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A HEAD-UP DISPLAY FOR MID-AIR DRONE RECOVERY

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SUMMARY

During mid-air retrieval of parachute packages, the absence of a natural horizon creates serious difficulties for the pilot of the recovery helicopter. A head-up display (HUD) was tested in an attempt to solve this problem. Both a roll-stabilized HUD and a no-roll (pitch only) HUD were tested.

The results show that fewer missed passes occured with the roll-stabilized HUD when the horizon was obscured. The pilots also reported that the workload was greatly reduced. Roll-stabilization was required to prevent vertigo when flying in the absence of a natural horizon. Any HUD intended for mid-air retrieval should display pitch, roll, sideslip, airspeed, and vertical velocity.

INTRODUCTION

One of the most successful ways to recover drones is the mid-air retrieval system (MARS). During these recoveries, a parachute system is deployed from a descending drone prior to retrieval. A typical parachute system consists of an engagement parachute connected by a load line to the drone and a main parachute canopy supporting the drone. The main canopy is designed to release when the load line from the drone to the engagement parachute is under tension. The load line is routed up the main canopy risers to a break-tie at its apex, then up to the engagement parachute.

To recover the drone or other object, the pilot flies the helicopter to approach the engagement parachute from the side opposite the load line.

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This location is shown by an aiming panel on the main canopy. The helicopter has three hooks rigged below it which catch load carrying members in the engagement parachute. These hooks are connected to an energy absorbing winch aboard the helicopter. As the load line absorbs the tension after engagement, the apex tie releases, followed by main canopy separation, and the drone is carried by the load line supported from the helicopter. Figure 1 shows the helicopter and parachute system just prior to engagement.

Safe and consistent MARS operations depend on the pilot's ability to match the helicopter's vertical velocity with the parachute's while closing with the top of the engagement parachute. At the same time, the helicopter must approach from a specific direction to ensure that the load line will not be pulled through the main canopy.

The pilot's primary visual cue is the alignment of the helicopter, the top of the engagement parachute, and the horizon. If the horizon is obscured by smoke, haze, or clouds, or if false horizons are present, the pilot has extreme difficulty in judging his position relative to the target. Under these circumstances, attempted recovery can be dangerous and fruitless.

Variations in the size of the parachute canopies can produce illusions of being too high or too low relative to the engagement parachute. The pilot must allow the canopy top to pass beneath the fuselage as the helicopter closes with the engagement parachute. The apparent change in position from level to approximately twelve feet below the helicopter can make engagement difficult to judge. These visual problems are compounded by the need for precise heading and roll control since any degree of uncoordinated flight is magnified in the pole position. Airspeed must be maintained within a small band (45 to 60 knots) for proper operation of the energy absorbing winch.

The head-up display has been used to assist pilots during visual tracking tasks. The HUD is an outgrowth of the reflecting gunsight and presents flight instrument data in the pilot's field of view as he looks at external visual cues. To date, HUDs have been applied to two main areas: weapons delivery(1) and landing approach(2,3). A survey of HUD technology is also available(4).

HUDs serve to combine real world visual cues with derived data. These data sources are complementary. It would be difficult to reproduce the real world cues artificially. At the same time, the derived data presents information that the pilot cannot perceive directly, or only with great difficulty. One must be careful, however, to ensure that both data fields are compatible. As Singleton points out(5), there is a basic incompatibility between the redundant, analogue data of the real world and the symbolic, often digital data of artificial displays. The problem is further complicated by the need for careful attention to retain proper balance, so that the proper display (real world or artificial data) dominates. During visual tracking, the real world must dominate with the flight instrument data providing supplementary information. The roles reverse during instrument flight. However, the HUD must not be such a compelling sight that the pilot fixates on it to the exclusion of the real world. This has definite implications on pilot learning and has been reported elsewhere(2). These comments were verified by conversations with HUD-qualified pilots prior to the development of the test plan for this study, as well as during preliminary HUD flights.

EQUIPMENT DESCRIPTION

The particular HUD evaluated in this study is a modified electro-mechanical unit manufactured by Sundstrand Data Control. The system consists of two pilot display units, a control module, and a computer. The HUD was developed from a commercial transport display known as the Visual Approach Monitor (VAM). The VAM presents pitch and longitudinal flight patch information to the pilot. No roll or heading information is supplied. The VAM was designed to minimize the problems of judging final approach path angles during visual approaches. It is presently in operational use with Pacific Western Airlines in their arctic support flights(3). It has also been evaluated in several military and civilian airplanes.

