An Obstacle Alerting System for Agricultural Application

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Abstract

Wire strikes are a significant cause of helicopter accidents. The aircraft most at risk are aerial applicators. The present study examines the effectiveness of a wire alert delivered by way of the lightbar, a GPS-based guidance system for aerial application. The alert lead-time needed to avoid an invisible wire is compared with that to avoid a visible wire. A flight simulator was configured to simulate an agricultural application helicopter. Two pilots flew simulated spray runs in fields with visible wires, invisible wires, and no wires. The wire alert was effective in reducing wire strikes. A lead-time of 3.5 sec was required for the alert to be effective. The lead-time required was the same whether the pilot could see the wire or not.

Introduction

Wire strikes have been identified as a significant cause of helicopter accidents (Ref 1). While any pilot can be at risk of a wire strike, particularly during take-off and landing, the pilots most at risk are those that routinely operate near the ground and in areas where there are many wires. These pilots include power line inspectors, photographers, and aerial applicators. Within this set, the aircraft most at risk are aerial applicators. The typical profile of a wire strike involves a high-time aviator, who has flown over the wire earlier in the mission. This profile fits the aerial applicator.

A typical farm field can have a small wire running through it to an irrigation pump.

It can have narrow gauge phone and power wires immediately bordering it. Larger power lines often run along property lines, and major rights-of-way contain soaring, high-tension lines. This environment not only provides plenty of wires to hit; it also makes them difficult to see. One can stand in a field and see ranks of wires marching into the distance. Small nearby wires can be hidden in the backdrop of larger more distant wires. Looming high-tension lines have been known to startle a pilot and cause him to lose track of known smaller wires nearby. Finally, the vegetation, both crops and trees, can hide wires.

The agricultural pilot must keep track of all this clutter while maintaining a very low altitude and a precise spray line. He must also monitor the aircraft, spray equipment, and spray drift. This task ensemble could certainly benefit from any technology that could reduce pilot workload. The economics of agricultural application mandate that any technology be both light and inexpensive.

The military has addressed the problem of wires in a number of programs. Radar, ladar, infrared, and electromagnetic field detectors have all been tried. Detection rates have never been satisfactory, and weight, cost, and reliability have been problems. Display work has been done (Ref 2, Ref 3). No generally acceptable display concept has been presented.

The agricultural wire environment is potentially more tractable than that faced by the military. Wire locations are known, and pilots visit the same fields repeatedly. This makes it possible to use GPS and a database to drive a wire alerting system. Developing such a system would entail significant technical and cost challenges. Therefore a reasonable first step is to evaluate the effectiveness of a wire alert.

Design of the alert is important. The flight and equipment control tasks place a substantial demand on the pilot's attention. Transitioning attention from such demanding tasks to the alert could take a long time, as much as a second or more (Ref 4). Showing the alert at a location already attended by the pilot can reduce shifting attention. The lightbar is a GPS-based guidance display used on agricultural helicopter to conform to OSHA and EPA requirements. The pilot attends continually to the lightbar in order to stay aligned on the spray swath. Presenting the alert by way of the lightbar can minimize the time needed to switch attention, since the pilot must monitor the lightbar continually. De Maio (Ref 5) found similar flashing of helmet display symbols to provide effective alerting. The present study addressed the usefulness of a lightbar-based wire alert.

Research has shown that a warning system must be viewed as relevant. It must be accurate and timely or operators will ignore it (Ref 6). Low accuracy has been described as the "cry wolf effect" (Ref 7; Ref 8). Operators ignore alerts if the false alarm rate is too high.

The false alarm rate should not be a problem in a GPS-based, database driven system, but if alerts were presented just before the pilot was ready to make a normal wire avoidance pull-up, they might be perceived as false alarms. Normally the pilot sees the wire and the alert is redundant. If the alert were presented too soon, it might be treated as a false alarm. Therefore the alert should come just as the pilot would normally pull up. Proper timing of the alert would keep it from being a distraction or annoyance when it was not needed.

Of particular concern was the speed of response to an alert when the pilot did not see the wire. Normally the pilot sees the wire and the alert is redundant. If the alert were presented too soon, it would be annoying. Therefore the alert should come just as the pilot would normally pull up. Proper timing of the alert would keep it from being a distraction or annoyance when it was not needed.

The present study examines the effectiveness of a wire alert delivered by way of the lightbar. The alert lead-time needed to avoid an invisible wire is compared with that to avoid a visible wire.

Method

Subjects

Test subjects were two NASA Ames test pilots. Both had extensive helicopter and flight simulator experience but no agricultural application experience.

