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SUMMARY

A short-eye-relief optical system, consisting of two monocular periscopes with overlapping fields of view, was mounted in an F-104B airplane to evaluate the feasibility of using this type of indirect viewing system in place of normal vision for performing simulated lifting-body approaches and landings. Three approach techniques were used in the study. Performance was evaluated by measuring touchdown distance from a marked touchdown point and rate of sink and airspeed at touchdown. Results obtained with the optics system were compared with normal-vision results.

The ability of the pilots to perform the simulated lifting-body tasks was not noticeably reduced with the optics system. The workload and other pilot acceptance factors, however, indicated that this particular system required improvement in design, even though the pilots could readily adapt to its use.

Preliminary efforts to provide inserted head-up display information in the optics system field of view were unsatisfactory. This was attributed to errors in format design and the basic desire of the pilots to concentrate their attention on outside visual cues during the flare and landing part of the task.

Although the results of this flight evaluation are acceptable in terms of optics-system evaluation, it was apparent that more effort is required in the development of local-area navigational techniques, specifically to include limited-visibility conditions, and the manner in which other forms of information can be combined with outside vision to augment these techniques.

INTRODUCTION

One of the critical flight tasks to emerge in the development of future space vehicles is the navigation and landing of wingless lifting bodies. With conventional aircraft, controllable thrust is used to simplify approach and landing problems. The lifting body, however, has less glide-slope control and therefore provides the pilot with a more limited capability to compensate for errors in judgment.

Recent terminal-area flight experience shows that the lifting bodies tested are reaching the point of operational feasibility (refs. 1 and 2). However, these current vehicles all have extensive glass surfaces which provide a large field of view to the pilot but present significant structural design problems because of entry vehicle dynamics and heating. Thus, one of the problems which must be overcome prior to design of an operational manned lifting entry vehicle is that of providing pilot visibility (ref. 3). Accordingly, a program to investigate the feasibility of using an indirect viewing system to provide visibility for terminal-area navigation and approach and landing tasks was undertaken.

NASA Flight Research Center pilots maintain proficiency for lifting-body flights by practicing steep approaches and landings in an F-104 airplane, using speed brakes, takeoff flaps, extended gear, and a low thrust setting to attain a lift/drag ratio (L/D) comparable to that available in a lifting body. Because of the suitability of the F-104 aircraft, the optical system used in this study was installed in the rear cockpit of an F-104B. This same system, which consists of short-eye-relief monocular periscopes, was used in an earlier study of conventional aircraft landings (ref. 4). The results of that study were that the optic system was basically acceptable for performing the normal landing task, but that the effects of exaggerated stereopsis on or near the ground left some doubt concerning the system's applicability to low L/D approaches and landings. Prior to the present study, it was felt that the pilot might need some additional information to safely flare and land when using the optics. Therefore, for a portion of this study, a display of pressure altitude, radar altitude, radar-altitude rate, and indicated airspeed was inserted into the field of view of the left periscope of the optics system.

Since it is not possible to separate optics results from navigation techniques, three different approach techniques were used in this study. The circling-approach technique was developed and used extensively at Edwards Air Force Base, Calif., with unpowered vehicles landing on marked runways on the dry lakebed. However, this pattern requires a greater field of view than was presented by the optics system, so the pilot would have to utilize side-window visibility as well as the optics. Therefore, it was desirable to include in the evaluation the investigation of two other approach patterns which require forward visibility only: a straight-in approach, and a three-turn multiple-aim-point approach.

This paper discusses the ability of the pilots to adapt to the indirect viewing system, the effects of exaggerated stereopsis in the system, and the acceptability of a head-up display inserted into the system. Comments by participating pilots are presented in a program-evaluation questionnaire in the appendix.

SYMBOLS

Measurements in this investigation were taken primarily in the U. S. Customary System of Units. Where applicable, equivalent values are indicated parenthetically in the International System of Units (SI). Factors relating the two systems of units are presented in reference 5.

d	distance from proposed touchdown point, feet (meters)
g	units of acceleration

h	altitude, feet (meters)
$\dot{h}$	rate of sink, feet/second (meters/second)
L/D	lift/drag ratio
Δ	root-mean-square deviation

SYSTEM DESCRIPTION

The system used for this investigation consisted of two 90° field of view periscopes mounted in the rear cockpit of an F-104B airplane (figs. 1 and 2) to provide the pilot with a total lateral field of view of 130° with a center overlap region of 50° (fig. 3). The optics are 1 to 1 magnification and therefore conserve visual direction. Their function can be described best as a displacement of the pilot's eyes to the position of the lens objectives. In the present system this results in six times normal eye separation, or exaggerated stereoscopic vision. The advantage of this type of optical system is that it provides the maximum field of view and light intensity for a minimum size of hardware, thereby making very efficient use of the light captured.

The general features of the system installation, geometry, and folding mechanism are shown in figures 2 and 3; a more detailed description is given in reference 4. The optics system design and optical properties are described in reference 6.

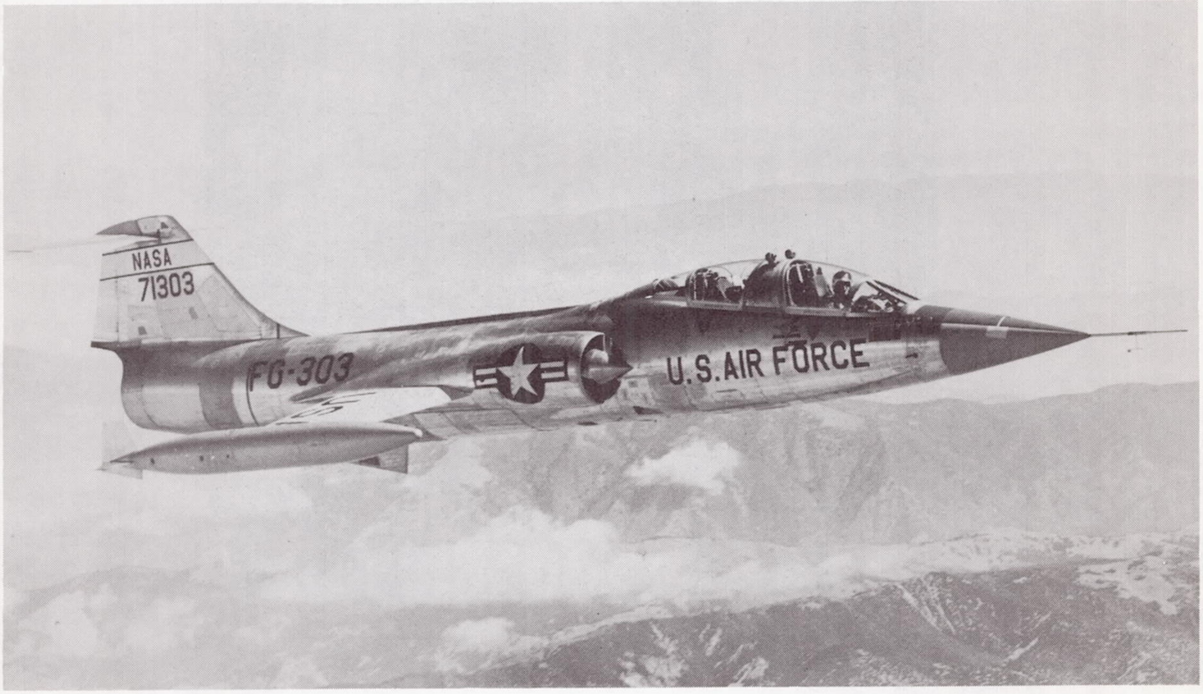

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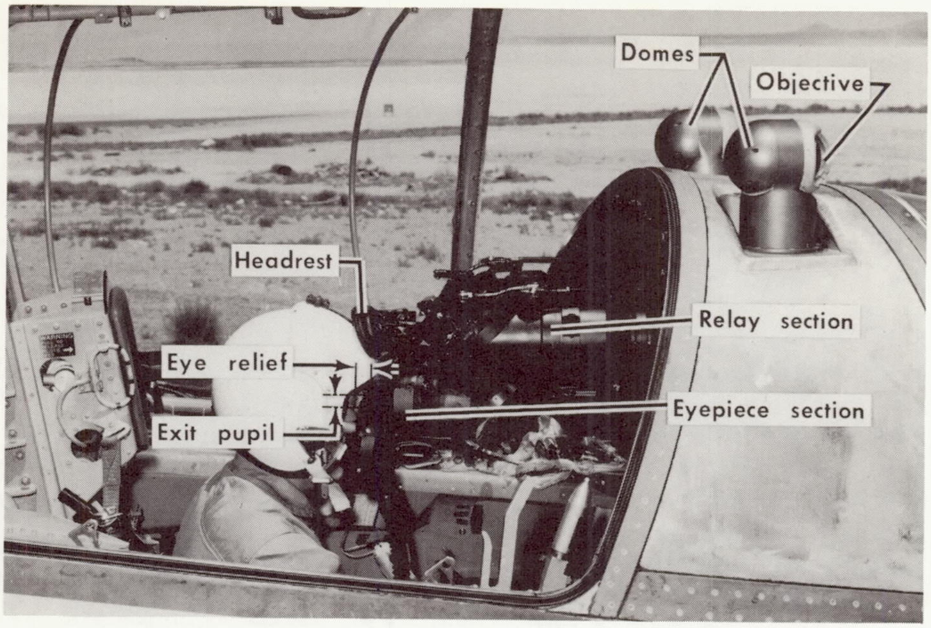
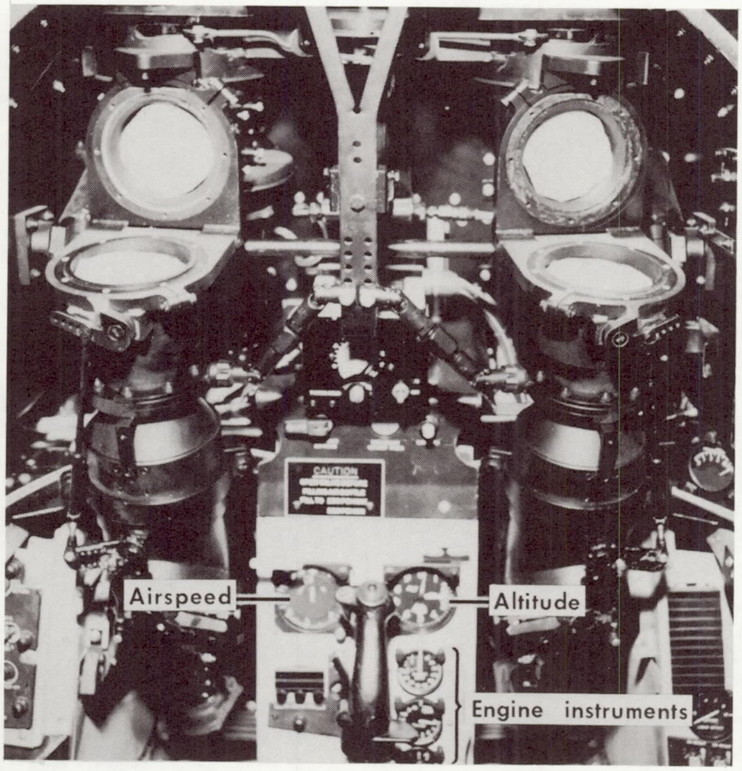
Figure 1.– Photograph of F-104B test airplane with the indirect viewing system.

