QUANTITATIVE EVALUATION OF DGPS GUIDANCE FOR GROUND-BASED AGRICULTURAL APPLICATIONS

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ABSTRACT. *The Global Positioning System (GPS) satellites provide positioning information which can be of significant use for agricultural applicators. This article presents the results of a quantitative evaluation of the precision of a commercial device which incorporates differentially corrected GPS signals (DGPS) to guide a ground vehicle along swaths. The precision of the cross-track displacement along the swath is determined with a video camera verification system and the results have been analyzed statistically.*

The quantitative tests have shown excellent cross track precision. For an automobile traveling at an average speed of 19 m/s over a total test distance of 23 km, the standard deviation from the unmarked centerline was 0.42 m. The 50 and 90 percentile distances from the centerline were 0.39 and 0.98 m, respectively. ***Keywords.*** *GPS, Swaths, Spraying, Row crops, Guidance.*

The potential of the Global Positioning System (GPS) for agriculture has previously been understood (Larsen, 1991; Auernhammer, 1991). Recent major advances in the use of the Global Positioning System (GPS) permit a sophisticated, yet affordable, solution to precision guidance for agricultural users (Hartt, 1992). The two concurrent trends of reduction in size and significant reduction in cost have made GPS a highly attractive base on which to build a precision location system.

Hand-held GPS locators currently provide a location solution with an accuracy of about ±30 m. A large percentage of this error is intentionally introduced into downlinked satellite data in the form of a signal drift in order to complicate the problem for a foe who wishes to use the data for targeting purposes. However, the development of differential GPS (DGPS) makes it possible to reduce this induced error, as well as errors due to propagation times through the ionosphere, by more than a factor of 10 (Falkenberg, 1992). By installing a fixed GPS receiver at a known, or at least stationary, location, the correction factors from the real-time GPS position solution to the actual location coordinates can be determined. These error signals, which are valid anywhere within a radius of approximately 100 km, are then sent to the GPS receiver of interest to correct the location solution.

APPARATUS AND TEST SITE

The objective of this testing is to quantitatively measure the precision of a commercial DGPS device under conditions simulating a ground spraying operation. The test vehicle was an automobile, and the test site was an airport runway. The sites and swaths were chosen to minimize visual line-up references and the driver used the guidance supplied by the DGPS device without other visual cues.

The GPS navigation aid for swath guidance tested was an AirStar (manufactured and registered trademark of SATLOC, Inc., Casa Grande, Ariz.). While the AirStar has numerous features, the capability which is of interest for this testing was its capability to use DGPS signals to provide a driver with information so that the driver can maintain a straight track. The AirStar consists of a computer, GPS receiver, a radio receiver/data modem, a cockpit display screen and keypad, a dash-mounted light bar display, and a power supply. The GPS receiver is a narrow correlation-type civilian receiver which is capable of tracking 10 satellites simultaneously and outputs position and velocity information every 0.2 s. The GPS differential correction data is supplied by a 900 MHz data radio link.

Centerline guidance is provided to the driver with a lightbar mounted above the instrument panel of the automobile. The AirStar lightbar consists of 63 LEDs arranged in two rows with 15 red lights on the left and 15 green lights on the right. Three vertically arranged yellow lights in the center are used to indicate when the vehicle is on track. The top row of red and green lights are used to indicate the cross-track error, with increasing number of lights lit indicating increasing cross-track error. Numerical displays on each side of the LEDs show the swath number to the driver.

Video cameras and recording equipment were set up on a test site to verify the position of the automobile. Two CCD monochrome video cameras, which have a horizontal resolution of 700 lines and a field of view of approximately 3° in the azimuthal and 2° in the ascension directions, were pointed down the center of test swaths. Each camera has a

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Article was submitted for publication in September 1994; reviewed and approved for publication by the Information and Electrical Technologies Div. of ASAE in December 1994.

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cross-hairs generator which places electronically generated vertical and horizontal lines on the picture. The vertical cross-hair is adjusted to bisect the swath in its field of view. A switch allows choice of one or the other camera to be sent to a time and date generator which displays time to hundreds of a second. This time was manually set to coincide with the time of the AirStar log (the coincidence between the two times is estimated to be no worse than a few tenths of a second). A video recorder records the view in S-VHS format, which has a horizontal resolution of approximately 425 lines. To measure the cross-track distance as a function of time, the recording is displayed on a large screen S-VHS monitor. This screen has a width of 558 mm, thus there is approximately 1.3 mm/line of horizontal resolution.

