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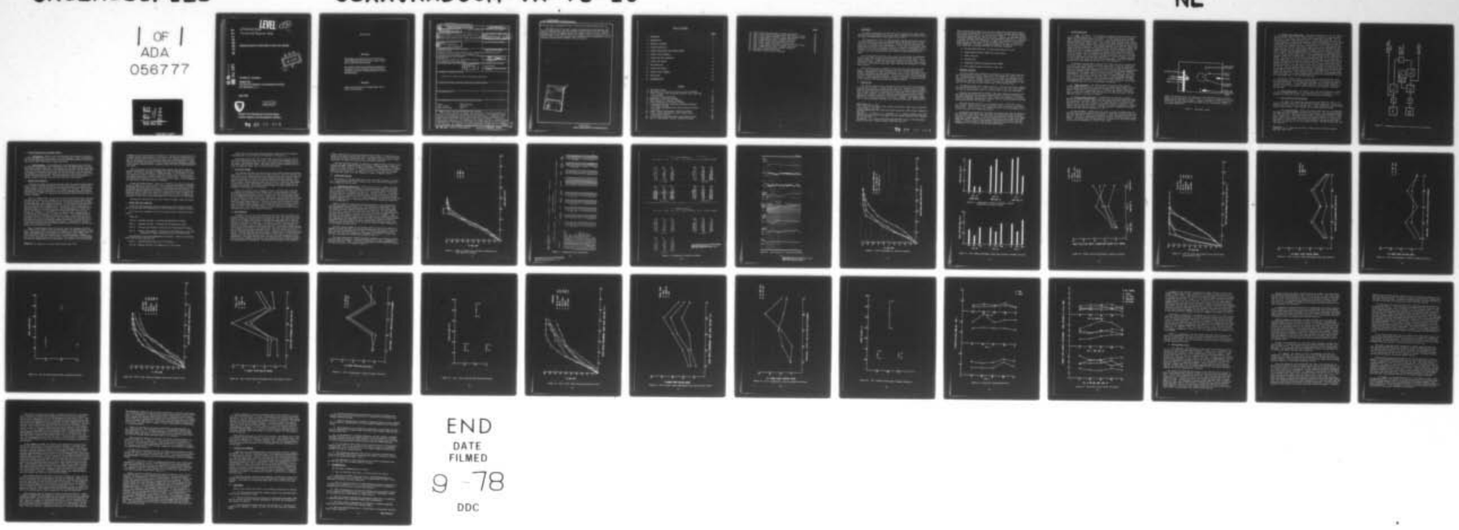

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DOPPLER HOVER SYSTEM (DHS) FLIGHT TEST REPORT

Christos M. Tsoubanos

Headquarters
USA Avionics Research and Development Activity
Fort Monmouth, N. J.

April 1978

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Research and Development Technical Report
Aviation Research and Development Command

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REPORT DOCUMENTATION PAGE

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14

1. REPORT NUMBER: USA AVRADCOM-TR-78-10

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (*and Subtitle*): 16 Doppler Hover System (DHS) Flight Test Report

5. TYPE OF REPORT & PERIOD COVERED: 9 Technical rept

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): 10 Christos M. Tsoubanos

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Simulation Team
Advanced Avionics Systems Technical Area (DAVAA-F)
Avionics Rsch & Dev Activity, Fort Monmouth, NJ 07703

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 694946-42571-02-98 1L6

11. CONTROLLING OFFICE NAME AND ADDRESS
Headquarters
USA Avionics Research and Development Activity
Fort Monmouth, New Jersey 07703

12. REPORT DATE: 11 Apr[redacted]78

13. NUMBER OF PAGES: 40

14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*): 12 44p.

15. SECURITY CLASS. (*of this report*): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Hover	PNVS Symbology
Hover Systems	Displays
Night Operations	PLIR

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report presents the flight test evaluation of a self-contained hover system concept design for the AAH and ASH helicopters. The configured system includes the Lightweight Doppler Navigation System (LDNS), a simulated Pilot Night Vision System (PNVS) utilizing a closed circuit daylight TV system and analog symbol generator. The emphasis of the flight test was to determine hover performance and the potential of the LDNS to provide adequate velocity information near zero. This velocity and other quantitative parameters were symbolically displayed with imagery on a panel-mounted CRT such that the (OVER)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) pilot was able to manipulate them to maintain an accurate manual hover.

The flight test of the above system was successfully completed and the results quantitatively show that standard deviation position errors incurred during a "bob-up" and remask maneuver may range as high as 30 feet radially. The potential of the LDNS to provide low frequency velocity information for the velocity vector drive was adequate when combined through complementary filtering with attitude (high frequency) derived velocity.

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1. BACKGROUND

The tactical deployment of Army helicopters equipped with night vision sensors during night operations revealed that a significant operational problem exists in maintaining a stable high altitude hover.[1]

The scenarios for a mid- to high-intensity conflict require that the future Army helicopters such as the Advanced Attack Helicopter (AAH), the Advanced Scout Helicopter (ASH) and others, operate at NOE (Nap-of-the-Earth) conditions to increase their survivability. In the area of operations, these helicopters must hover and remain concealed by natural and man-made objects, "bob-up" to an altitude sufficient to acquire, identify, and designate or fire a missile and then rapidly descend until masked to avoid detection by the enemy.

It is during these maneuvers that a pilot has difficulty in maintaining a stable hover when viewing a Forward-Looking Infrared (FLIR) night vision sensor, whether it is gimballed or rigidly mounted on the helicopter. Tests conducted at CDEC[1], as well as flight tests conducted by Night Vision Laboratory (NVL)[2], and Avionics Laboratory (AVL)[3] verified the existance of a night hover problem.

This problem was also recognized by the Army helicopter procuring community. The procurement specifications written for the AAH helicopter included a requirement for hover aid symbology. Due to cost constraints, an additional stipulation was added which required that the hover aid be provided from the planned AAH onboard sensors. In view of the above, the Avionics Laboratory at Fort Monmouth initiated a program to provide a potential solution to the tactical hover problem using AAH onboard sensors.

2. INTRODUCTION

For the past several years the Avionics R&D Activity has been investigating the hover problem.[3] Several flight tests were conducted on its Research Aircraft Visual Environment/Experimental Vehicle for Avionics Research (RAVE/EVAR) project helicopter to evaluate hover sensor and hover system concepts.[4,5] Some of these concepts utilizing symbology representing quantitative flight information, primarily position, velocity and acceleration (attitude) superimposed on a terrain presentation, were very successful. The position sensor was a critical component required for a precision hover task. When position

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[1] CDEC Experiment 43.711B.

[2] *"Pilot Night Vision System (PNVS) Display Evaluation,"* Night Vision Laboratory In-House Report, July 1975.

[3] Systems Engineering Team, *"Low Level Night Operations (LLNO) Study,"* ECOM-4417, June 1976.

[4] Milelli, R. S., Johnson, D. C., Tsoubanos, C. M., *"Manual Precision Hover With Superimposed Symbology on FLIR Image,"* AHS 31st Annual National Forum, Washington, DC, May 1975.

[5] Tsoubanos, C. M., *"Design and Flight Test Evaluation of an IR Hover System,"* Avionics Laboratory Technical Report ECOM-4520, Aug 1977.

errors were derived visually from the scene (stabilized downlooking image) or from a position sensor such as the Actron Industries daylight system, Random Scene Motion Sensor (RMS),[3] the results were optimum.[3,4] If position information was not available, the results were poor. However, the AAH PNVS specification and funding constraints do not allow additional sensors (i.e., position) to provide the hover aid. Therefore, a flight test evaluation was conducted utilizing the concepts stated in the AAH PNVS specification to provide the hover capability. The basic equipment, planned for the AAH, on which this hover capability is centered includes the following subsystems.

a. Turreted PNVS FLIR with a field-of-view (FOV) 30° by 40°.

b. Helmet Mounted Display (HMD) with head tracker

c. Symbol Generator

d. Vertical Gyro

e. Lightweight Doppler Navigation System (LDNS)

f. Other onboard sensors (altimeter, IVSI, etc.)

3. TECHNICAL APPROACH

The Pilot Night Vision System was simulated on the EVAR Project Helicopter by utilizing its existing closed circuit TV system with a FOV of 45° by 60°. The head tracker concept could not, at this time, be integrated due to the lack of a turret. Instead, the daylight TV system line-of-sight in the vertical axis was electrically altered to increase the downlook angle to that which can be achieved by a head tracker and a turret-mounted FLIR.

The display medium used in these tests was a panel-mounted 8-inch diagonal CRT situated approximately 24 inches from the pilot's eye. The symbol generator was an analog version used in a previous hover flight test experiment.[5]

Finally, the Engineering Development (ED) model LDNS was integrated with the symbol generator and associated instrumentation to drive one of the key displayed parameters, the velocity vector. Thus in the absence of a position sensor, the symbolic presentation of doppler velocity and acceleration information became the heart of this hover aid.

The above system referred to as the Doppler Hover System (DHS) concept was initially tested in the Avionics Laboratory Tactical Avionics System Simulator (TASS). The results of this simulation proved to be encouraging and reinforced the need for a flight test effort.

It should be noted that for the flight test phase there were two Engineering Development (ED) LDNS models available, one designed by Singer Kearfott, the other by Teledyne Ryan. The Army was evaluating these and would eventually select one of these dopplers to go into production for use on AAH, Cobra, and UTTAS helicopters. Each of these dopplers was separately tested in the DHS concept. A quick disconnect and changeover from one system to the other was implemented to allow ease of testing both LDNS systems.

4. SYSTEM DESCRIPTION

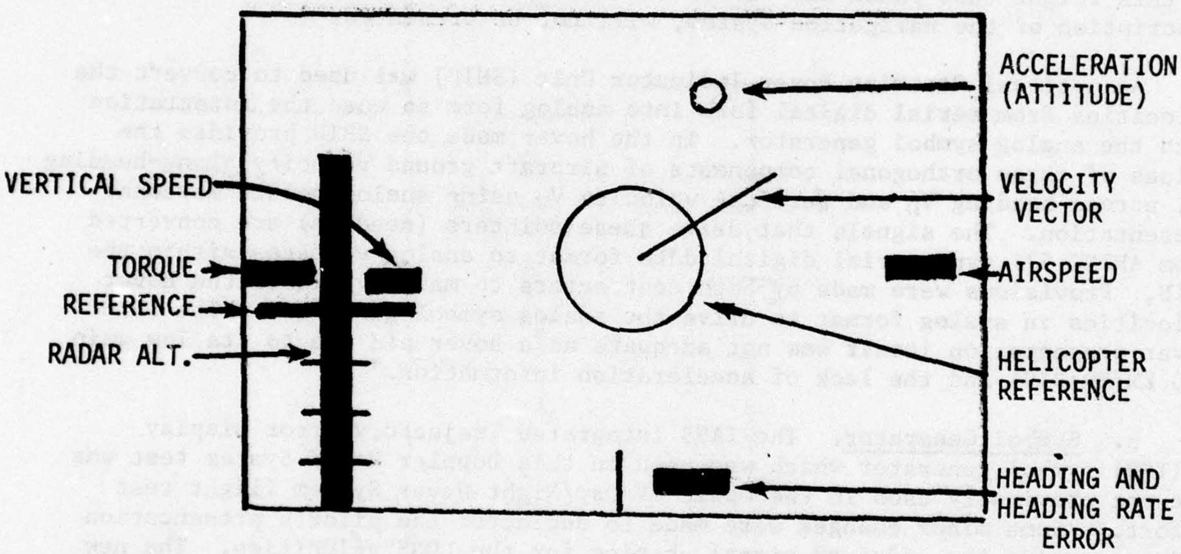
a. LDNS. The LDNS is a self-contained navigation system and does not require any ground-based aids. It consists of a Doppler Radar Velocity Sensor (DRVS), and a Computer Display Unit (CDU). For the Singer Kearfott version only, the DRVS is packaged in two LRU's, a Signal Data Converter (SDC), and a Receiver/Transmitter Antenna (RTA). The RTA is rigidly mounted on the airframe and aircraft angular motions are decoupled analytically through the use of vertical gyroscope information. With suitable heading, pitch and roll inputs from standard aircraft attitude and heading systems, the LDNS supplies aircraft velocity, position and steering information in both visual and serial digital (ARINC 571) form. The DRVS transmits microwave energy toward the ground in four non-coplanar beams, and measures the doppler frequency shift in the backscattered energy. The four doppler frequency shifts are then sent to the CDU for use in navigation and steering computations. Since the primary interest of this flight test phase was the hover aid capability, a detailed technical description of the navigation system, will not be presented.

An optional Steering Hover Indicator Unit (SHIU) was used to convert the velocities from serial digital form into analog form to ease the integration with the analog symbol generator. In the hover mode the SHIU provides the values of three orthogonal components of aircraft ground velocity along-heading V_H, across heading V_D and vertical velocity V_V using analog needle movement presentation. The signals that drive these pointers (needles) are converted from ARINC 571 type serial digital data format to analog voltages within the SHIU. Provisions were made by both contractors to make available the hover velocities in analog format to drive the analog symbol generator. The SHIU hover presentation itself was not adequate as a hover aid due to its low gain (30 KM/HR/DIV) and the lack of acceleration information.[4]

b. Symbol Generator. The TASS Integrated Trajectory Error Display (TITED) symbol generator which was used in this Doppler Hover System test was the one previously used in the Optic IV Day/Night Hover System flight test effort.[5] Some minor changes were made to declutter the pilot's presentation and to provide the required signal shaping for the LDNS velocities. The new symbology format is as shown in Figure 1.

c. Closed Circuit TV System. The EVAR project helicopter includes a daylight TV camera fixed-mounted on the nose and a second one inside the "hook well" mounted to look down. Each of the TV systems has a 45° vertical by 60° horizontal FOV. The line-of-sight of the camera located in the nose of the aircraft was electrically biased to increase its downlook capability to approximately -20° from the horizontal. This was required to approximate the anticipated AAH PNVS downlook capability of -30°.

The second camera, looking down, was used to record the ground scene for eventual data reduction application and also in some cases to provide the pilot with -90° downlook to assess any improvement in hover performance over the -20° downlook. More will be presented on this in the data collection section of the report. The subject pilot was provided with a switch on his collective control to allow him the capability to select either scene.



(NOTE: The position cross has temporarily been eliminated since a position signal was not available. In the future it is planned to integrate the doppler velocities for the position signal. However, this must be done digitally to obtain the required accuracy and the capability for this was not present in this symbol generator.)

Figure 1. DHS symbol format

d. Symbol Drive Requirements. The required sensors to drive the symbology include the vertical gyro, radar altimeter, instantaneous vertical speed indicator (IVSI), engine torque transducer, heading gyro, and LDNS. The acceleration, torque, radar altitude, rate of climb, and heading rate error deviation symbols all required the identical signal conditioning as for the Optic IV Day/Night Hover System tests.[5] The velocity vector drive and its signal conditioning was changed from these previous tests. Due to the inherent doppler noise, the velocity vector drive signal for hover was comprised of integrated attitude for the high frequency and doppler velocity for the low frequency, combined through complementary filtering with the crossover frequency at 0.1 radian. This technique was shown to be successful in simulation and also in the early RAVE flight tests.[4] Some experimentation was conducted during this flight test training phase on the time constant for the LDNS velocity signal. The time constant was varied incrementally from 2.5 to 10 seconds. At the lower value (2.5 sec), the velocity vector became unpredictable and the pilot's workload (stick movement) greatly increased. The time constant of 10 seconds was selected for use in the flight test. Figure 2 shows this complementary filtering. Note that there are two signals which may drive the velocity vector. The raw doppler signal scaled at 11 fps/inch is primarily for use in the approach mode symbology, with provisions implemented in the symbol generator for use with the hover symbology mode. The other signal is only used during the hover mode. Once the pilot stops the aircraft in the general hover area, he switches to the hover symbology mode having the complemented velocity with the higher gain of 2.5 fps/inch displayed.