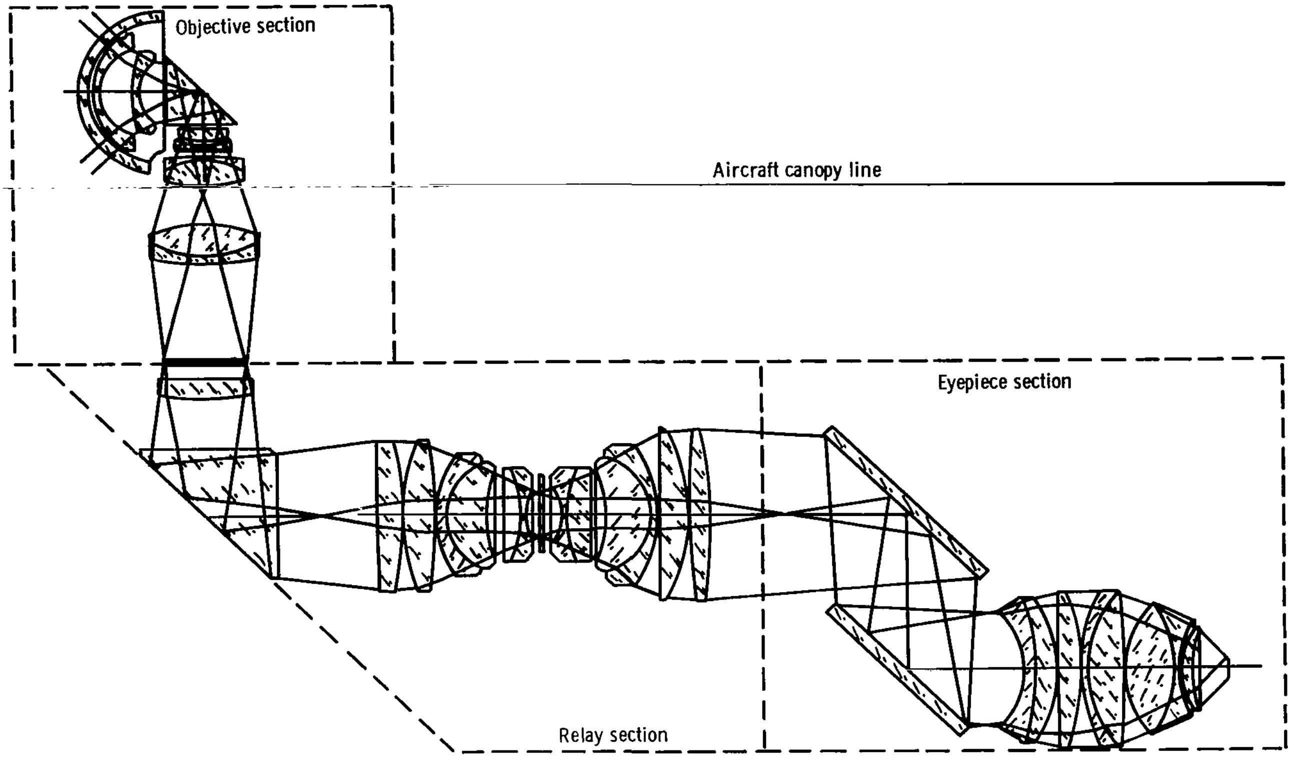


(a) Side view.

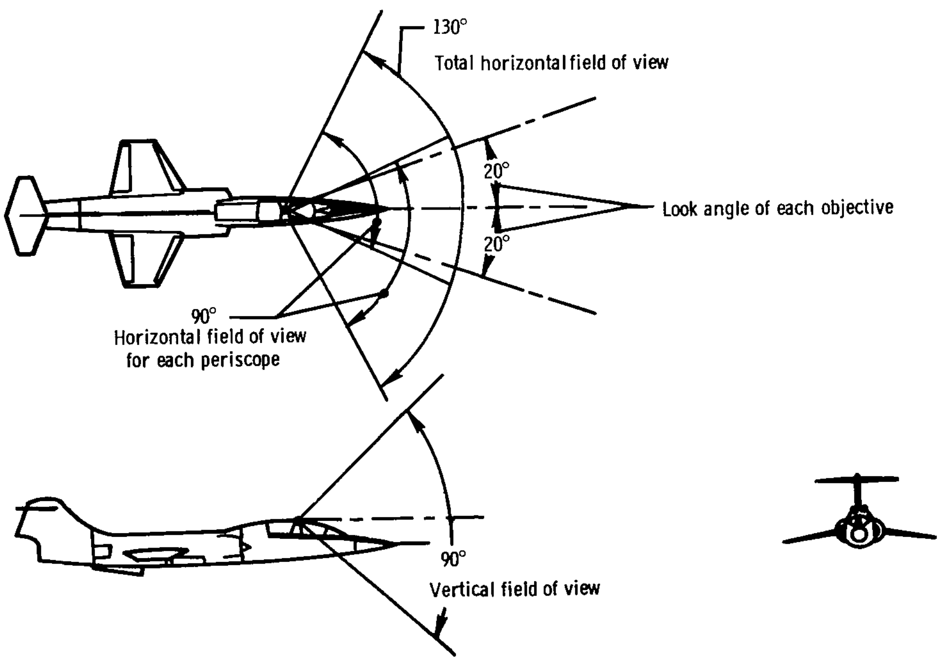


(b) Folded optics.

Figure 2.– Optics system and instrument panel in the rear cockpit of the F-104B aircraft.



(a) Optical layout of the system.



(b) Field of view of the system.
Figure 3.– Optical system geometry.

The inserted display system investigated consisted of a symbol generator and associated electronics used to generate pointers on the face of a cathode-ray tube. Through the use of a beam splitter included in the left periscope, these arrows appear on the scales of a fixed reticle within the optic system. Both the reticle (dark lines) and pointers (bright lines) are at optical infinity. The format used in the display is shown in figure 4. Multiple arrows in the radar altitude and radar-altitude rate scales read the same values with different scale factors.

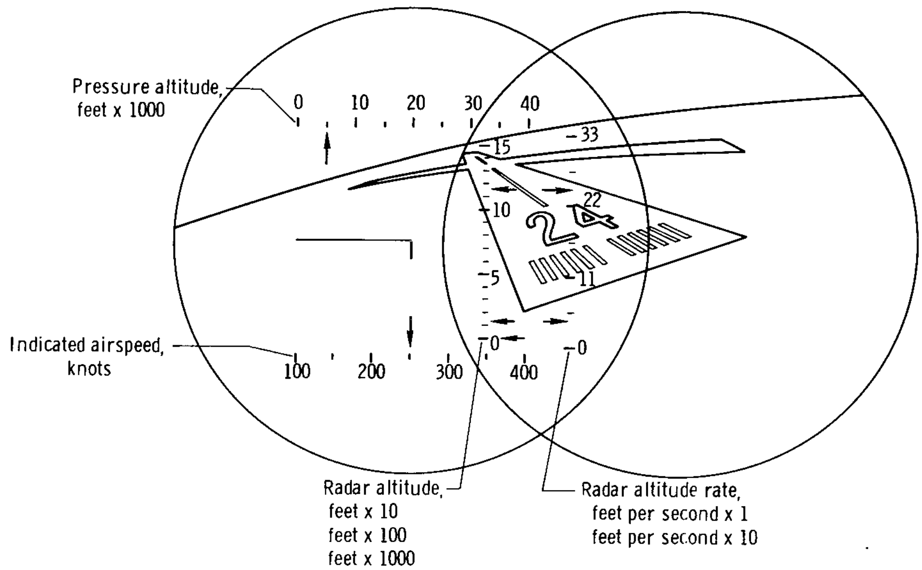


Figure 4.– Inserted display format with runway and horizon in background.

