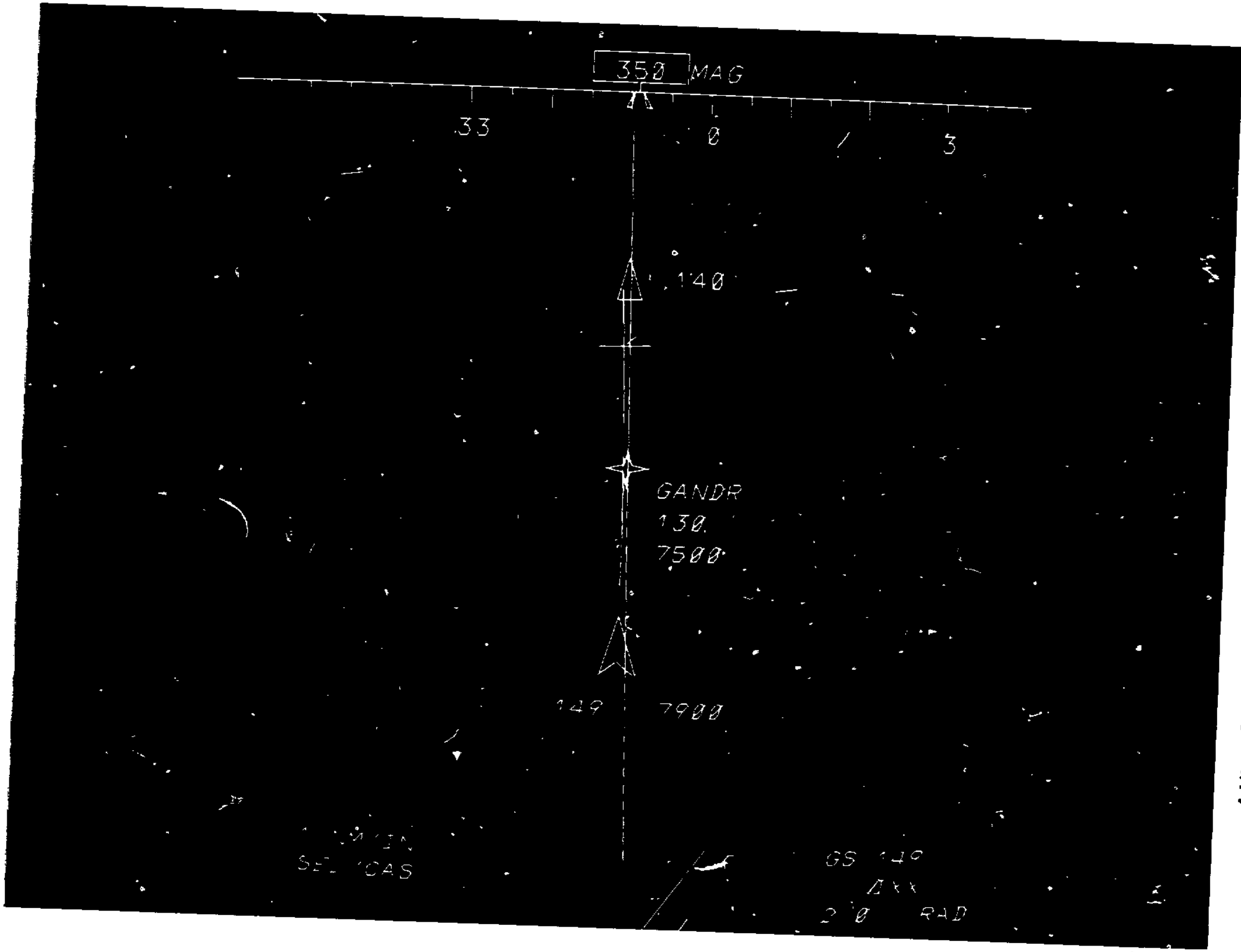

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Figure 4.- CDTI with waypoint tag.

