NRL Report 6581

Optical Guidance Systems: Analysis, Design, and Development

A Summary Report of NRL Research on Night Carrier Landing

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July 20, 1967

NAVAL RESEARCH LABORATORY
Washington, D.C.

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Project Personnel

This report summarizes the significant accomplishments to night carrier landing safety by the Human Engineering Development Section of the Engineering Psychology Branch.

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ABSTRACT

The Naval Air Systems Command is conducting a program to increase the safety of landing high-performance aircraft aboard carriers, particularly during nighttime operations. Believing that this objective could be achieved only by a general increase in the precision of the total system, NRL undertook an analysis of the configuration in use. Two primary sources of system inaccuracy, and therefore accident potential, were located in the use of the present display system. These are (a) insufficient display gain or sensitivity, and (b) the absence of a direct presentation of any derivative signals, or alternatively of an error signal from which the necessary rate information can be accurately derived by the pilot.

Efforts were directed, therefore, toward development of a new display to provide optimum guidance information to the pilot in an optimum manner. During the five years spent on this project, a number of new display schemes evolved which can be categorized in two general types: (a) direct displays of rate-error information, and (b) displays of position-error information in a form such that the pilot is able to extract the necessary rate information. The main displays of type a are the Rainbow Optical Landing System and the Altitude Rate Command (ARC) System. Other display concepts in this category include several modifications to the Rainbow system, namely a different color sequence to encode error rate, a different beam pattern for generating error-rate corrections, and the so-called Rainbow meatball, which is the precise combination of Rainbow and Fresnel lens systems. The outstanding display of type b is the Depth of Flash Optical Landing System. Other display concepts of this class are the Laterally Compounded Fresnel Lens Optical Landing System, the Ten-fold Fresnel Lens Optical Landing System, the Shadow Box Optical Landing System, which reproduces the optical characteristics of the Fresnel lens system, the Audio system, the Phi Flash system, and several variations of a Depth of Flash system.

New, unique concepts in error-signal encoding are the basis for most of the displays named previously. The most significant of these are color-sequence, intensity-sequence, and depth-of-flash encoding. Another novel concept, characteristic of the new displays, is the utilization of the principle of backward viewing of a projected beam pattern to receive highly precise information at extremely long range, with no sensors required other then the pilot's eye and no data link other than the visual one.

Fabrication of the various displays for the purpose of validating new concepts led in turn to development of new techniques. A particular innovation is the mechanism developed primarily to produce the Rainbow presentation, but which is capable of providing several other types of displays. The heart of this mechanism is a "rotating slide," or drum, upon which are superimposed various patterns. The colored transparency pattern developed for the Rainbow system required that new techniques be used to preserve color characteristics through the numerous photographic stages necessary to obtain the required pattern precision. The nature of the Rainbow system led to and made possible the application of the analytical technique described in the approach-path study. The design of the ARC drum pattern is based on an idea for achieving precise levels of light attenuation by means of a moving pattern of opaque vertical bars, the amount of attenuation being determined by the duty cycle of these "screening" bars. The process of obtaining continuously changing gradation in intensity in a projected image by means of defocused shadow bars is exploited in the dual-projector Depth of Flash system. A lensless projection system was developed and called the Shadow Box system. Evaluations of several systems were made at NATC Patuxent River.

Various characteristics of the human eye were considered and utilized in the determination of desirable display characteristics: the eye's ability to act (a) as a summing device for light projected from two adjacent sources, (b) as a signal differentiator of sequencing colors or intensities, or flash depth, or (c) as an "averaging" device which causes duty-cycle change to appear as light-level change.

PROBLEM STATUS

This is a final report; work on this problem under this project has been completed.

AUTHORIZATION

NRL Problem Y02-21
Project A34-537/016/652-1/F012-06-02

Manuscript submitted April 12, 1967.

OPTICAL GUIDANCE SYSTEMS: ANALYSIS, DESIGN, AND DEVELOPMENT

A Summary Report of NRL Research on Night Carrier Landing

INTRODUCTION

The general safety of carrier operations and particularly the accident rate of aircraft landings aboard ship are matters of prime importance to the Navy. Almost every incident which contributes to the accident statistics represents a significant loss of manpower and equipment. Some accidents are attributed to aircraft malfunction, which includes such factors as power failure, landing gear failure, or electrical malfunction; and some are assigned to pilot error, which includes errors in judgment or poor control technique.