Roll information is not considered essential since the VAM was designed for use on final approach in visual conditions only. Later VAMs incorporate an airspeed index showing deviation from a reference speed. A color-coded index shows deviation with a red S for slow, a yellow F for fast, and a green O for correct airspeed. This peripheral cue is similiar to the angle-of-attack indexes on some military airplanes.

The Light Line is a further development of the basic VAM display. Developed under support from the AFFDL, the Light Line presents both pitch and roll information as well as a flight path angle display appearing as a beam of light emanating from the airplane to the projected impact point. This display was evaluated as an approach aid in USAF T-38 airplanes at the Instrument Flight Center(6).

The HUD used in this study is a further development of the VAM/Light Line displays. At the start of the program, it was not clear if roll-stabilization would be required. Therefore a roll/no-roll option was provided through a roll cut-out switch. Airspeed data was provided with a VAM-type airspeed index, and a "ball bank" indicator showed sideslip information. Figure 2 shows the symbology of the test MARS HUD.

SCOPE OF EXPERIMENT

The overall purpose of this program was to determine whether a HUD will assist the pilot of a MARS helicopter with recoveries in low visibility conditions and will also enhance training and standardization. The experimental objective was to determine whether a no-roll presentation is acceptable for MARS operations. If not, is a roll-stabilized horizon bar acceptable? Specific questions to be answered were: (1) What changes in MARS performance (precision and smoothness of control, airspeed control, and maintenance of the sight picture) are attributed to the HUD? (2) What is the pilot workload change induced by the HUD? (3) What are pilot preferences for, and potential operational problems associated with roll-stabilized and non-roll-stabilized HUD formats? and (4) What changes in HUD format, data, or procedures will help improve MARS performance?

The evaluation was originally planned to be conducted in two phases, both to be flown from Davis-Monthan AFB, Arizona, in visual flight conditions. Phase I was to be flown using 80 lb weights with modified personnel parachutes (TWs) as targets. Actual engagement was not planned. A counterbalanced experiment was designed using the two HUD presentations (roll-stabilized - RH, and no-roll - NR) and a no HUD control (NH). The experiment was arranged to yield useful data with as few as four subjects and six sorties, although the planned numbers were six subject pilots and ten sorties.

Phase II was to follow and consist of two MARS recoveries of 1800 lb dummy vehicles (DVs) with tandem parachutes (main and engagement parachute system described above). This phase was intended to validate the results of Phase I which used single parachutes as targets with no recoveries. During Phase I, the advantages of the HUD were so obvious that Phase I was curtailed at the minimum allowed in the experimental design. Phase II was expanded to include a thirty day operational evaluation at an operating location (OL). During this evaluation, eighteen operational drones were recovered using the HUD.

PHASE I: INITIAL TESTING

Each subject pilot flow on one or two sorties. A sortie consisted of approximately thirty minutes of familiarization with the HUD, followed by up to twelve simulated MARS passes to TWs. All three HUD configurations were used on a given sortie: RH, NR, and NH. The order was varied to minimize the effect of learning. Each subject pilot completed a pre-experiment questionnaire, rating cards after each series of passes, a post-flight questionnaire, and a post-experiment questionnaire. The safety pilot completed a rating card after each pass.

A total of six sorties were flown using four subject pilots. All four subjects were well qualified in CH-3 MARS operations. CH-3 flying experience ranged from 800 to 1800 hours with a total flying experience range of 2500 to 2950 hours. All pilots were CH-3 instructor pilots. The safety pilots were also CH-3 instructor pilots. One of the subjects also served as a safety pilot after he completed his flights as a subject. None of the pilots had flown any HUD-equipped aircraft prior to this evaluation.

Pre-experiment Questionnaire

In addition to establishing the subjects' qualifications, the questionnaire asked for their assessment of the MARS mission. Counting the safety pilot and the copilot on one Phase II DV recovery, six questionnaires were completed. The consensus was that the most significant visual problem was determining the position relative to the engagement parachute in the absence of a natural horizon. The pilots also commented on the difficulty of transitioning from keeping the parachute on the horizon to passing over the canopy just prior to engagement. Two pilots felt that roll information would be very important in a MARS HUD, but not essential. Three felt that it would be desirable, and one pilot had a neutral opinion.