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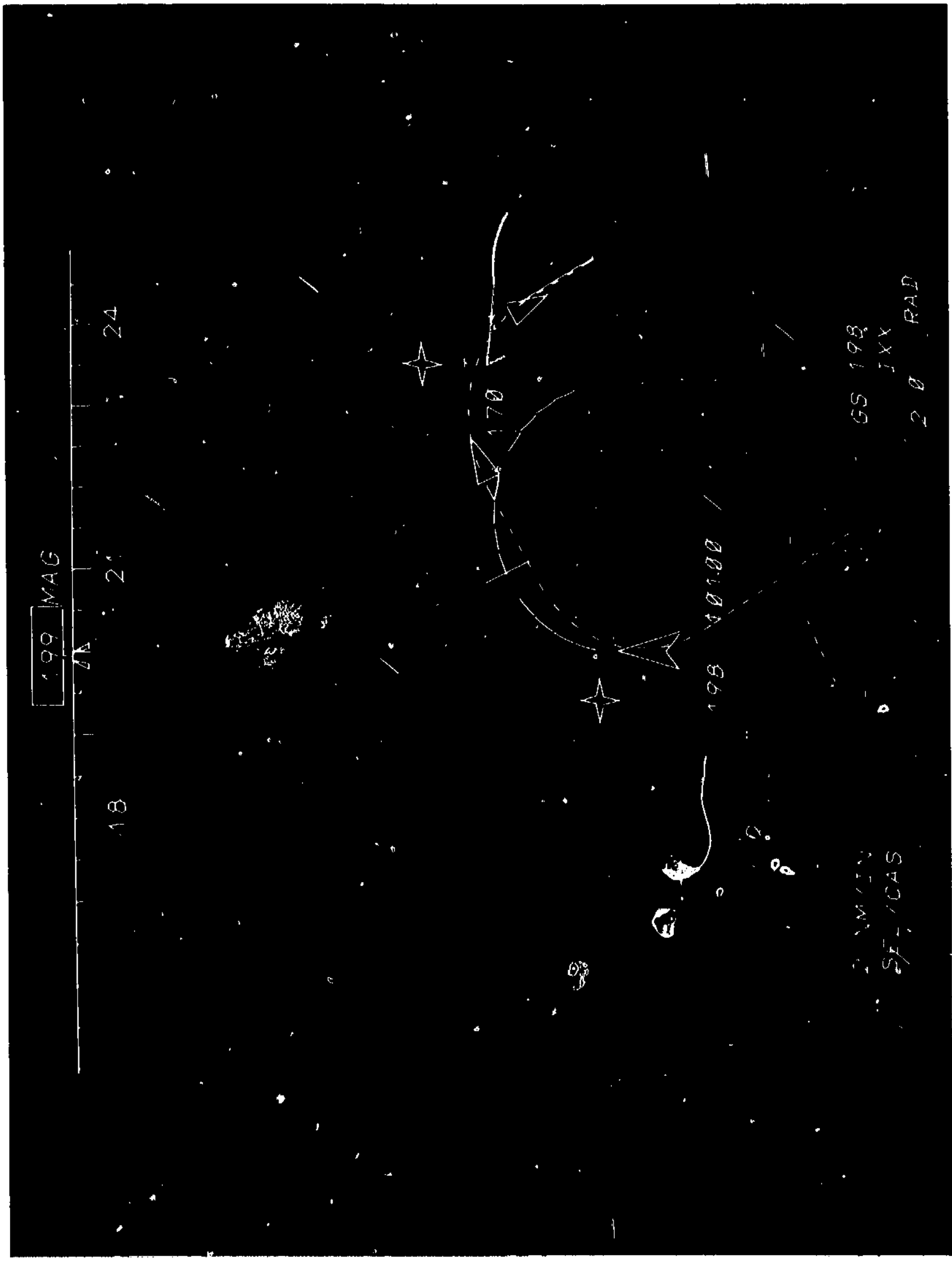

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Figure 5.- CDTI display during base turn.

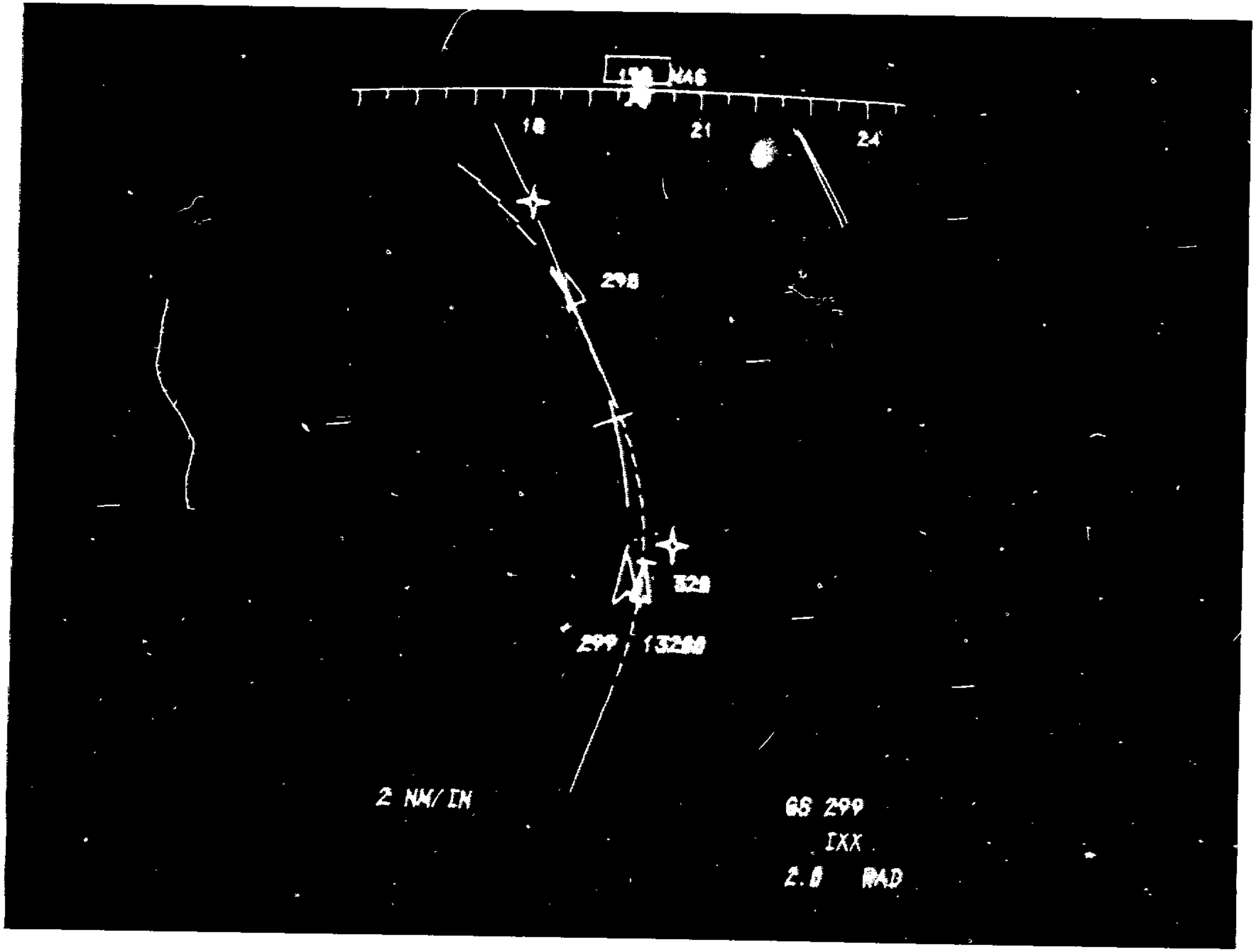

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Figure 6.- CDTI format with CTD symbology.