The Naval Research Laboratory believes, however, that many accidents attributed to pilot error are results not of poor pilot performance but rather of the nature of the system, made up of the pilot, his aircraft, the displays, and the environment. In fact, NRL has suggested that pilot performance during an approach to a safe landing may be qualitatively no different from that on an unsuccessful approach which results in a bolter (aborted landing), or perhaps an accident. According to this theory, such accidents are blamed on the inherent lack of precision of the man-machine system, and are even predictable on a statistical basis.

For the past several years, NRL has conducted a research project oriented toward reducing the accident rate by increasing the accuracy of the man-machine system. The work has encompassed analysis, design, development, and experimental validation of new concepts. Concurrently, consultative services on subjects related to the general topic of carrier landing have been provided to government agencies and contractors. These services include attendance at meetings where work on the problem is reported, evaluations of written proposals or reports, and numerous discussions with interested people working in the area or with cognizant naval personnel. These conferences are documented in 76 Consultative Service Reports (1).

The analytical effort was primarily a study of the pilot-aircraft-display-environment system, to discover the nature of the control task required of the pilot if the overall system is to achieve a predetermined level of accuracy. The mathematical description of his "required" task was then examined in the light of general knowledge of and experience with the control capabilities of the human. When it appeared that the accuracy requirements and the nature of the control system were placing exceptionally high demands on the pilot, attention was directed toward locating the source from which such demands on pilot performance stemmed.

The difficulty was found to arise in the characteristics of the display system presently in use. Attention was then directed toward modifying this display or designing new optical landing aids to provide the pilot with the control information necessary for an accurate landing. In the course of development of these displays, various types of light

modulation were used as new means of signal encoding. Some basic work in this area was required to optimize the displayed signal with respect to the characteristics of the human eye. Fabrication of some of the new displays led to the development of unique mechanisms to produce the desired projected light-modulation patterns. New photographic techniques were evolved which preserved color characteristics throughout a number of processes and which provided in a simple manner the precise attenuation of a light source. All of the new techniques developed in the course of this work will be discussed more fully with reference to the specific systems to which they were applied.

The purpose of fabricating some of the displays was primarily to permit in-flight validation of the new concepts. The research scientists made many flights in light aircraft to observe the displays from the air in order to optimize various parameters and to determine operationally their potential contribution toward increased accuracy in landings aboard ship. Demonstration flights were also made to acquaint other scientists and interested naval officers with the various systems.

ANALYSIS

STATISTICAL NATURE OF ACCIDENTS

Many of the accidents in landing aircraft on carriers occur because the aircraft is in an inappropriate position, attitude, or direction of motion at the termination of the approach to the carrier deck. These accidents, which are clearly not a result of some aircraft malfunction, such as engine failure, are generally attributed to "pilot error." This is another way of saying that the pilot was not controlling the aircraft with sufficient accuracy at the time of touchdown.

This question of "pilot error" leading to an accident can also be viewed as a statistical event, however. In the control of any vehicle there is, at any one time, an ideal value for each parameter of vehicular control. Further, there is, at nearly all times, some deviation from the ideal, however small. If the nature of the distribution of these deviations as observed at various instances is known, it is a relatively simple matter to predict the frequency with which deviations of a given size will occur.

In the case of carrier landings, there is both an ideal point of touchdown and an ideal direction of motion at the time of touchdown. These ideals are almost never exactly achieved, and there is therefore some deviation from each ideal to be expected in nearly every landing. The criterion of success is a "safe" landing. However, an examination of these deviations and the establishment of the nature of their distribution will underline the fact that there will be a small percentage of the landing events which, while drawn from the same population which makes up these satisfactory events, constitute deviations sufficiently large to result in an accident. Such an accident would be commonly attributed to pilot error, yet it is not an occurrence which is qualitatively different from successful landings. Rather it is an event near the extreme of the distribution of landings.

Let us consider hypothetically a typical distribution curve for the location of touchdown points along the deck and for the direction of aircraft motion at the moment of touchdown. These particular parameters were chosen for discussion because the precise control of each is critical to the execution of any successful landing, but particularly aboard ship, where the envelope of acceptable touchdown points is much smaller than for the ten-thousand-foot runways available at most naval airfields.