Apparatus

The Rotorcraft Part-Task Laboratory (RPTL) was configured to simulate an agricultural application helicopter. The RPTL uses an enhanced stability derivative flight model (ESD) running on an Octane computer. The ESD model is described in Whalley (Ref 9)[1]. EasyScene, running on the same computer, generates a single-channel out-the-window visual scene. Designer's Workbench, running on an Indigo 2, generates the panel instruments. Scenario Builder, running on an Indy, controls the simulation. Ethernet connects the three computers. An enclosed cockpit isolates the pilot during the simulation. A 21-inch monitor at about eye level presents the out-the-window scene. Its field-of-view is 30 degrees X 45 degrees. The display for the cockpit instruments is a 19-inch monitor located below the out-the-window display and to the left. A three-axis BG Systems side-arm controller on the right provides cyclic and yaw control (see Figure 1). A short collective control is mounted on the left

The simulated visual environment consisted of farm fields containing row crops. Each

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[1] ESD is the Enhanced Stability Derivative model. The drive equations are given below:

Roll: $\phi/\delta_a = 0.7/(s^2 + 4.5s + 2.5)$
Pitch: $\theta/\delta_c = 0.3/(s^2 + 3.5s + 2.5)$
Yaw: $r/\delta_p = 0.3/(s + 2)$ (plus turn coordination)
Heave: $w/\delta_c = -96.6/(s + 0.7)$

Where:

$\phi \equiv$ Roll angle, rad
$\theta \equiv$ Pitch angle, rad
$r \equiv$ Body axis yaw rate, rad/sec
$w \equiv$ Body axis heave rate, rad/sec
$\delta_{lon} \equiv$ Longitudinal stick displacement, in
$\delta_{lat} \equiv$ Lateral stick displacement, in
$\delta_{ped} \equiv$ Side-stick twist displacement, deg
$\delta_{col} \equiv$ Collective stick displacement, in

row was a box, 2.8 meters high, 2 meters wide, and 574 meters long, with a green texture pattern on the top. The rows were two meters apart (see Figure 2). The brick pattern provided some indication of speed, but was so spread out that the speed cue was limit-ed. There was a cyclic trim control that eliminated the need for continual pressure to maintain groundspeed. The pilot still needed to exert regular cyclic control because the maneuvering caused significant change in speed. The primary speed indication was a digital readout as described below. No winds were simulated.

Each field was 192 meters wide. A wire was placed midway down the field, running across the entire width of the field. The wire was a catenary, with a height of about 11 meters at the ends and 4.8 meters in the center (see Figure 2). This wire was considerably taller than the pump wire typically found in a field. The wire was visible over the entire length of the field.
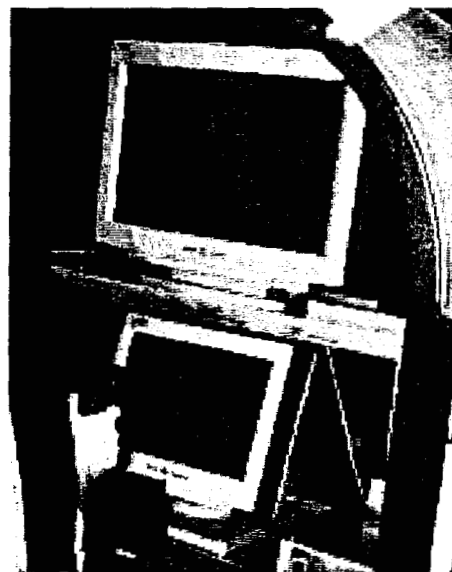

Figure 1. RPTL cockpit.

A logical wire triggered the alert. The logical wire was made up of reference points at half-meter intervals along the course of
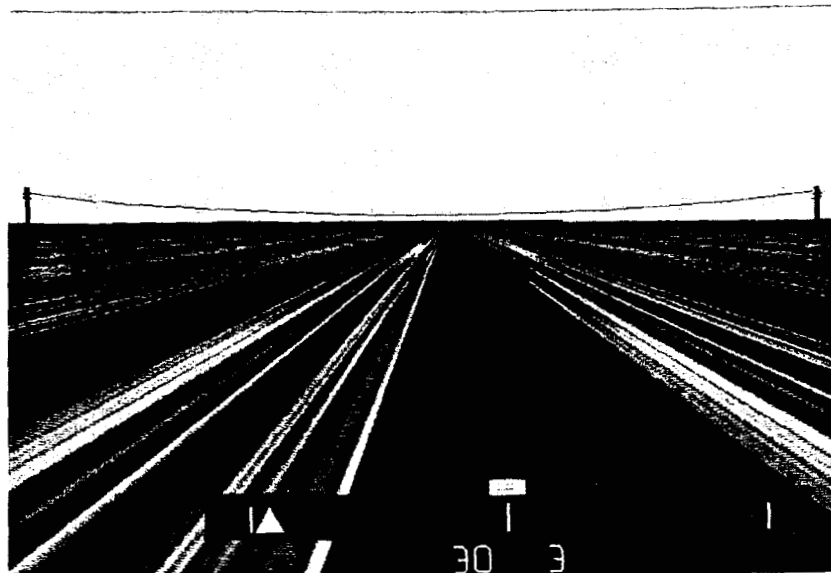
Figure 2. Row crops and wire hazard at desired flying height

the visible wire. A typical swath, determined by the length of the spray booms is 12 meters. Thus the field was 16 swaths across. The spray run consisted of 16 fields in a line. Bare ground, with only the base texture pattern lay between the fields. These areas were 426 meters long. The pilot flew the length of one field then moved over one swath and flew the next field (see Figure 3). This arrangement was necessary because the 45-degree field-of-view did not support the aggressive maneuvering needed to spray a single field.

There were two sequences of fields, each having a different order of environ-mental conditions. Each sequence consisted of 16 fields with three environ-mental conditions placed in random order. These conditions controlled the alert system. There were three environmental conditions. The visible wire condition had visual and logical models of the wire were placed midway down the field. The invisible wire condition had a logical model of the wire was placed midway down the field, but there was no visual model. There was neither a visual

wire nor a logical wire in the no wire condition. The order of environmental conditions is shown in Table 1.