PROCEDURES

General

Three pilots, all highly experienced in the low L/D approach and landing task, participated in the flight tests. Three approach techniques, described in the following section, were flown. To compare results with optics to results without optics, each pilot flew each of the three approach techniques from the front cockpit of the F-104B using normal vision and from the rear cockpit using the optics system. A total of 18 data flights was performed. A safety pilot occupied the front cockpit during all flights in which landings were made using the optics. Approximately four touchdowns per flight were made at Edwards Air Force Base, some on a marked runway on the lakebed and some on the main concrete runway. Additional flights, for which no data were recorded, were performed for familiarization purposes and head-up display evaluation.

On all data flights in which the optics system was used, the system had no inserted display information; however, the pilot could obtain pressure altitude and airspeed information by moving his head slightly back from the periscopes and looking downward at the instrument panel (fig. 2(b)).

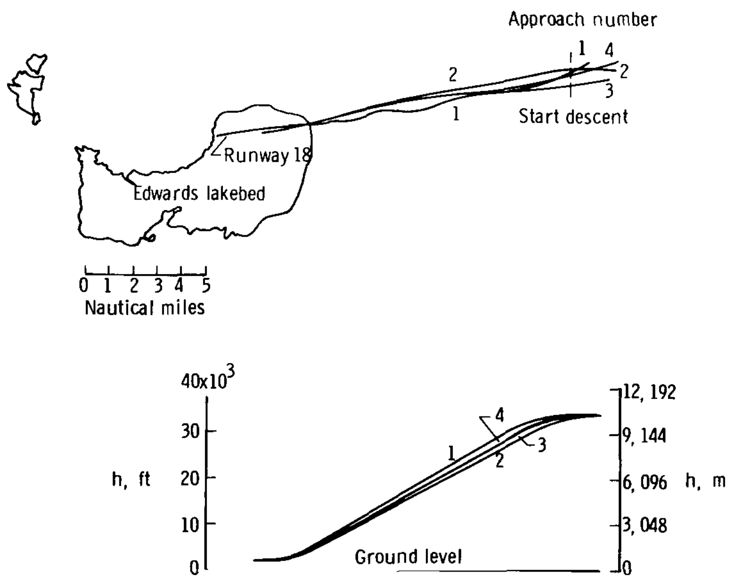
Because of considerable variation in flight conditions (such as haze, wind, turbulence, time of year), the limited number of pilots participating, and the limited number of flights with each approach technique, the results of this study are based as much on opinion as on quantitative measurements.

Approach Patterns Flown

Examples of the three local-area approach patterns flown both with and without optics are shown in the ground radar plots of figure 5. On all approaches the geometry of the F-104B was set to obtain maximum drag with low thrust at the start-descent position. The pilot's only control inputs were through the rudder pedal and stick; thus, no change in thrust or speed-brake setting was permitted.

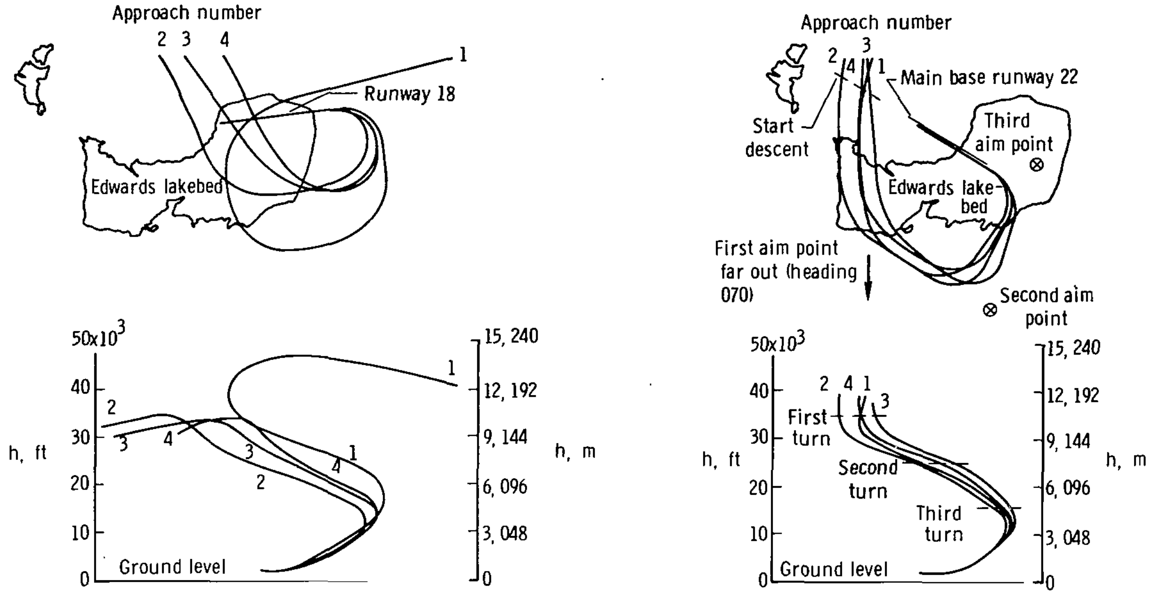
The straight-in approaches (fig. 5(a)) were made from 30,000 feet (9144 meters) pressure altitude, with the ground controller indicating by voice communication when the predetermined start-descent line was reached. Because of the limited number of flights, no deliberate attempt was made to examine the acceptable range of start-descent positions, nor was any compensation made for changing vehicle gross weight on successive runs.

Circling approaches of about 270° (fig. 5(b)) were initiated from about 30,000 feet (9144 meters) pressure altitude without ground assistance. The pilots were allowed to use whatever techniques and visual cues they had developed in normal low L/D proficiency training, including the use of side vision when in the rear cockpit using the optics.



(a) Straight-in approach pattern (flight 2 to runway 18).

Figure 5.– Approach patterns flown.



(b) Circling-approach pattern (flight 3 to runway 18).

(c) Multiple-aim-point approach pattern (flight 18 to runway 22).

Figure 5.– Concluded.

A technique called multiple-aim-point approach (fig. 5(c)) was developed as a substitute for side visibility in the circling approach. With this technique, the ground controller called out when the start-descent line was reached. The pilot then began the descent from 40,000 feet (12,192 meters) pressure altitude and flew toward the first ground aim point (a preselected natural geographic location) until a predetermined pressure altitude was reached. He then turned left and flew directly toward the next aim point until he passed through the next predetermined pressure altitude. This procedure was continued until the final turn was completed. The natural focusing of the pattern made it unnecessary to have an exact start-descent position; however, this focusing required that a significant portion of the approach be straight flight, which necessitated starting at a higher altitude than for the circling approach.

Flare Maneuver

To insure adequate flare and post-flare adjustment capability for landing, it is necessary to increase the approach airspeed to some predetermined value prior to flare. In all cases the start-flare condition was 300 knots indicated airspeed at 1000 feet (305 meters) pressure altitude. Prior to the start-flare point, airspeeds as low as 250 knots were flown to extend the glide capability and provide the pilot with a greater degree of control over ground range. Once the flare was initiated, the touchdown point was variable only by adjusting the airspeed for touchdown; that is, touchdown airspeed and touchdown distance from flare were directly related. The task was to land at a predetermined touchdown spot at approximately 200 knots indicated airspeed with a low rate of sink. Obviously, fulfilling all these criteria after flare was started was unlikely, and the pilots tended to put greatest emphasis on achieving the touchdown point at a sacrifice of touchdown airspeed. To help solve the problem, pilots found it useful to establish a preflare glide slope which would intersect the ground approximately 1 mile (1609 meters) short of the desired touchdown point.

RECORDED DATA

A photographic technique was used to evaluate the landing performance. A camera was placed 2000 feet (610 meters) to the side of the desired touchdown point to photograph each landing, and a cord with markers to provide increments of 100 feet (30.5 meters) on the runway was positioned 25 feet (7.62 meters) in front of the camera parallel to the runway. From the film, the horizontal position of the rear wheels of the F-104B was estimated to the nearest 5 feet (1.5 meters), and vertical height above the runway, to the nearest 0.25 foot (0.076 meter). Wherever possible, height and position readings were taken at touchdown and at about 500 feet (152 meters) and 1000 feet (305 meters) short of touchdown. Using these values and film speed, which was established from a filmed 30-second stop-watch interval immediately before each flight, ground speed and rate of sink at touchdown were estimated. The touchdown position was easily identified from the resultant dust cloud on lakebed landings or from the tire smoke on main-runway landings. Values of velocity obtained from the films were cross-checked with pilot estimates of touchdown indicated airspeed after the necessary temperature, pressure altitude, and wind correction factors were applied. The values were found to be in reasonable agreement, considering the difficulty experienced by the pilots in obtaining such readings (the indicated airspeed dropped off an average of 10 knots per 500 feet (152 meters) near touchdown).

Ground control radar plots, such as shown in figure 5, were recorded for all straight-in and multiple-aim-point approaches and some circling approaches. These plots were valuable in reviewing the navigational techniques and procedures used.

Immediately after each flight, pilot comments were solicited. After completing all six required flights, each pilot filled out a questionnaire (appendix).