For the sake of illustration, suppose that the most frequent point of touchdown is located at a point along the deck such that the aircraft will engage the third arresting wire. However, a large number of landings are characterized by touchdown points such that the second or fourth wire is engaged. A few landings have touchdown points which lead to engagement of either the first or the last wire, and fewer still have touchdown points so far from the desired point of impact that the last wire is missed, and occasionally there is a deviation in the landing sufficiently great as to constitute a ramp strike. Figure 1 shows such a hypothetical distribution curve of touchdown points along the carrier deck. (A similar curve could be drawn, of course, for lateral deviation, i.e., lineup.) From this curve it is apparent that the cases of ramp strikes or missed wires leading to bolters fortunately would occur so rarely that they would fall along the extremes of the distribution curve.

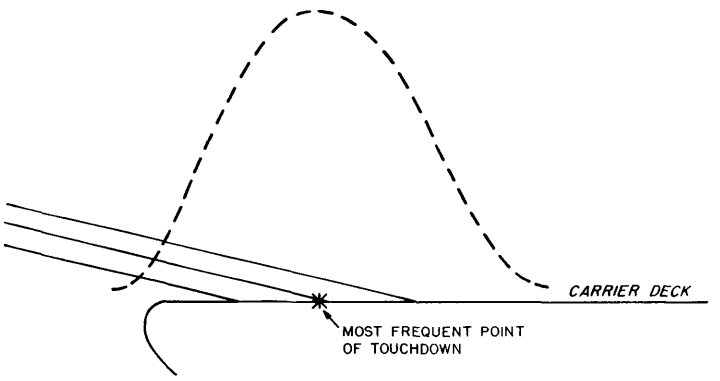


Fig. 1 - Hypothetical distribution of touchdown points along the deck

Acceptable control of a given parameter can be defined, then, as that control which places the individual values within a given number of standard deviations from the mean. Likewise, an event falling near the extreme of the distribution is considered to represent insufficient accuracy of control and, therefore, to be the cause of an accident. Once the nature of the distribution of touchdown points is determined from actual data, it is a straightforward matter to predict the frequency with which accidents due to improper touchdown point will occur. By the same procedure, it is possible to predict the rate of accidents arising from the improper control of other parameters.

A similar analysis could be made, for instance, of the control of direction of motion of the aircraft at the time of touchdown. This flight parameter is of particular interest in carrier landings, since the pilots fly the aircraft into the deck, rather than flaring just prior to touchdown. Large errors in direction of motion often result from last-minute corrections in flight path when it appears that an error in touchdown point is developing. Diving for the deck results in increased airspeed and can lead to hard landings and collapsed gear. At the other extreme, too shallow a glide path can easily terminate in a ramp strike or in touching down beyond the last wire. A hypothetical distribution curve is drawn for aircraft direction of motion at the time of touchdown (Fig. 2). Once again, it is evident that the events leading to successful landings are located near the mean on the distribution curve, while those falling along the extremes represent accidents. It follows, therefore, that the manner of reducing the accident rate would be to reduce the spread of the distribution of all the critical parameters until more standard deviations are included within the bounds of a safe landing. Ideally, one would like

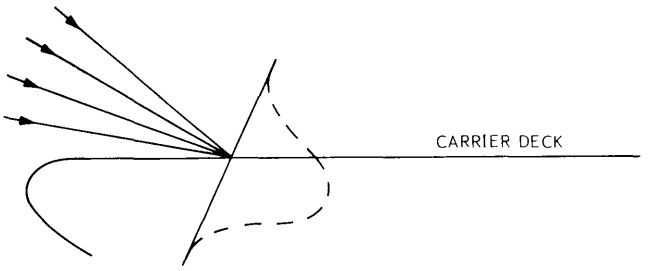


Fig. 2 - Hypothetical distribution of aircraft directions of motion in the vertical plane at the moment of touchdown

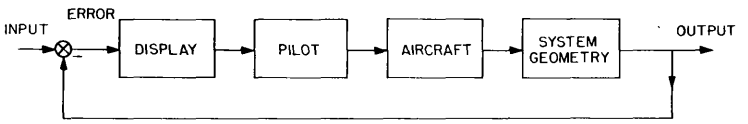


Fig. 3 - Generalized block diagram of a typical man-machine control system

to encompass even the extremes of each of the distribution curves within the domain of safe landings. Reducing the spread of the distribution for control of these parameters is accomplished by increasing the general level of system precision, making it possible for the pilot to execute his landings with consistently improved accuracy.