There were five experimental, lead-time conditions. No Alert was the baseline condition. In this condition no alert was displayed, regardless of the presence of a logical wire. The pilot avoided the wire using his own judgement of the out-the-window visual cues.

There were four alert system conditions, in which a pull-up cue was displayed when the aircraft approached the logical wire. These varied in the amount of lead-time between alert onset and the impending strike. Lead-time was calculated by dividing the distance to the nearest reference point on the wire by the instantaneous groundspeed. Actual lead-times changed due to variation in groundspeed and lateral position relative to the reference points. There were 45 reference points at 0.5-meter intervals along the wire. The lead-time computation did not take into account direction of travel. So the alert would flash as the aircraft approached

Table 1. Order of environmental conditions.

Field Sequence 1	Field Sequence 2
Wire Type	Wire Type
Visible	Visible
None	Invisible
Visible	Visible
Invisible	Invisible
Visible	None
Invisible	Invisible
None	Invisible
Visible	Visible
None	Invisible
Invisible	None
Invisible	Invisible
Visible	Visible
None	None
Invisible	None
None	Visible
Invisible	Invisible

the wire and would continue to flash after the aircraft passed the wire and was moving away from it, unless the aircraft reached an adequate height.

The four nominal lead-times were 2.2, 2.9, 3.5, and 4.2 seconds. These were estimated in trial runs prior to the experiment. Actual lead-times were determined following data collection by averaging the results of all runs in each lead-time condition. Table 2 shows the experimental and environmental conditions. "V" means that a visual model of the wire was present. "A" means that a close approach to the wire generated an alert. "S" means that a minimum approach to the wire generated a wire strike. "N" means that character was not present in that experimental-environmental condition. All environ-mental conditions were presented in each experimental run.

The lightbar provided an alert signal when the aircraft approached the wire, along with a steering cue (see Figure 4). The primary signal was the flashing of the three simul-
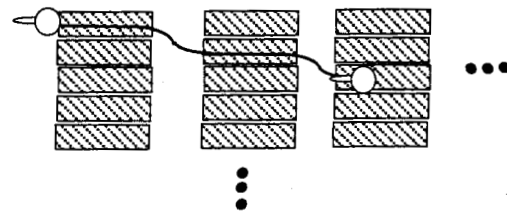

Figure 3. Spray Run

ated LEDs composing the steering cue. In addition, two turning indicators and a red "pull-up" indicator flashed. The former had been added to the ends of the lightbar to try to facilitate the turn, and they were never removed. They flashed as pull-up cues. In an actual system, the outboard LEDs would be out during the spray run, so they could be used in this way. The red "pull-up" cue was

Table 2. Experimental conditions.

Alert System	Field Environment		
	Visible Wire	Invisible Wire	No Wire
No Alert	V, NA, S	NV, NA, S	NV, NA, NS
2.2 sec lead-time	V, A, S	NV, A, S	NV, NA, NS
2.9 sec lead-time	V, A, S	NV, A, S	NV, NA, NS
3.5 sec lead-time	V, A, S	NV, A, S	NV, NA, NS
4.2 sec lead-time	V, A, S	NV, A, S	NV, NA, NS

next to the swath number. It was added as a potential stand-alone cue, but all the available cues were used in the present experiment. Flashing consisted of alternating between images like Figure 4a and Figure 4b. The flashing continued until the aircraft altitude exceeded the height of the wire or passed beyond the threshold distance from the wire. A red rectangle indicated a strike. It appeared superimposed on the lightbar for 1.5 seconds after a strike.

Procedure

The experimenter explained to the pilot the agricultural application task, use of the lightbar, and the wire alert. Each pilot then flew practice runs to get used to the simulated aircraft's flying qualities and the visual cues. The pilots felt that they had reached stable performance after about one hour. They then flew two data collection trials in each of the five experimental, lead-time conditions.

Each pilot was instructed to use his judgement in the No Alert condition. In the alert conditions, the pilot was instructed to delay his pull-up until the alert if the lead-time were shorter than he would like. When the lead-time was longer than he would like, he was to respond to the cue immediately.

Each pilot flew two trials in each experimental condition at a nominal groundspeed of 40 kt. Each trial consisted of a spray run down one of the field sequences. The pilot encountered at most one wire in each field. Each trial lasted about 20 minutes. The entire data collection time was between three and four hours per pilot. The pilots flew about one hour per session.
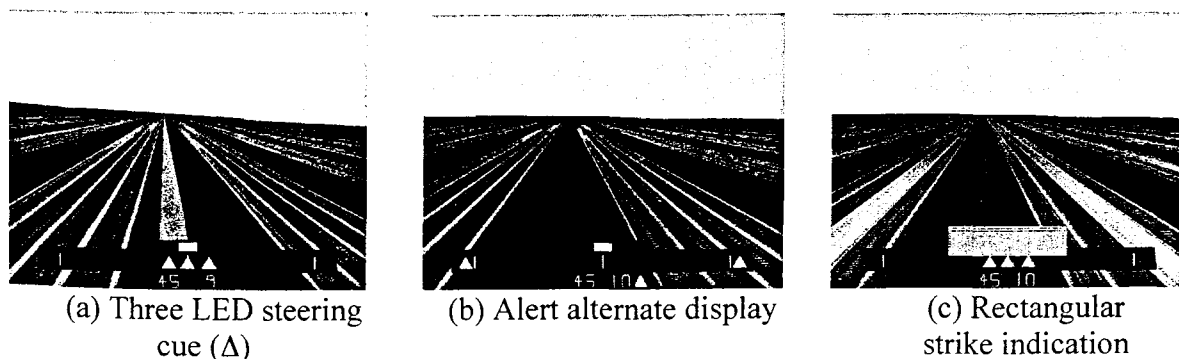

| (a) Three LED steering cue (Δ) | (b) Alert alternate display | (c) Rectangular strike indication |