During the training flight, a velocity (V_H, V_D) offset appeared. This bias was apparent for both dopplers and appeared to be caused by the digital to analog conversion. A bias adjustment was added to the symbol generator to correct this problem. A digital symbol generator, such as that planned for the AAH, would use the digital velocity directly, and therefore, eliminate this problem.

e. Pilot Control Unit. The subject pilot had at his disposal a control unit which allowed him to select the symbology mode to be displayed. A description of this unit and its functions may be found in reference 5.

f. Data Collection and Recording.

(1) DAU. The onboard Data Acquisition Unit (DAU)[6] was used to record the aircraft states which included the following parameters: pitch, roll, heading, pitch rate, roll rate and yaw rate, cyclic, collective, pedal position, torque, radar altitude, rate of climb, and raw LDNS velocity outputs.

(2) Video recorder. During the actual hover test runs, the downlooking image video was recorded for future data reduction. The recorded downlooking image was used to measure position accuracy as the pilot attempted to maintain a stable hover. The video recorder audio track was used to record a composite normal audio conversation during the flight as well as a 1-second time code pulse of a 5-KHz tone. The tone was required to synchronize the video tape with the DAU tape for the data reduction phase. The DAU recorded the time code directly.

[6] Gunderson, R. P., *"RAVE Project Phase II Final Report,"* Technical Report ECOM 5001, March 1975.

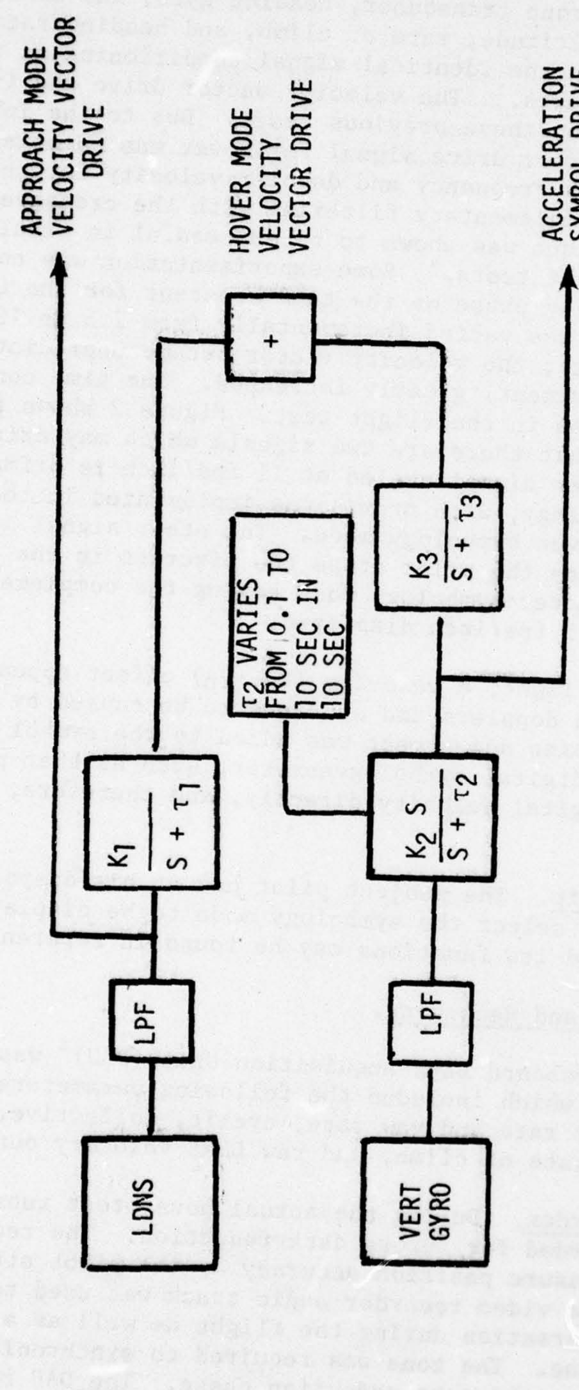


Figure 2. Complementary filtering for velocity vector symbology

5. SYSTEM INSTALLATION AND GROUND TESTING

a. Installation. Most of the above equipment was previously installed on board the EVAR project helicopter. The new equipment, LDNS, tone generator, and the downlooking TV camera installation was performed by Naval Air Development Center (NADC) EVAR project support personnel.

b. Ground Testing. At the completion of the mechanical and electrical installation, ground tests were performed by NADC and ECOM personnel to check the overall system integration. The interface of the LDNS with the symbol generator and the pilot control unit was checked and verified. The polarity and/or phasing of the doppler outputs and the velocity vector were also verified. The downlooking camera picture quality and the pilot video select control were checked and found satisfactory. The tone generator output was checked by making a sample video tape recording and verifying it by playback.

6. SUBJECT PILOT TRAINING

Although the subject pilots were familiar with the concepts being investigated, adequate time was allocated to the two subject pilots to train on the proposed cells. Both pilots were CH-53 qualified and had flown the EVAR project helicopter from the 3rd station,[3] in a variety of projects. Some initial simulator training was conducted at the Avionics Laboratory Tactical Avionics System Simulator (TASS) for conceptual and procedural familiarization prior to aircraft training.

For the training phase, as well as for the data collection phase, the EVAR helicopter was flown by the command pilot from the front seat to the vicinity of the hover area. The subject pilot was at his station monitoring the superimposed symbology on the forward-looking TV. He was instructed to have selected the "Approach Mode" symbology on his control unit and be observing the hover performance of the command pilot. The velocity vector presented on the displayed image was raw doppler velocity scaled approximately 11 ft/sec per inch on the display. As the command pilot approached the hover area and brought the aircraft to a stable hover, the subject pilot assumed control of the helicopter and attempted to continue the hover. These attempts were unsuccessful since the low velocity gain was not easily resolved by the pilot especially for very low drift rates. This low velocity gain presentation did not provide the pilot with adequate damping information to assist him in stabilizing the helicopter and minimizing its drift. Increasing the velocity vector gain only increased the inherent doppler noise and did not aid the test subject in performing his task.

When it became apparent that the subject could not eliminate the drift, the command pilot resumed control of the helicopter and re-established a stable hover. The subject pilot now switched the symbology to "Hover Mode" which presents complemented velocity information on the velocity vector (Figure 2). This action also allows the velocity vector attitude component to washout and operate about the helicopter trim attitude.[7] The subject pilot then coordinated with the command pilot and at his consent took control of the aircraft and

[7] Shupe, Dr. N., Clark, R. G., Quad A Hover Paper, April 1976.

attempted to hover using symbolic information of velocity and acceleration and a forward image TV presentation of the terrain. The initial training was at a constant altitude (60 ft) with the front seat pilot holding altitude and heading. As the subject pilot's performance improved, he was requested to assume control of altitude and heading. As pilot proficiency and confidence increased at the constant altitude hover, the bob-up, high altitude and remask maneuvers were added.

Due to the nature of the conceptual hover system, the initial position reference selected by the subject disappeared from view during the bob-up maneuver. As the pilot ascended to a higher altitude, in the absence of a position reference, he had to minimize both the velocity vector and the accleration symbols excursions in order to maintain a stable hover. Having achieved the desired high altitude, the pilot once again had to look to the TV presentation and select a new hover position reference.

During the remask maneuver, again in the absence of a position reference, he had to minimize the velocity vector and acceleration excursions to maintain established hover and slowly descend. As he approached the desired altitude, he searched the TV image for his initial low altitude position reference. If during the remasking procedure the subject pilot could not locate the initial reference point, he would not continue to descend or move about randomly, but would turn control over to the front seat safety pilot. This was especially true when he could not see what was beneath or on the sides of the helicopter.

Training was completed when the pilot showed confidence using the system.

7. FLIGHT TEST CELL SELECTION

The hover flight maneuvers conducted during the testing phase were primarily the "bob-up" and "remasking" and a hover maneuver at constant altitude.

Four cells were configured for the test phase using TV imagery with symbology.

These are:

Cell 1a. Constant altitude - utilizing 90°-depression TV image.

Cell 1. Constant altitude - utilizing the 20°-depression image.

Cell 2. "Bob-up" and "remask"- utilizing the 20°-depression TV image.

Cell 3. "Bob-up" and "remask" - utilizing the 20°-depression or the 90°-depression TV image, selected at the pilot's discretion.

Two additional cells were implemented as baselines. These two cells were flown from the front seat and are:

Cell ϕ. Baseline 60-feet hover out of the window.

Cell 2a. Baseline "Bob-up" and "Remask" out of the window.

Some "bob-up" trials were attempted without symbology but were quickly terminated due to pilot inability to stabilize the helicopter.

Approximately 100 runs, 50 for each LDNS, were flown by subject pilots CW3 Chuck Tidey and Mr. Chuck Nay (NVL). Each run was approximately 2-5 minutes long. Unfortunately not all runs were recorded due to a malfunction of the Data Acquisition Unit (DAU). The usable runs for data reduction were 30 runs, 13 using the Singer and 17 using the Ryan Doppler.

8. FLIGHT TEST EFFORT

The simulated AAH PNVS and Doppler Hover System (DHS) concept was successfully flown by the subject pilots at the NADC Airfield. Prior to lift-off, the LDNS velocity bias (described previously) would be adjusted. With the helicopter rotor turning, a reflector was placed underneath the LDNS antenna. The Doppler system would go into the track mode and the displayed velocity vector would indicate voltage magnitude which was verified by a voltmeter measurement. By adjusting the bias potentiometer implemented in the symbol generator, the offset was cancelled. This procedure was performed for every flight and rechecked at the completion of the flight.

Before each subject pilot attempted to hover, the front seat pilot had to stabilize the helicopter into a stable hover for approximately 1 minute. This technique was required to allow sufficient time for the attitude portion of the complemented derived velocity to "wash out." This problem was solved in the simulator by using filters with time-varying time constants while switching modes. However, there was insufficient time to implement this fix in the aircraft analog symbol generator. Once the velocity vector reached the helicopter reference symbol (Figure 1) indicating the filter was properly initialized, the subject pilot assumed control of the helicopter and attempted to hover in place. From this stable hover at 60 feet altitude the subject pilot performed the specific cells described earlier.

9. DATA REDUCTION

To generate the X-Y position information from the video recording of the downlook image, an electronic light pen system was used. The light pen system generates a voltage proportional to the movement of the light pen on the surface of the TV image. The operator initiated the digitizing of the video information by holding the light pen on the surface of the TV monitor over some prominent reference in the TV image. He then allowed the video recorder to replay the recorded imagery of the particular run. As the ground image information changed, the observer would manually move the light pen to follow the movement of the initial selected reference point. Every 0.1 second the X and Y voltages representing light pen position were automatically recorded in digital format. This new digitized tape with samples of data every 0.1 second was synchronized with the DAU flight data tape for the actual ground position error computation. The ground position error computation, which accounted for helicopter attitude, heading and altitude, was calibrated using a video recording of a measured grid on the ground. To determine the accuracy of the video to digital conversion one run was reproduced several times. The cumulative frequency of the mean of the several trials is shown in Figure 3 with the minimum and maximum deviations about this mean. This small error (less than 5 feet) induced by the light pen conversion was considered acceptable.

The data reduction program, in addition to computing ground position error, computes the mean, standard deviation, variance, maximum, minimum, range and initial and final values of a number of variables. A sample copy of a computer printout is shown in Figure 4. In addition to the above computations, histograms and time histories of the doppler velocities, V_H and V_D, the altitude, and positional errors, are also computed, as shown in Figures 5 and 6.

10. FLIGHT TEST RESULTS

The results of the DHS flight test effort are shown in Figures 7 through 24. To best explain the various figures, each cell flown will be analyzed and a comparison will be made.

a. Constant Attitude Trials. Cell ϕ, Cell 1a, Cell 1 (Figure 7) shows the cumulative frequency of the hover radius performance about the mean position as flown by the front seat subjects (Cell ϕ) and the third seat subject pilots using Cell 1a (downlook TV) and Cell 1 (forward-look TV). This figure indicates that for a constant altitude hover, the front seat pilot, with all the cues that are available to him as he views the world outside the cockpit, performs a better hover. There is a slight degradation in positional hover performance using the Cell 1a configuration and a further degradation using the Cell 1 configuration.

Figure 8 shows the positional standard deviations in the longitudinal, lateral, and vertical (altitude) axis. One significant observation is that the longitudinal position standard deviation of Cell ϕ is much greater than the lateral position standard deviation of the same Cell. The only explanation for this is that the front seat pilot must look over the instrument panel for some ground reference to control the fore-aft aircraft movement. This reference is some distance away from the helicopter and it appears to move not only when the helicopter translates but also with altitude and attitude changes. This coupling in the longitudinal axis of altitude, attitude, and fore-aft translation adversely affects the pilot causing larger position errors. The coupling is not as pronounced in the lateral axis and a probable explanation for the smaller position errors.

Altitude control appears to be somewhat difficult for Cell 1a and Cell 1. Whereas the front seat subject altitude deviations are less than 2.5 feet, the other two cells are greater than 7.5 feet. It is the experimenter's belief that the front seat pilot neglected to disengage the automatic altitude hold and thus the reason for the small deviations for Cell ϕ.

The hover radius mean, standard deviation and RMS of the constant altitude cells are shown in Figure 9. The hover radius about the mean is minimum for the front seat case. There is very little difference in the standard deviation for Cell 1a and Cell 1, as shown in Figure 9.

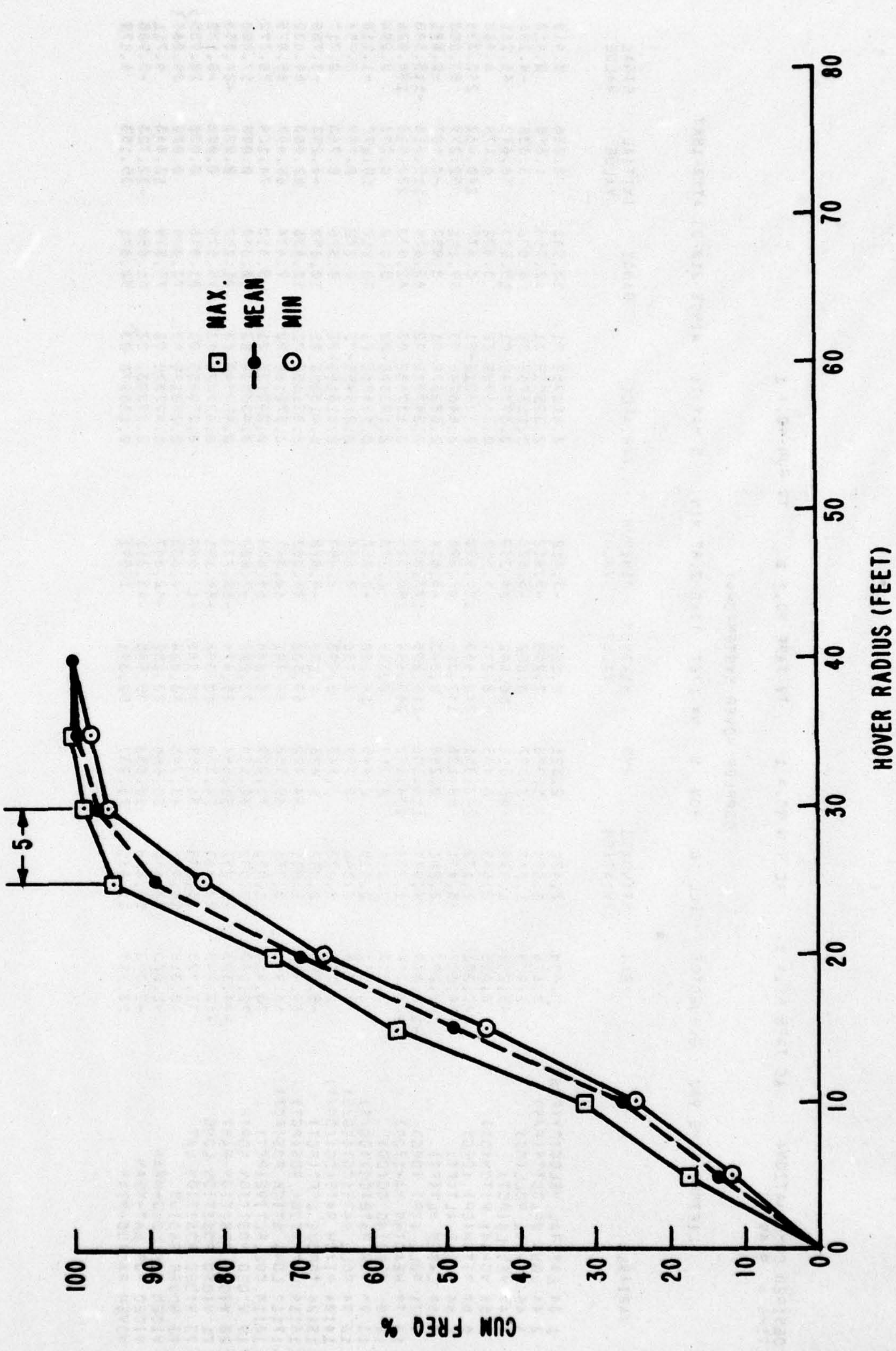


Figure 3. Video to digital data conversion expected error from light pen tracking