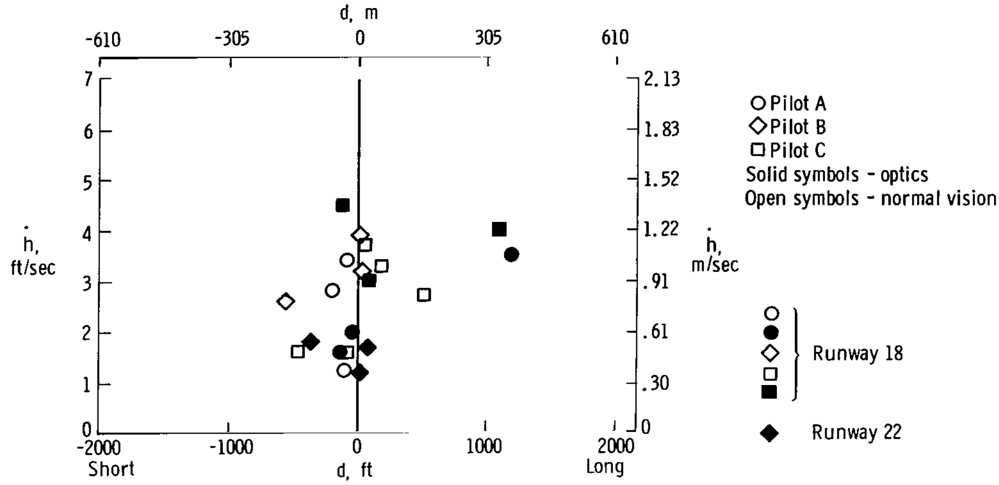
RESULTS AND DISCUSSION

The touchdown parameters measured for the F-104B airplane in this evaluation with each of the three pilots in each of the three approach patterns using either normal vision or the optics system are shown in table I. Average values of these parameters are summarized in tables II and III.

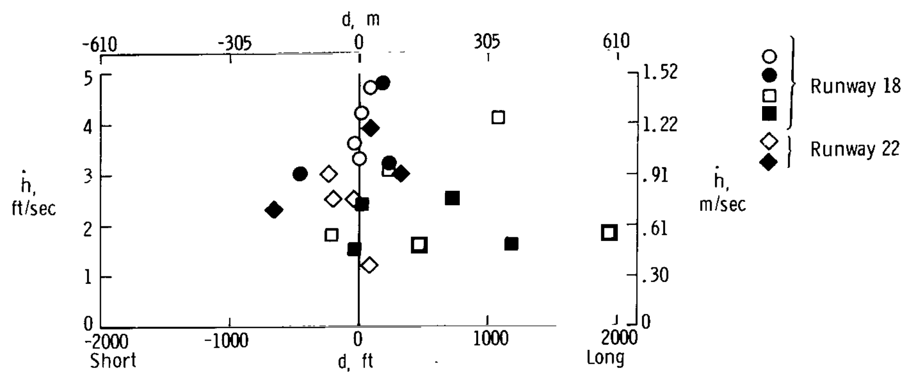
Optics Versus Normal Vision for Flare and Landing

Touchdown data. – Plots of rate of sink at touchdown versus touchdown position and indicated airspeed at touchdown versus touchdown position show no significant difference between landing performance with the optics and with normal vision (figs. 6 and 7). Deviations in touchdown parameters are attributable mainly to pilot proficiency, weather conditions, pattern variations, and vehicle weight.

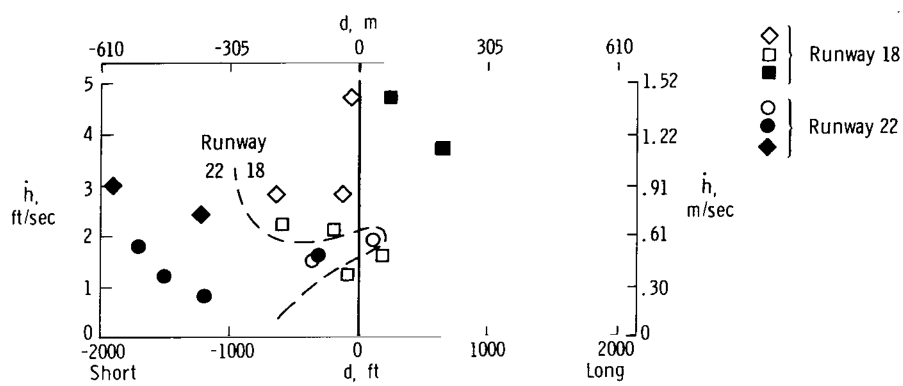
Pilot proficiency: Since practice flights were few, it was typical for the first approach of each flight with each approach pattern to provide the poorest performance results. The problem was primarily in pattern navigation and occurred both with and without optics. The pilot's first estimation of wind conditions contributed to the navigational error.



(a) Straight-in approach.

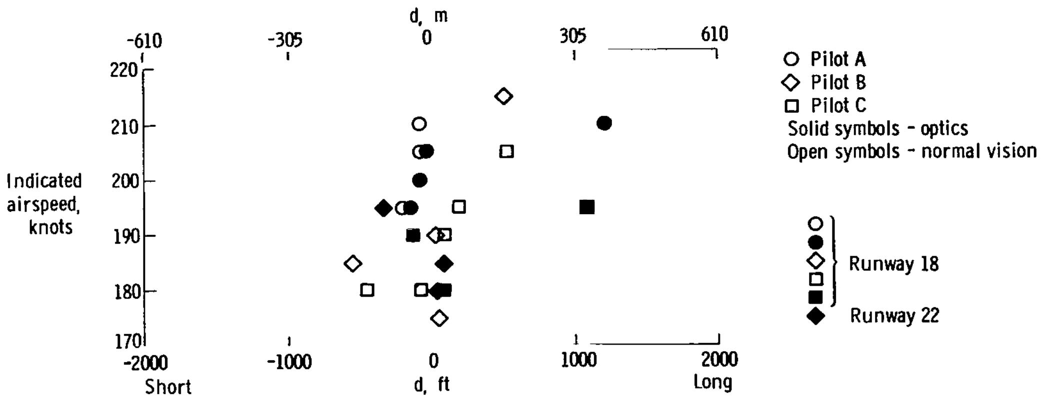


(b) Circling approach.

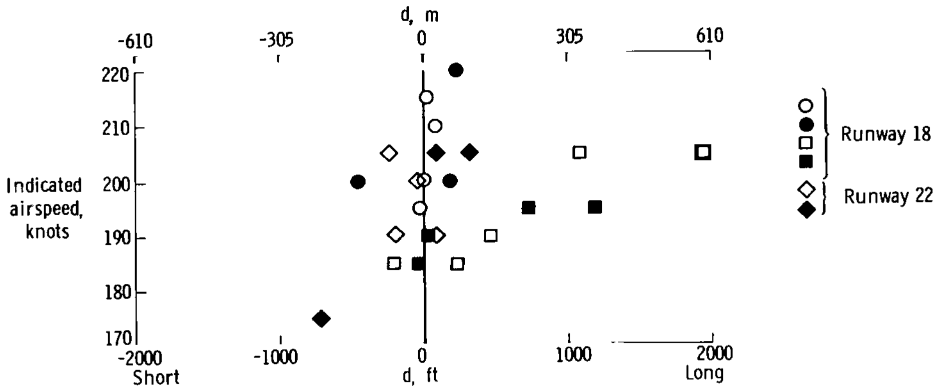


(c) Multiple-aim-point approach.

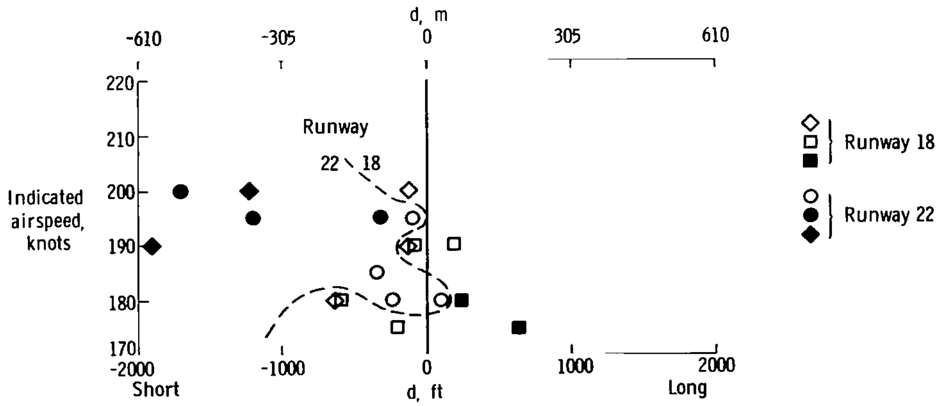
Figure 6.– Rate of sink at touchdown versus touchdown distance for the three approach patterns.



(a) Straight-in approach.



(b) Circling approach.



(c) Multiple-aim-point approach.

Figure 7.– Indicated airspeed at touchdown versus touchdown distance for the three approach patterns.