Figure 4. Lightbar

Results

The data were treated as classic psychophysical data. The small number of subjects did not lend itself to statistical analysis. The data analysis consisted of direct examination of individual pilot's data.

No Alert

A wire strike occurred whenever the center of gravity of the simulated aircraft came within five meters of a reference point on the wire. In normal operations, wires strikes are very rare events. In the present study, the environment was designed so that there was a higher than normal rate of strikes, to provide a basis for comparison between the Alert and No Alert conditions. This is the reason for the invisible wire condition. Figure 5 shows the flight profiles for the No Alert condition. Only the visible wire profiles are shown because there were no pull-ups in the two conditions without visible wires. When the logical wire was present, but there was no alert, a strike was counted when the pilot did not pull up.
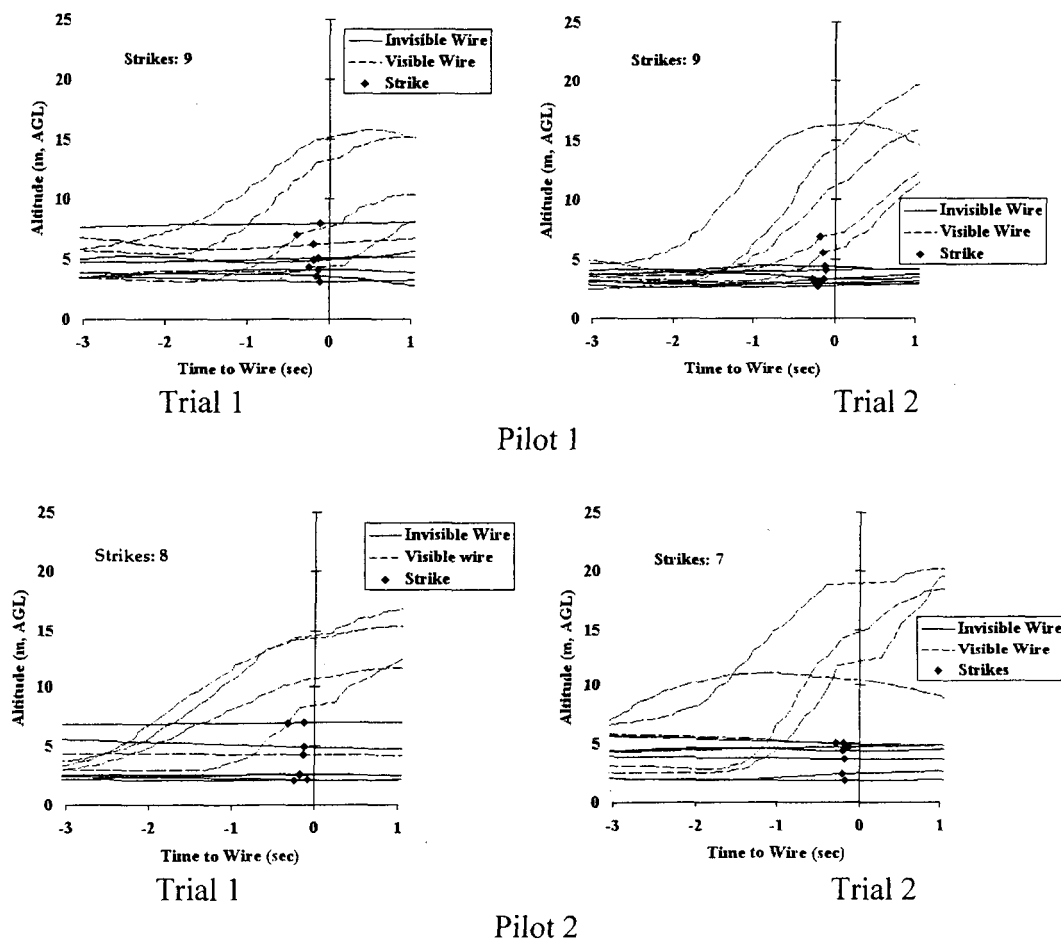
Figure 5. Altitude profiles: No alert.

Wire strikes were common – seven to nine per run - even when the wire was visible. The "Invisible Wire" fields still contained a logical wire, and they were counted in the number of strikes. Most of the strikes when the wire was visible were likely due to the difficulty of judging distance to the wire and closure rate. It can be seen that the "Visible Wire" profiles in Figure 5 are highly variable.

Alert

The wire alert had a profound effect on the pilots' performance. The pull-up point (time) and climb were much more consistent, even when the warning lead-time was not adequate, as can be seen in the "Visible Wire" profiles in Figures 5 and 6.