DESIRED COMBINATION: AC TAPE NO.= 1 AC RUN NO.= 1 TV TAPE NO.= 1 TV RUN NO.= 1
TIME = 9:49: 9

DOPPLER HOVER SYSTEM(DHS)

LIFTOFF TIME 930 SUBJECTCT CELL 10 RUN 1 N= 1707 TIME 2.87 MIN 5 MAY 76 WINDS 210 DG AT10-15KT

VARIABLE	MEAN	STANDARD DEVIATION	RMS	MAXIMUM VALUE	MINIMUM VALUE	VARIANCE	RANGE	INITIAL VALUE	FINAL VALUE
1 34 LATERAL VELOCITY(F/S)	2.498	2.471	2.521	8.118	-5.412	0.61071E 01	13.530	8.036	0.410
2 44 LONG VELOCITY(F/S)	2.675	1.874	1.993	7.298	-5.412	0.32551E 01	12.710	1.640	0.410
3 46 VG-341 ROLL(DG)	-2.978	1.067	3.197	0.000	-6.678	0.11376E 01	6.678	-3.036	-4.286
4 47 PEDALS(PCT)	45.248	1.995	45.312	56.642	38.059	0.39794E 01	18.583	56.642	46.161
5 56 VG-341 PITCH(DG)	6.418	0.589	6.445	8.379	4.557	0.34670E 00	3.822	6.174	6.468
6 67 PITCH(CP) (DEG)	240.351	0.102	240.351	240.666	239.990	0.10321E-01	0.677	240.462	240.336
7 66 RADAR ALT(FT)	84.377	25.431	88.126	137.017	47.896	0.64674E 03	89.121	52.279	53.253
8 69 LASER ALT(FT)	-0.057	0.261	0.268	0.343	-8.614	0.68267E-01	8.957	-0.187	-0.081
9 71 ROLL (CP) (DEG)	-116.349	4.977	116.156	-115.205	-177.830	0.24771E 02	62.625	-115.618	-115.840
10 72 HEADING MA-1(DG)	243.794	11.734	244.132	245.654	182.725	0.13768E 03	62.930	200.918	198.896
11 81 HEADING CG(DG)	0.317	0.014	0.317	0.355	0.273	0.18350E-03	0.082	0.273	0.294
12 93 YAW RATE(CG)(DG/S)	-0.183	2.438	2.445	14.200	-5.817	0.59456E 01	20.017	10.270	-1.110
13 94 ROLL RATE(CG)(DG/S)	0.798	0.046	0.799	0.936	0.664	0.21545E-02	0.272	0.709	0.754
14104 PITCH RATE(CG)(DG/S)	0.737	0.078	0.742	0.993	0.487	0.61518E-02	0.506	0.763	0.717
15106 TORQUE LEFT(PCT)	-5.028	2.032	5.423	1.050	-9.800	0.41308E 01	10.850	-6.250	-3.700
16116 LAT STICK POS(PCT)	64.446	1.821	64.492	69.500	59.063	0.33165E 01	10.438	62.063	64.438
17117 LONG STICK POS(PCT)	65.946	0.756	65.950	69.781	62.347	0.57216E 00	7.434	65.497	65.875
18118 COLLECTIVE(PCT)	73.913	1.556	73.929	78.048	69.638	0.24212E 01	8.410	74.104	76.772
19 VIDEO POSITION NORTH	22.082	20.580	30.194	73.000	-7.000	0.42353E 03	80.000	0.000	17.000
20 VIDEO POSITION EAST	-24.353	20.237	31.664	25.474	-65.733	0.40954E 03	91.207	0.000	-24.553
21 VIDEO POSITION LONG	-12.843	20.666	24.332	10.388	-65.191	0.42707E 03	75.579	0.000	-8.132
22 VIDEO POSITION LAT	32.723	15.838	36.355	68.268	-13.588	0.25083E 03	81.856	0.000	20.735
23 HOVER RADIUS	40.318	16.976	43.746	73.004	0.000	0.28817E 03	73.004	0.000	29.844
VIDEO POS LONG-MEAN	-0.000	20.666	20.666	23.232	-52.347	0.42707E 03	75.579	12.843	4.711
VIDEO POS LAT-MEAN	-0.000	15.838	15.838	35.545	-46.311	0.25083E 03	81.856	-32.723	-3.980
HOVER RADIUS-MEAN	23.295	11.631	26.037	52.391	1.591	0.13527E 03	50.801	35.153	6.172

Figure 4. Statistical data presentation

DOPPLER HOVER SYSTEM(DHS)

LIFTOFF TIME 930 SUBJECTCT CELL 10 RUN 1 N= 1707 TIME 2.87 MIN 5 MAY 76 WINDS 210 DG AT10-15KT

CELL LIMITS	REL FREQ	CUM FREQ
< -8	0.00	0.00
-8- -6	0.00	0.00
-6- -4	2.34	2.34
-4- -2	13.88	16.23
-2- 0	27.01	43.23
0- 2	30.58	73.81
2- 4	16.87	90.69
4- 6	7.85	98.54
6- 8	1.11	99.65
8- 10	0.35	100.00
> 10	0.00	100.00

LAT VEL(DOP)

CELL LIMITS	REL FREQ	CUM FREQ
< -8	0.00	0.00
-8- -6	0.00	0.00
-6- -4	1.29	1.29
-4- -2	7.21	8.49
-2- 0	21.79	30.29
0- 2	51.26	81.55
2- 4	16.11	97.66
4- 6	2.05	99.71
6- 8	0.29	100.00
8- 10	0.00	100.00
> 10	0.00	100.00

LONG VEL(DOP)

CELL LIMITS	REL FREQ	CUM FREQ
< 0	0.00	0.00
0- 25	0.00	0.00
25- 50	0.12	0.12
50- 75	51.67	51.79
75-100	21.15	72.93
100-125	15.70	88.63
125-150	11.36	100.00
150-175	0.00	100.00
175-200	0.00	100.00
200-225	0.00	100.00
>225	0.00	100.00

RADAR ALTITUDE

CELL LIMITS	REL FREQ	CUM FREQ
<-40	16.87	16.87
-40--30	3.57	20.45
-30--20	2.40	22.85
-20--10	14.24	37.08
-10- 0	30.05	67.14
0- 10	32.26	99.41
10- 20	0.59	100.00
20- 30	0.00	100.00
30- 40	0.00	100.00
40- 50	0.00	100.00
> 50	0.00	100.00

VIDEO POS LONG

DOPPLER HOVER SYSTEM(DHS)

LIFTOFF TIME 930 SUBJECTCT CELL 10 RUN 1 N= 1707 TIME 2.87 MIN 5 MAY 76 WINDS 210 DG AT10-15KT

CELL LIMITS	REL FREQ	CUM FREQ
<-40	0.00	0.00
-40--30	0.00	0.00
-30--20	0.00	0.00
-20--10	2.11	2.11
-10- 0	2.17	4.28
0- 10	4.98	9.26
10- 20	11.42	20.68
20- 32	16.23	36.91
30- 40	28.18	65.08
40- 50	22.85	87.93
> 50	12.27	100.00

VIDEO POS LAT

CELL LIMITS	REL FREQ	CUM FREQ
< 0	0.00	0.00
0- 10	1.82	1.82
10- 20	15.41	17.22
20- 30	10.54	27.77
30- 40	16.52	44.29
40- 50	24.25	68.54
50- 60	16.87	85.41
60- 70	13.12	98.54
70- 80	1.46	100.00
80- 90	0.00	100.00
> 90	0.00	100.00

HOVER RD

CELL LIMITS	REL FREQ	CUM FREQ
< 0	0.00	0.00
0- 5	1.87	1.87
5- 10	8.67	10.54
10- 15	12.30	22.85
15- 20	28.76	51.61
20- 25	12.42	64.03
25- 30	9.14	73.17
30- 35	7.56	80.73
35- 40	7.91	88.63
40- 45	5.39	94.02
> 45	5.98	100.00