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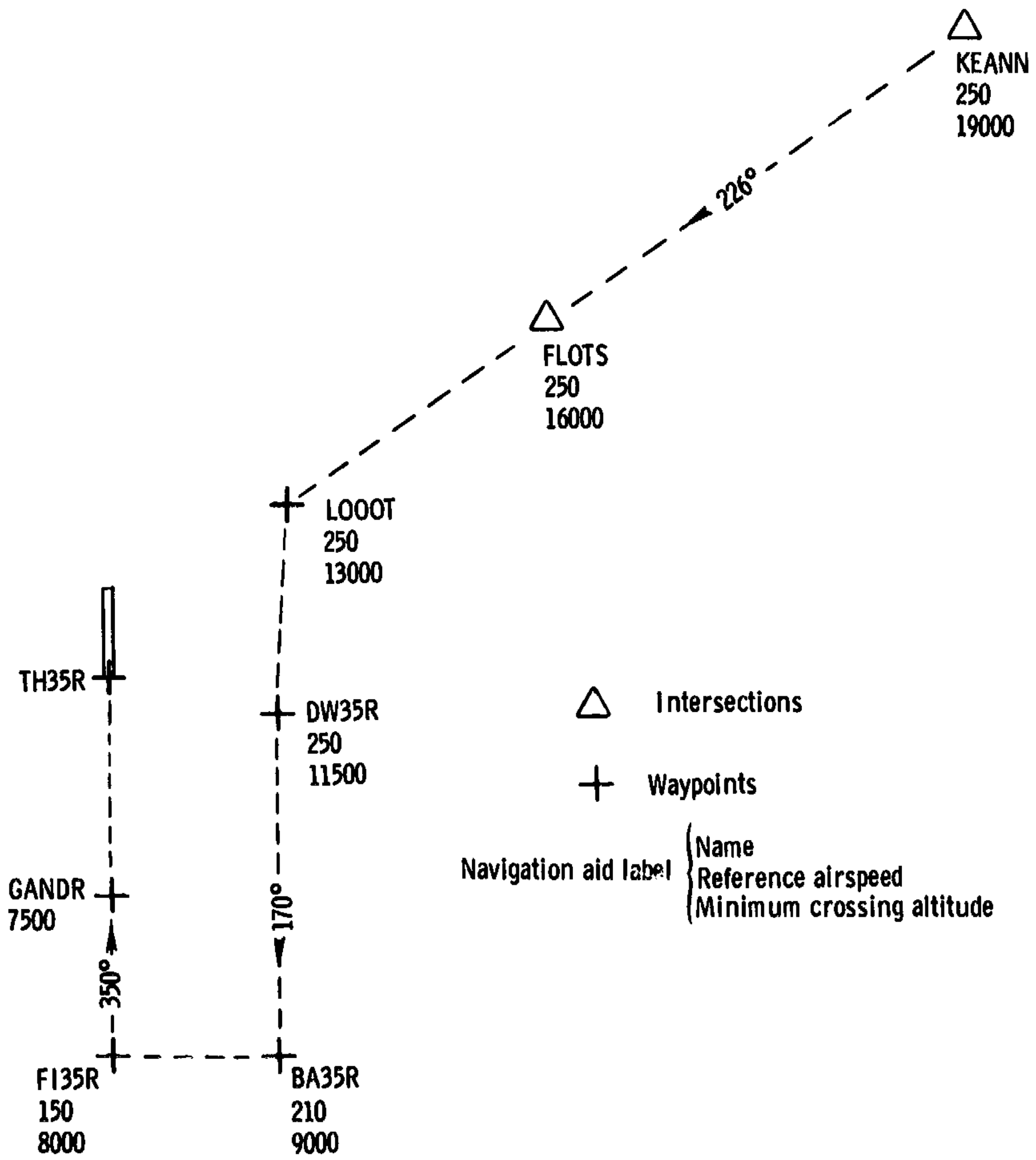

Figure 7.- STAR geometry.