Although the pilots flew more consistently, they consistently hit the wire. The range of wire strikes was seven to 10 per run.

Both pilots showed a strong tendency to pull up earlier in the "Visible Wire" condition than in the "Invisible Wire" condition. The pilots were asked to delay their pull-up until they got the alert, even when they could see that this would lead to a strike. The trend in the 2.2-sec data could be due to failure to follow this instruction fully, or it could be due to a faster reaction when the alert reinforced the visual information. If the latter were true, then the effect should persist even when the lead-times were adequate.
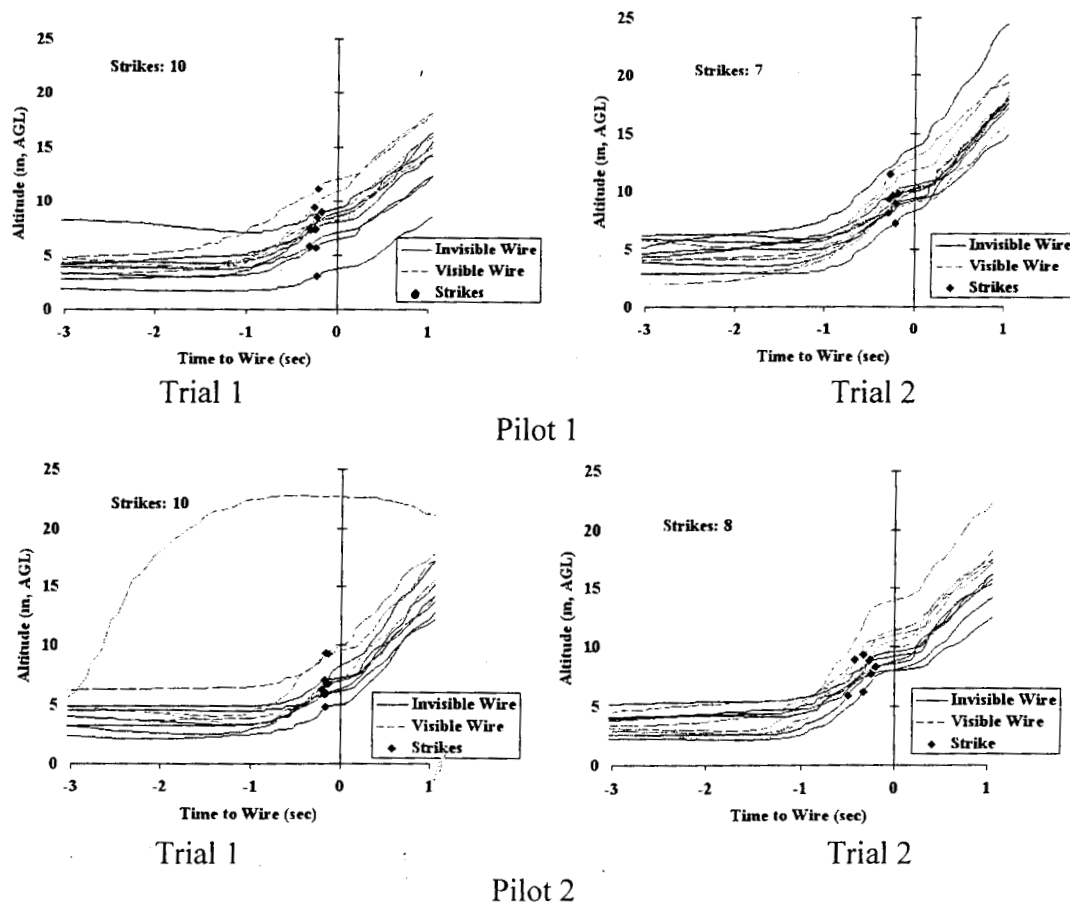
Figure 6. Altitude profiles: 2.2-sec lead-time alert.

Raising the alert lead-time to 2.9 sec reduced the number of wire strikes substantially (see Figure 7). The range was zero to five, compared to eight to 10 in Figure 6. Both pilots still pulled up sooner when the visible wire was present.

Figure 8 shows altitude profiles and wire strikes for the 3.5-sec lead-time alert condition. This lead-time further decreased number of strikes. On two runs there were no strikes. The pilot's tendency to pull-up earlier in response to a visible wire is also reduced. Pilot 1 showed no consistent bias in this regard, and Pilot 2's bias is reduced

compared to the shorter lead-time conditions.