HOVER RD-MEAN

Figure 5. Histograms of selected variables

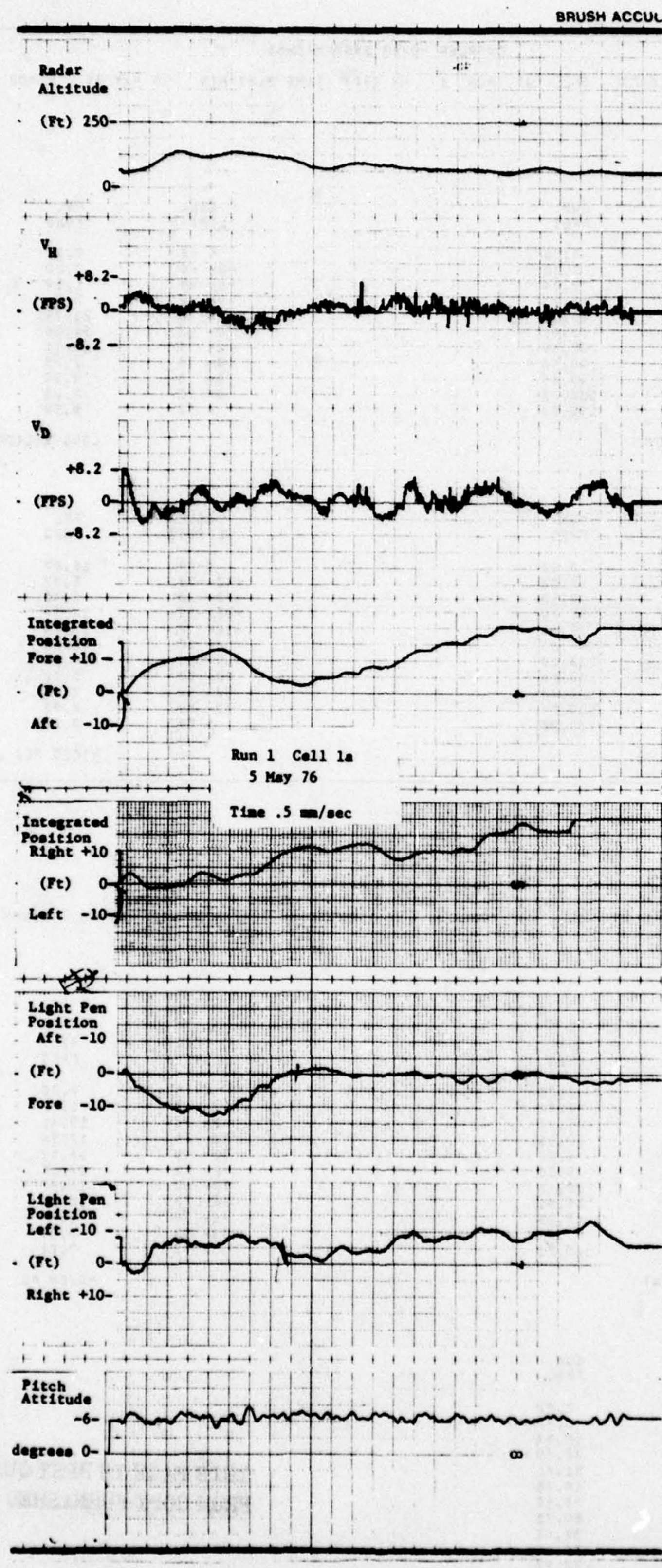


Figure 6. Time histories of selected variables

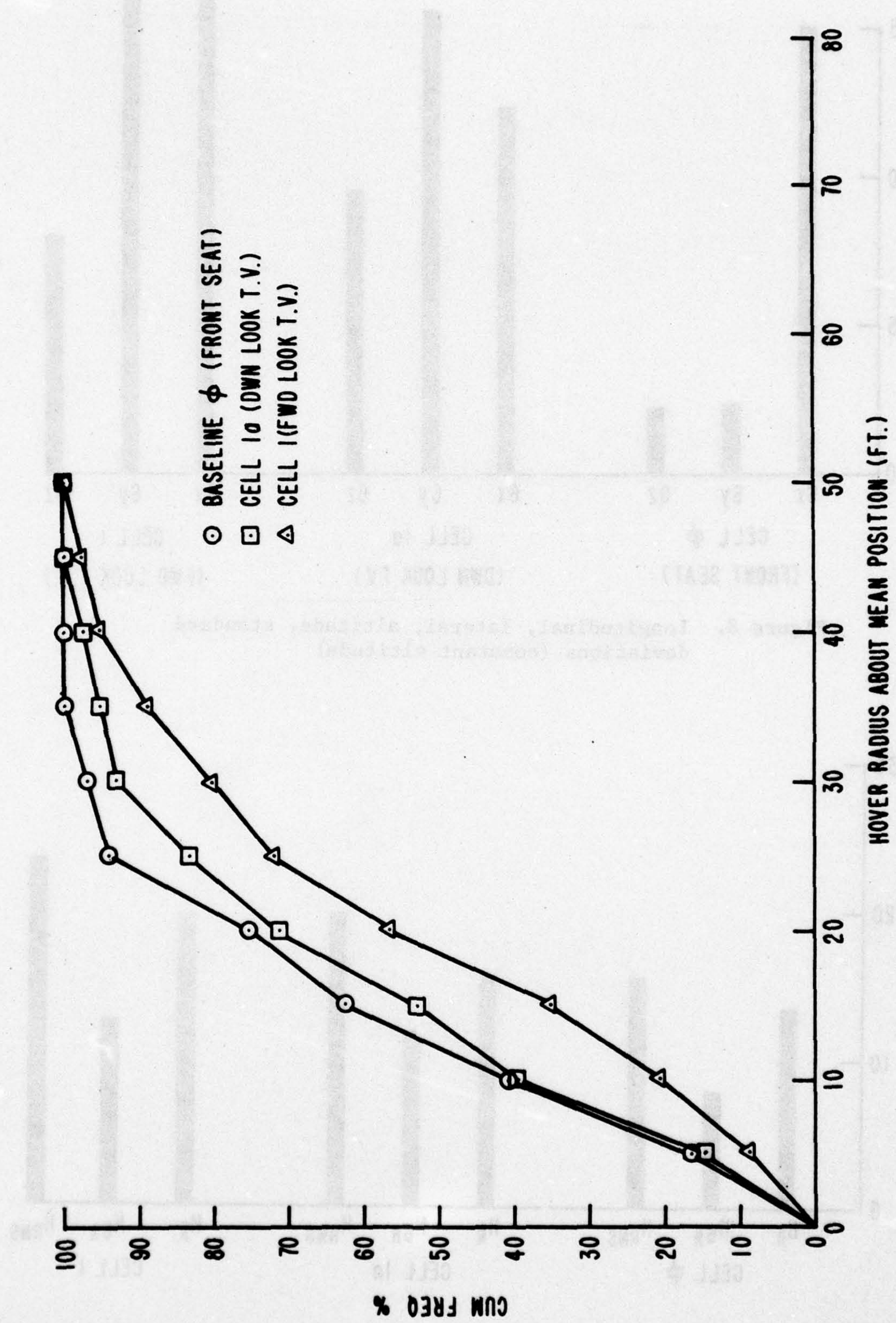


Figure 7. Hover performance at constant altitude

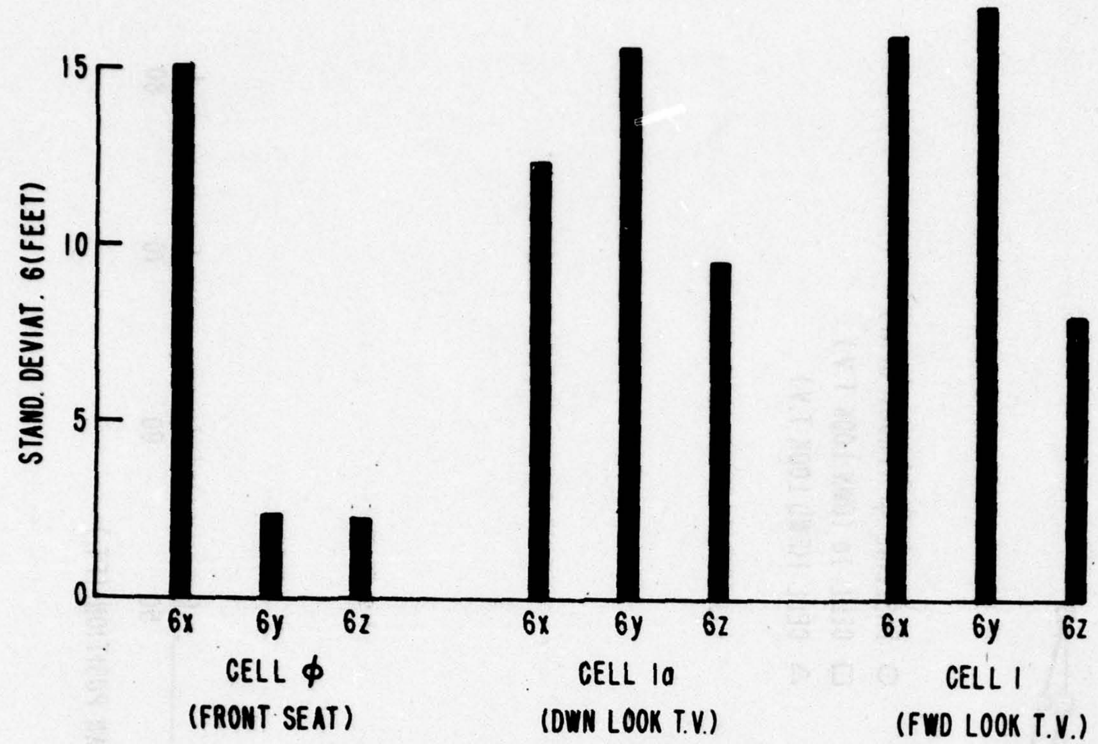


Figure 8. Longitudinal, lateral, altitude, standard deviations (constant altitude)

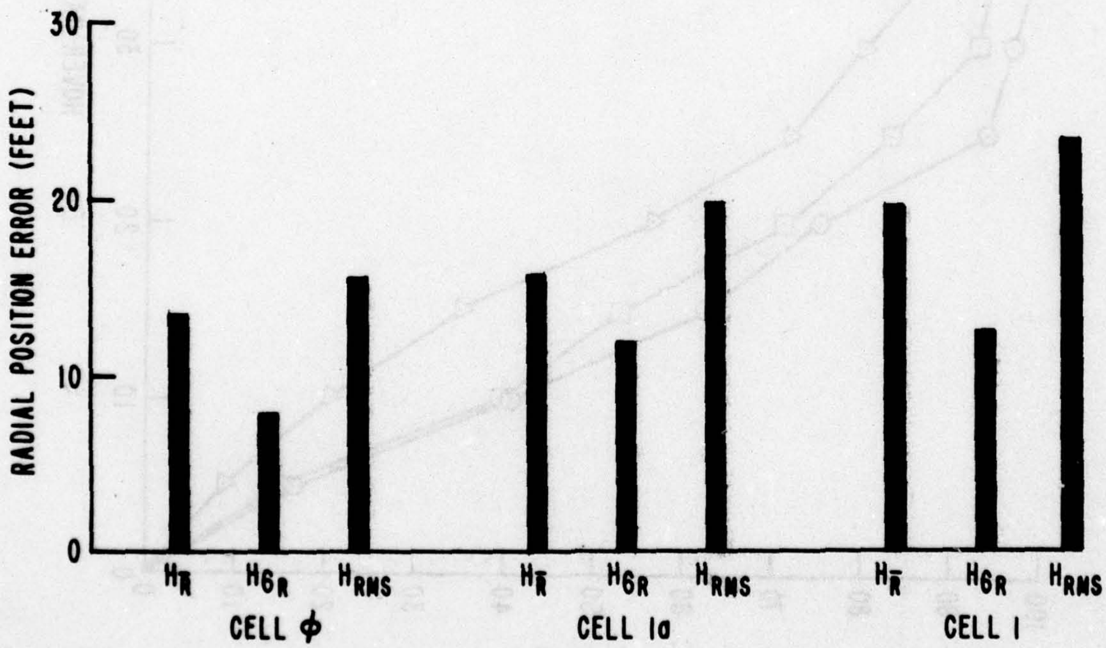


Figure 9. Hover radius performance about mean position (constant altitude)

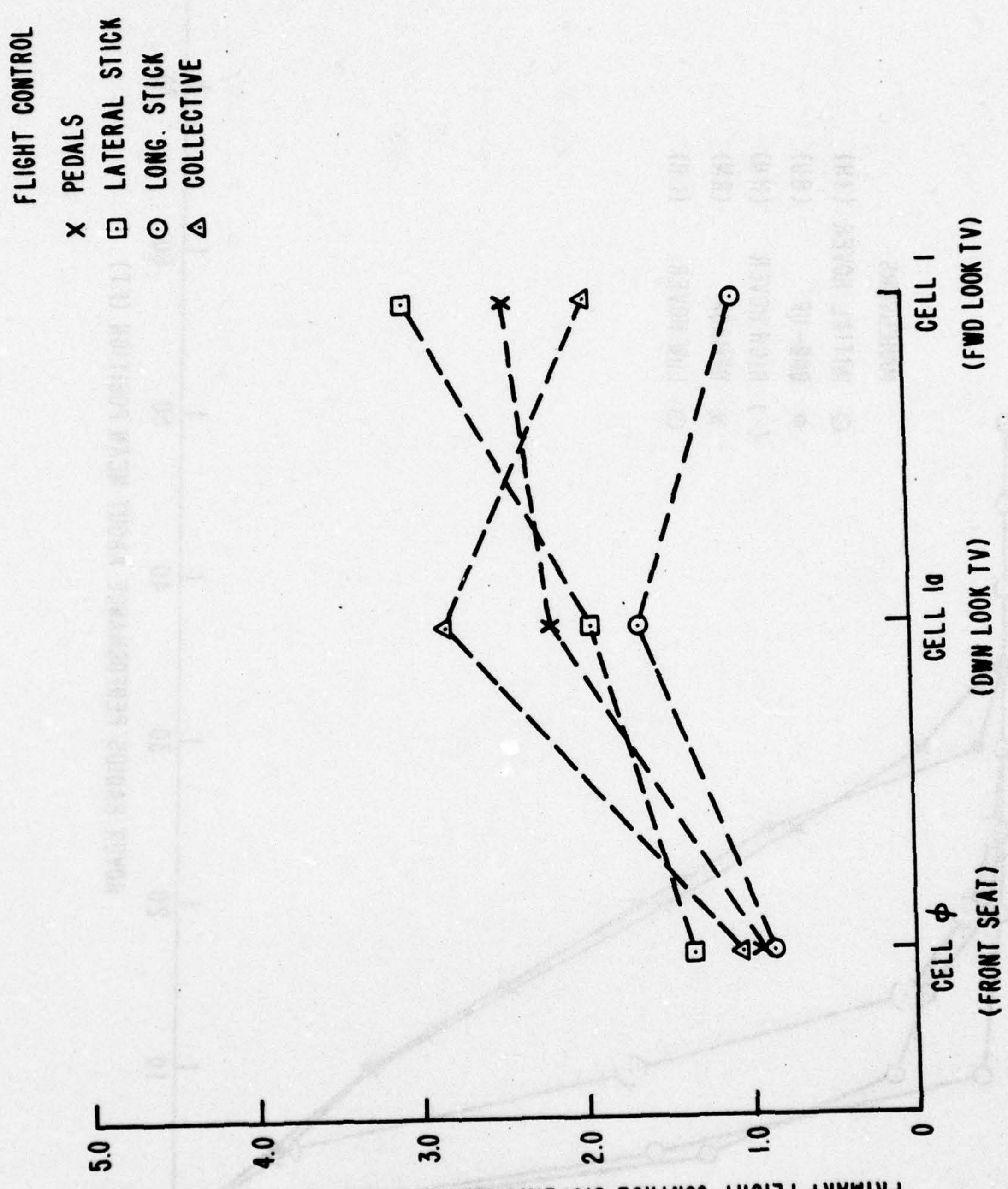


Figure 10. Flight control displacement (constant altitude)

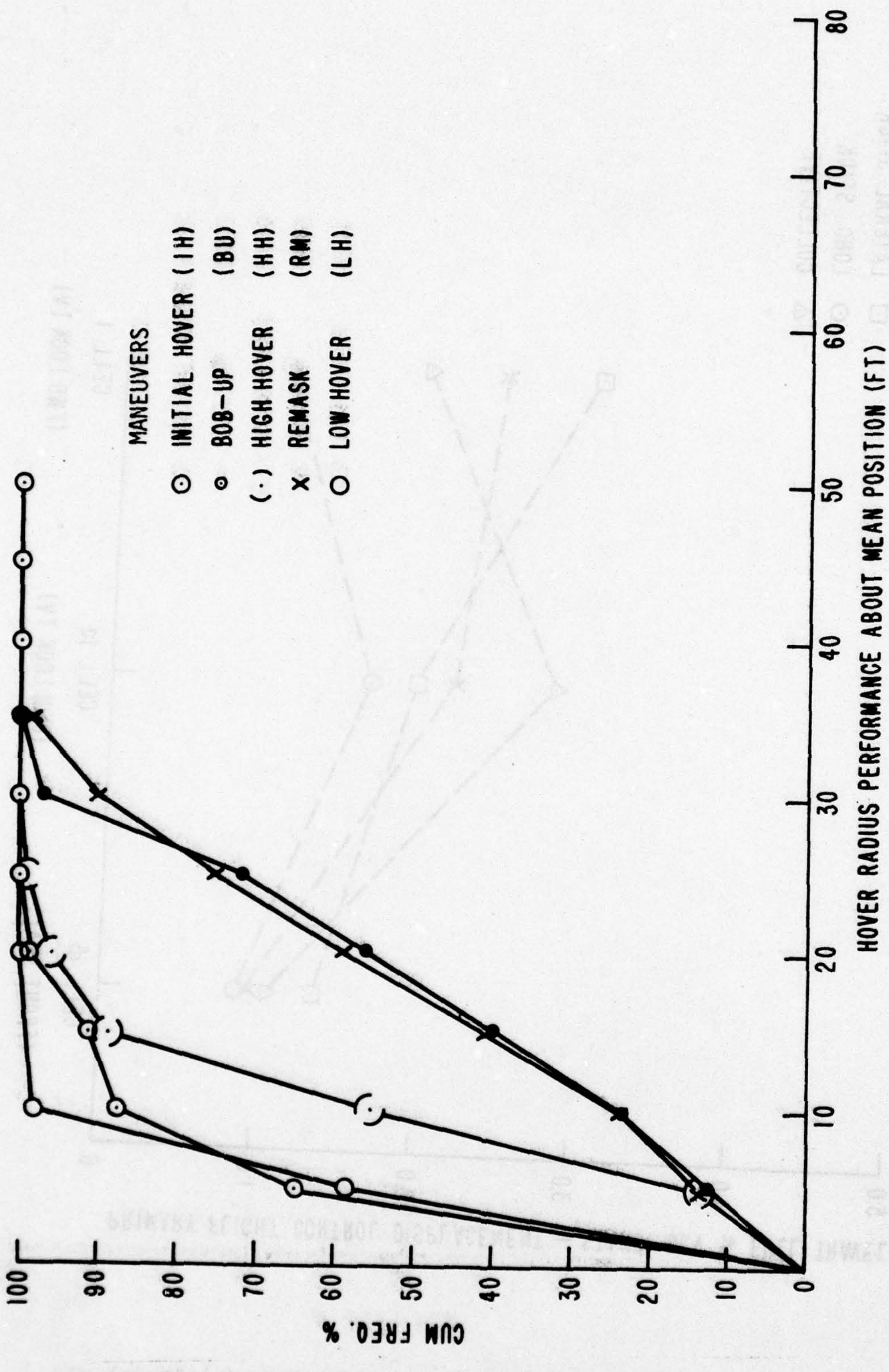


Figure 11. Cell 2a (front seat subject) hover radius about mean position (feet)