Subjective Workload

There was no major change in overall subjective workload as reported by the pilots. However, sideslip was perceived as easier to control with either HUD than with no HUD. Roll was reported to be easier with the RH configuration than with the NR HUD. Table I shows the data.

Need for Additional Data

The pilots all felt a need to come "inside" for more data than was shown on the HUD. All reported a need for airspeed until they adapted to the airspeed indexes. All required vertical velocity data. Most required sideslip information with NH, but either HUD provided this data to the pilots' satisfaction. Roll and pitch data were required in the absence of a HUD by some pilots; the RH configuration eliminated the need to come inside for either. One pilot felt a need for torque or RPM.

The need for additional data is summarized in Table II. The HUD was felt to be useful only during final approaches since the horizon bar was displaced beyond the limits of the combiner glass during the turns to final approach.

No focus or visual conflict was reported. Two pilots reported difficulty with the airspeed cue. Comments were also made about the HUD blocking the view of the parachute as it passed beneath the helicopter.

Performance

Under the excellent visibility conditions present at Davis-Monthan AFB, there was no difference in the miss rates (reported by the safety pilot or by the pole operator) between the RH and the NH configurations. Both had miss rates of 22% (4 misses in 18 passes). The absence of roll data causes the miss rate to increase to 28% (4 misses in 14 passes). This is not statistically significant.

Concern Over High or Low Passes

The pilots were generally less concerned over high or low passes with the HUD than without. One pilot commented that while he was less concerned in general, the loss of sight of the parachute on short final (blocked by the HUD hardware) did bother him. (Note: this subject pilot also flew as a safety pilot and as a subject pilot during Phase II and felt that it was not a problem after adaptation.) Either HUD configuration caused the "hits" to be concentrated at the pole tips.

Other Comments

Additional comments were made. Significant comments (paraphrased) are: (1) Airspeed too far from center (3 subjects), (2) Display should be moved closer to pilot (3 subjects), (3) HUD would help training by providing a common sight picture to instructor and student (3 subjects), (4) Practice time was too limited (3 subjects) and the learning curve was slow for airspeed control (1 subject), and (5) The horizon line should be made more intense than the aiming V (1 subject).

PHASE II: OPERATIONAL EVALUATION

Following the decision to conduct an operational evaluation at the OL, the two pilots chosen to fly the evaluation each flew a training sorties consisting of practice MARS approaches to two TWs, followed by a sorties with an actual recovery of an 1800 lb DV. The two pilots were already experienced with the HUD, having flown as safety pilots in Phase I (one also flew as the first subject).

The HUD was removed from the helicopter used for Phase I and for the four sorties described above. It was then taken to the OL and installed in another CH-3. Eighteen operational recoveries were made at the OL during the month of April 1975. Only the RH display was used for recoveries during this phase, although the NR mode was briefly evaluated during other flying in the haze conditions prevalent at the OL.

Both DV recoveries at Davis-Monthan AFB were made on the first pass. Of the eighteen HUD-assisted engagements at the OL, sixteen were made on the first pass*, one on the second, and one on the third pass. One mission had a no-HUD recovery (4th pass) because of excessive display vibration. The miss rate using the HUD was 14% (per pass).

Benefit of HUD

The second operational sortie typifies the benefit of the HUD. On this sortie, the load line break-ties had separated from the main canopy resulting in the engagement parachute lying over and remaining at the same altitude as the main canopy. With the horizon obscured by haze, rain, and clouds, the HUD allowed a successful recovery on the first pass. The pilots felt that in the absence of a HUD, there would have been multiple missed passes and very likely a lost drone.

The pilots felt that pilot workload was much lower with the HUD.

Visual Illusions

Both pilots commented on an illusion during passes with the HUD in marginal weather. They had the illusion of being correctly lined up with the engagement parachute, but the HUD showed them to be high. Confidence in the

* Counting one tear-out as a successful pass

HUD from their experience in Arizona allowed them to use the HUD to correct their flight paths and make consistent catches.