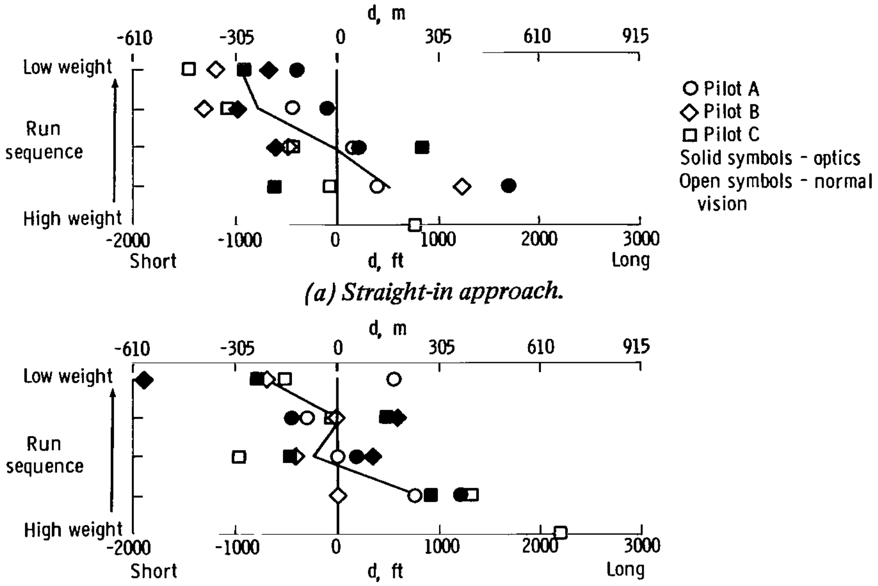
Weather conditions: Wind velocity and turbulence did not have an obvious effect on performance after the first approach of each flight because of the ability of the pilots to compensate. Haze conditions, however, complicated some approaches, since the pilots could not identify desired aim points as easily as in clear-visibility conditions.

Pattern variations: The straight-in approach was originally thought to be the easiest task. In practice, however, this technique offered such limited control of energy that it was difficult for the pilot to compensate for differing aircraft weight conditions during a given flight. This lack of energy control was due in part to the 300-knot gear-down limit, the safety constraint of 300 knots indicated airspeed at 1000 feet (305 meters) altitude for start of flare, and the restriction on the use of speed brakes. The start-descent point seemed very critical in its effect on touchdown positions. The use of optics rather than normal vision appeared to make little difference in the results.

In the circling approach, energy is controlled primarily through the total path length, which can be corrected at any position in the pattern prior to final alinement with the runway. In the circling-approach patterns, pilots initiated their own descents from 30,000 feet (9144 meters) altitude without ground help. Here, flying with the optics was a disadvantage, since the pilot had to make use of side windows for navigational reference to the runway and the optics for forward vision. It was not possible to see forward and sidewise simultaneously, as with normal vision in the front seat.

The multiple-aim-point technique is intended to favor situations in which only forward visibility is possible. As in the circling approach, energy is controlled through path length. Approximately 50 percent of the time must be spent in straight flight, however, to result in proper "focusing" of the paths from an area of start-descent points to a common touchdown point (fig. 5(c)). Thus, it was necessary to fly patterns initiated from 40,000 feet (12,192 meters) altitude rather than 30,000 feet (9144 meters) altitude. Since all turns are initiated on the basis of pressure-altitude readings and all headings are taken from visual aim points, pilot technique should not play a significant role. Thus, approach-pattern results should be the same with the use of optics as with normal vision. The untimely closure of lakebed runway 18, because of rain, made it necessary to transfer to main runway 22 for part of the flights. Unfortunately, the multiple-aim-point pattern flown to runway 22 did not have well-defined natural geographical aim points, so the touchdown position data cannot be considered typical. (The three flights using a multiple-aim-point pattern flown to runway 22 averaged 843 feet (257 meters) short of the desired touchdown position, whereas the three flights to runway 18 averaged 62 feet (18.9 meters) short.)

Vehicle weight: In general, pilots tended to land the airplane beyond the planned touchdown point under high weight conditions and prior to the touchdown point under low weight conditions. Since the start-flare conditions were 300 knots indicated airspeed at 1000 feet (305 meters) altitude, the higher energy and increase in L/D due to higher weight increased the amount of glide time and distance before touchdown (at about 200 knots). This is most easily seen by correcting all touchdowns to 200 knots indicated airspeed, using the correction factor of 10 knots equals 500 feet (152 meters) of distance and plotting the corrected distances versus landing sequence (fig. 8). The multiple-aim-point approaches have been disregarded because of pattern difficulties which tended to invalidate some of the data. The average touchdown distances are seen to fall off about 500 feet (152 meters) for each successive touchdown as fuel weight decreases. The actual weights were not recorded, so a more accurate plot is



(a) Straight-in approach.

(b) Circling approach.

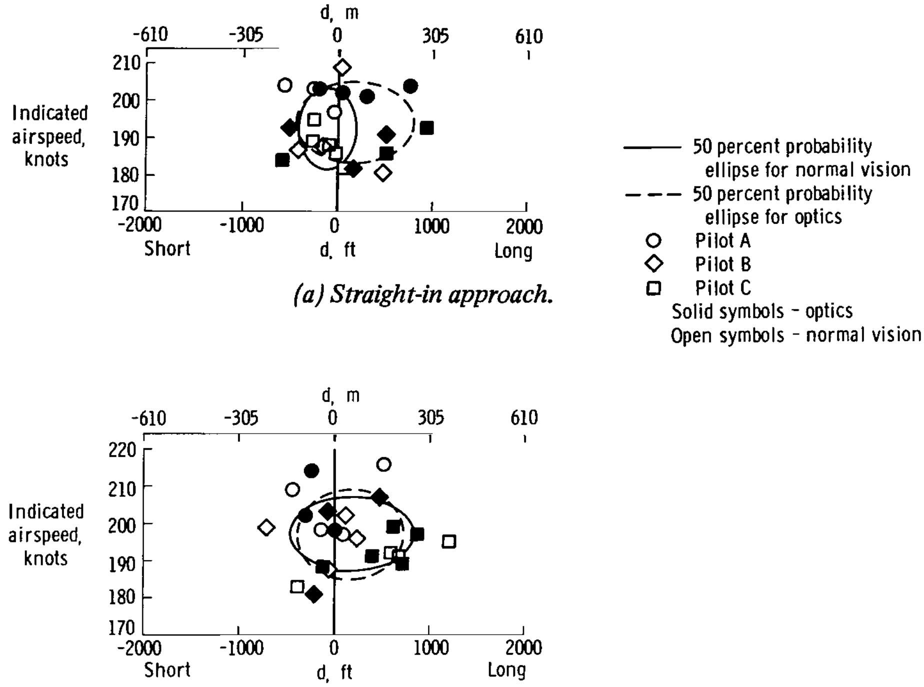
Figure 8.– Vehicle weight versus touchdown distance (corrected to indicated airspeed of 200 knots at touchdown) for straight-in and circling approach patterns.

not possible. When high on energy, the pilot tended to land fast as well as long, the ratio being about 4 knots per 300 feet (91.4 meters). An estimate of the distributions of touchdown velocity and distance from the planned touchdown point for an F-104B airplane at constant gross weight can be made by applying the following corrections to figure 7:

	Touchdown velocity, knots	Touchdown distance, d, ft (m)
Low weight	+6	+450 (+137.2)
↑	+2	+150 (+45.7)
	-2	-150 (-45.7)
	-6	-450 (-137.2)
High weight	-10	-750 (-228.6)

The corrected distributions (fig. 9) are about 15 percent smaller than the uncorrected ones (fig. 7), and the data points are much more symmetrically positioned. Although not apparent, the correlation between velocity and distance is still present but has been subdued by the fact that pilot A tended to land about 10 knots faster than pilot B, who tended to land about 5 knots faster than pilot C. Neglecting these relationships, ellipses of 50-percent probability are shown. It can now be seen that even with the correction for variation in airplane gross weight, there is no consistent difference between optics and normal-vision data. Table IV lists the average values for the touchdown parameters corrected for the gross weight of the aircraft.

Perhaps the most significant measure of the optic system's acceptability is the rate of sink at touchdown. With the optics, the average rate of sink was 2.62 ±0.15 ft/sec (0.80 ±0.05 m/sec), and with normal vision the average was 2.80 ±0.14 ft/sec (0.85 ±0.04 m/sec) (table II and fig. 6). Although this difference is not



(a) Straight-in approach.

(b) Circling approach.

Figure 9.– Indicated airspeed at touchdown versus touchdown distance (corrected to constant gross weight) for straight-in and circling approach patterns.

statistically significant, the pilots may have put greater emphasis on maintaining a low sink rate while landing using the optics system because of less confidence in the system. There can be no doubt, however, that the rate-of-sink information available to the pilot when he is using the optics is adequate for touchdowns to be made safely.

Exaggerated stereoscopic effects. – Whether or not exaggerated stereopsis leads to a more critical sense of rate of sink at touchdown is debatable. In the study on normal landings using the same optics system (ref. 4), the effects of six times normal eye separation consistently provided a low, slow impression just prior to touchdown. In this study of the higher speed landings, however, these effects were largely unnoticed, or appeared only as a lack of certainty concerning height close to the ground. The difference in the two cases could be due to a greater significance of the blur field (the lack of capability of the eye to track large angular rates, causing the areas closest to the observer to appear blurred), which tends to counteract the stereoscopic effects in the following two ways:

1. Stereoscopic effects arise from viewing objects in focus in the near field of view. The blur field forces the pilot to obtain this type of information farther out, and it is therefore less observable. To emphasize this point, the exaggerated stereoscopic effects are observed to be most dominant in taxiing or while stationary where no blur field is present.

2. The blur field itself may provide strong cues in altitude, rate of sink, and velocity interpretation. Although the blurred region is not directly useful in these respects, its extent is a definite function of velocity and altitude, and the pilot is well aware of its presence.