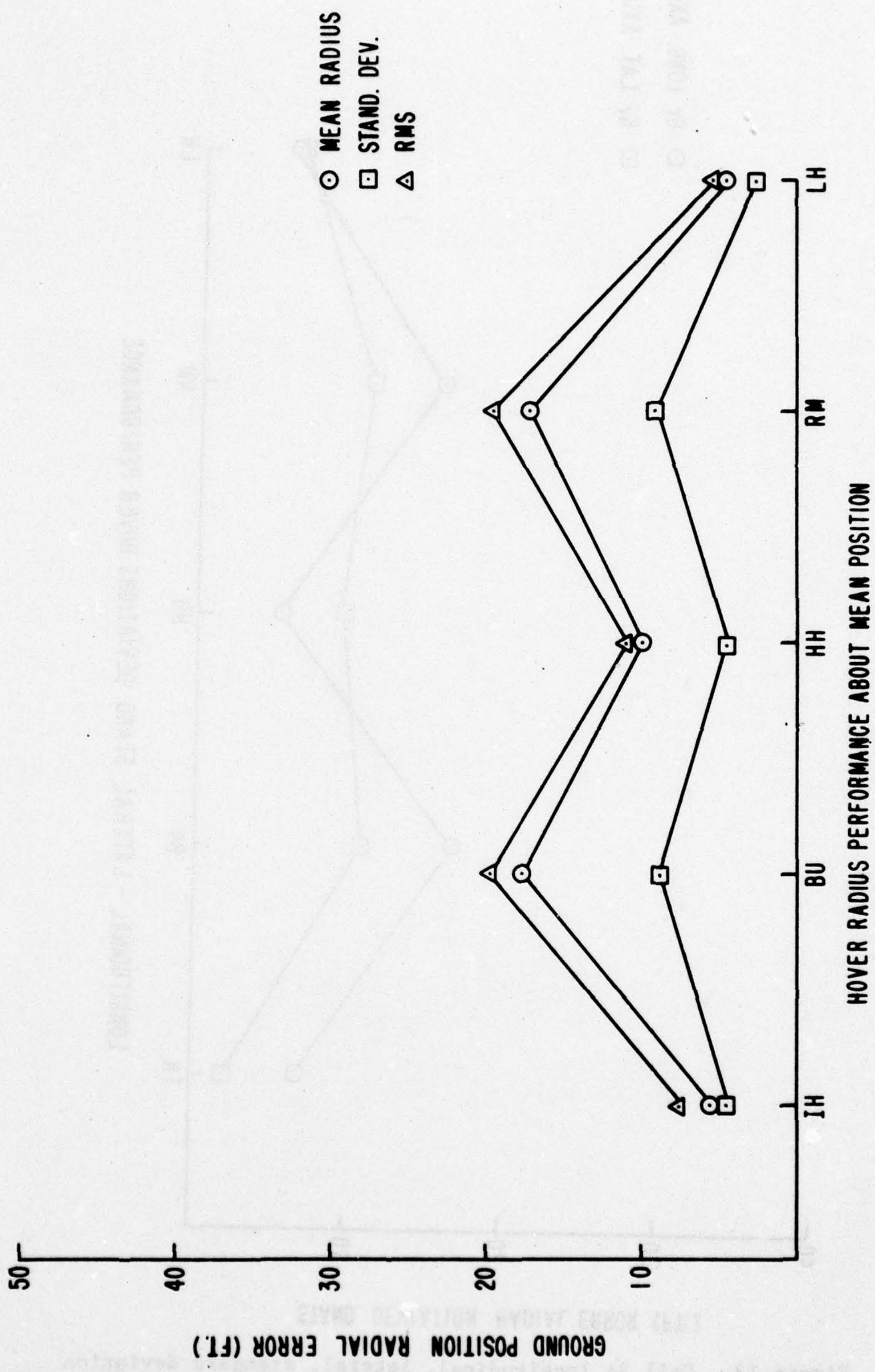


Figure 12. Cell 2a hover radius performance about mean position

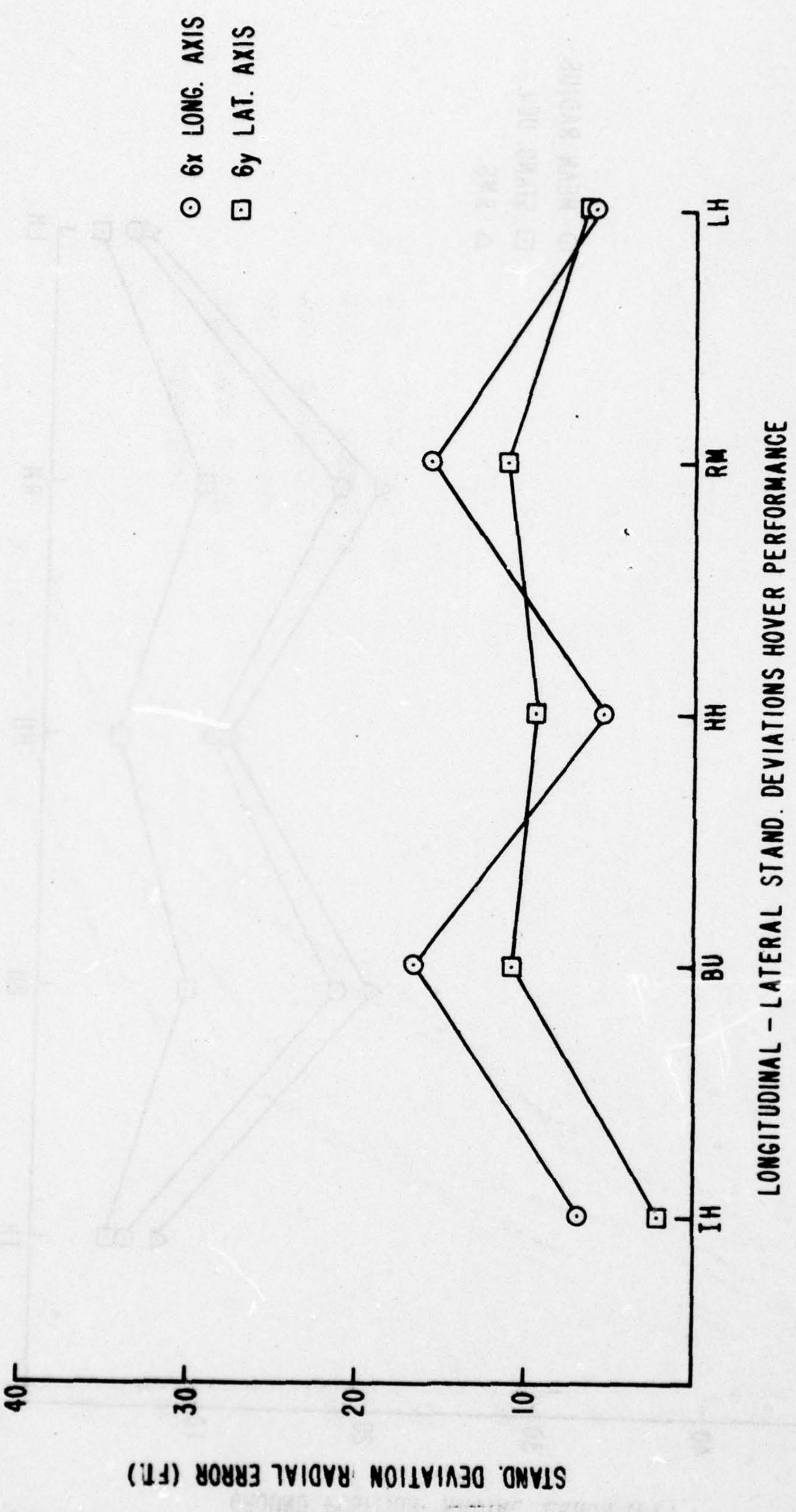


Figure 13. Cell 2a longitudinal, lateral, standard deviation

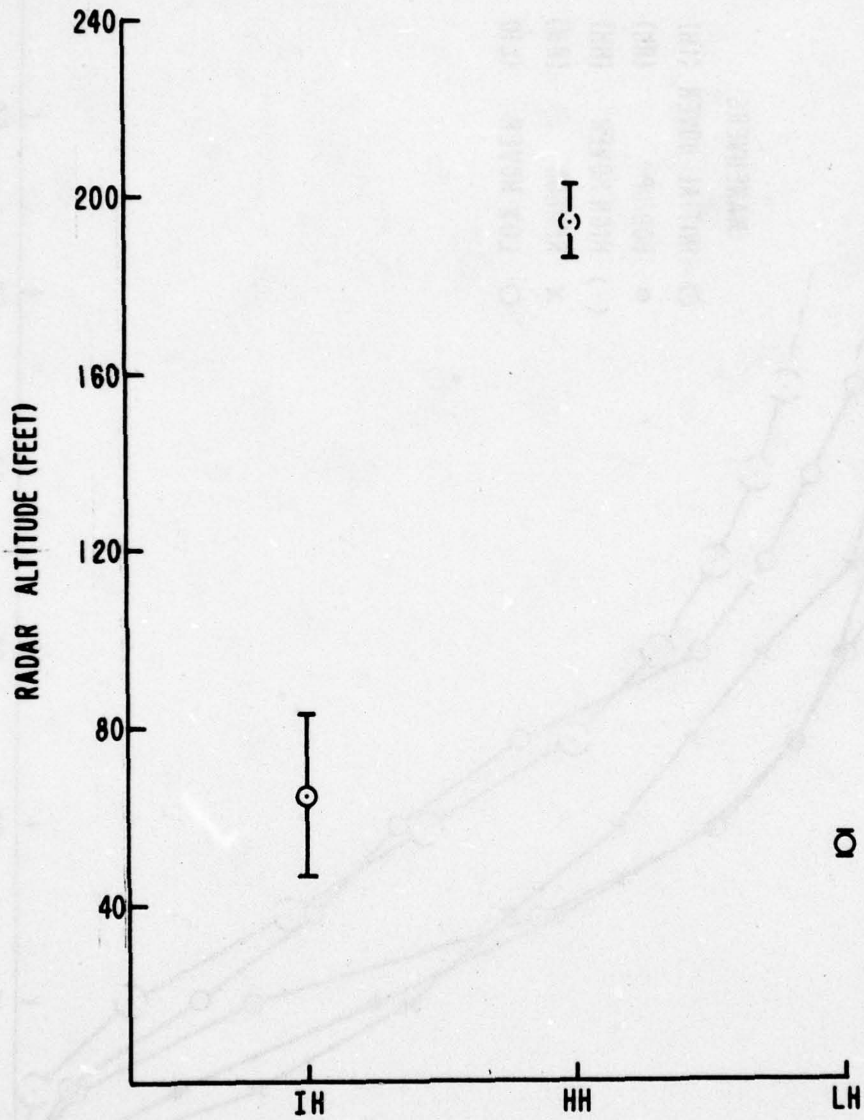


Figure 14. Cell 2a radar altitude (mean, standard deviation)

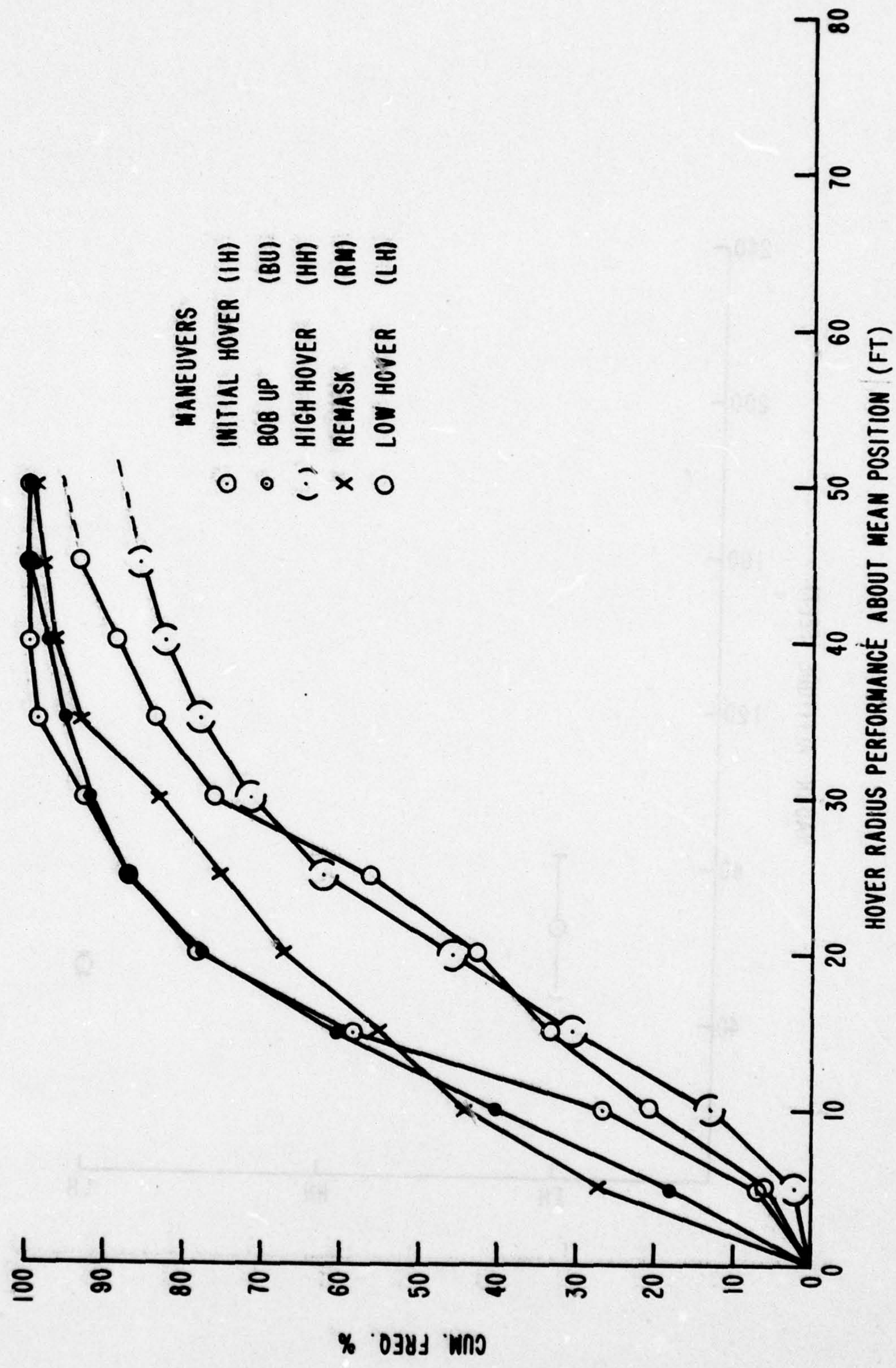


Figure 15. Cell 2 hover radius performance about mean position (feet)

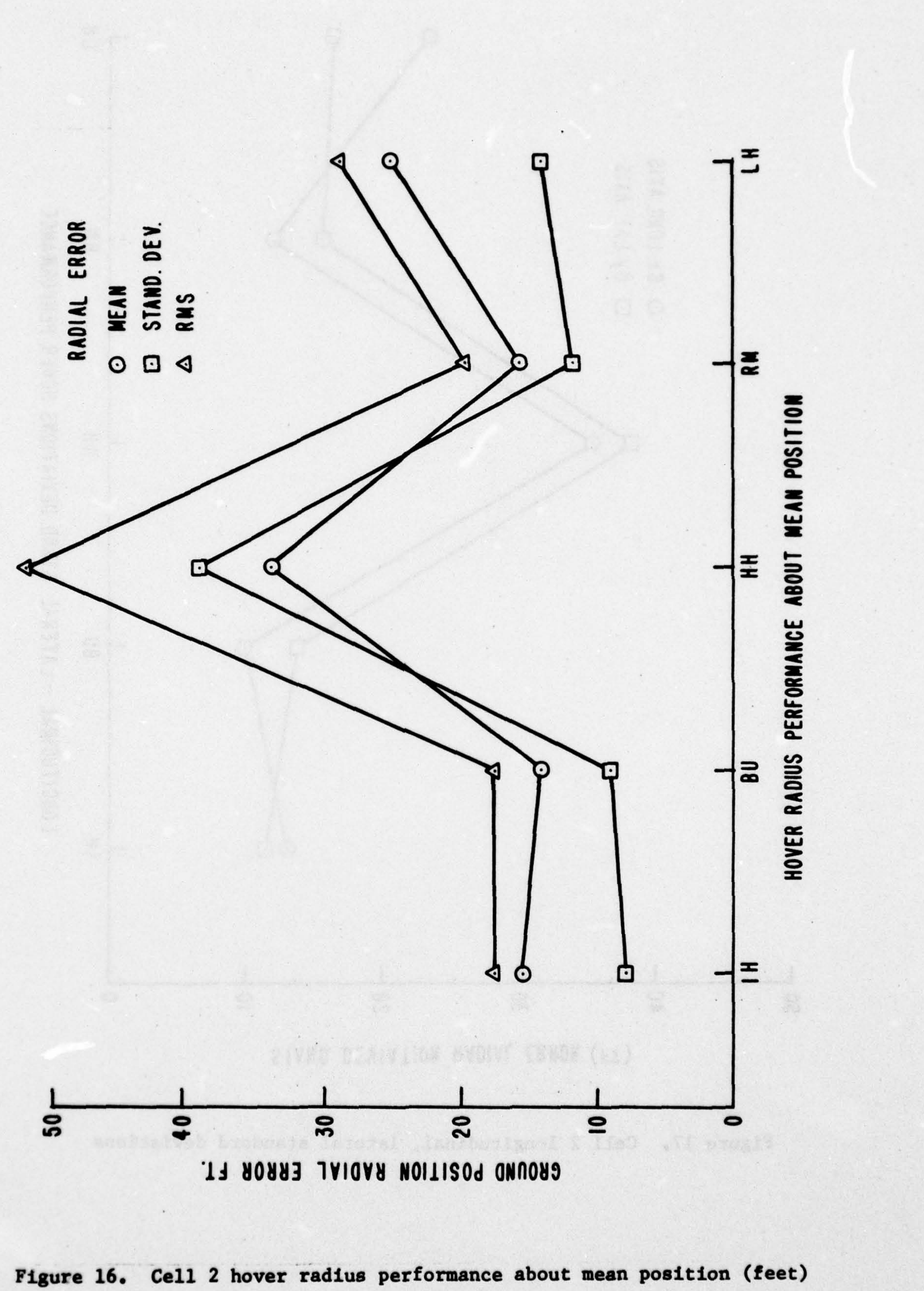


Figure 16. Cell 2 hover radius performance about mean position (feet)