MAN-MACHINE CONTROL SYSTEM: CONCEPTS AND TECHNIQUES

On the basis of past experience with man-machine control systems, such as the pilot-aircraft pair, the best approach to increasing the precision of system performance is the consideration of the control loop involved in the man-machine system. It is necessary to study the control loop made up of man, vehicle, display, and geometry (time-space environment) in order to determine the dynamic contribution of each system element to overall system performance and also to learn the dynamic interactions among these elements.

The nature of the control system can be represented generally by means of a simple block diagram (Fig. 3). Such a representation of the system serves to clarify the interrelationships which develop among the system elements and which are critical both to a description and to an understanding of system behavior. Once a system is configured in this way, it can be analyzed (a) to determine the overall performance to be expected of this combination of elements, and (b) to locate the sources of any inaccuracies in present system performance. This general philosophy of design of man-machine systems has evolved over a long period of time and experience with manual control systems. It was first used and stated as such specifically, however, with reference to carrier landing precision. The following discussion, presented upon invitation in a working paper prepared for the International Air Transport Association, Fifteenth Technical Conference in April, 1963 (2), is quoted for the purpose of illustrating this philosophy and its implementing methodology.

> In our current work towards the reduction of the accident rate of landings aboard carriers, a general method has evolved to facilitate both the selection of an effective modification to a system and the evaluation of proposed modifications.
>
> Before it is practical to design or select any instrument to aid the pilot in his task, it is first necessary to be able to define explicitly what he must do in order that the man-machine combination may satisfy the criteria describing an optimum response. This definition implements the determination of instrumentation to reduce his task.
>
> It is apparent by now that this method of analysis has as its basis the systems approach to man-machine control problems. Any attempt at such an analysis requires consideration of the human in engineering terminology. Generally, problems of this nature involve a given vehicle which must operate within a given system. The system is itself characterized by an inherent geometry which arises from the physical properties of the configuration.
>
> For purposes of analysis, the vehicle is represented by the transfer function derived from the dynamic equations of motion describing the vehicle. The

dynamics of any display to be included in the analysis can likewise be represented by a describing transfer function. From geometric and trigonometric principles, the transfer function showing the effects of the system geometry and the display geometry can be derived. The only element in the system which cannot be so represented is the human.

Also given in problems of this nature are the required characteristics of the overall, or closed-loop, system response. Such requirements might include, e.g., specifications on the response time of the system, the amount of error tolerable, and/or the necessary degree of stability. These predetermined requirements make it possible to derive the closed-loop system transfer function which the system must exhibit if its response is to satisfy the given criteria.

The inability to write or derive the human's transfer function is a result of the fact that it varies as a function both of the control task confronting him and also of learning. The immediate purpose of this analysis becomes, then, the determination of how the pilot would need to behave in this configuration in order for the system response to satisfy the criteria established for its overall performance.

The emphasis on what the pilot needs to do in the given configuration rather than on what he actually is doing is the distinctive aspect of this method of analysis. The derived function, shown to be required of the pilot in the unmodified configuration, provides a reference for the design of appropriate modifications to simplify his task. . .

In order to illustrate the techniques involved in an analysis such as this, let us take a greatly simplified system and derive the function which must be supplied by the pilot in order for the system to exhibit satisfactory performance. . .

Let this example be restricted, for the sake of simplicity, to the vertical coordinate and the pilot be required to control altitude by matching it to a command altitude. The aircraft is represented by the transfer function which relates flight path angle γ to a stick input δ_e. For simplicity, in this example let this transfer function be $1/s$.* This assumption is a gross over-simplification for purposes of illustration. The actual transfer functions representing such operations are generally of much higher order. Altitude h, however, is the integral of the product of airspeed and flight path angle. If constant speed is assumed, again for the purpose of simplifying the example, the dynamic relationship between h and γ becomes K/s. Let the scaling of the problem be such that $K = 1$. The block representing system geometry can then be represented by $1/s$. One more assumption, for the sake of simplicity, is that the display gain is constant throughout the flight and that there are no time lags inherent in the display. As a result the display geometry can be represented by a transfer function of 1.

Let the unknown transfer function depicting the human be called x. The block diagram for this specific example can now be constructed as shown below.†

Further assume that the required closed-loop system transfer function is $(2s + 1)/(s^2 + 2s + 1)$. (The derivation of this transfer function from the given response criteria can be accomplished by various familiar methods. The selection and application of one of these therefore will not be discussed in this paper.) This required closed-loop system transfer function describes a response which will be characterized by both zero position error and also zero rate error.