A 1985 Toyota Cressida was used for the ground vehicle testing. The AirStar was placed into the vehicle with the lightbar display in the driver's view above the dashboard and the keypad and auxiliary display near the drivers right hand. The GPS antenna was placed on a 9 in. standoff with a magnetic mount and was placed on the centerline of the roof of the car at a longitudinal position over the driver's head. Lights were attached onto the front and back bumpers on the centerline of the car to identify the center of the car to the video cameras. The driver for the testing, subject WHF, was a 38-year-old male; he is color normal and has 20/20 vision without corrective lenses. Although WHF was familiar with the operation and displays of the AirStar, he had no previous experience using it for precision centerline guidance testing. WHF also had no previous experience driving the test vehicle. To provide training for WHF and the ground crew, the test procedures were run through on a taxiway on the day preceding the tests reported here.

The test site was the Coolidge Airport in Coolidge, Arizona. The test area was laid out on Runway 17-35, which is oriented true north and south. This runway has 75-ft-wide pavement with no centerline stripe or edge markings. The runway is approximately 1.3 km long and is virtually flat.

The 1000-m-long test section was set up to be approximately centered along the axial length of the runway. A reference line, which is designated as swath 1, was laid out east edge of the pavement with the end points set 1.14 m west of the pavement edge. Two test swaths, swaths 2 and 3, were chosen to the west of the swath 1 with a swath width of 20 ft (6.10 m). Each end of these three swaths were marked on the taxiway with small orange triangles. Similar marks were placed on the projection of the line defined by the two ends of the test section 50 m south of the south end of the test section. The cameras were located at these marks, 1 m above the ground. Camera 1 was placed directly over the mark for swath 2 and camera 2 was placed directly over the mark for 3. The video recording equipment and ground crew were located half-way between the cameras, 3 m further south.

TEST PROCEDURES

The testing was performed in the early morning hours just after dawn. This minimizes the effects of shimmer caused by convection of the air due to heating of the pavement by the sun. The test day was divided into four sequences within which the environment and settings of the AirStar were kept the same. Each of the sequences is further divided into individual passes from one end of the test section to the other. Within a sequence, different passes represent changes of only the swath and direction of motion.

The test sequences were numbered with a two place numeric code where the first digit represents the project test day and the second digit represents the order of sequences for that day. For example, sequence 52 was the second sequence run on the fifth test day. This project involved many types of testing and the fifth test day was the one in which cross-track guidance of the ground vehicle was quantitatively tested. The sequences were further broken down into individual passes through the test sections, which were numbered consequently from one for each sequence.

The basic pattern of the first four passes in a sequence is as follows: set a reference line (swath 1) in one direction; follow the guidance provided by the AirStar on the adjacent swath (swath 2), but headed in the opposite direction as the reference line was set; follow the guidance of the AirStar on the next swath (swath 3) in the same direction as the reference line; then the opposite direction on swath 3; finally, the same direction on swath 2. In this manner, each of the two swaths with cameras are traversed in both directions. Additional passes are performed in a sequence to increase the database. The next sequence follows this pattern, but with the reference line set in the opposite direction and the first four of the passes in the reverse direction from the preceding sequence.

To obtain the data for the actual position of the vehicle, the video tapes of the tests are played back in the single frame advance mode. The frame closest to, but greater than the integer second was stopped on the screen and the distance on the screen from the vertical cross-hair (which represents the center of the swath) to the center of the vehicle is measured. These data are processed with a computer program which uses the data of axial distance as a function of time from the AirStar log to interpolate values of axial distance as a function of time for the video data and converts the distance measured on the monitor into angle, then to cross-track displacement.

The values of the statistical functions are rounded to the centimeter. However, the data are not significant at that level. The least significant increment in the cross-track displacement varies with distance from the camera (i.e., position in the test section) from 0.004 m at the end close to the camera to 0.10 m at the farthest point in the test section. Thus, the average increment is approximately 0.05 m. Thus, even though statistical values are reported to the centimeter, the last figure is not necessarily significant.