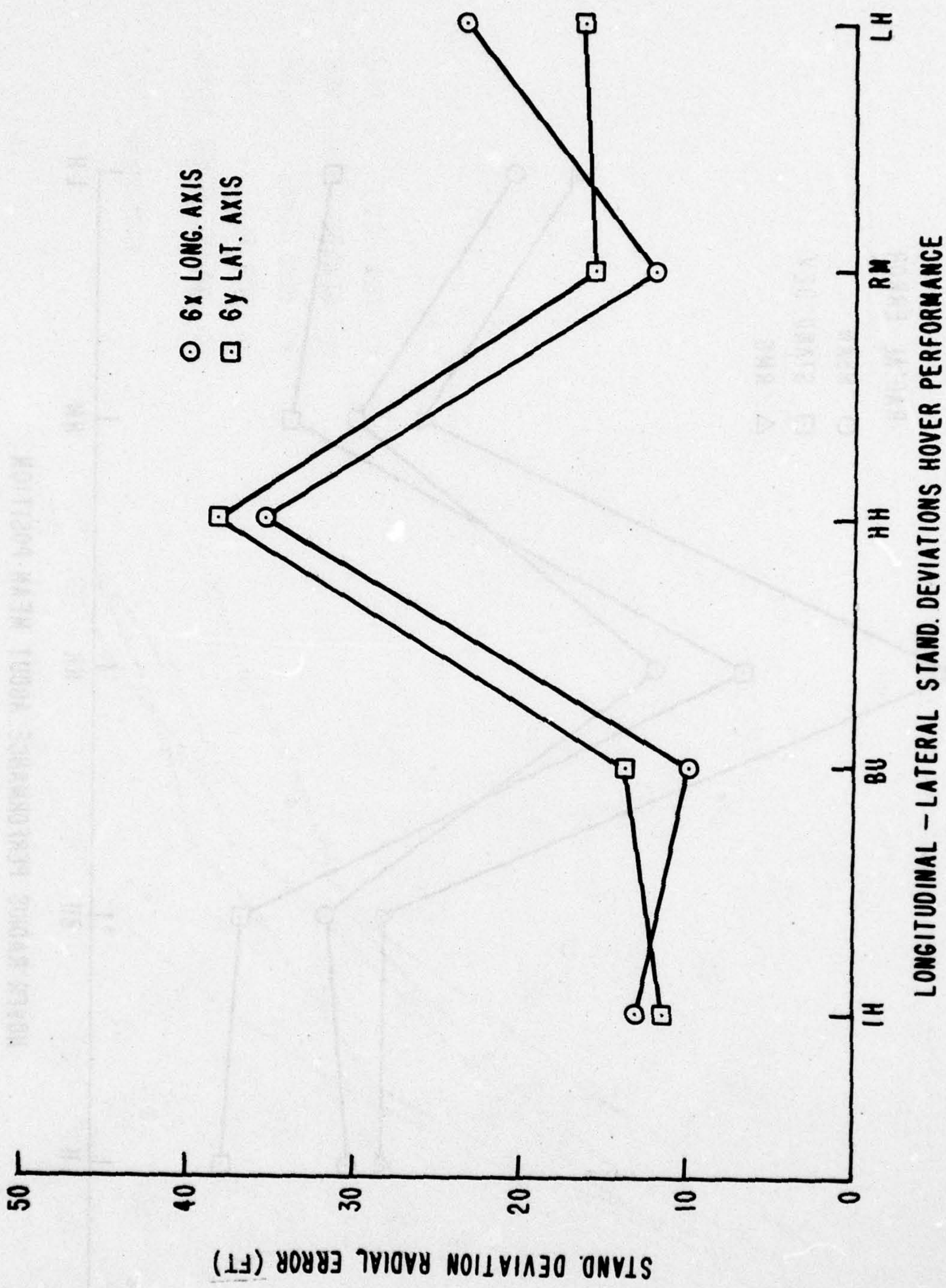


Figure 17. Cell 2 longitudinal, lateral standard deviations

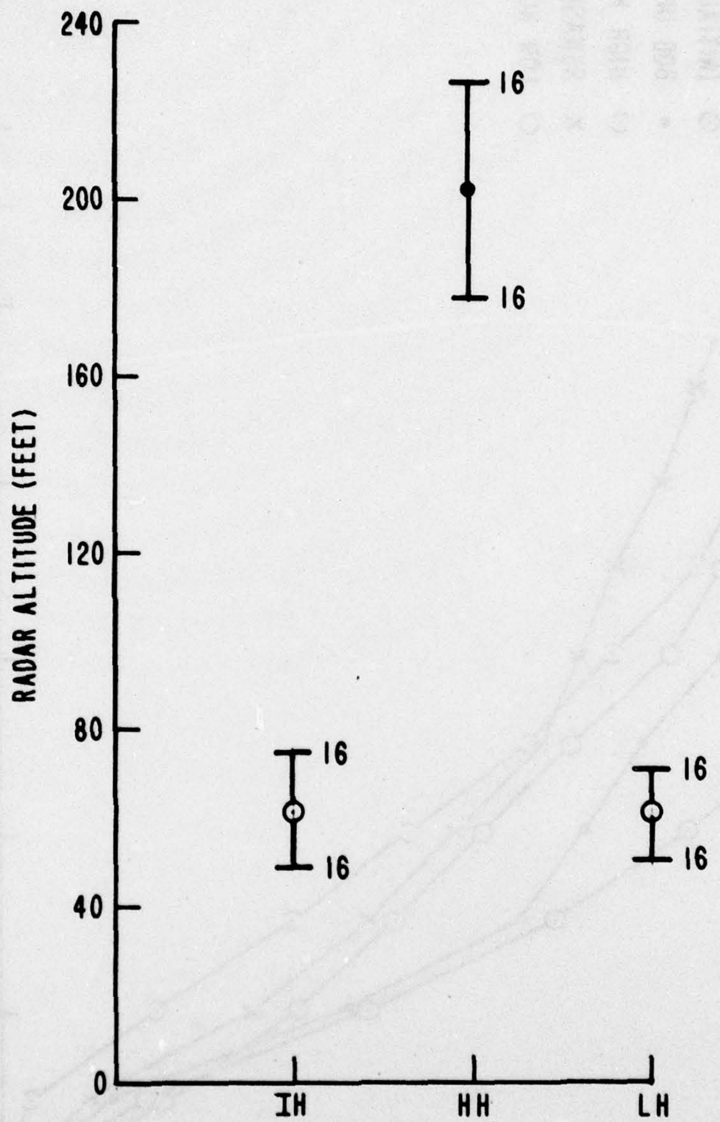


Figure 18. Cell 2 radar altitude mean standard deviation

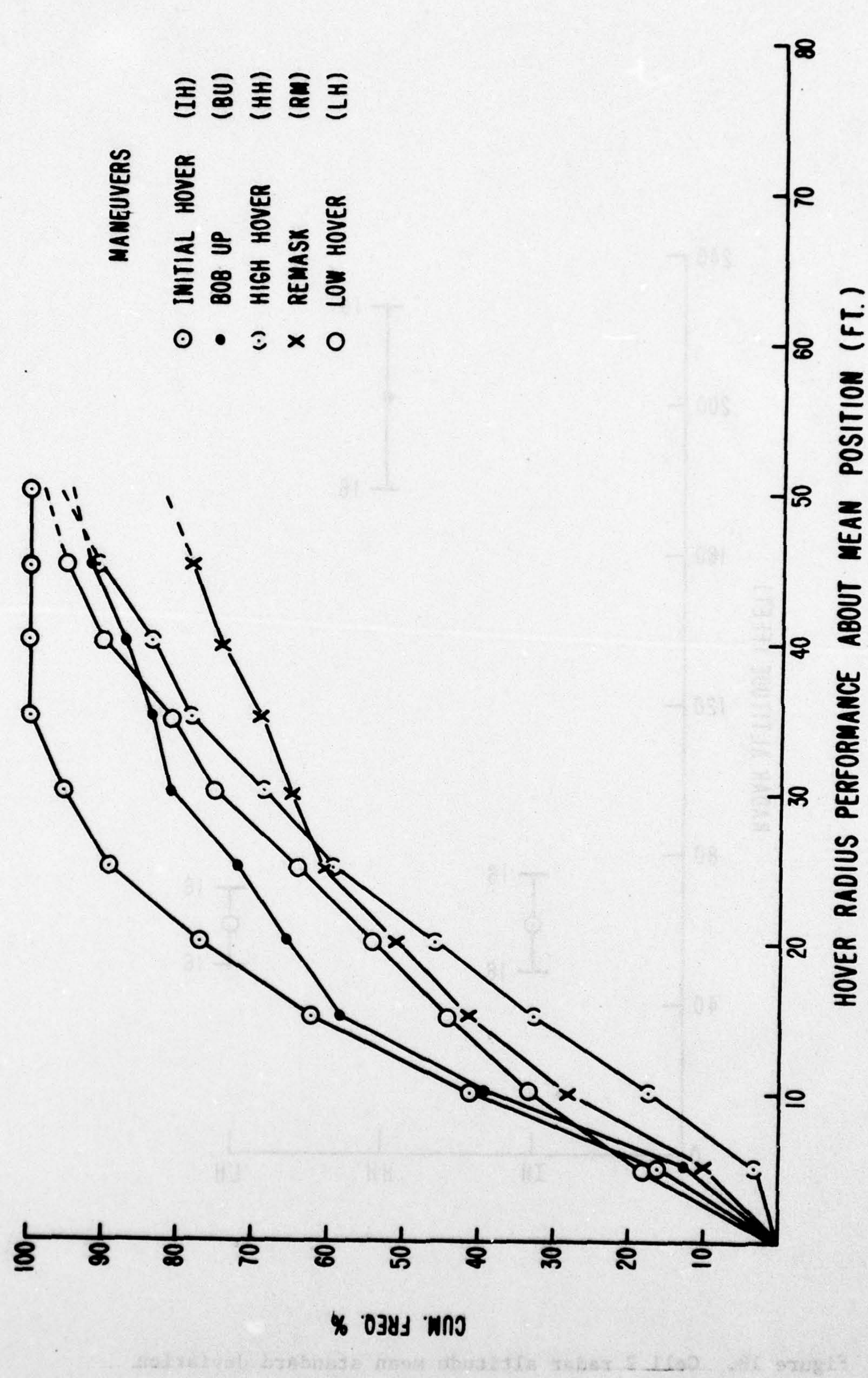


Figure 19. Cell 3 hover radius about mean position (feet)

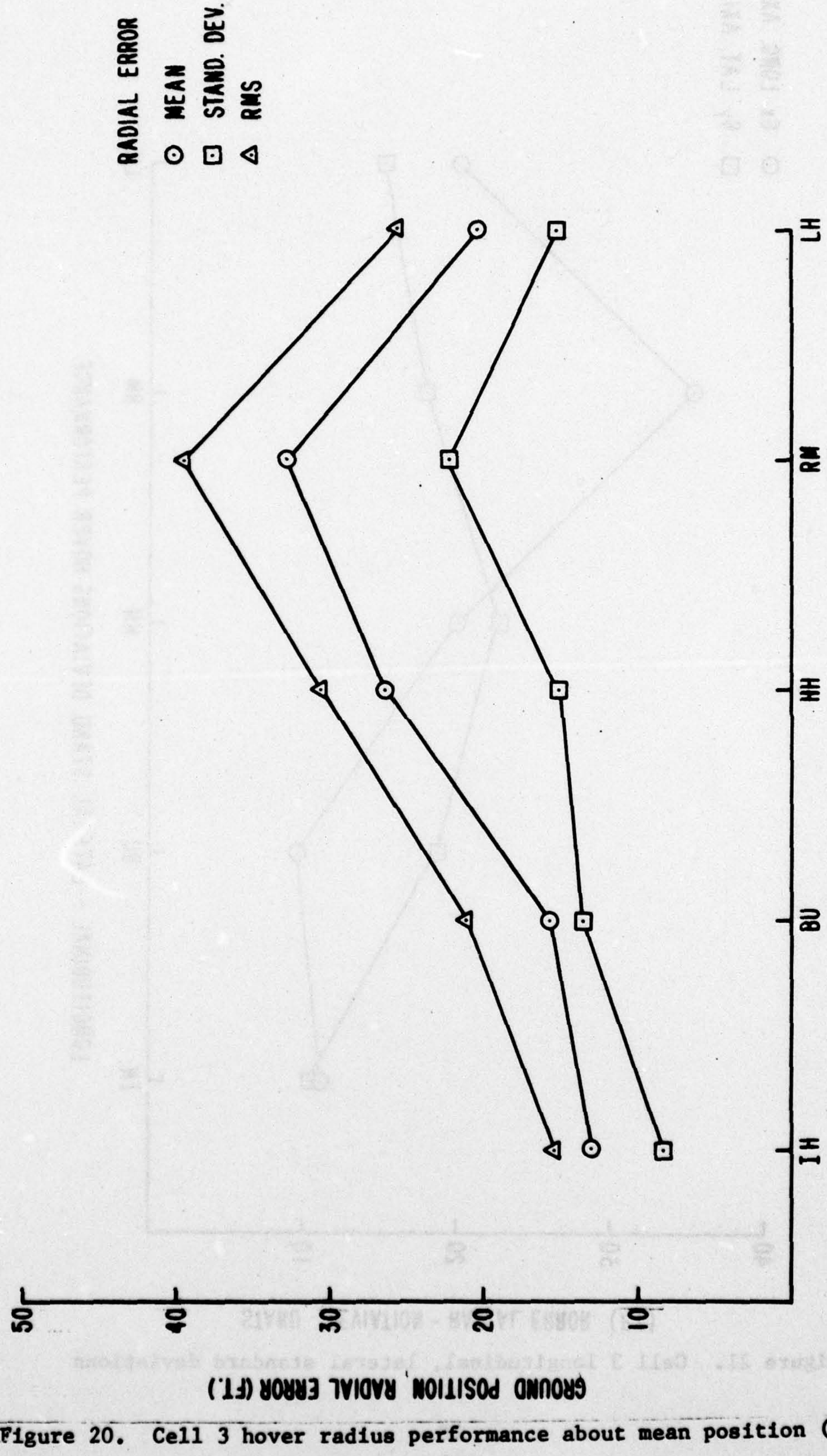


Figure 20. Cell 3 hover radius performance about mean position (feet)