From the block diagram of Fig. 2,† the closed-loop system transfer function exhibited by our system can be derived.

*In standard Laplacian terminology "s" represents the differential operator and therefore "$1/s$" the integral operator.
†Figure 4 in this report.

Since $\dot{h} = (h_c - h)(1)(x)(1/s)(1/s)$ and $h(s^2 + x) = h_c(x)$; then

$$\frac{h}{h_c} = \frac{x}{s^2 + x} .$$

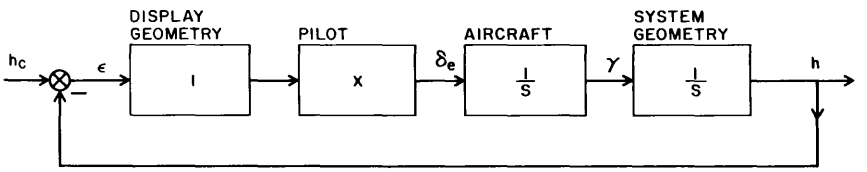


Fig. 4 - System block diagram (see Ref. 2)

If this system is to exhibit a response conforming to the given criteria, then its closed-loop transfer function must be equal to the required closed-loop system transfer function, i.e.,

$$\frac{x}{s^2 + x} = \frac{2s + 1}{s^2 + 2s + 1} .$$

From this equation, it is possible to determine x, the function required by the system of the pilot.

$$x = 2s + 1 . \tag{1}$$

This function, then, represents that element which, if properly inserted in the loop, would cause the closed-loop to behave in the desired manner. Note that no claim is made that this is what the pilot is doing. The function merely represents what he would <u>need</u> to do within the system.

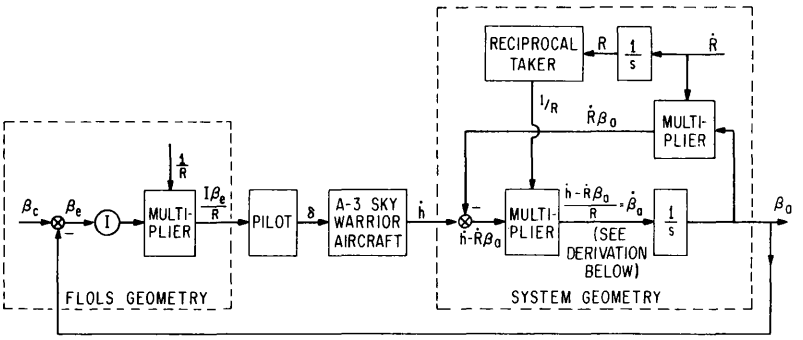
Once this required function has been determined, decisions concerning system modifications to simplify the pilot's task are in order...

...Previous work indicates that the human performs optimally when required to behave only as a simple amplifier. An appropriate modification, then, would be an instrument which performs the necessary time-dependent function for him, that is, an instrument described by the transfer function $2s + 1$ positioned to operate on system error, ϵ, as its input...

Frequently it may be impossible, practically speaking, to design an instrument characterized by the required function. In other words, it is not practical to reduce the pilot's task to simple error detection and amplification. However, in such cases, it often is possible to build an instrument which is characterized by part of the required function. Such an instrument will relieve the pilot of the more complex part of his task and thus reduce his required function to one that he can better perform.

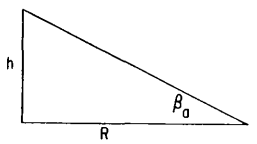
RESULTS

The example in the excerpt was of course greatly oversimplified for purposes of the presentation. It is used here merely to illustrate the concepts and methods generally applied to the problem. Such an analysis was actually carried out, based on the dynamic equations of the A-3 Sky Warrior aircraft and the presently used Fresnel Lens Optical Landing System (FLOLS). The block-diagram configuration of this overall system is shown in Fig. 5.



β_c = COMMAND GLIDE PATH ANGLE
β_a = ACTUAL ANGULAR POSITION OF AIRCRAFT
β_e = ANGULAR ERROR OF AIRCRAFT
δ = CONTROL
h = AIRCRAFT ALTITUDE
R = RANGE TO TOUCHDOWN
I = IMAGE DISTANCE OF FRESNEL LENS = 150 FT.