RESULTS

Tests of cross-track guidance of an automobile were performed on 22 October 1993. There were four sequences run on this test day. Sequences 51 and 52 were run with a mask angle (minimum angle that a satellite is above the horizon before it is used in the position solution) of 5°, then after a short break, two additional sequences were run with a higher mask angle of 15° to simulate the conditions of higher DOP (dilution of precision). The light bar was set with the red and green off-centerline lights corresponding to distances of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, and 35 ft (0.30, 0.61, 0.91, 1.22, 1.52, 1.83, 2.13, 2.44, 2.74, 3.05, 4.57, 6.10, 7.62, 9.14, and 10.67 m). The AirStar log was set to record at intervals of every 1 s with a minimum ground speed for logging to occur at 1 mile/h (0.45 m/s). The passes are listed with values of parameteric data in table 1.

The axial length of each pass through the test section was 1000 m. The axial distance coordinate was set up with its origin at the south end of the test section, so that it increased towards the north. The cross-track displacement coordinate runs east-west with positive values east of the swath lines. The latitude and longitude of the center of each swath was determined by averaging static DGPS measurements of latitude and longitude made with the GPS antenna held over the marks on the runway. The automobile was moving while in the test section for all of the passes; all line-up and pull offs were outside of the test section.

The track of the vehicle during a typical pass is shown in figure 1. Also shown on this plot is the position as determined by DGPS solution. The abscissa corresponds to axial distance through the test section. The cross-track displacement is the distance from the center of the vehicle to the centerline of the swath. A cross-track displacement of zero represents both the physical center of the swath for the video data and the swath line (line defined by the end points of the reference line plus the appropriate swath offset distance) which was recorded by the AirStar. The track of the vehicle during a good pass is shown in figure 2.

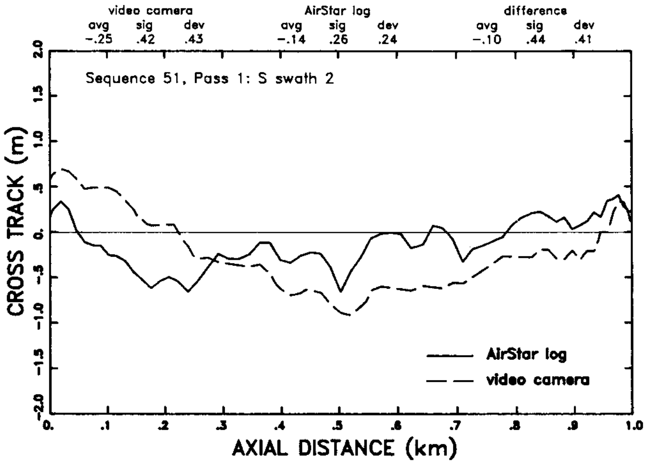

Figure 1–The cross-track displacement of an automobile driven through a 1-km-long test section using the DGPS based AirStar for guidance. The solid line represents the cross-track displacement as determined by the DGPS position solution, and the dashed line indicates the actual position as measured with the video system. At the top are the arithmetic mean (avg), standard deviation (sig), and mean deviation (dev) for both curves and for the difference between them. This pass is typical, as the values of the statistical functions are close to their median values.

The three statistical functions of the average arithmetic mean (avg), standard deviation (sig), and mean deviation (dev) of the measured cross-track displacement of the vehicle from the centerline of the swath for each pass are listed in the three columns of table 2 headed by "video camera". The units of each of the statistical functions is m. To obtain these values, the continuous forms of these statistical parameters were used and the distances from the centerline were fit with a trapezoidal approximation. The middle three columns are the same three statistical functions for the position data in the AirStar log, thus represent the DGPS solution location. The three values to the right are the same three statistical parameters for the difference between the video camera data and the AirStar data.