Although there are many ways in which the effects of stereopsis may be observed, they are all based on the concept of distance. Thus, physical parameters such as velocity, energy, and force will also appear modified (i.e., transformed) in the region of exaggerated stereopsis (the near field of view only) in direct relation to their dependence on distance. There is, therefore, a definite consistency, in the sense that these observable parameters are affected to the same extent. (It is not possible, for example, to have an exaggerated stereoscopic concept of depth without a proportionate change in the concept of velocity.) Thus, the blur field, by creating an illusion of speed (through the combination of angular rate and linear extension of the nonblurred region), can counteract the exaggerated stereoscopic impression of altitude as well as velocity. It seems likely from these observations that in fast landings the pilot uses different cues for sink-rate control immediately before touchdown than he uses in slow landings.

Exaggerated stereoscopic effects did appear to be present during flare before the onset of the blur field, but only to a weak extent consistent with the lack of objects in the near field of view. On the basis of this study, though, it is not possible to conclude definitely either from landing results or direct observation that exaggerated eye separation is an advantage or a disadvantage in the performance of the low L/D flare and landing task with the optics system used. This does not imply that nonstereoscopic vision, such as for a pilot using only one eye or a screen-type indirect viewing system, would be acceptable. Resolution and field of view play an important role and were quite generous in this optics system, thereby minimizing to some extent the necessity for stereopsis.

Of further interest was the ability of pilots to observe exaggerated stereoscopic effects through the optics system while using only one eye in normal landings and taxiing. At first this would seem to be self-contradictory; however, these effects were observable only while the aircraft was in motion, which implies that even stereoscopic "depth" is as much a mental conception as a direct visual observation. Further evidence of this is that the stereoscopic effects were observed over the entire field of view when the optics system was used with both eyes, even though only the center region is overlapped. Thus, it may be possible to mentally "compute" exaggerated stereopsis from the combination of motion cues and displaced one-eyed vision. If so, the impression of depth while in motion could be a result of nonvisual as well as visual information.

Adaptation to the optics. — The ability of the pilots to adapt readily to the optics was apparent in both the normal-landing study (ref. 4) and the present study. The third pilot in this study had never flown with the optics system and yet required only one practice flight before making three data flights of low L/D approaches using the optics. A possible factor facilitating pilot adaptability to the optics system is the use of 1 to 1 magnification, which allows the outside world to appear the same as it would with normal vision, except for eye-displacement effects. Also, this magnification minimizes blurring from optics-system vibration. The difficulty of maintaining the best eye position in the optics and the associated eye strain were the pilots' major complaints. These problems seemed to diminish with each flight. The use of the optics is somewhat equivalent to adaptation problems associated with ordinary glasses. Observers who either normally wear glasses or have imperfect vision and who flew in non-piloting roles in the rear cockpit of the F-104B experienced no significant eye strain. It would appear that eye strain is directly related to the individual's quality of vision and developed tolerances. It should be noted, however, that the observers had no task to perform during their use of the optics.

In contrast to the situation that existed when piloting from the front cockpit of the F-104B (with normal vision), no head movements were permitted while piloting from the rear cockpit, using the optics. Thus, the pilot's information was limited for flare and touchdown to clear visibility in the forward direction and peripheral vision to the sides. Pilot comments indicated that this increased the criticality and workload of the task, but not to an extent that would affect the touchdown data. The resolution of the optics was not perfect, but, with the system adjusted to give clear visibility in the forward direction, this was not the limiting factor. The greatest hindrance was the problem posed by the small exit pupils (14-mm diameter). Normal eye rotations and vibrations in flight often displaced the pilot's eyes to the edges of the pupils. Even this would have been satisfactory except that the edges of the pupils provided considerably deteriorated vision compared to the centers. Therefore, it was necessary for the pilot to continuously seek to reposition his eyes to the center of the pupils to maintain clear forward vision. Since this involved both vertical and horizontal positioning, the workload was undesirably high. Less critical eye-position requirements would be a major improvement to the system.

Another factor affecting the resolution of the system was the poor transmission characteristics (about 10 percent) and scattering from internal contamination. This problem could be solved by reassembling the optics and improving the optical coatings. Because a folding mechanism is necessary to accommodate pilot ejection capability, each optical periscope was individually mounted. This resulted in excessive (possibly noncoherent) vibration at times. Also, the periscopes could not be perfectly alined with respect to one another. The right periscope was tilted slightly upward, which tended to provide a right exit pupil significantly lower than the left one. This necessitated certain alinement compromises. Fortunately, the discrepancies in the optical system did not prevent the pilots from obtaining the necessary visual information to perform the task, and the performance data, if not the workload, are believed to be realistic for this type of system.

Inserted Display as an Aid to the Lifting-Body Task

A head-up display format utilizing pressure altitude, indicated airspeed, radar altitude, and radar-altitude rate was inserted into the optics system field of view for evaluation for the simulated lifting-body approach and landing task (fig. 4). Numerous discrepancies became apparent:

1. The scales covered too much area and were difficult to read near the edges of the field of view because of the restriction on head movement.

2. None of the information presented was in a usable form below 1000 feet (305 meters) altitude.

3. The pressure-altitude, velocity, and radar-altitude presentation could be usable as an aid to navigation and for setting up preflare conditions, but the format was poor.

4. More inserted information, including heading and attitude, would be desirable to allow the optics to be used in flight under poor visibility conditions, such as in clouds, or for ground controlled approaches.

5. Electronic drift in the inserted display symbol generator and cathode-ray tube electronics caused inaccuracies in the presentation.

Even though head-up display information is easier to use than panel instruments, the flare maneuver is a particularly critical task, and pilots are reluctant to divert their attention, even momentarily, from the rapidly changing outside visual cues. It is important to emphasize the desirability of completely solving the energy control problem prior to the flare-initiation point. Even the communication of information other than outside observation after the flare has started may be difficult. On the other hand, for the portion of the flight preceding the flare, the presentation of navigational and other energy control information in a head-up display form is thought to be reasonably straightforward.

CONCLUDING REMARKS

A short-eye-relief optical system was mounted in an F-104B airplane to evaluate the feasibility of using this type of indirect viewing system in place of normal vision for performing simulated lifting-body approaches and landings. The system provided adequate visual information for the flare and landing tasks and landing performance characteristics comparable to those obtained with normal vision. Pilots had little difficulty adapting to the use of the optics system. If specific inadequacies, such as the undesirably small exit-pupil size, were corrected in an improved optic design, this type of system could be seriously considered for entry-vehicle application. Since exaggerated stereopsis played only a minimal role during the high-speed landings, the separation of the objective lenses is not critical, and they should therefore be positioned to provide the best field of view to the pilot. The restriction on head motion did not seem to be significant for flare and landing since there was a generous field of view with high resolution in the forward direction. Optics with 1 to 1 magnification are highly desirable, since this magnification factor minimizes blurring with optics-system vibration.

Preliminary efforts to provide inserted head-up display information in the optics system field of view were unsatisfactory. This was attributed to errors in format design and the basic desire of the pilots to concentrate their attention on outside visual cues during the flare and landing part of the task. The use of inserted display information as a means of providing navigational guidance, attitude control, start-flare cues, and landing cues remains to be developed if the theoretical advantages of the head-up display technique are to be realized.

Although the results of this flight evaluation are acceptable in terms of optics-system evaluation, it was apparent that more effort is required in the development of local-area navigational techniques, specifically to include limited-visibility conditions, and the manner in which other forms of information can be combined with outside vision to augment these techniques.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., April 21, 1969,
125-19-01-02-24.

APPENDIX

OPTICS PROGRAM PILOT QUESTIONNAIRE

1. Do you think the field of view was adequate for the task?

Approach	Pilot	
Straight in	(A)	Yes.
	(B)	Yes.
	(C)	From the pushover point it was. I would have had one whale of a time getting there without receiving any vectoring or looking out the side.
Circling	(A)	No.
	(B)	No.
	(C)	Barely.
Multiple aim point	(A)	No.
	(B)	No.
	(C)	It was, once I had started the approach. A heading indicator and attitude indicator are required to ease the task of initial positioning.

2a. Was establishment of glide slope any problem?

Approach	Pilot	
Straight in	(A)	No.
	(B)	No comment.
	(C)	Not really--I could not see any reference to establish the flight path I desired.
Circling	(A)	No.
	(B)	No comment.
	(C)	No.
Multiple aim point	(A)	No.
	(B)	No comment.
	(C)	No--due to the wind it was pretty much max L/D until well into the final.

2b. Maintenance of glide slope once established?

Approach	Pilot	
Straight in	(A)	Slight.
	(B)	No comment.
	(C)	No problem--just cross-check airspeed.
Circling	(A)	No.
	(C)	Easy.
Multiple aim point	(A)	Slight.

3. Is pitch attitude control difficult (i.e., is fuselage reference adequate)?

Approach	Pilot	
All	(A)	No.
	(B)	Fuselage reference is never used even without optics. Desired airspeed determines pitch attitude.
	(C)	It is fair--I would like to see something like a gunsight (ring and bead, etc.) to set up the approach.

4. How did you judge or determine altitude for flare initiation?

Approach	Pilot	
All	(A)	Reference to pressure altimeter for all three.
	(B)	From barometric altimeter in all cases.
	(C)	Altimeter.

5. Were you able to anticipate touchdown accurately and consistently?

Approach	Pilot	
Straight in	(A)	No; generally thought it was going to touch down early for all three.
	(B)	No--the last 5 to 10 feet of altitude are difficult to determine.
	(C)	Yes--after the first one.
Circling	(A)	See straight in comment.
	(B)	See straight in comment.
	(C)	Pretty well.
Multiple aim point	(A)	See straight in comment.
	(B)	See straight in comment.
	(C)	Not as well with the strong crosswind.