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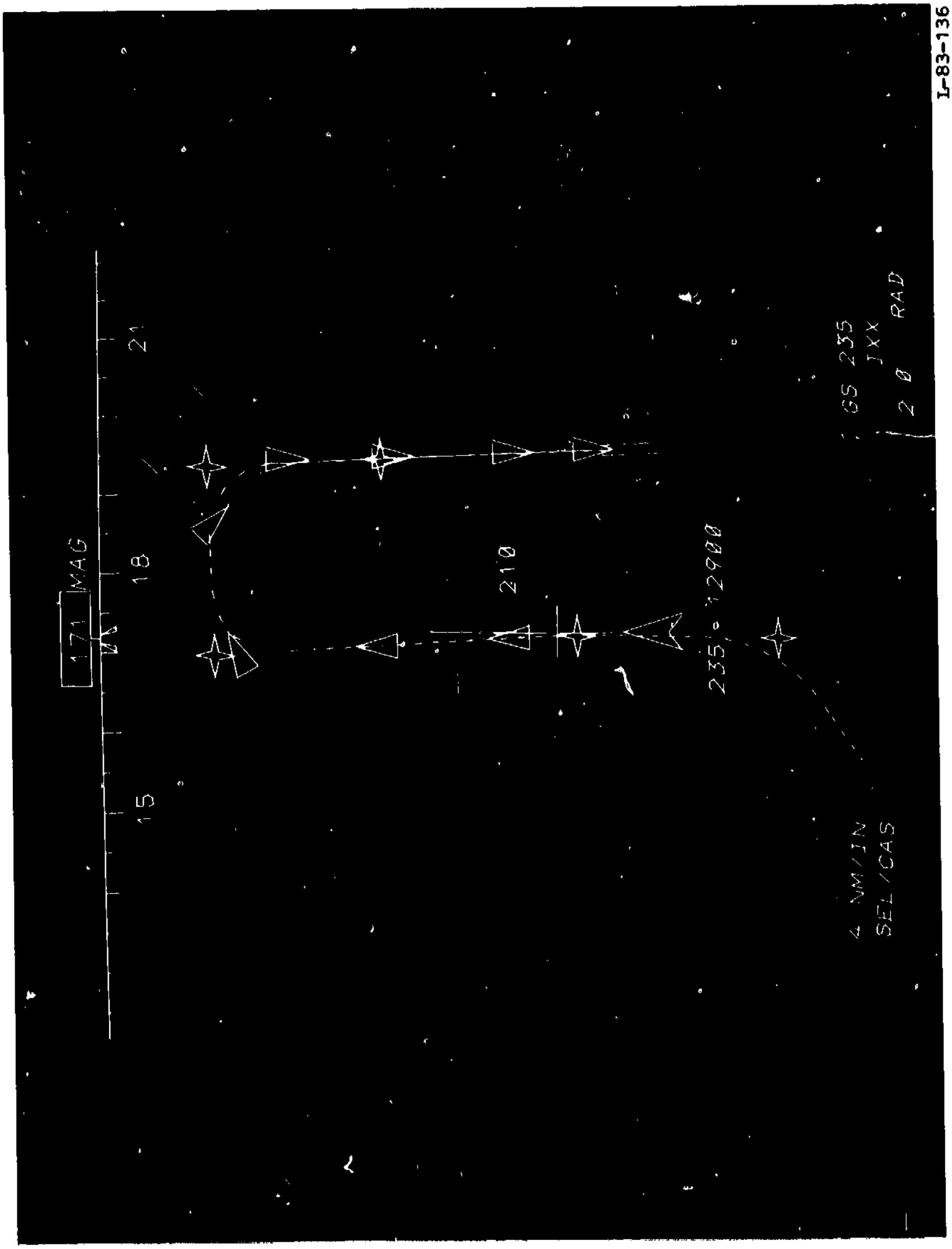

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Figure 8.- CDTI showing queue of nine aircraft.