Increasing the alert lead-time to 4.2 sec caused a negligible drop in the number of strikes (see Figure 9). There were three strikes in the 3.5-sec condition and two in the 4.2-sec condition. Both pilots showed no tendency to pull up sooner when the wire was visible. It appears that a lead-time of 3.5, sec or slightly more is adequate in the test environment.
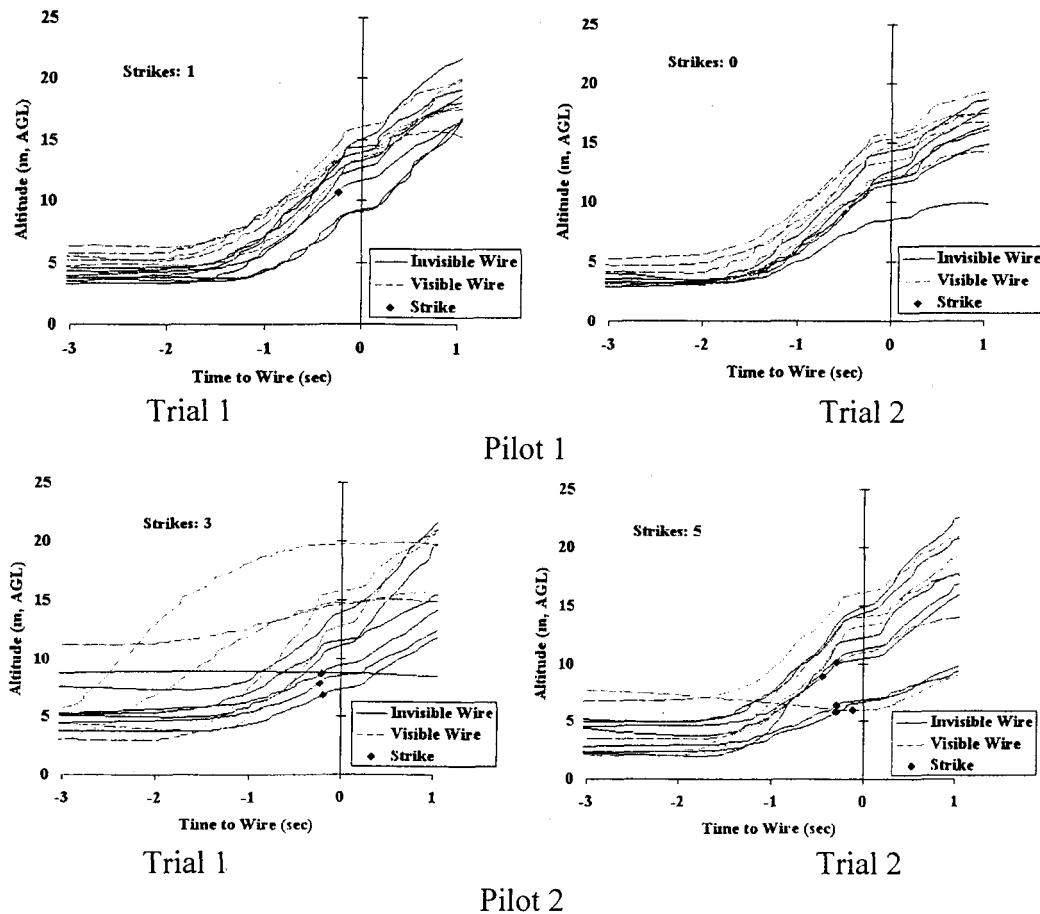

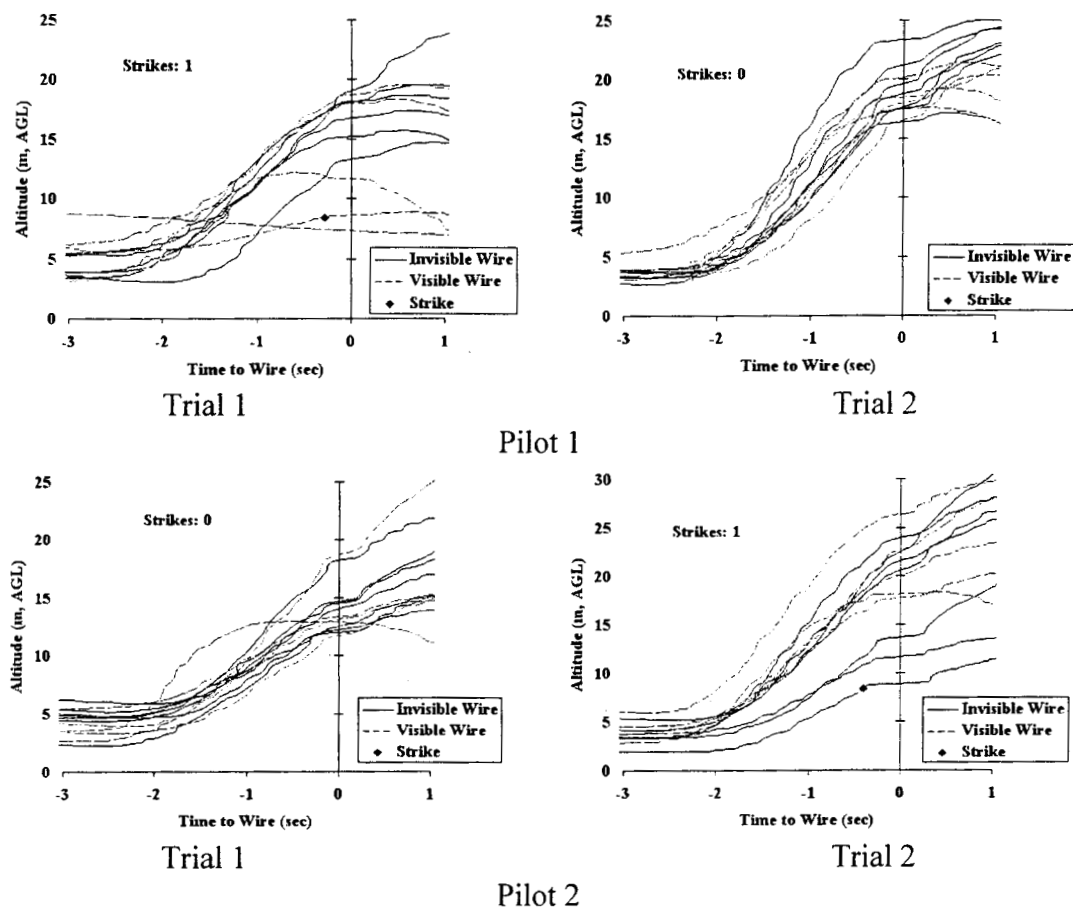Figure 7. Altitude Profiles: 2.9-sec lead-time alert.