6. Did you have any difficulty with pitch-angle control during rotation and climb out?

Approach	Pilot	
All	(A)	No.
	(B)	No.
	(C)	No. Monitor airspeed on climb and aircraft nose and runway relationship on takeoff.

7. Was touchdown g consistent with visual perception of rate of sink just prior to touchdown?

Approach	Pilot	
All	(A)	Yes.
	(B)	No.
	(C)	Yes.

8. Could you positively control rate of sink before touchdown?

Approach	Pilot	
Straight in	(A)	No--because I didn't know when touchdown was going to occur.
	(B)	Not as well as I would like to.
	(C)	Fairly well--adequately.
Circling	(A)	No--because I didn't know when touchdown was going to occur.
	(B)	See straight in comment.
	(C)	Yes.
Multiple aim point	(A)	No--because I didn't know when touchdown was going to occur.
	(B)	See straight in comment.
	(C)	Not as well as before with the crosswind.

9. Did you tend to make pitch inputs just prior to touchdown?

Approach	Pilot	
All	(A)	Yes.
	(B)	No undue pitch inputs.
	(C)	No more than normal.

10a. Where does definite knowledge of height above the ground occur?

Approach	Pilot	
All	(A)	It doesn't with optics.
	(B)	At touchdown.
	(C)	Just a rough guess, approximately 50 feet.

10b. How do optics and normal vision compare?

Approach	Pilot	
Straight in	(A)	About the same down to 50 feet.
	(B)	The optics limit the available information considerably; the optics tend to make you flare too high.
	(C)	Better than I anticipated.
Circling	(A)	See straight in comment.
	(B)	See straight in comment.
	(C)	See straight in comment.
Multiple aim point	(A)	See straight in comment.
	(B)	See straight in comment.
	(C)	They compare fairly well close to the ground, but on the approach everything appears out of focus and hazy.

11a. Did fuel weight have a noticeable effect on the task?

Approach	Pilot	
All	(A)	The more fuel, the longer I tended to land.
	(B)	No.
	(C)	Not really.

11b. Do you compensate in any way?

Approach	Pilot	
All	(A)	Generally flew heavier approaches faster.
	(B)	Yes--high and low key altitude are varied to compensate for changes in wing loadings.
	(C)	Not directly for weight. I just maneuvered or varied airspeed in an attempt to set up the flight path I wanted.

12. Any tendency to change procedures with successive trials?

Approach	Pilot	
Straight in	(A)	No.
	(B)	No.
	(C)	Yes, I find it better to be high in energy most of the way--it is much easier to get rid of energy than to get energy.
Circling	(A)	No.
	(B)	See straight in comment.
	(C)	----
Multiple aim point	(A)	No.
	(B)	See straight in comment.
	(C)	No procedures, but some pattern changes to produce better accuracy.

13a. Does experience seem to improve ability?

Approach	Pilot	
All	(A)	Yes.
	(B)	Yes.
	(C)	Yes.

13b. Confidence in the optics?

Approach	Pilot	
All	(A)	Yes.
	(B)	Yes.
	(C)	Confidence that I can successfully use them is increasing.

14a. What part of the task is most critical?

Approach	Pilot	
Straight in	(A)	Determining the winds aloft and planning a pattern for it.
	(B)	The final portion of the flare.
	(C)	First part of flare for safety--getting correct flight path for accuracy.
Circling	(A)	See straight in comment.
	(B)	See straight in comment.
	(C)	Getting to pre-flare point on this pattern.
Multiple aim point	(A)	See straight in comment.
	(B)	See straight in comment.
	(C)	Flare initiation to level at the proper altitude approaching touchdown.

14b. At what point, if any, do you feel you "have it made"?

Approach	Pilot	
All	(A)	At about 5000 feet when I can see that I'm not long or short.
	(B)	At no point.
	(C)	At touchdown.

15. Using the optics, does –

a. Velocity at touchdown seem consistent with IAS?

Approach	Pilot	
All	(A)	Less so than with naked eye.
	(B)	Yes, although this question is not relevant either with or without optics.
	(C)	Yes.

b. Maximum g in flare seem normal?

Approach	Pilot	
All	(A)	Yes.
	(B)	Yes.
	(C)	Yes.

c. Height above the runway appear normal prior to and during touch and go?

Approach	Pilot	
All	(A)	No--always feel lower with optics than I really am.
	(B)	No--this is the area of greatest uncertainty.
	(C)	No--I felt I was just a bit higher than with normal vision, but it presented no problem after the first approach.

16. Did you feel particularly fatigued at any point in the flight?

Approach	Pilot	
Straight in	(A)	No.
	(B)	Yes, particularly if I did all the flying from the back seat. It was much better if the safety pilot flew the climb back to high key.
	(C)	Eyes hurt after a couple of approaches.
Circling	(A)	See straight in comment.
	(B)	See straight in comment.
	(C)	See straight in comment.
Multiple aim point	(A)	See straight in comment.
	(B)	See straight in comment.
	(C)	Eyes ached right after first approach.

17a. Is airspeed and altitude information (on the panel) adequately presented for the task?

Pilot
(A) Yes, on the aircraft instruments. I never developed any confidence in heads-up display.
(B) No.
(C) Yes.

17b. Would additional information be desirable?

Pilot
(A) Yes. A full aircraft panel would be desirable.
(B) Heading and attitude would be helpful.
(C) I'd like an attitude indicator.

18. Is pre-flare key position (10,000 to 15,000 ft) more easily obtained in straight-in or circling approaches?

Pilot
(A) Circling.
(B) Circling.
(C) Given a good pushover point, the straight-in is easier, but starting from scratch the circling is easier.

19. Are bank angles and turn rates easy to maintain in making turns in patterns?

Pilot
(A) Yes.
(B) Yes, if visibility is unrestricted and the terrain is familiar.
(C) Yes.

20. Do you consider side vision necessary in making multiple-aim-point patterns?

Pilot
(A) No, but desirable.
(B) Yes, until we refine the technique.
(C) Not really in the pattern, but it would help in navigation phase to high key.

21. Does side vision seem preferable to turning on altitude for the final turn?

Pilot
(A) Yes.
(B) Yes.
(C) I would want altitude information with or without side vision. I could see the runway through the optics as I started turning final on all the approaches.

22. Does optics contribute in any way to the navigational problem of establishing pre-flare position compared to front seat operation:

a. Straight in approaches?

Pilot
(A) Pre-flare position not as precisely established with optics.
(B) No.
(C) I could not pick up the 1-mile marker for reference as well through the optics.

b. Circling approaches?

Pilot
(A) Same as a.
(B) Yes--side vision is mandatory.
(C) ----

c. Multiple-aim-point approaches?

Pilot

(A) Same as a.

(B) Yes--side vision is generally desirable.

(C) I think with a "good" set of optics and practice I could do equally as well as flying in the front seat.

23. Compare the three types of patterns in terms of workload.

Pilot

(A) Straight in

(A) Circling

Multiple aim point

Straight in

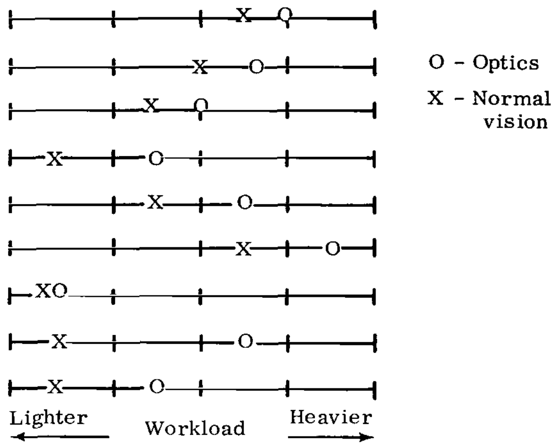
(B) Circling

Multiple aim point

Straight in

(C) Circling

Multiple aim point



24. Can you think of any reasons to prefer one type of pattern over another?

Pilot

(A) Prefer circling solely because of much more practice.

(B) The circling approach with side vision allows one to continually update current energy with respect to the projected desired flight path. This desired flight path is not easily visualized in a straight-in approach and of course cannot even be visualized on the multiple aim point approach until it is almost too late to make any significant change in energy.

(C) Given a good pushover point, the straight-in is easier, but starting from scratch the circling is easier.