Table 1. Summary of test parameter data

Seq	Pass	Swath	Dir	Mean Speed (m/s)	Mask Angle (°)	DOP
51	1	2	S	15.0	5	1.5
51	2	3	N	17.5	5	1.5
51	3	3	S	17.9	5	1.4
51	4	2	N	18.0	5	1.4
51	5	2	S	16.9	5	1.6
51	6	3	N	18.4	5	1.8
52	1	2	N	18.1	5	1.8
52	2	3	S	18.3	5	1.6
52	3	3	N	18.0	5	1.5
52	4	2	S	19.6	5	1.3
52	5	2	N	20.0	5	1.4
52	6	3	S	21.0	5	1.4
52	7	3	N	20.5	5	1.6
52	8	2	S	21.9	5	1.7
53	1	2	S	19.0	15	1.9
53	2	3	N	18.3	15	1.9
53	3	3	S	20.3	15	1.9
53	4	2	N	21.4	15	1.9
54	1	2	N	19.6	15	1.9
54	2	3	S	19.6	15	2.2
54	3	3	N	20.0	15	2.2
54	4	2	S	20.3	15	2.3
54	5	2	N	20.3	15	2.3

PRECISION OF DGPS POSITION

A comparison of the cross-track displacements measured by the video camera data and in the AirStar log provides a measure of the precision of the position solution

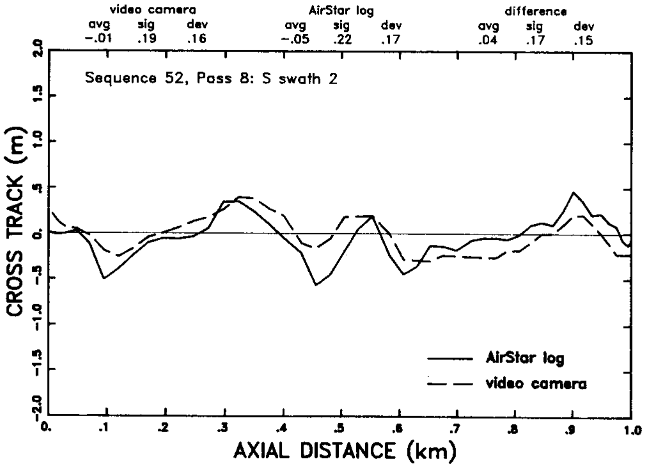

Figure 2–The cross-track displacement of an automobile driven through a 1-km-long test section using the DGPS based AirStar for guidance. This pass is statistically a good one.

Table 2. Summary of statistical data

		Video Camera			AirStar Log			Difference		
Seq	Pass	Avg	Sig	Dev	Avg	Sig	Dev	Avg	Sig	Dev
51	1	–0.25	0.42	0.43	–0.14	0.26	0.24	–0.10	0.44	0.41
51	2	0.07	0.48	0.40	–0.17	0.24	0.24	0.23	0.39	0.39
51	3	–0.08	0.17	0.16	–0.08	0.22	0.20	–0.01	0.23	0.19
51	4	0.22	0.51	0.47	0.03	0.23	0.19	0.19	0.41	0.40
51	5	0.35	0.37	0.43	–0.13	0.29	0.25	0.48	0.31	0.50
51	6	–0.02	0.51	0.41	0.00	0.29	0.24	–0.02	0.34	0.26
51	Mean	0.05	0.41	0.38	–0.08	0.26	0.23	0.13	0.35	0.36
52	1	0.07	0.64	0.56	–0.05	0.23	0.19	0.12	0.48	0.44
52	2	–0.33	0.41	0.40	–0.11	0.27	0.24	–0.21	0.45	0.41
52	3	0.15	0.60	0.54	0.12	0.39	0.33	0.03	0.59	0.47
52	4	–0.40	0.25	0.42	–0.05	0.24	0.21	–0.35	0.20	0.36
52	5	0.12	0.45	0.40	–0.15	0.16	0.17	0.27	0.50	0.49
52	6	–0.21	0.31	0.28	–0.01	0.21	0.17	–0.20	0.31	0.28
52	7	0.24	0.58	0.52	0.00	0.25	0.22	0.24	0.43	0.42
52	8	–0.01	0.19	0.16	–0.05	0.22	0.17	0.04	0.17	0.15
52	Mean	–0.05	0.43	0.41	–0.04	0.25	0.21	–0.01	0.39	0.38
53	1	–0.74	0.28	0.74	–0.04	0.24	0.18	–0.70	0.32	0.70
53	2	–1.06	0.66	1.08	–0.02	0.17	0.14	–1.05	0.67	1.08
53	3	0.11	0.27	0.23	–0.05	0.27	0.24	0.17	0.33	0.33
53	4	–0.31	0.84	0.80	–0.15	0.30	0.26	–0.17	0.79	0.74
53	Mean	–0.50	0.51	0.71	–0.07	0.25	0.21	–0.44	0.53	0.71
54	1	–0.04	0.35	0.28	–0.11	0.29	0.20	0.07	0.25	0.22
54	2	–0.31	0.62	0.60	–0.20	0.21	0.25	–0.11	0.67	0.58
54	3	0.65	0.22	0.65	0.14	0.26	0.24	0.52	0.32	0.52
54	4	0.05	0.35	0.30	–0.18	0.18	0.24	0.24	0.31	0.27
54	5	0.58	0.23	0.58	0.13	0.16	0.18	0.45	0.21	0.45
54	Mean	0.19	0.35	0.48	–0.04	0.22	0.22	0.23	0.35	0.41
All	50s	–0.05	0.42	0.47	–0.06	0.24	0.22	0.01	0.40	0.44