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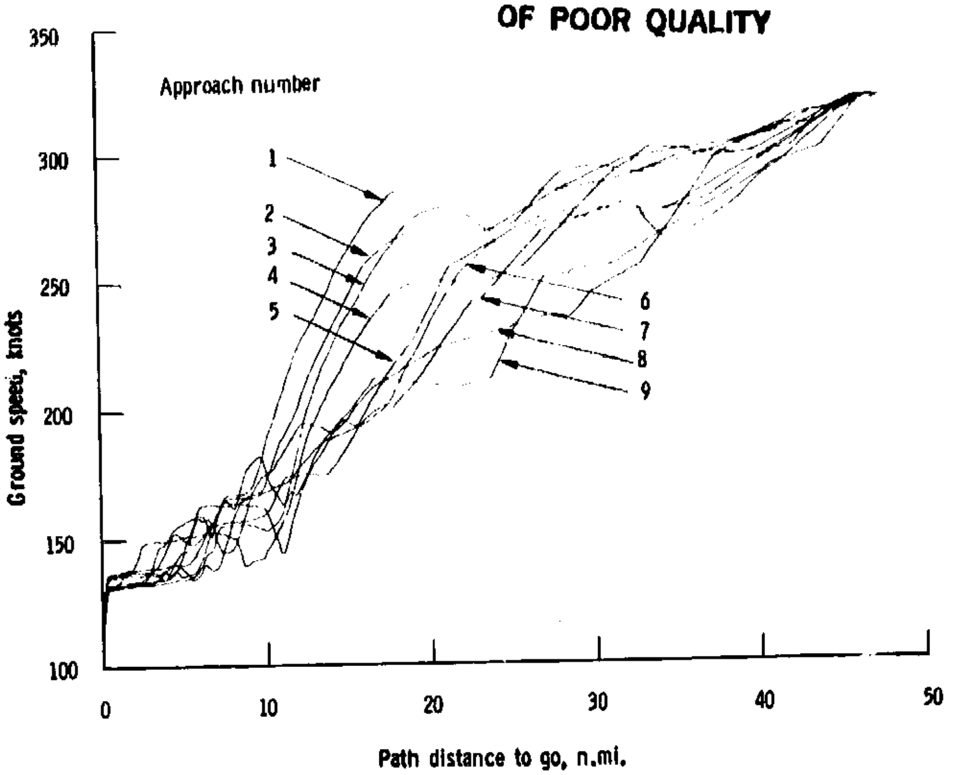
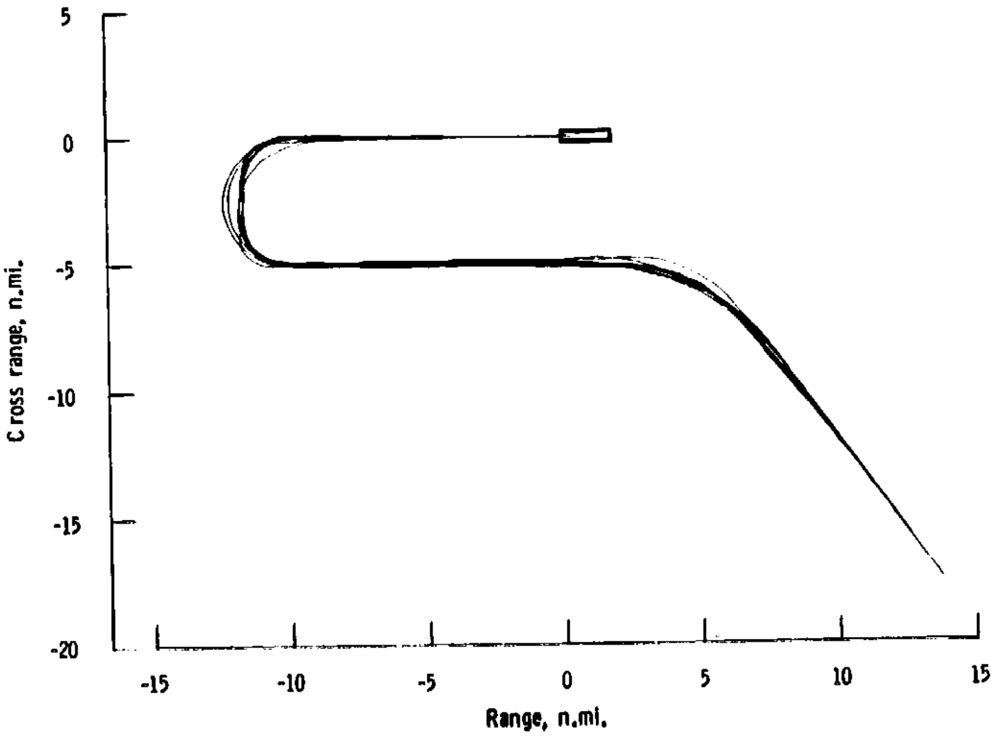