DERIVATION OF THE RELATION FOR $\dot{\beta}_a$:



FOR SMALL ANGLES, $\beta_a = h/R$.

DIFFERENTIATING, $\dot{\beta}_a = (R\dot{h} - \dot{R}h)/R^2$.

BUT $h = R\beta_a$.

$\dot{\beta}_a = (R\dot{h} - \dot{R}R\beta_a)/R^2 = (\dot{h} - \dot{R}\beta_a)/R$.

Fig. 5 - Block diagram of pilot-aircraft-geometry-FLOLS control loop

The analysis revealed the reasons that overall system performance is not sufficiently accurate to include an adequate number of standard deviations of the critical parameters within safe-landing limits. Two primary sources of system-performance inaccuracy were located in the current use of the FLOLS. The system inadequacies arising in the use of this display were shown to be (a) insufficient gain or sensitivity, and (b) the lack of derivative information or of any error signal from which this necessary rate information can be derived by the pilot. The type of solution sought was a relatively simple modification to the overall system: to be usable by several aircraft simultaneously, to require no extensive sensing equipment, and to require no additional instrumentation in the aircraft.

In short, a systems analysis of the display-pilot-aircraft combination in the carrier-landing configuration reveals a significant absence of a necessary signal at a specific point in the system. This lack is interpreted as a defect in the presently used optical landing system, a defect which is compounded by the characteristics of the element sensing the display signal--namely the human eye. The solution to the problem has been sought through the development of an alternate display system designed to provide an optimum signal in a manner which is optimally compatible with the human eye.

THE PRESENT DISPLAY SYSTEM: THE FRESNEL LENS OPTICAL LANDING SYSTEM

A discussion of any landing system intended to correct the deficiencies of the present system must be based upon a thorough understanding of the nature of these deficiencies. Therefore, the relevant characteristics of the FLOLS, already familiar to all carrier pilots, as well as those of the human eye, will be discussed in order to establish a basis for the subsequent discussions.

The Fresnel Lens Optical Landing System is a visual display of angular error above or below a prescribed glide path. This unit is located on the deck of the ship adjacent to the desired point of touchdown. The error display consists primarily of five lens cells stacked vertically between two horizontal rows of lights, called datum arms (Fig. 6). An elongated bar of light, known as the "meatball," appears to move up or down on the face of the cells as the aircraft moves above or below the prescribed glide path. Error from glide path is presented to the pilot as an apparent vertical displacement between the moving meatball and the stationary datum arms. A high meatball appears when the aircraft is high, and a low meatball is seen when the aircraft sinks below glide path. A "roger meatball" — in perfect alignment with the datum arms — is visible to the pilot only when his aircraft is on the desired glide path.

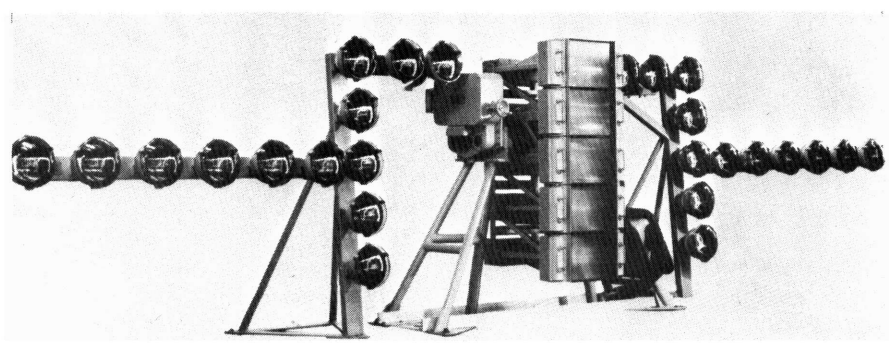


Fig. 6 - The Fresnel Lens Optical Landing System

Each of the five cells consists of three source lamps, a Fresnel lens, and a lenticular lens which spreads the beam horizontally to encompass a field of 40 degrees without affecting the vertical dimensions or characteristics of the beam. The cells, which are 10 in high, are oriented at an angle of 18 min to each other. A virtual image is formed 150 ft behind the assembly. Temperature changes within the cells alter both the dimensions and the density of the plastic Fresnel lenses, causing, in turn, variations in their effective focal length. Variable focal length results in variable image size, rough image motion between cell center and transition line, changed sensitivity, and altered vertical field of view. To minimize these effects, temperature control must be maintained to relatively close tolerances (3).