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TABLE I. – FLIGHT AND FILM DATA

Flight	Date	Pattern	Visual condition	Pilot	Run	$\dot{h}$ at touchdown, ft/sec (m/sec)	Indicated airspeed at touchdown, knots	d, ft (m)	Weather	Remarks
						Lakebed runway (18)				
1	Aug. 9, 1967	Straight in	Normal vision	A	1	--------	---	------------	85° F (29° C) Wind, calm	Omit--traffic
					2	1.2 (0.4)	210	-105 (-32)		
					3	3.4 (1.0)	205	-80 (-24)		
					4	2.8 (0.9)	195	-190 (-58)		
					5	--------	---	------------		Omit--traffic
2	Aug. 17, 1967	Straight in	Normal vision	B	1	7.0 (2.1)	215	500 (152)	94° F (34° C) Wind: 180°/5 knots Haze	High energy--S turns
					2	3.9 (1.2)	190	15 (5)		
					3	2.6 (0.8)	185	-560 (-170)		
					4	3.2 (1.0)	175	40 (13)		
3	Aug. 18, 1967	Circling	Normal vision	A	1	4.2 (1.3)	215	15 (5)	95° F (35° C) Wind, calm	360° pattern from 45,000 feet
					2	3.3 (1.0)	200	0 (0)		
					3	3.6 (1.1)	195	-50 (-15)		
					4	4.7 (1.4)	210	70 (21)		
4	Aug. 23, 1967	Circling	Optics	A	1	3.2 (1.0)	220	220 (67)	95° F (35° C) Wind, calm	360° pattern from 45,000 feet
					2	4.8 (1.5)	200	175 (53)		
					3	3.0 (0.9)	200	-455 (139)		
5	Oct. 6, 1967	Circling	Normal vision	C	1	1.8 (0.5)	205	1940 (591)	57° F (14° C) Wind: 340°/4 knots	
					2	4.1 (1.2)	205	1070 (326)		
					3	1.8 (0.5)	185	-225 (-69)		
					4	1.6 (0.5)	190	460 (140)		
					5	3.1 (0.9)	185	225 (69)		
6	Oct. 16, 1967	Multiple aim point	Normal vision	C	1	1.2 (0.4)	190	-70 (-21)	63° F (17° C) Wind, calm	
					2	1.6 (0.5)	190	185 (56)		
					3	2.2 (0.7)	180	-600 (-183)		
					4	2.1 (0.6)	175	-110 (-34)		
7	Oct. 16, 1967	Straight in	Normal vision	C	1	2.7 (0.8)	205	515 (157)	70° F (21° C) Wind: 90°/5 knots	
					2	3.3 (1.0)	195	185 (56)		
					3	3.7 (1.1)	190	65 (20)		
					4	1.6 (0.5)	180	-70 (-21)		
					5	1.6 (0.5)	180	-455 (-139)		
8	Oct. 24, 1967	Straight in	Optics	C	1	--------	---	≈-3500 (-1067)	81° F (27° C) Wind. 90°/5 knots Heavy haze	Omit--cannot see aim point
					2	4.5 (1.4)	190	-125 (-38)		
					3	4.0 (1.2)	195	1090 (332)		
					4	--------	---	≈-2700 (-823)		Omit--cannot see aim point above 7000 feet
					5	3.0 (0.9)	180	70 (21)		

TABLE I.– FLIGHT AND FILM DATA (Concluded)

Flight	Date	Pattern	Visual condition	Pilot	Run	$\dot{h}$ at touchdown, ft/sec (m/sec)	Indicated airspeed at touchdown, knots	d, ft (m)	Weather	Remarks
Lakebed runway (18) (Continued)										
9	Oct. 25, 1967	Multiple aim point	Optics	C	1	--------	---	------ ------	80° F (26° C)	Omit--start-descent point way off
					2	3.7 (1.1)	175	635 (194)	Wind: 220°/10 knots	
					3	4.7 (1.4)	180	230 (70)	Strong cross wind	
10	Oct. 26, 1967	Circling	Optics	C	1	1.6 (0.5)	195	1175 (358)	Wind, calm	
					2	2.4 (0.7)	190	20 (6)		
					3	2.5 (0.8)	195	725 (221)		
					4	1.5 (0.5)	185	-50 (-15)		
11	Nov. 8, 1967	Multiple aim point	Normal vision	B	1	--------	---	≈-1000 (-305)	71° F (22° C)	Omit--start-descent position way off
					2	4.7 (1.4)	200	-60 (-18)	Wind, calm	
					3	2.8 (0.9)	180	-645 (-197)	Heavy haze	Cannot see ground above 25,000 feet
					4	2.8 (0.9)	190	-125 (-38)		
12	Nov. 9, 1967	Straight in	Optics	A	1	3.5 (1.1)	210	1205 (367)	Wind: 230°/20 knots	
					2	2.0 (0.6)	205	-35 (-11)	Gusty	
					3	--------	200	≈-100 (-30)		Not filmed
					4	1.6 (0.5)	195	-140 (-43)		
Main runway (22)										
13	Dec. 12, 1967	Circling	Normal vision	B	1	3.0 (0.9)	205	-240 (-73)	Wind, calm	
					2	1.2 (0.4)	190	75 (23)		
					3	2.5 (0.8)	200	-35 (-11)		
					4	2.5 (0.8)	190	-210 (-64)		
14	Dec. 20, 1967	Circling	Optics	B	1	3.9 (1.2)	205	85 (26)	35° F (2° C)	
					2	3.0 (0.9)	205	325 (99)	Wind: 240°/7 knots	
					3	2.3 (0.7)	175	-660 (-201)		
15	Dec. 20, 1967	Straight in	Optics	B	1	--------	---	----- ------		Omit--start-descent too far back
					2	1.8 (0.5)	195	-350 (-107)		
					3	1.2 (0.4)	180	20 (6)	Wind: 270°/10 knots	
					4	1.7 (0.5)	185	80 (24)	Gusty	
16	Jan. 16, 1968	Multiple aim point	Normal vision	A	1	--------	195	≈-100 (-30)	Wind: 220°/10 knots	Not filmed
					2	--------	180	≈-250 (-76)		Not filmed.
					3	1.5 (0.5)	185	-350 (-107)		
					4	1.9 (0.6)	180	105 (32)		
17	Jan. 26, 1968	Multiple aim point	Optics	B	1	--------	---	≈-4000 (-1219)	Wind: 270°/20 knots	Omit--wrong aim point
					2	2.4 (0.7)	200	-1220 (-372)		
					3	3.0 (0.9)	190	-1900 (-579)		
					4	--------	---	≈-3000 (-914)		Omit--initial heading way off
18	Jan. 29, 1968	Multiple aim point	Optics	A	1	1.8 (0.5)	200	-1700 (-518)	47° F (8° C)	
					2	1.6 (0.5)	195	-320 (-96)	Wind, calm	
					3	0.8 (0.2)	195	-1190 (-363)		
					4	1.2 (0.4)	---	-1500 (-457)		

TABLE II. – SUMMARY OF RATE-OF-SINK DATA AT TOUCHDOWN

Figure	Approach pattern	Visual condition	Average $\dot{h}$, ft/sec (m/sec) (1)	$\Delta\dot{h}$, ft/sec (m/sec)
6(a)	Straight in	Normal vision Optics	3.08 ±0.29 (0.94 ±0.09) 2.59 ±0.27 (0.79 ±0.08)	±1.02 (±0.31) ±0.81 (±0.25)
6(b)	Circling	Normal vision Optics	2.88 ±0.21 (0.88 ±0.06) 2.82 ±0.21 (0.86 ±0.06)	±0.74 (±0.23) ±0.67 (±0.20)
6(c)	Multiple aim point	Normal vision Optics	2.31 ±0.24 (0.70 ±0.07) 2.40 ±0.32 (0.73 ±0.10)	±0.72 (±0.22) ±0.89 (±0.27)
Total		Normal vision Optics	2.80 ±0.14 (0.85 ±0.04) 2.62 ±0.15 (0.80 ±0.05)	±0.81 (±0.25) ±0.75 (±0.23)

(1)Average shown is the mean value plus or minus the probable error of the mean. Probable error of the mean for n measures a_1, a_2, $a_3 \ldots a_n$, the mean of which is m, is given by the expression

$$\frac{0.6745}{\sqrt{n-1}} \sqrt{(m-a_1)^2 + (m-a_2)^2 + \ldots (m-a_n)^2}$$

TABLE III. – SUMMARY OF AIRSPEED AND AIRCRAFT POSITION DATA AT TOUCHDOWN

Figure	Pattern	Condition	Average indicated airspeed, knots (1)	Δ indicated airspeed, knots	Average d, ft (m) (1)	Δd, ft (m)
7(a)	Straight in	Normal vision Optics	194 ±2.5 194 ±2.1	±8.7 ±6.7	-12 ±62 (-4 ±19) 172 ±113 (52 ±34)	±216 (±66) ±357 (±109)
7(b)	Circling	Normal vision Optics	198 ±1.8 197 ±2.6	±6.6 ±8.3	238 ±116 (73 ±35) 156 ±112 (48 ±34)	±418 (±127) ±355 (±108)
7(c)	Multiple aim point	Runway 18 Runway 22	184 ±1.9 191 ±1.7	±5.7 ±5.2	-62 ±90 (-19 ±27) -843 ±157 (-257 ±48)	±269 (±82) ±496 (±151)

(1) See footnote, table II.

TABLE IV. – SUMMARY OF AIRSPEED AND AIRCRAFT POSITION DATA AT TOUCHDOWN (CORRECTED FOR GROSS WEIGHT)

Figure	Pattern	Visual condition	Average indicated airspeed, knots (1)	Δ indicated airspeed, knots	Average d, ft (m) (1)	Δd, ft (m)	a, ft (m) (2)	b, knots (2)
9(a)	Straight in	Normal vision Optics	192 ±1.8 194 ±1.8	±6.1 ±5.6	-112 ±52 (-34 ±16) 202 ±109 (62 ±33)	±180 (±55) ±344 (±105)	±314 (±96) ±600 (±183)	±10.6 (±3.2) ±9.8 (±3.0)
9(b)	Circling	Normal vision Optics	197 ±1.6 197 ±2.1	±5.6 ±6.5	180 ±99 (55 ±30) 156 ±95 (48 ±29)	±358 (±109) ±300 (±91)	±625 (±191) ±524 (±160)	±9.8 (±3.0) ±11.3 (±3.4)

(1) See footnote, table II.

(2) For 50-percent ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$, the uncorrelated Gaussian distribution curve is $\frac{1}{2\pi} e^{-\frac{1}{2}\left(\frac{x^2}{\Delta x^2} + \frac{y^2}{\Delta y^2}\right)0.6745^2}$ where Δ is the 50-percent probability range of a single parameter. Integration yields $a = 1.745\ \Delta x$ and $b = 1.745\ \Delta y$.

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