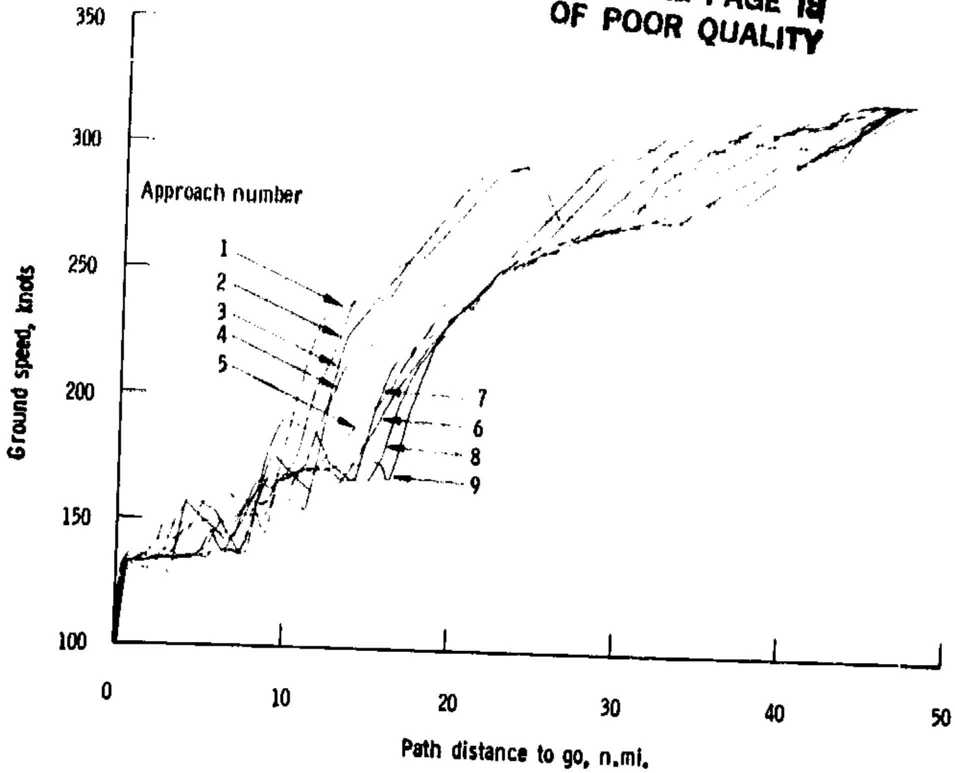


(a) Ground-speed composite.

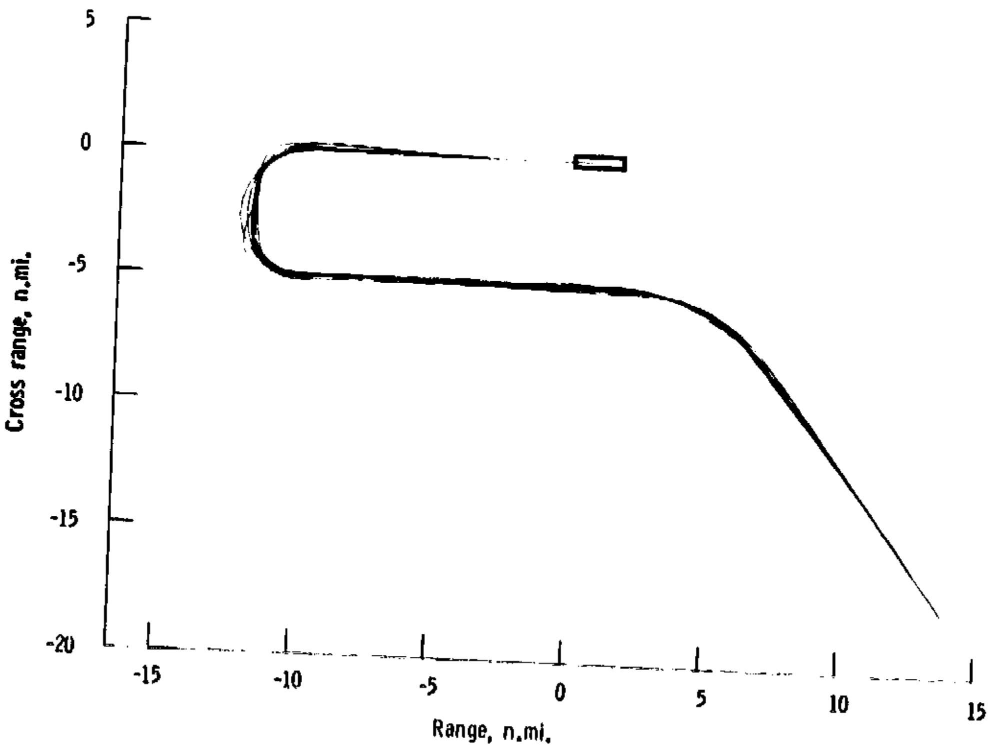


(b) Ground-track composite.