of this DGPS system tested in a manner similar to that for ground based spraying or other agricultural application. The average difference between the video camera data and the DGPS position was 0.01 m, which is below the level of significance. The average standard deviation of the difference was 0.40 m, and the average mean deviation of the difference was 0.44 m.

The difference between the actual position of the vehicle and the position in the AirStar log is shown for sequence 52, pass 8 in figure 3. These data correspond to the cross-track displacements shown in figure 2. The increment of time between data points is 1 s.

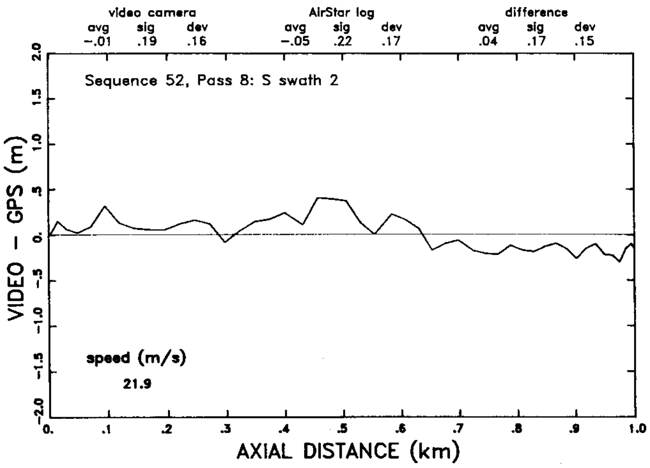

Figure 3–The difference between the actual position and the DGPS solution for the position data shown in figure 2.

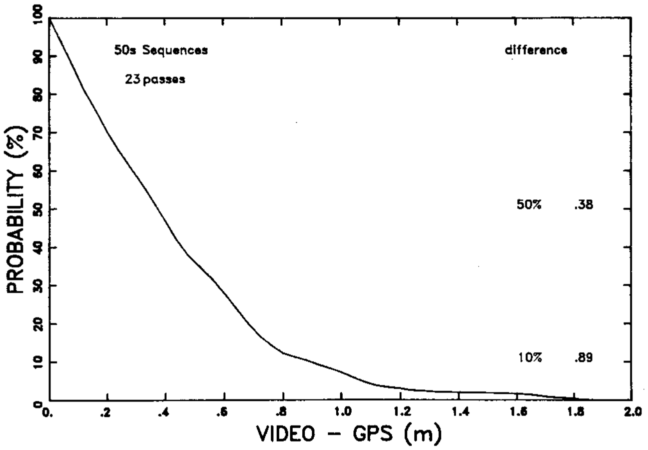

Figure 4–The percentiles for the difference between the actual position and the DGPS solution for all passes. A point on this curve represents the percent of the time that the difference between the actual and GPS solution was greater than the distance on the abscissa. The 50/50 percentile (farther/closer to) distance is 0.38 m and the 10/90 percentile distance is 0.89 m.