Need for Roll-Stabilization

The HUD proved to be highly satisfactory under adverse weather conditions with roll-stabilization; but without roll a serious problem was encountered. Both pilots felt that manuevering in haze induced vertigo. They considered that roll-stabilization was an essential requirement for use in reduced visibility.

DISCUSSION

Operational Effectiveness

There were 77 MARS passes during the evaluation. Of these, fifty passes were made to 80 lb TWs and success/failure was estimated by the safety pilot or pole operator. The remaining 27 passes were made to DVs or to actual drones with success being defined as an engagement (or a tear-out). Of the 77 total passes, twenty-five were made during drone recoveries in haze at the OL. The remaining passes (50 TWs and 2 DVs) were made in good weather in Arizona.

We must further separate the data into learning and steady-state performance. To do this, we shall classify all no-HUD passes as steady-state since all subjects were considered to be highly qualified by their organizations. All Phase I passes with either HUD should be considered as learning passes. The actual recoveries made using the roll-stabilized HUD, both DVs and operational drones, can be classed as steady-state performance. Thus we have 32 learning passes and 45 steady-state performance passes.

The performance comparison between the two HUD versions can only be based on the learning data. Because of the small sample size, the difference in miss rates is not significant.

To compare the performance of the RH and the no-HUD baseline, we must use steady-state performance and, as a result, equate the difficulty of making passes to TWs and to tandem parachutes, although the motion of the tandem parachute system makes actual recoveries harder. Likewise, we must equate the difficulty of operating in Arizona in good visibility to the difficulty of operating at the OL in haze and smoke. Since the NH passes were mostly made to TWs at Davis-Monthan AFB, these assumptions are heavily weighted against the HUD.

Nevertheless, the miss rates were much lower with the HUD (3 misses in 23 passes or 13%) than without the HUD (32% missed). Again the limited data precludes any statistical test (χ^2=2.29, df=1, 0.2>p>0.1). However, in view of the heavily biassed test conditions, this difference in miss rates should be considered valid.

Mission Success Rate

To convert from miss rate (i. e., fraction of passes missed) to mission success rate (i. e., fraction of drones recovered), we use the familiar parallel redundancy formula:

$$\text{MISSION SUCCESS RATE} = 1 - (\text{MISS RATE})^n$$

where n is the number of passes possible before the drone is too low for a safe pass. With a typical value of n = 3, we can compute the mission success rates. For the roll HUD, the learning curve performance is 98.9% and the steady-state performance in 99.8% of all drones recovered. The steady-state baseline (no HUD) performance is 96.8%.

Again, the assumptions favor the no HUD case. If we look at the one sortie where the HUD malfunctioned (3 misses out of four passes), the corresponding mission success rate for no HUD in haze would be 58%. This figure is consistent with mission recovery rates of less than fifty percent which have been reported in no-horizon conditions.

Flight Safety

The primary hazard during MARS operations is collision with the parachute. During Phase I, it was noticed that the successful passes with the HUD were concentrated at the pole tips. This effect is probably the result of the aiming V helping the pilot to make a smooth transition to allow the parachute to pass beneath the helicopter into the engagement window. While this effect was only noticed with passes to TWs, it will undoubtedly reduce the number of nose or belly slaps during training and certainly minimize the risk of a catastrophic collision. It is not clear whether the aiming V should be adjustable to accommodate different size parachutes. The pilot opinions were divided and no tests were conducted.

While no particular problems with the no-roll HUD were noted during flights in good weather, the pilots at the OL did report a strong tendency toward vertigo when flying the no-roll HUD in restricted visibility. This represents an unacceptable hazard.

One sortie was cancelled because of invalid pitch data on one HUD. This can be a serious hazard in instrument weather conditions or if the horizon is not visible. Serious consideration should be given to incorporating an instrument comparator to warn against invalid data. Failing this, crew procedures must be developed to ensure that discrepancies are noted. However, it will be difficult for the non-flying pilot to crosscheck his HUD with his panel instruments.

Displayed Data Requirements

The basic MARS HUD was intended to display pitch, sideslip, and airspeed with an optional roll display. The pitch display was the primary display needed for MARS. Since sideslip and airspeed were critical for successful engagements, they were also included. Part of the experimental design was to evaluate the need for roll. The HUD also included an aiming V to assist the pilot during the transition just prior to engagement. During the evaluation, pilot comments suggested that vertical velocity data be added.