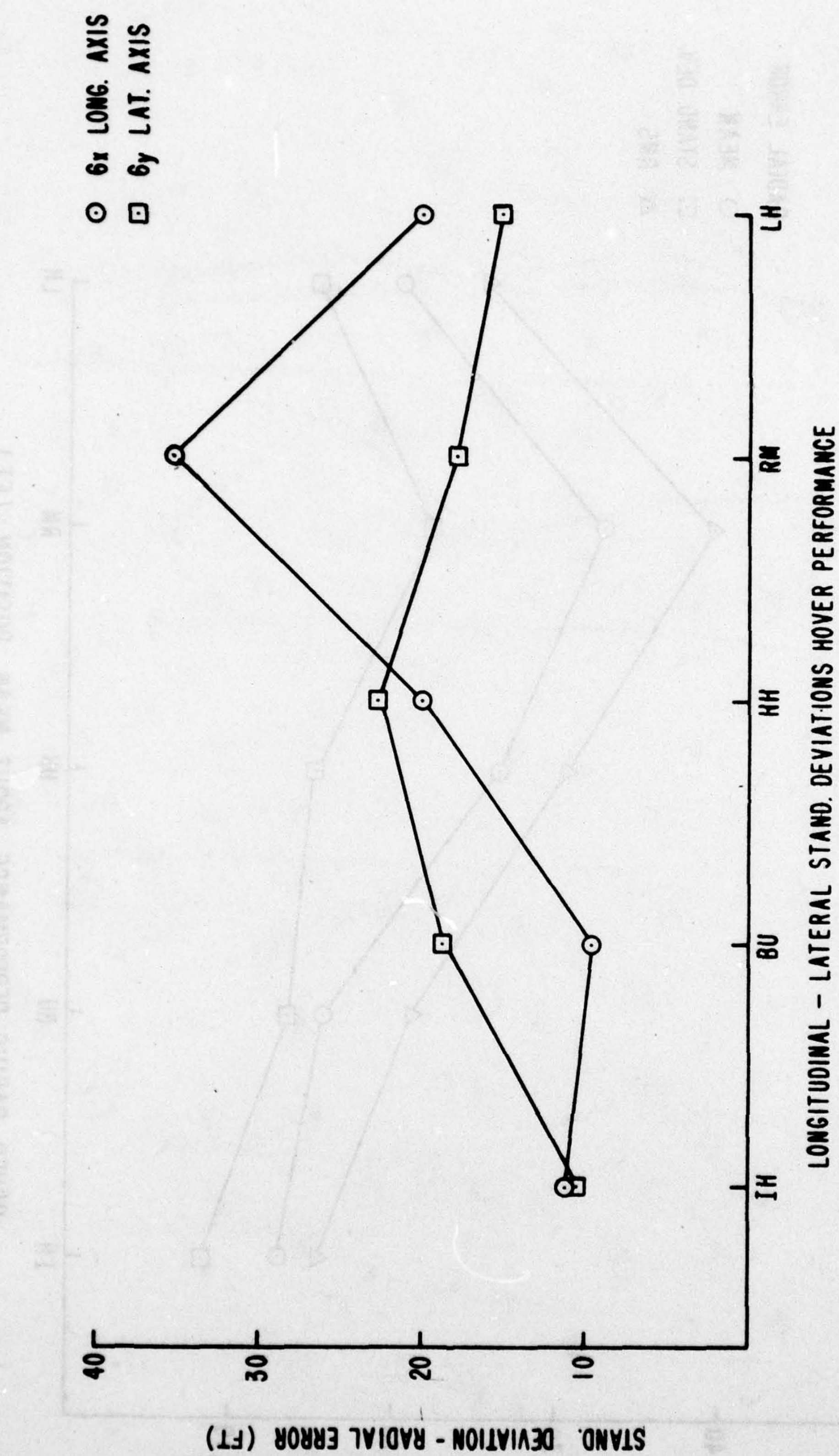


Figure 21. Cell 3 longitudinal, lateral standard deviations

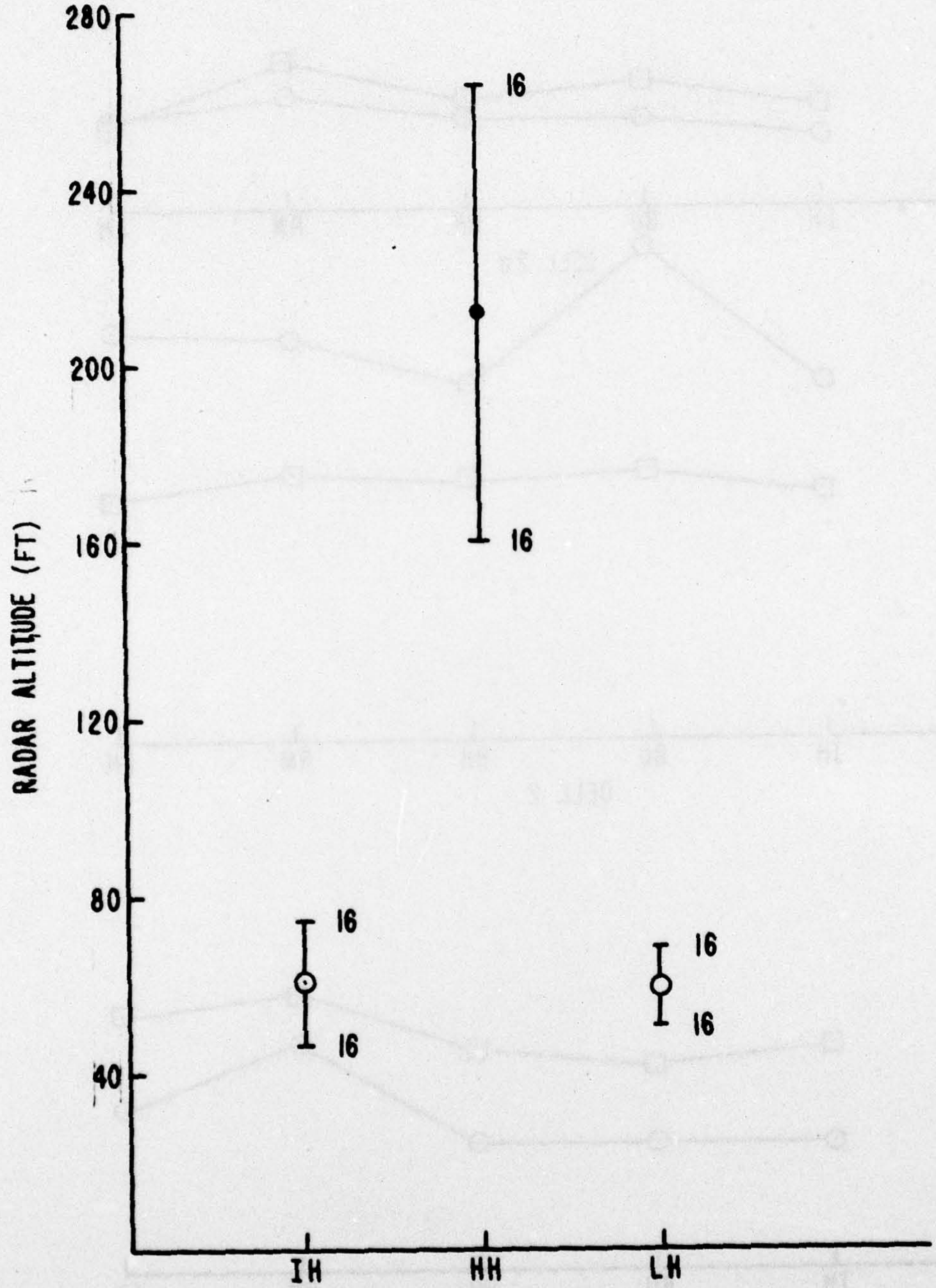


Figure 22. Cell 3 radar altitude mean, standard deviation

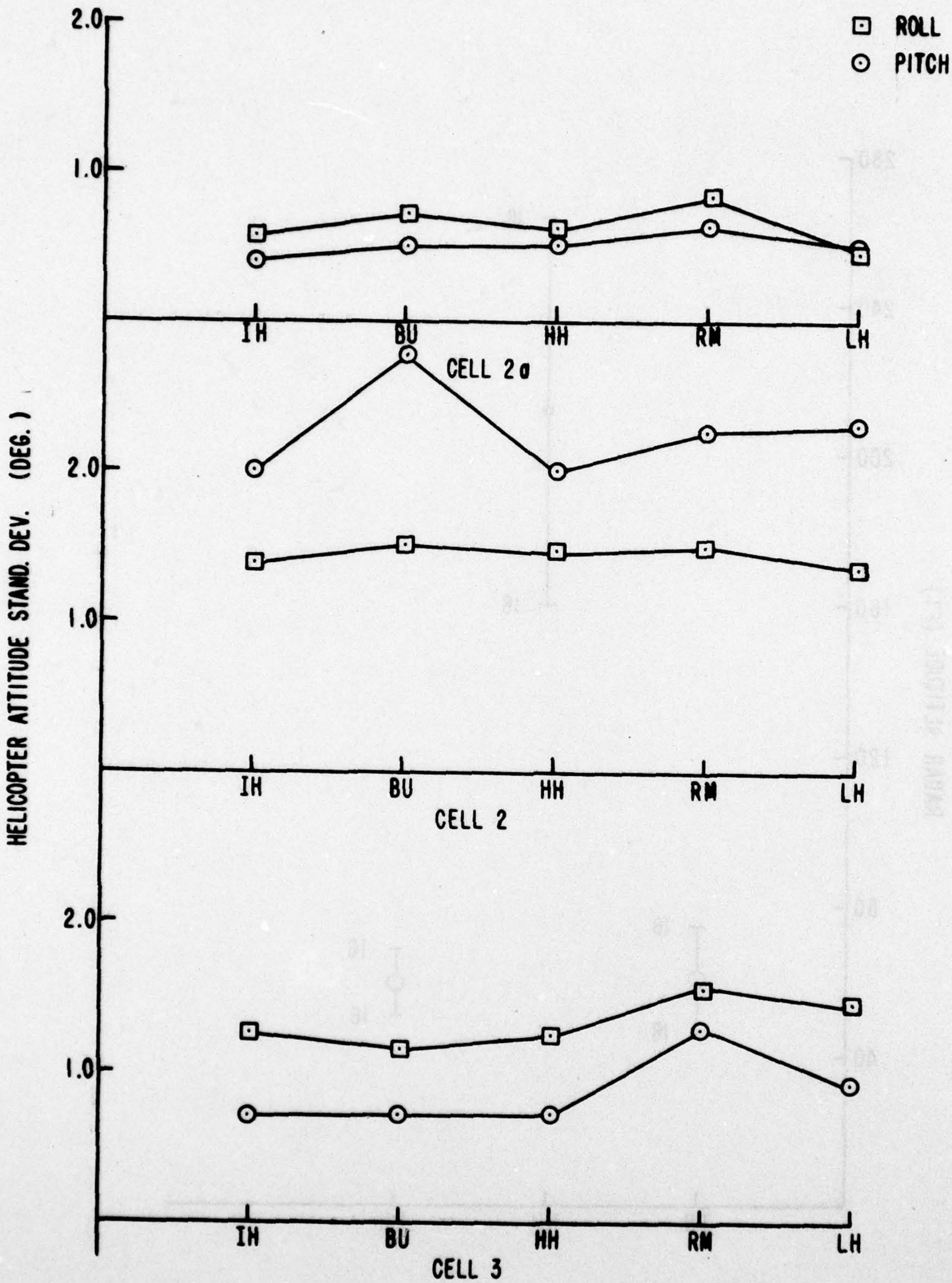


Figure 23. Helicopter attitude deviations

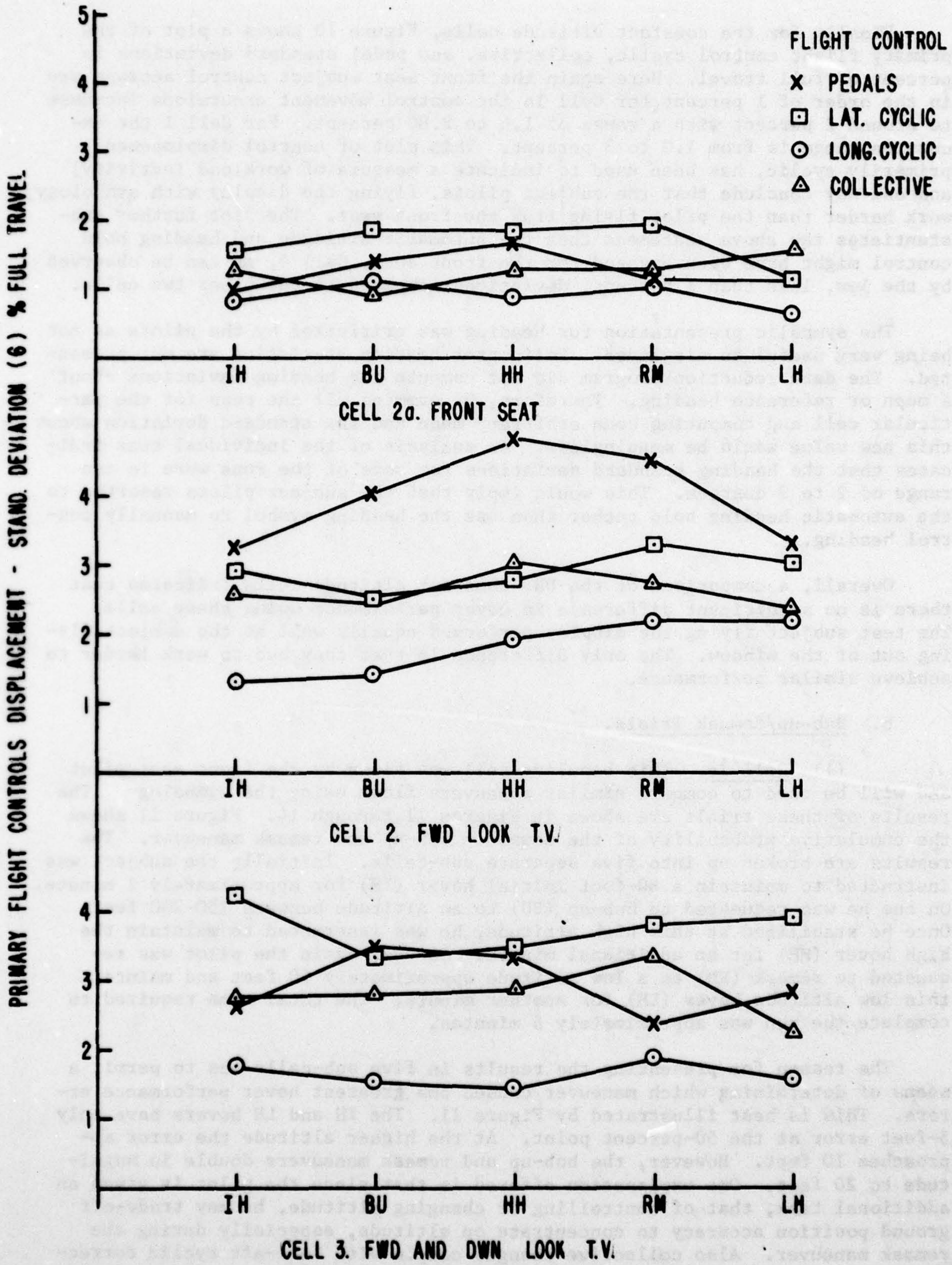


Figure 24. Helicopter flight control deviations

Finally for the constant altitude cells, Figure 10 shows a plot of the primary flight control cyclic, collective, and pedal standard deviations in percent of full travel. Here again the front seat subject control actions are in the order of 1 percent for Cell 1a the control movement excursions increase to around 2 percent with a range of 1.6 to 2.80 percent. For Cell 1 the excursion range is from 1.0 to 3 percent. This plot of control displacement, primarily cyclic, has been used to indicate a measure of workload (activity) and one may conclude that the subject pilots, flying the display with symbology, work harder than the pilot flying from the front seat. The plot further substantiates the above statement that the automatic altitude and heading hold control might have been engaged for the front seat, Cell ϕ, as can be observed by the low, less than 1 percent, deviations compared to the other two cells.

The symbolic presentation for heading was criticized by the pilots as not being very useful as displayed. Helicopter heading statistics are not presented. The data reduction program did not compute the heading deviations about a mean or reference heading. Therefore, by summing all the runs for the particular cell and computing some arbitrary mean and the standard deviation about this new value would be meaningless. An analysis of the individual runs indicates that the heading standard deviations for some of the runs were in the range of 2 to 3 degrees. This would imply that the subject pilots resorted to the automatic heading hold rather than use the heading symbol to manually control heading.

Overall, a comparison of the DHS constant altitude cells indicates that there is no significant difference in hover performance using these cells. The test subject flying the display performed equally well as the subject flying out of the window. The only difference is that they had to work harder to achieve similar performance.

b. Bob-up/Remask Trials.