The low gain inherent in this display system results from the "displacement" coding of the error signal, together with the limited physical dimensions of the display and its relatively long distance from the pilot's eye. This statement is best verified by brief consideration of the geometry associated with the FLOLS from which the expression for the sensitivity of the displayed error is derived. Display sensitivity, or display gain, is defined as the ratio of the angle subtended at the pilot's eye by the error indication to the actual error of the aircraft from glide path. It will be shown to be directly proportional to the image distance of the lens and inversely proportional to the range from touchdown.

Figure 7 represents the geometry associated with the FLOLS from which display sensitivity is derived. In Fig. 7,

β_c is the prescribed glide-path angle

R is the horizontal range (in feet) to the lens

R' & R'' are slant ranges

h is the altitude (in feet) prescribed by the glide-path angle β_c

β_e is the angular error of the aircraft in the beam

$\bar{h}$ is the altitude error in feet which corresponds to β_e

d is the displacement on the lens which represents an altitude error $\bar{h}$

ϕ_{FLOLS} is the angle subtended at the pilot's eye by the error indication d; and 150 ft is the image distance of the lens.

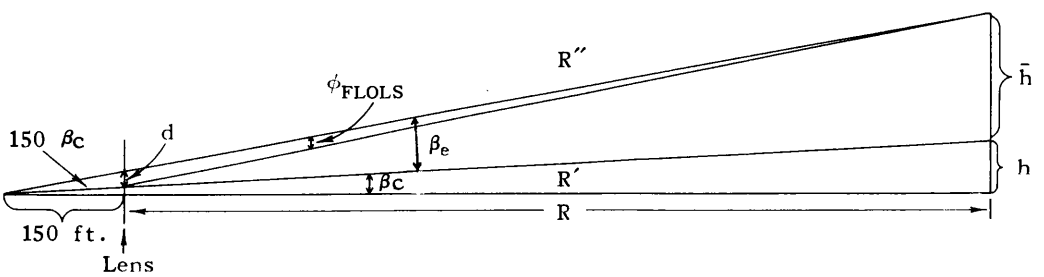


Fig. 7 - The beam geometry of the Fresnel Lens Optical Landing System

By similar triangles,

$$\frac{d}{150/\cos\beta_c} = \frac{\bar{h}}{R' + 150/\cos\beta_c} .$$

However, since the angles β_c and β_e are both very small (β_c is generally about 4 degrees), the maximum β_e such that the light is still seen in the lens is ±0.7 degrees, $150 \cos\beta_c \approx 150$ and $R \approx R' \approx R''$, and

$$\frac{d}{150} \approx \frac{\bar{h}}{R+150} .$$

For $R >> 150$, $d \approx 150\bar{h}/R$. The angle subtended at the pilot's eye by this displacement is

$$\tan \phi_{\text{FLOLS}} = \frac{d}{R''} \approx \frac{d}{R} .$$

Therefore, for small angles,

$$\phi_{\text{FLOLS}} \approx \frac{150\bar{h}}{R^2} \text{ (rad)} . \tag{2}$$

Thus the angle subtended at the eye by the error indication is directly proportional to the image distance of the lens and to the altitude error in feet, and inversely proportional to the square of the range.

If the display sensitivity DS_{FL} of the FLOLS is defined as the ratio of the indicated error ϕ_{FLOLS} to the altitude error $\bar{h}$, then

$$DS_{\text{FL}} = \frac{\phi_{\text{FLOLS}}}{\bar{h}} = \frac{150}{R^2} \text{ (rad/ft)} . \tag{3}$$

This relationship points out that the display sensitivity to altitude error varies inversely as the square of the range.*

Pilots, of course, are well aware that the FLOLS gives, at best, a very insensitive error indication, particularly at the longer ranges. In order to put the preceding discussion into context for the nonpilot readers, however, it is interesting to note that using the Fresnel lens at a range of about one mile (which is about 20 sec from touchdown) is comparable to tracking a signal on a 3/4-in.-diameter cathode-ray tube from a distance of about 83 ft. Further, at this range of one mile, a change of 69 ft in altitude will move the dot only 3/8 in. on the hypothetical crt.