Figure 4 shows the DGPS performance during these tests. Any point on this curve represents the percent of the time (more accurately the percent of the total axial distance through the test section) that the vehicle was outside of a particular distance given on the abscissa. The 50 percentile cross-track difference was 0.38 m and the 90 percentile cross-track difference was 0.89 m. The maximum difference over the 23.0 km axial length of testing was 1.88 m.

DRIVER PERFORMANCE

Comparison of the reference line and the cross-track displacement from the AirStar log on the plots of cross-track displacement as a function of axial distance are an indication of the ability of the driver to maintain the course set by DGPS guidance. While this comparison encompasses both the jitter of the DGPS position solution and the ability of the driver to follow the light bar signals, it provides a measure of one limitation of this DGPS guidance. The mean cross-track displacement as measured by the AirStar for the passes on test day 5 was –0.06 m. The average of the standard deviations of the passes was 0.24 m and the average mean deviation was 0.22 m.

Figure 5 shows the probability density of the displacement from the swath centerline as measured by the AirStar as a function of cross-track displacement. Any point on this graph indicates the relative axial distance through the test section that the vehicle was at a particular cross-track displacement. The units of this probability density are km/m, and the interval for the plot is 0.08 m. Figure 6 shows in histogram format the percent of the axial distance through the test section for which the cross-track displacement was within the intervals set by individual lights on the AirStar lightbar. The AirStar log file indicated that the driver was within the center corridor (where the central yellow lights are on, indicating that no correction is necessary) for 70.8% of the total axial distance through the test section.

The 50 percentile cross-track distance as measured by the AirStar was 0.19 m and the 90 percentile cross-track

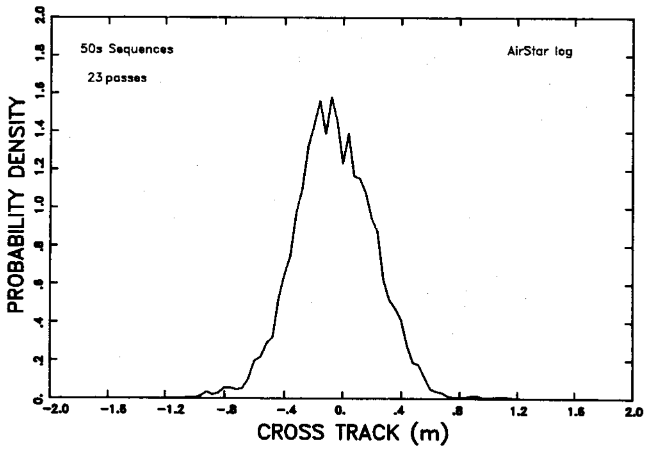

Figure 5–The probability density (in units of km/m) of the cross-track displacement as determined by the DGPS position solution for all of the passes. Note that the full width of the central peak is approximately 2 ft (0.6 m), the distance between the first left and first right off centerline lights.

distance was 0.45 m. This means that the driver was able to remain within 0.19 m of the centerline position as determined by the AirStar 50% of time and within 0.45 m 90% of the time.

The light bar was set so that the driver would not receive any off-centerline indications unless the DGPS position was at least one foot (0.30 m) from the swath centerline. As indicated by the AirStar log, the driver was within the center corridor, where the yellow lights indicate that no correction is necessary, 70.8, 73.3, 78.8, and 75.0% for sequences 51, 52, 53, and 54, respectively. These data indicated that the system was not driver limited, so that improved performance could have been obtained by decreasing the increment for the lightbar display. The consequence for such a change would be increased driver workload; the test subject had the opinion that increased workload would not be a problem.