Figure 9.- Constant time predictor performance during first simulation session.



(a) Ground-speed composite.



(b) Ground-track composite.

Figure 10.- Constant time predictor performance during second simulation session.

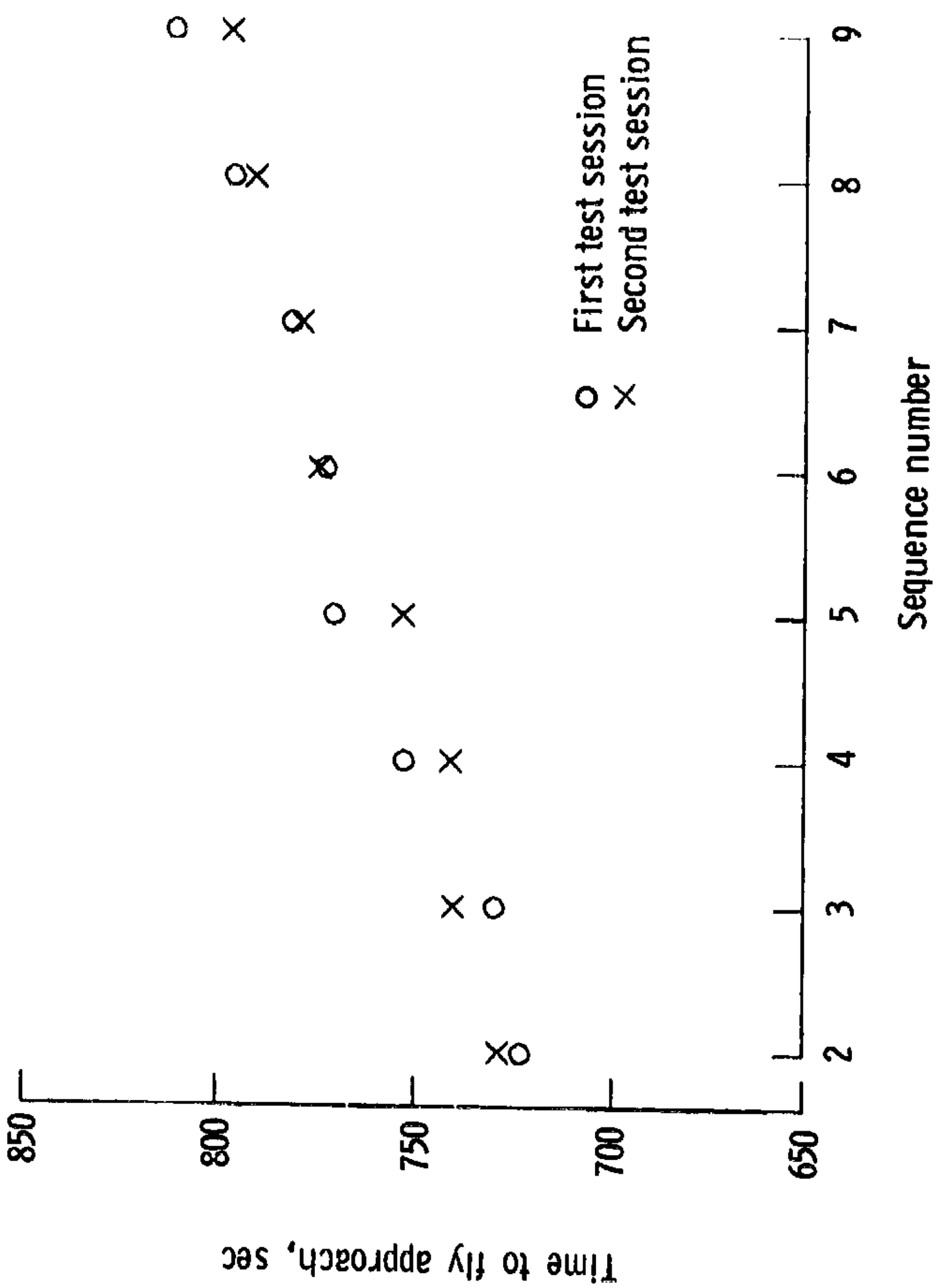
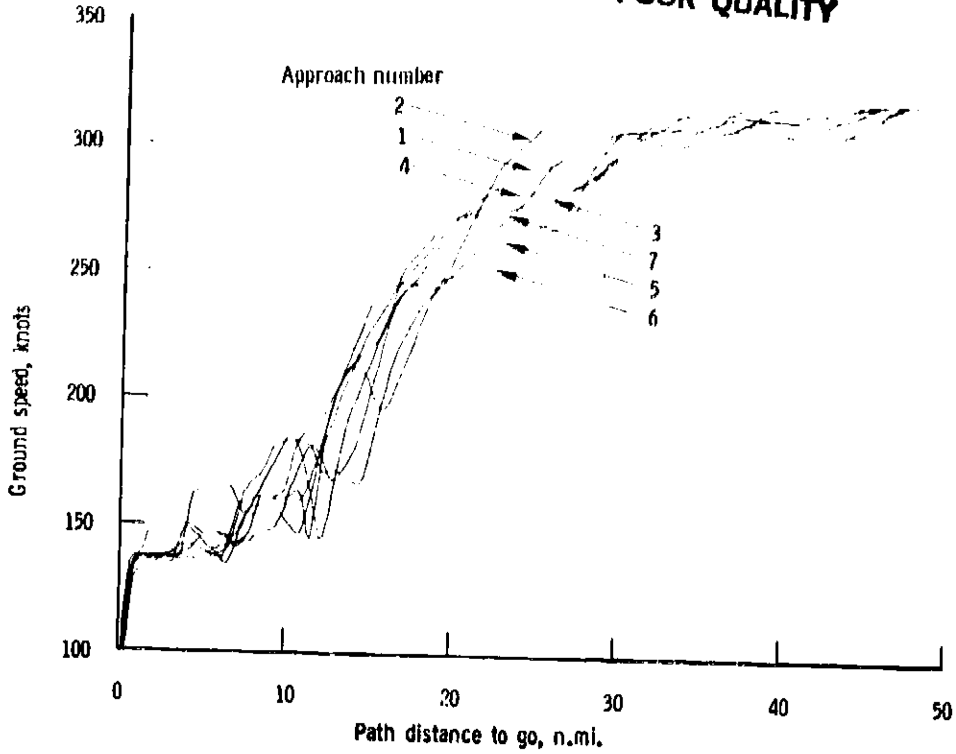
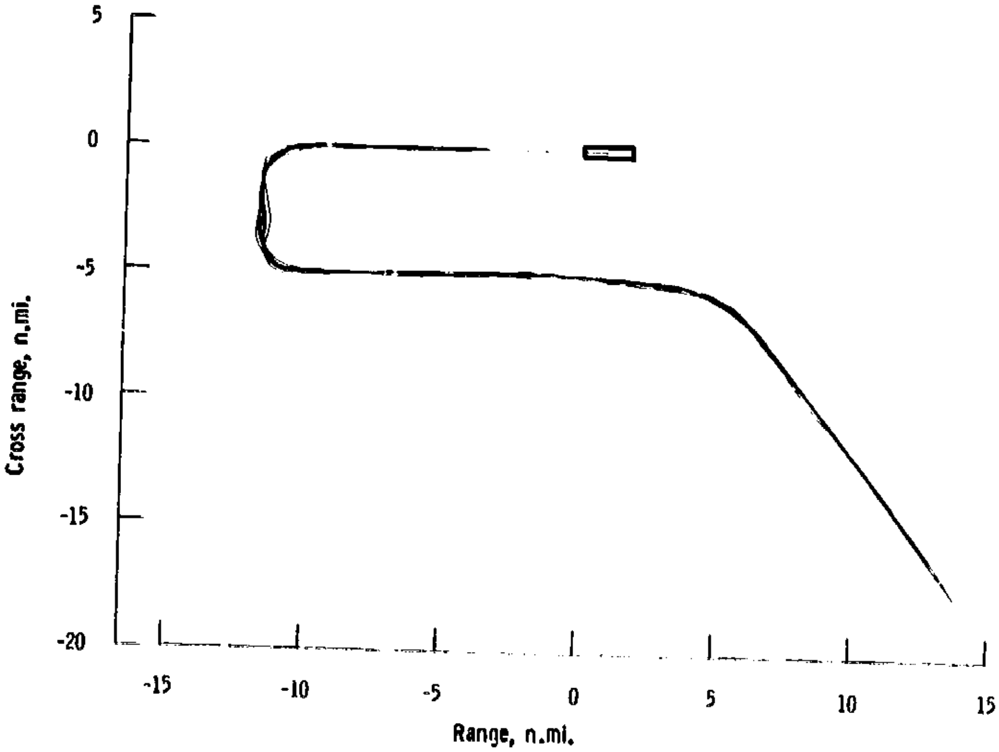