Pitch. Lack of adequate pitch cues from the horizon was the original reason for the HUD. We can, therefore, presume that pitch is a requirement for a MARS HUD. However, with a pitch malfunction, the airspeed, sideslip, and vertical velocity data would still be useful. Pitch failure, then, need only extinguish the pitch and roll displays (and the aiming V).

Roll. Roll can be considered a requirement primarily as a vertigo avoiding measure. Roll failure must extinguish the pitch and roll displays.

Airspeed. No test without airspeed was conducted. We conclude from pilot comments that it is required. Airspeed failure need only extinguish the speed indexes.

While the use of the three symbol airspeed display is adequate for determining both the actual airspeed and trends, some learning over and above the normal HUD familiarization seems to be needed.

Sideslip. Likewise, no specific evaluation of a no-sideslip HUD was done. Based on pilot comments, we conclude that it is a requirement. The original ball bank display was too hard to read for small sideslip angles. As a result, the opaque ball was changed to a triangular shaped sideslip index. The display, as modified, is adequate for the MARS mission. Bad sideslip data need only extinguish the ball bank display.

Vertical Velocity. The original display had no vertical velocity data. However, the majority of the pilot comments indicated a need for such data. The reason for this can be found in the Air Force handbook on instrument flying(7). This approach divides the flight instruments into control and performance instruments. The pilot makes his control inputs be reference to the control instruments (such as ADI or power/thrust) and monitors the aircraft's response by reference to the performance instruments (airspeed, heading, or vertical velocity).

The MARS pilots, having made a pitch or power correction to fly up or down relative to the parachute, felt the absence of a vertical performance instrument to monitor their corrections. This explains the need for vertical velocity data. Apparently, they felt able to do without a power control instrument. Perhaps, kinesthetic feedback from the collective position was sufficient. One pilot did comment on the absence of torque or RPM data.

During the recovery after engagement, the pilot must, at maximum torque, trade altitude for airspeed. During this transition, the vertical velocity data is also needed. A torque display is not needed since the pilot can sense maximum torque from the RPM droop. As a result of these observations, the production MARS HUD incorporates a vertical velocity display. Preliminary pilot comments to this addition were favorable.

Aiming V. The aiming V was commented on favorably by the subject pilots. However, no concensus could be reached on the need for different Vs for different sized parachute canopies.

Modified Display. As a result of the testing and pilot comments, the symbology was changed for the production MARS HUD hardware. The revised format it shown in Figure 3.

CONCLUSIONS

The HUD system (with roll) will enhance MARS performance during periods of reduced visibility. It will also enhance safety during training by causing the passes above the target parachute to be higher — reducing the chances of the helicopter's striking the parachute. Roll stabilization is a safety-of-flight requirement to avoid vertigo in no-horizon weather conditions. Roll-stabilization appeared to improve performance over the no-roll case; however insuffient data was available for a statistically valid test.

Pilot workload is much lower when using the HUD. Training to use the HUD should require practice passes to 2-4 training weights, assuming a MARS-qualified pilot. The ability to make full use of the airspeed cue on the HUD may require additional time. The airspeed learning curve seems to be quite variable from pilot to pilot.

The MARS HUD should display pitch, roll, sideslip, airspeed, and vertical velocity data. A reliable self-test circuit is highly desirable. The horizon line should be more distinct than the aiming V.

While the HUD should enhance crew training and standardization as well as mission performance, operational flight procedures should be reviewed shortly after fleet use begins.

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HUD	Controlled Parameter	Number of Responses 1 Very Easy	2 Easy	3 Medium	4 Hard	5 Very Hard	Mean Value
No HUD	Airspeed		1	2	1	1	3.4
	Vertical Velocity		1	2	1	1	3.4
	Pitch		2	3			2.6
	Sideslip		2	2	1		2.8
	Roll		3	2			2.4
	Overall		1	2	1	1	3.4
Roll HUD	Airspeed		1	3	1	1	3.33
	Vertical Velocity			4	1	1	3.5
	Pitch		3	2	1		2.67
	Sideslip	1	4	1			2.0
	Roll		5	1			2.17
	Overall		1	3	1	1	3.33
No-Roll HUD	Airspeed		2	1	3		3.17
	Vertical Velocity		2	1	3		3.17
	Pitch		3	2			2.4
	Sideslip	1	4	1			2.0
	Roll		4		1	1	2.83
	Overall		1	3	2		3.17