Figure 8. Altitude profiles: 3.5-sec lead- time.

Overall Trends

The averaged data show overall trends, when used to supplement individual data. Averaging was tricky since the time sequences were not synchronized from field to field or run to run due to variations in track and speed. So there was only a rough temporal correspondence from one field to the next. All the pull-ups in each data run were averaged in the following way. The data from the fields in each run were combined and sorted them by time from the wire. Taking an eleven-frame running average smoothed the resulting "curve". This curve gives a good picture of the "typical" wire avoidance maneuver profile.

Figure 10 shows the averaged altitude profile data. An asterisk indicates the average pull-up point (time). This point was determined by averaging the pull-up times and altitudes on for the individual runs. On most approaches to the wire, the vertical speed alternated around zero. So the pull-up point was defined to be the last time that the vertical speed went from negative to positive before the aircraft reached the wire. In just over 10% of the cases, the pilot drifted upward slowly over the entire approach to the wire. In these cases the pull-up was determined by visual inspection.

Increasing alert lead-time affects performance by shifting the pull-up point to the left (earlier) without altering the altitude profile (see Figure 10). When there was no
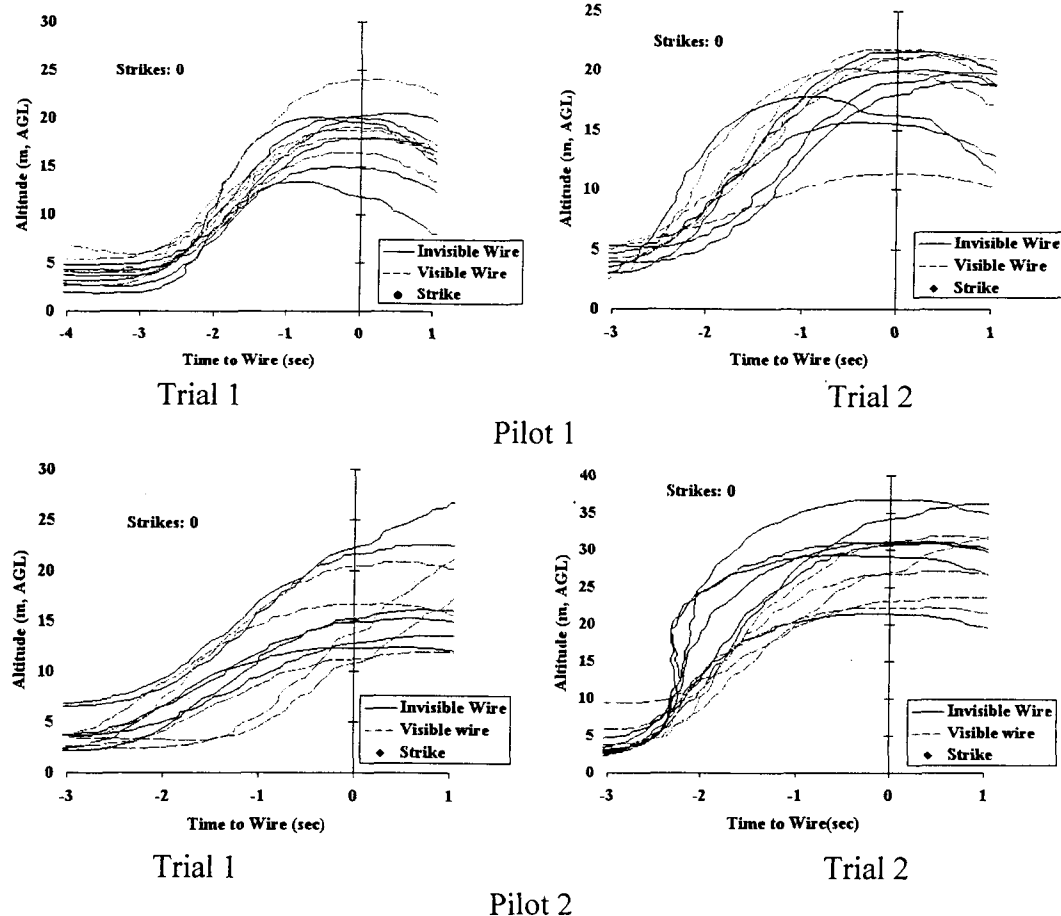
Figure 9. Altitude profiles: 4.2-sec lead-time.

alert, the pull-up time was comparable to the 2.9-sec lead-time, but the number of strikes was substantially greater. This was because the pilots did have a different profile when there was no alert. They climbed less aggressively in the No Alert condition. Both pilots expressed concern that a too-rapid pull-up would cause mast bumping in actual flight. Mast bumping was not modeled in the simulation, so the pilots used their judgement about how aggressively to pull up. Apparently they were more conservative when there was no alert system. This is viewed as a simulation artifact. In any event, it is not possible to tell whether mast bumping would ever have occurred.