(1) Cell 2a. This baseline cell was flown by the front seat pilot and will be used to compare similar maneuvers flown using the symbology. The results of these trials are shown in Figures 11 through 14. Figure 11 shows the cumulative probability of the complete bob-up and remask maneuver. The results are broken up into five separate sub-cells. Initially the subject was instructed to maintain a 60-foot initial hover (IH) for approximately 1 minute. On cue he was requested to bob-up (BU) to an altitude between 150-200 feet. Once he stabilized at this high altitude, he was instructed to maintain the high hover (HH) for an additional minute. On cue, again the pilot was requested to remask (RM) to a low altitude approximately 60 feet and maintain this low altitude hover (LH) for another minute. The total time required to complete the run was approximately 5 minutes.

The reason for presenting the results in five sub-cells was to permit a means of determining which maneuver caused the greatest hover performance errors. This is best illustrated by Figure 11. The IH and LH hovers have only 5-feet error at the 50-percent point. At the higher altitude the error approaches 10 feet. However, the bob-up and remask maneuvers double in magnitude to 20 feet. One explanation offered is that since the pilot is given an additional task, that of controlling or changing altitude, he may trade-off ground position accuracy to concentrate on altitude, especially during the remask maneuver. Also collective changes couple with fore-aft cyclic corrections further contributing to the position error increase.

Figure 12 shows the mean, standard deviations and RMS. The mean radius and RMS jump from approximately 5 and 7 feet at the IH to 17 and 20 feet during the bob-up and settle back to 10 feet at the higher altitude. They again jump to 17 and 20 feet during the remask and settle back to around 5 feet at the low hover. The maximum standard deviation for this cell is less than 9 feet which occurs during the remask and the minimum standard deviation is 2.5 feet occurring at the low hover.

A comparison of standard deviations of longitudinal and lateral position errors (Figure 13) indicate that the major contributing factor in the radial hover errors during bob-up and remask are errors in the longitudinal direction. Since, during the bob-up and remask, collective changes also effect the cyclic, which mechanically couples into the pitch axis, it is very possible that this coupling may affect the longitudinal position accuracy.

Another parameter of interest, as shown on Figure 14, is the mean and standard deviation of the altitude for the IH, HH, and LH. The excursions about the mean altitude at the IH is 16 feet. At the higher altitude this is reduced to 8 feet and at the LH it is reduced to 4 feet. From this plot one may give the explanation that for the initial hover the front seat pilot manually controlled altitude. At the higher altitude as well as the low hover, it appears that the automatic altitude hold might have been engaged. However, since there was no recording of the actual altitude hold state, one can only raise the possibility that the front seat pilot did, in fact, have the altitude hold engaged. This can also be inferred from the flight control characteristics, that the altitude hold will maintain altitude within 5 feet of the selected value.

Overall, as was expected, the front seat pilot performed a normal, not a precise hover. It should be noted that the subjects flying in the front seat were all Navy pilots. The bob-up and remask maneuvers are not typical Navy maneuvers. It is possible that with additional training, the performance for the bob-up and remask maneuvers may be improved.

(2) Cell 2. The results of Cell 2 are presented in Figures 15 through 18. For this cell, the subject pilot used the DHS with the 20°-depression fixed forward TV image and hover symbology to perform the bob-up and remask maneuvers. The cumulative frequency of the hover radius about the mean position (Figure 15) shows some interesting results.

Due to the nature of the configuration with only a 20° depression, the pilot ground position reference is some distance away from the helicopter. As he attempts to perform the Initial Hover (IH), using the displayed information, it is quite difficult to distinguish between altitude and fore-aft movement. Thus the position errors increase. In comparison to the results of Cell 2a at the 50 percent point, there is an increase of almost 10 feet for Cell 2. However, the bob-up and remask errors are reduced by at least 5 feet. It is rather difficult to explain the reduction in position errors when the pilot loses his selected initial ground reference during the bob-up and remask maneuvers. The technique devised for these maneuvers was to have the pilot null the velocity vector and the acceleration (attitude) excursions. By nulling these quantities there should not be much short term position variation. It may be deduced that the technique was effective since it reduced the position errors. Once the subject ascended to a higher altitude, he searched the TV image for a new hover reference point. During the remask maneuver, the above technique of nulling the velocity and acceleration vectors was again applied.

In comparison, the front seat pilot has to interpret ground velocity or acceleration visually. As the helicopter increases altitude, these cues tend to become less reliable, thus a potential for a less accurate hover. In the Cell 2 implementation, the pilot did have a very accurate velocity and acceleration cue. By minimizing their magnitudes, the position errors naturally are also reduced. There is, however, a large increase in positional error for the Cell 2 high altitude hover (HH) and low altitude hover (LH). The symbology only provides the pilot with damping information, it does not provide him with low frequency (position) drift information. Therefore, he is dependent upon the imagery movement which is less effective at higher altitudes, to obtain position information. At the higher altitude, the ground posiion reference, selected by the subject pilot at the completion of the maneuver, is at a much greater distance away from the helicopter. The farther the ground reference is from the aircraft the more difficult it becomes to sense image movement and to distinguish between altitude changes, attitude changes and fore-aft movement.

At the low altitude hover (LH), the subject pilot might have tried to reacquire the initial ground reference point and, in the process of wandering, did increase his position errors. Again the data in Figure 15 show the hover radius about the mean position of the individual sub-cells and not the errors measured about the initial or starting point of the hover run.

The trend of position error excursions is further shown in Figure 16. Here the mean standard deviation and RMS of the hover radius about the mean all indicate that for the IH, BU, and RM the errors are substantially less than for the HH and somewhat less than for the LH. The standard deviations of the longitudinal and lateral axis (Figure 17) appear to indicate similar errors with the lateral axis being slightly greater.

Altitude deviations about the mean for the IH, HH, and LH are shown in Figure 18. The altitude standard deviation for the IH and LH is about 12 and 10 feet, respectfully, while the HH is about 24 feet. This high altitude standard deviation at 200 feet may be attributed to the displayed altitude information. The range of altitude displayed was from 0 to 1,000 feet. The information displayed is linear from 0 to 200 feet. Beyond this value the scale becomes non-linear and has a lower gain. Since the mean altitude recorded was centered at 200 feet, the pilot would have been observing the altitude above 200 feet in the non-linear range. The decreased sensitivity of the display above 200 feet could possibly account for the large standard deviation.

(3) <u>Cell 3</u>. As described earlier, Cell 3 is similar to Cell 2 with an added attraction. The subject pilot was given control for selecting either forward-looking imagery (Cell 2) or completely -90°-downlook imagery. Thus, Cell 3 provided the pilot with whichever imagery he desired as he performed the various maneuvers. It was anticipated that this cell would provide the best hover position accuracies throughout the maneuvers.

The results of this cell are shown in Figures 19 through 22. The cumulative frequency of the hover radius (Figure 19) shows that at the 50-percent point, the position errors for the five maneuvers are less than 22 feet. This plot of Cell 3 compared to Cell 2 is very similar, with the exception that the remask and bob-up maneuvers of Cell 3 show more deviation between them in position accuracy as compared to the same maneuvers of Cell 2, Figure 15. The performance of the high altitude hover and low altitude hover are statistically similar. They do tend to be slightly better than the results of the same maneuvers for Cell 2. Looking at the hover radius about the mean position (Figure 20), it is quite apparent that the greatest error is accumulated during the remask maneuver, while for Cell 2 the greatest error is during the HH. From the longitudinal and lateral deviations (Figure 21), it is obvious that the greatest error is caused by the fore-aft axis or the pitch axis of the helicopter. One explanation for this error increase is due to the Cell 3 configuration and the technique the pilot used to maneuver the helicopter during the remask maneuver.

At the command to remask, the subject pilot selected the downlook image and searched the picture for the initial ground reference. As stated previously, the 90°-downlook was rigidly mounted on the helicopter, thus causing helicopter attitude changes to appear as transitional movements in the image. This had a destabilizing effect as the pilot attempted to hold position. The strategy used successfully by the pilots to fly the symbology with a stabilized downlook image in a previous test[4] was to place the acceleration symbol on the selected ground reference. In their attempt to use the above technique with the unstabilized image, they discovered that an instability resulted. As the pilot moved the acceleration symbol over the target, the helicopter attitudes would couple with the displayed image and the point being chased would move farther away. This movement became more pronounced at lower than at higher altitudes. The subject pilots finally resorted to use the downlook image only to locate the original ground reference. During the remask they would use the downlook only for a quick look to assure themselves that they were in the vicinity of the initial ground reference. The main remask maneuver was completed mainly with the forward look with only quick downlook glimpses.

The altitude deviations for Cell 3 are shown in Figure 22. Here only the altitude deviations for the maneuvers of interest are depicted. Again, as in Cell 2, the subject pilot using the DHS does maintain altitude with sufficient accuracy (less than 15 feet) for the initial and low hover. He does appear to have a problem holding an accurate altitude at the high hover. The explanation for the high deviation of 45 feet is as explained for Cell 2. Since the pilot is beyond the linear scale of displayed altitude, he does not easily see changes in altitude. This problem can be avoided by displaying altitude linearly to an altitude greater than is expected to be used for high hover.

Some additional data of interest are shown in Figures 23 and 24. Figure 23 depicts a comparative presentation of the helicopter pitch and roll attitude standard deviation. As can be seen from this figure, the Cell 2a attitudes are quite small (0.6°) with very little deviation (0.2°) for the individual sub-cell. There is, however, an appreciable increase for Cell 2. Both pitch and roll deviations increase to greater than 2.0 and 1.5°, respectively. No significant deviation for any individual sub-cell for the roll attitude can be seen. There is, however, a significant excursion of the pitch axis during BU.

One explanation offered is that in order for the pilot to perform the BU maneuver, he may have desired to maintain the original sight picture as long as possible. In attempting to do this he would cause a rocking-type motion, which would increase the attitude deviations and not the position errors. An alternative to this is to translate the aircraft aft as he increases altitude to maintain the original sight picture. This action naturally produces greater position errors. The data shown in Figures 17 and 23 substantiate the explanation of the rocking motion.

Figure 23 also shows an increase in helicopter attitude deviation for Cell 3 over Cell 2a. This increase, however, is substantially smaller than that depicted for Cell 2. One explanation may be that since Cell 3 includes a downlook image, the subject pilot can readily see the selected ground reference, and the rocking motion described above is not required.

There appears on Figure 23 a reversal of aircraft attitude behavior between Cell 2 and Cell 3. While Cell 3 follows the normal trend shown on Cell 2a with roll attitude having the larger deviations, the reverse is true for Cell 2. The most likely explanation may be that in the absence of a position reference, the pilot requires larger changes in pitch attitude to maintain the original sight picture.

On Figure 24 are plotted the results of flight control deviations in percent of full travel. Once again the results of Cell 2a or the front seat pilot, activity is centered around 1.3 percent with lateral cyclic having the maximum displacement. The deviations from maneuver-to-maneuver tend to be insignificant.

For Cell 2 and Cell 3, there is significantly greater cyclic control displacement as compared to Cell 2a. This displacement can be associated with pilot increased workload as he tries to maintain an accurate hover using the DHS. Collective control deviations have more than doubled for Cell 2 and Cell 3 as compared to Cell 2a. There appears to be no significant difference of collective deviations between Cell 2 and Cell 3.

Again it should be stressed that while using the DHS and flying from the third pilots seat, the pilots experience difficulty in holding an accurate heading. One explanation was that the heading symbol could not be readily observed due to its shape and location on the bottom of the display. In addition, the symbolic presentation of heading error information which also contained heading error rate information, might not have been understood by the subject pilots as to what the symbol represented and how to use it to cancel heading deviations. It became apparent when the pilots could not maintain heading they resorted to the automatic heading-hold. The data reduction results of the individual heading standard deviation for a large number of runs confirmed that the heading hold system was engaged. The heading standard deviation calculations were in the order of 2 to 4° which is within the capability of the heading-hold system of the helicopter. This explanation tends to contradict the previous statement about the pilots holding heading manually. However, it is possible that the automatic hold was engaged and the heading deviations are probable if the helicopter was not heading directly into the wind. The front seat pilot would be able to achieve this much easier than the 3rd station subject pilot.

At the completion of the data collection phase, some transition test runs were made fron an approach to a hover, terminating with the bob-up and remask maneuvers. For this task, the subject pilot utilized the forward-looking image and the raw doppler velocity vector information set at 11 fps/inch. He made an approach to a specified ground reference at a 60-foot altitude and tried to hover by zeroing out the doppler velocity. He then switched to the downlook image and to the high gain velocity signal of 2.5 fps/inch derived from the complementary filtering. At this point, he attempted to maintain position by using the downlook imagery only, while the velocity vector transient, due to the large attitude change upon coming to a hover, "washed" out and presented useful information.

This maneuver was much too difficult to perform. The subject pilots could not readily bring the helicopter to a complete stop at the selected site. They would either undershoot or overshoot the hover spot. These results reinforce the need for a transition to a hover symbology mode and the implementation of the time varying time constants for the complemented velocity information for future tests.

11. SUBJECT PILOT COMMENTS

In general, the participating subject pilots provided favorable comments on the DHS. They flew the system with very little training and experienced no disorientation or vertigo. Of the different cells flown they preferred Cell 3. "The downlooking (90°) capability provides the pilot with absolute assurance that the remask portion of the bob-up maneuver can be accomplished quickly into an obstruction free area." One further states "The elimination of the downlooking capability will be detrimental to both the attempting of and the accomplishment of night vision hover and bob-up maneuvers in tactical situations." As far as the other cells, Cell 1a did not provide "...adequate information in regard to maintaining adequate aircraft heading and rotor blade clearances from obstacles." Cell 2 was deficient in providing "...adequate information in regard to maintaining the aircraft's position over a selected hovering point."

It was their opinion that the hover symbology acceleration, velocity and altitude was necessary to stabilize the helicopter and to improve hover performance. They felt that the heading symbol was of very little use as presented.

12. CONCLUSIONS

Based on this flight test effort, the following conclusions are reached.

a. The hover system derived from concepts stated in the AAH PNVS specifications was successfully flown.

b. Velocity derived from each contractor's engineering development LDNS and the vertical gyroscope through complementary filtering was successfully used during the testing.

c. Raw (unfiltered) doppler velocity from the LDNS at 11 fps/inch displayed was not adequate to assist the pilot in the hover task due to doppler noise.

d. Symbolic presentation of acceleration, velocity, and altitude are necessary to stabilize the helicopter and to improve hover performance when flying a PNVS-type system.

e. Symbolic presentation of heading as displayed, based on pilot comments, was not adequate, forcing them to use the automatic heading hold of the helicopter.

f. There appears to be no significant difference in pilot hover performance at constant low altitude between the Doppler Hover System (DHS) and that achieved under VFR.

g. In the absence of a position reference, the test subjects performed the high altitude, bob-up and remask maneuvers with less accuracy. Standard deviation position errors may range as high as 30 feet radially with the largest errors occurring during the high altitude hover and remask maneuvers.

h. Of the various cells flown, the one with the option of forwardlook or downlook image (Cell 3) was selected by the subject pilots as the preferred configuration, since the presentation of the downlook image increased pilot confidence during the remask maneuver.

i. The unstabilized downlook image of Cell 3 may have a destabilizing effect and decreases positional accuracy during remask as compared to the results of the forward-look image of Cell 2.

j. The approach to a hover maneuver was not readily accomplished with the selected cells and the symbol generator tested.

13. RECOMMENDATIONS

The following recommendations are offered:

a. That the AAH PM be made aware of the DHS flight test effort.

b. That since AAH PNVS constraints do not allow implementation of a Cell 3 configuration, Cell 2 which very nearly approximates the PNVS, be implemented to provide the hover capability.

c. That the research effort to provide displayed position information be continued with a flight test effort to determine the potential of digitally integrating the LDNS velocity to derive this parameter.

d. That the heading error and derived heading error rate symbol be modified to display only heading error in a horizontal tape (thermometer) format on the upper portion of the display in future trials.

e. That an in-house investigation followed by flight test, be conducted to determine manual versus automatic heading hold requirements.

f. That some further investigation be conducted to optimize symbology gains when used with an unstabilized downlook image.

g. That the approach/transition to a hover mode be incorporated into the hover system capability.