TABLE I

SUBJECTIVE DIFFICULTY OF MAKING PASSES

Configuration	Number of Questionnaires	Number of Times Parameter Cited by Pilot						
		Airspeed	Pitch	Roll	Sideslip	Altitude	Vertical Velocity	RPM or Torque
No HUD	6	6	2	3	4	1	6	1
Roll HUD	6	3				1	3	1
No-Roll HUD	5	3		2		1	2	1

TABLE II

NEED FOR ADDITIONAL DATA

NOT SUPPLIED BY HUD

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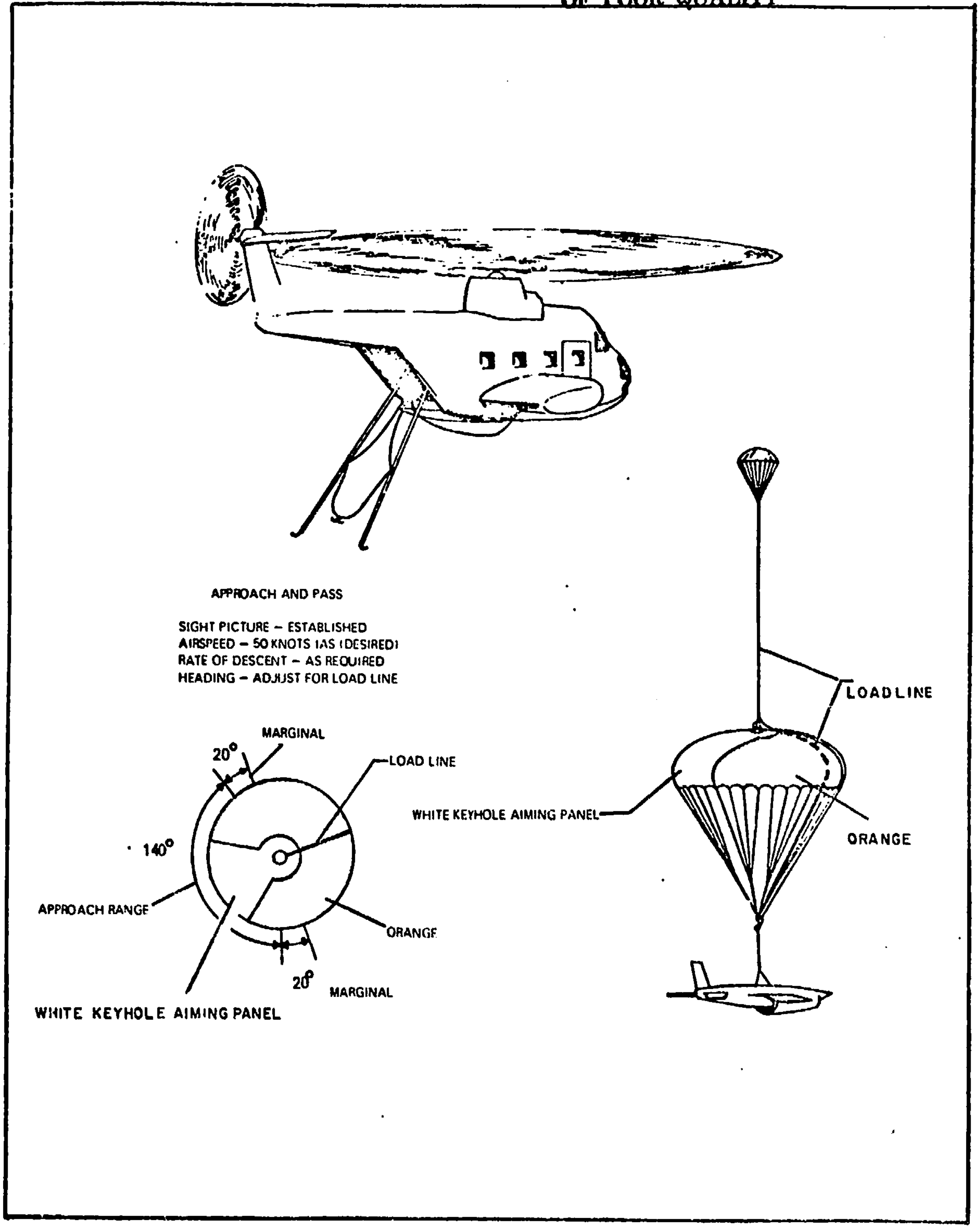