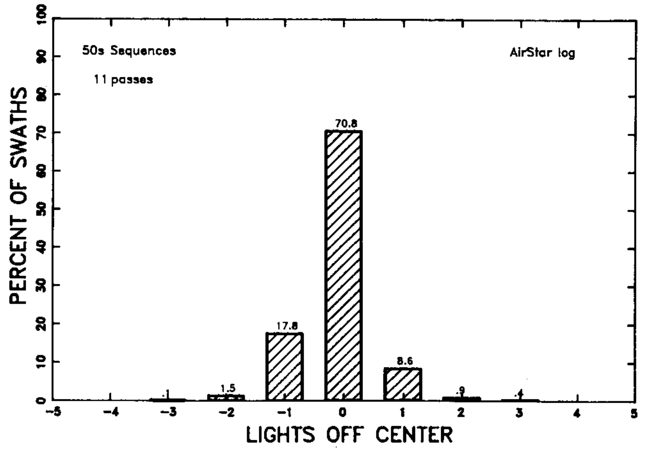

Figure 6–The percent of the time that the centerline guidance light patterns on the AirStar lightbar were displayed. The vertical yellow center lights were lit for the value of 0. The other bars are for the corresponding number of lights, either red or green depending on the side, lit for the off-centerline displacements. The off-centerline lights correspond to increments of 1 ft (0.30 m) per light.

TOTAL SYSTEM PERFORMANCE

The actual measure of the total system performance is obtained by analysis of the positions determined by the video camera. This incorporates all of the aspects: GPS solution; DGPS corrections; position display on the lightbar; and operator response. The system performance was excellent for these tests.

The mean cross-track displacement as measured by the video camera for the passes for Test Day 5 was −0.06 m. The average of the standard deviations of the passes was 0.24 m and the average mean deviation was 0.22 m. These are impressive numbers, particularly when the driver is not receiving any correction guidance until the path deviates at least 1 ft (0.30 m).

Figure 7 shows the percent of the axial distance through the test section that the absolute value of the cross-track displacement was greater than that distance. This is a percentile plot as any point on the curve represents the percent of the time (actually the percent of the axial distance through the test section) that the vehicle was outside of a particular distance on the abscissa. Thus, the 50% point represents the distance at which the vehicle is equally likely to be found closer to the centerline and farther than the centerline. Similarly, the 10% point represents the distance at which the vehicle was found closer to the centerline for 90% of the time and farther than the centerline for 10% of the time. The 50 percentile cross-track distance as measured by the video camera was 0.39 m and the 90 percentile cross-track distance was 0.98 m. This means that the driver was able to remain within 0.39 m of the centerline position as determined by the video camera (which is the absolute position) 50% of the time and within 0.98 m 90% of the time.

CONCLUSIONS

The GPS satellite signals, corrected for local and induced distortion, provide the agricultural aviation user with a mechanism for determining and recording positions with high precision. Quantitative tests with a commercial device (SATLOC AirStar) using differentially corrected GPS (DGPS) have shown excellent performance.

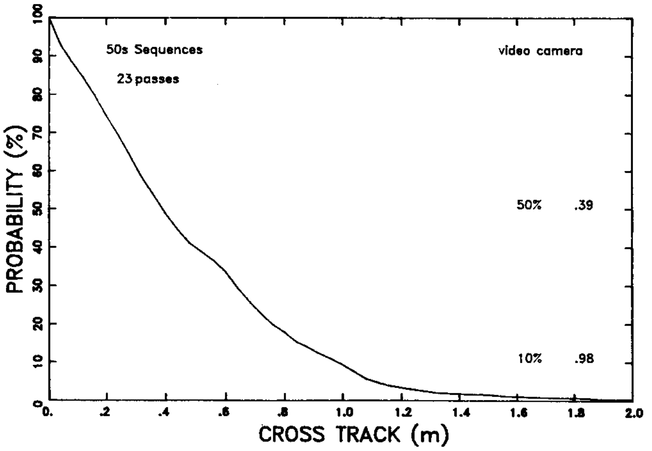

Figure 7–The percentiles for the location of the automobile outside of the cross-track distance on the abscissa for all of the passes. The combined axial length was 23.0 km.

For an automobile traveling over an aircraft runway with the driver using guidance provided by the AirStar, the 50 percentile cross-track distance as was 0.39 m and the 90 percentile cross-track distance was 0.98 m. Since the light bar was set so that the driver would not get any off centerline indications unless the DGPS solution for cross-track distance was at least 1 ft (0.30 m), this is excellent performance. The performance could have been even better if the testing occurred during a period of lower DOP and if the increments on the light bar where set smaller.

Acknowledgment. This project was supported by a Phase I grant from the USDA under the Small Business Innovation Research Program. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect the view of the USDA.

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