Conclusions

1) The wire alert was effective in reducing wire strikes. Strikes were reduced to zero from seven to nine without and alert.

2) Adequate lead-time was needed for the alert to be effective. The alert was marginally effective at a lead-time of 2.9 sec. A 3.5-sec lead-time was nearly as effective as a 4.2-sec lead-time.

3) Extra lead-time is not needed when the pilot does not see the wire. The data show that pilots respond similarly to the alert whether or not they see the wire.

a) No Alert Pilot 1

Trial 1 Trial 2 Trial 1 Trial 2

Pilot 2

b) 2.2-sec alert Pilot 1

Trial 1 Trial 2 Trial 1 Trial 2

Pilot 2

c) 2.9-sec alert Pilot 1

Trial 1 Trial 2 Trial 1 Trial 2

Pilot 2

d) 3.5-sec alert Pilot 1

Trial 1 Trial 2 Trial 1 Trial 2

Pilot 2

e) 3.9-sec alert Pilot 1
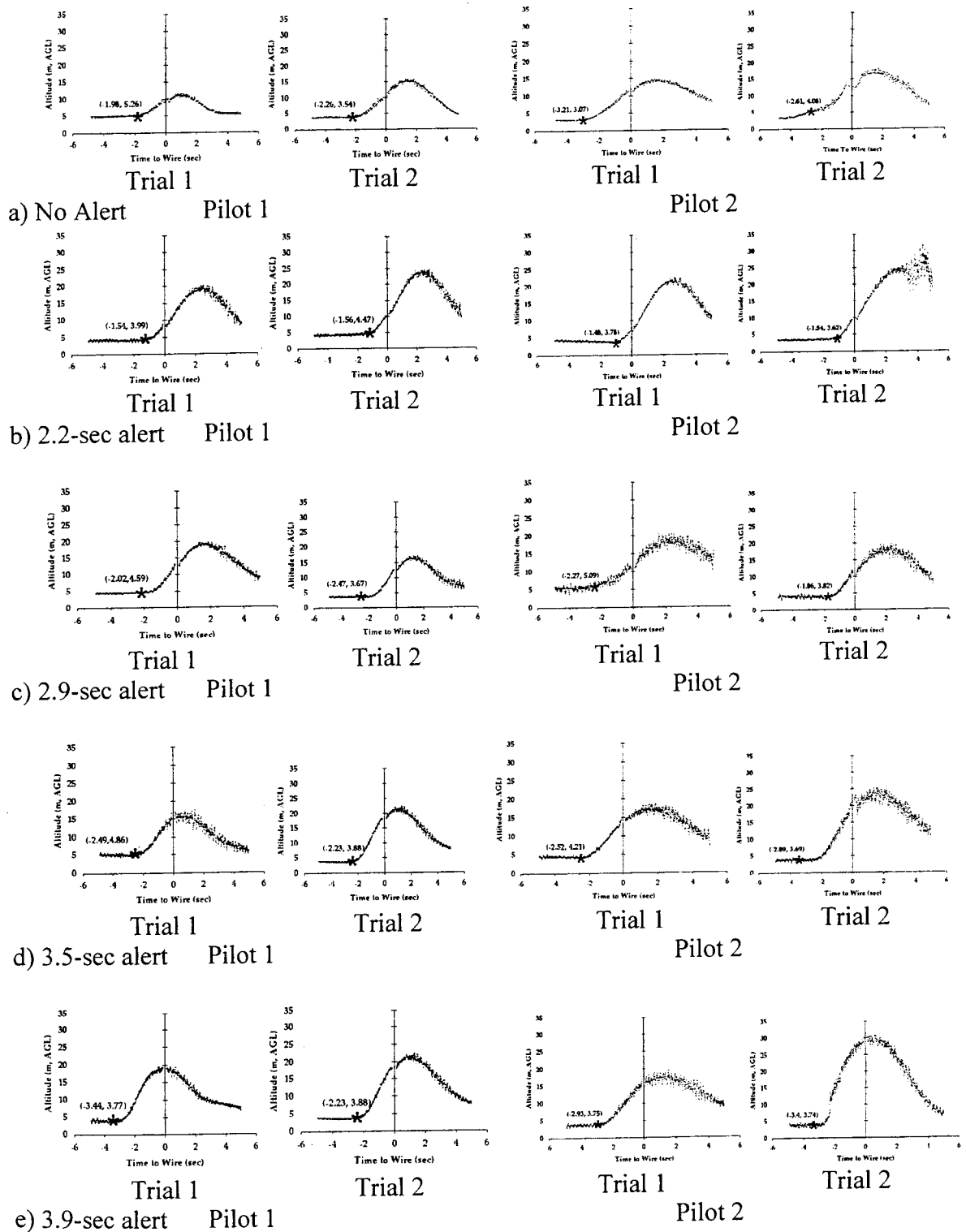
Trial 1 Trial 2 Trial 1 Trial 2

Pilot 2

Figure 10. Averaged data for fields in which a pull-up was executed.

Properly timed, an alert could be minimally annoying under normal conditions and still be effective when the pilot fails to see a wire.

4) Integrating the alert into the lightbar facilitates rapid responding since the pilot must watch the lightbar continually during the spray run.

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