Figure 1

Helicopter Approach and Pass

(From Reference 8)

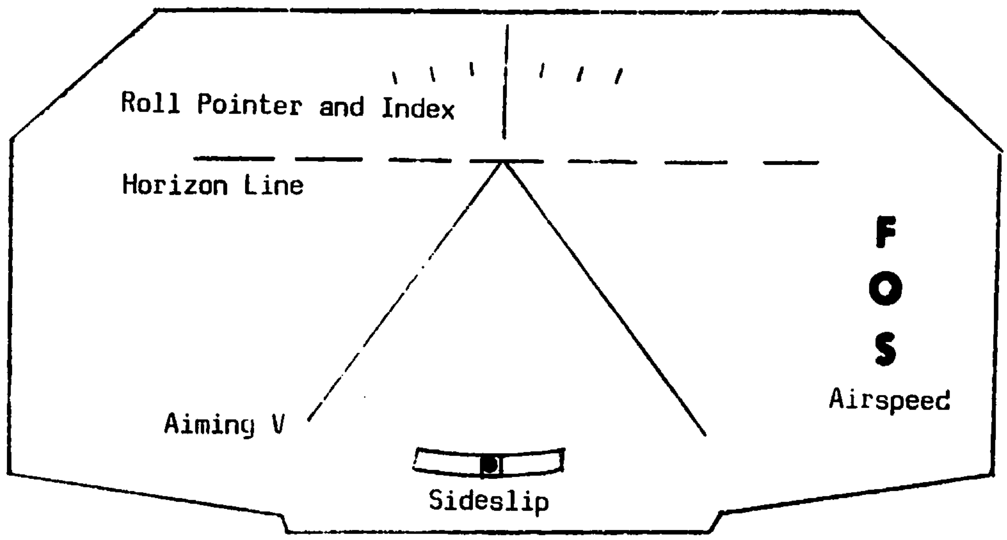

Figure 2

MARS HUD Display Format

(As Tested)

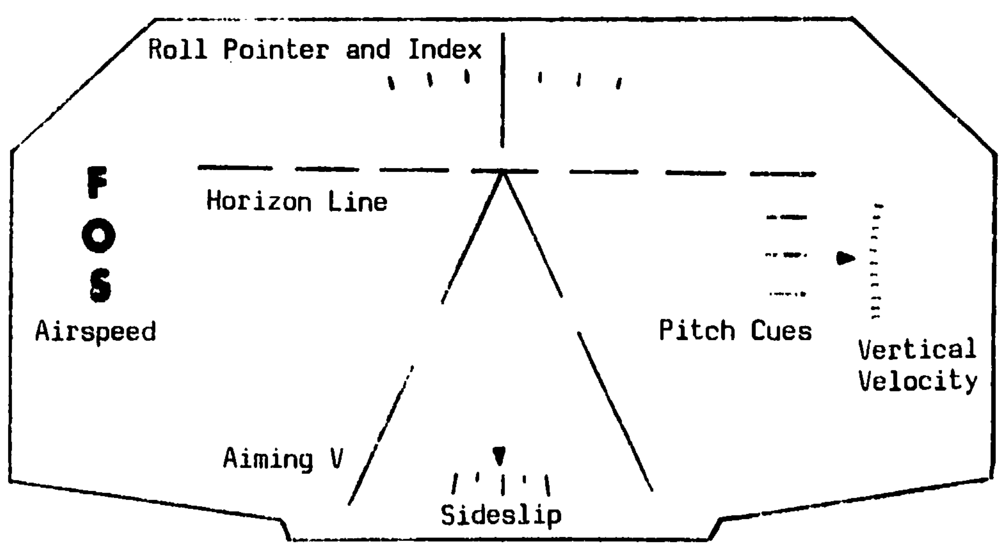

Figure 3

Revised Display Format