Figure 11.- Approach time with CTP spacing.



(a) Ground-speed composite.



(b) Ground-track composite.

Figure 12.- Constant time delay performance.

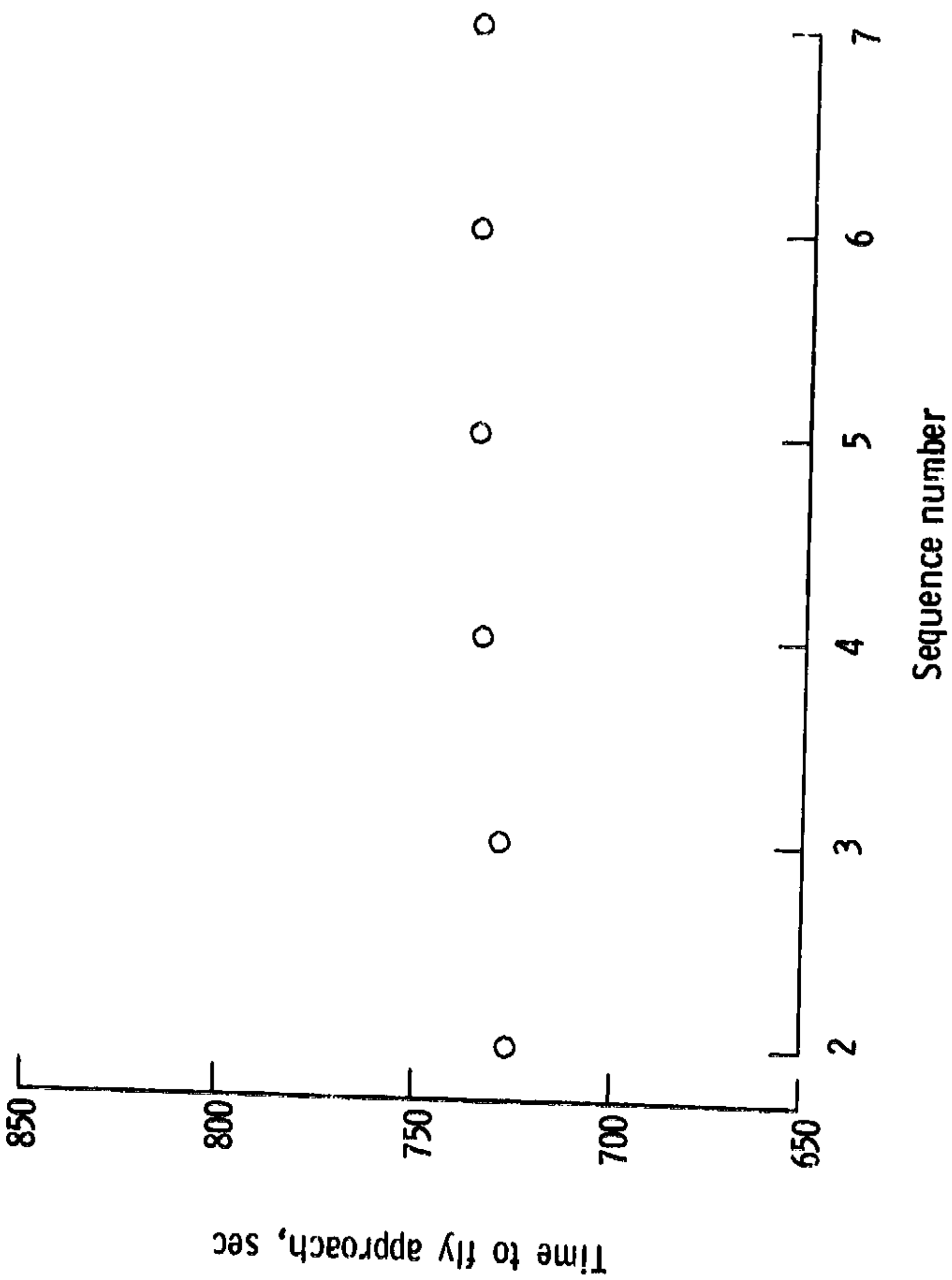


Figure 13.- Approach time with CTD spacing.

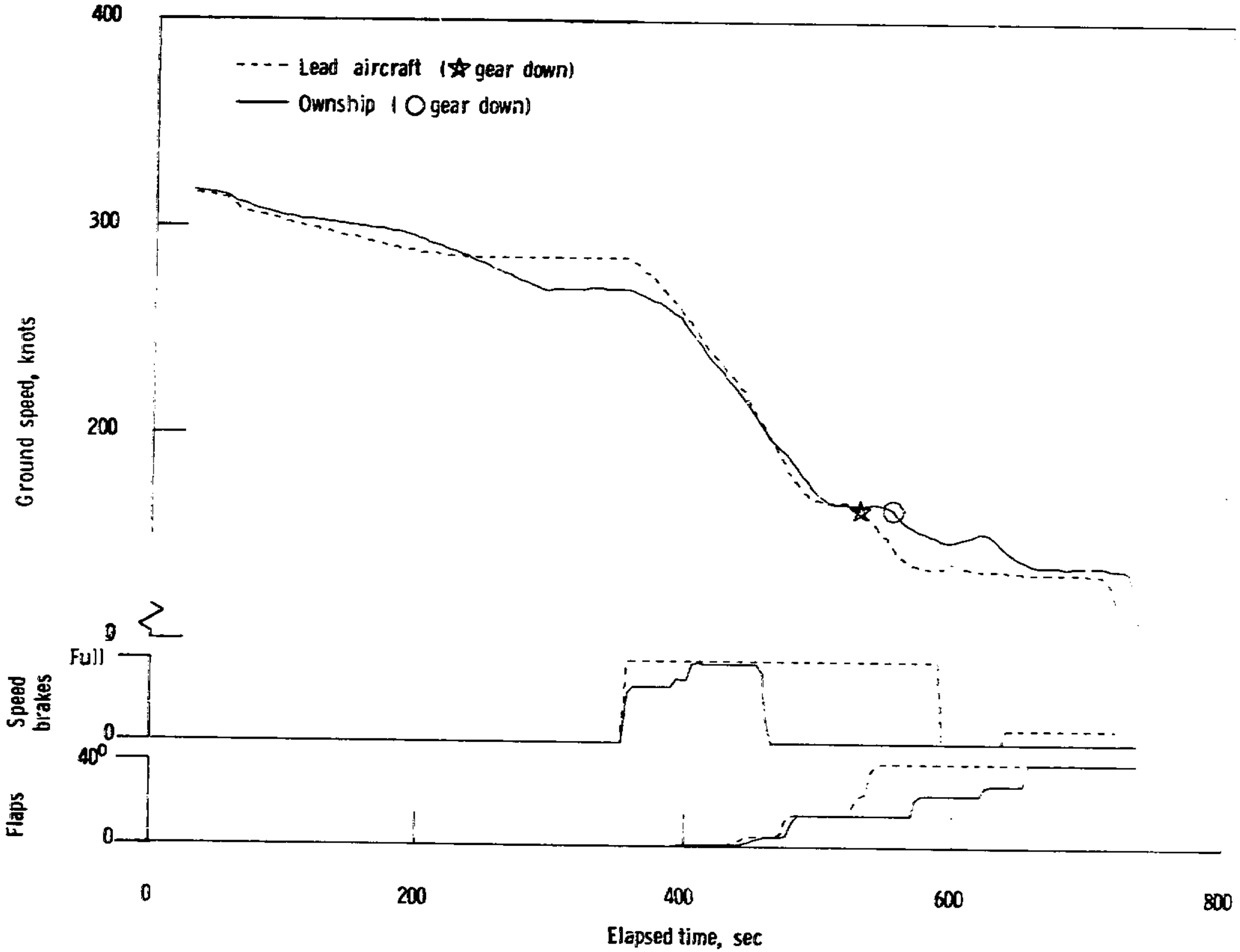


Figure 14.- Typical landing gear, speed brake, and flap schedules for lead-follower pair. CTD spacing criterion.