The lack of rate, or derivative, information in the FLOLS, identified as the other source of system inaccuracy, is due to the fact that this system displays only a signal which is proportional to the instantaneous altitude error of the aircraft and which is presented in terms of the vertical displacement between the set of stationary datum lights and the meatball. The present display system gives no direct indication of the rate at which the aircraft's altitude is changing or, for that matter, of the rate at which its altitude rate should change if the pilot is to acquire the prescribed glide path. Such lead information, however, is precisely what the analysis showed to be required for display directly to the pilot or to be developed by the pilot from the display of altitude error. It is clear that only altitude error, not altitude error rate, is displayed to him directly by the FLOLS.

The human has been shown to be a relatively poor differentiator, in comparison with electrical or mechanical elements, even under ideal circumstances (5,6). When the signal to be differentiated is characterized by extremely low gain and further is masked by high noise (generated at the display, by the atmosphere, or within the eye), the problem is compounded and the chances of a precise estimate of derivative information are almost nil.

*A complete derivation and detailed discussion of this characteristic of the FLOLS appear in Ref. 4.

For these reasons, it became increasingly apparent that the most fruitful approach toward the development of new displays must be based on entirely different signal-encoding techniques. However, as an interim measure, NRL continued to provide NAVAIRSYSCOM with consultative services regarding various aspects of the FLOLS. One of these services dealt with the determination of the ideal range at which the glide-path beam should be stabilized in order to keep beam error due to ship motion at a minimum value for all ranges (7).

The "point-in-space" method of glide-path stabilization was the accepted method at the time of the study. The only question was the optimum location of the stabilization point. Ideally, in the point-in-space stabilization method, the height of the glide-path stabilized beam is maintained constant at a specified distance behind the lens system (Fig. 8). This height should be the height of the basic glide path (i.e., no roll, no pitch) at the specified distance behind the lens system. In practice, however, for the purpose of simplification this height is approximated by the expressions derived in Ref. 8. As outlined by the text, tables, and figures in Ref. 8, stabilization minimizes the error at the selected range, but in turn induces beam errors at other ranges which are a function of ship roll and pitch.

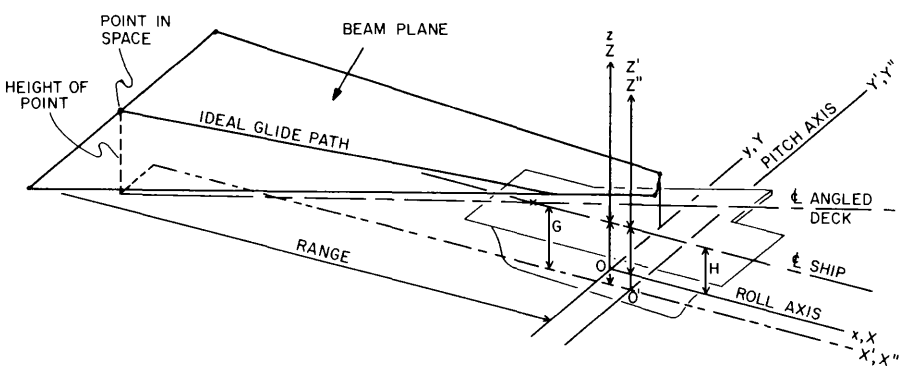


Fig. 8 - Geometry of the Fresnel Lens Optical Landing System beam stabilization (no roll, no pitch). The symbols are those used in Ref. 8.

Three factors were considered of primary importance in the selection of an optimum stabilization range in order to derive the maximum benefit from stabilization. These factors are: (a) the nature of the variation of beam errors at all ranges for various stabilization ranges, (b) error due to visual limitations, and (c) aircraft dynamics.

The nature of the glide-path-error variation for selected stabilization ranges was determined by calculating beam errors at ten checkpoint distances for various conditions of ship roll and pitch. The majority of the values for the different stabilization ranges were rather closely grouped in the critical region, as determined by a preliminary set of calculations. The remaining values were selected at the extremes, to illustrate the effects of stabilization at these ranges also. In order to show the relative magnitude of the error, which is of primary importance, the absolute values of the angular error were plotted versus range. Figure 9 shows a graph for a single condition of ship motion. Similar graphs for other conditions of ship motion are contained in Ref. 7. Angular, rather than vertical, error indicates more clearly the relative importance of the errors, because a given displacement occurring at a great range is represented by a smaller angular error than the same displacement at shorter ranges.

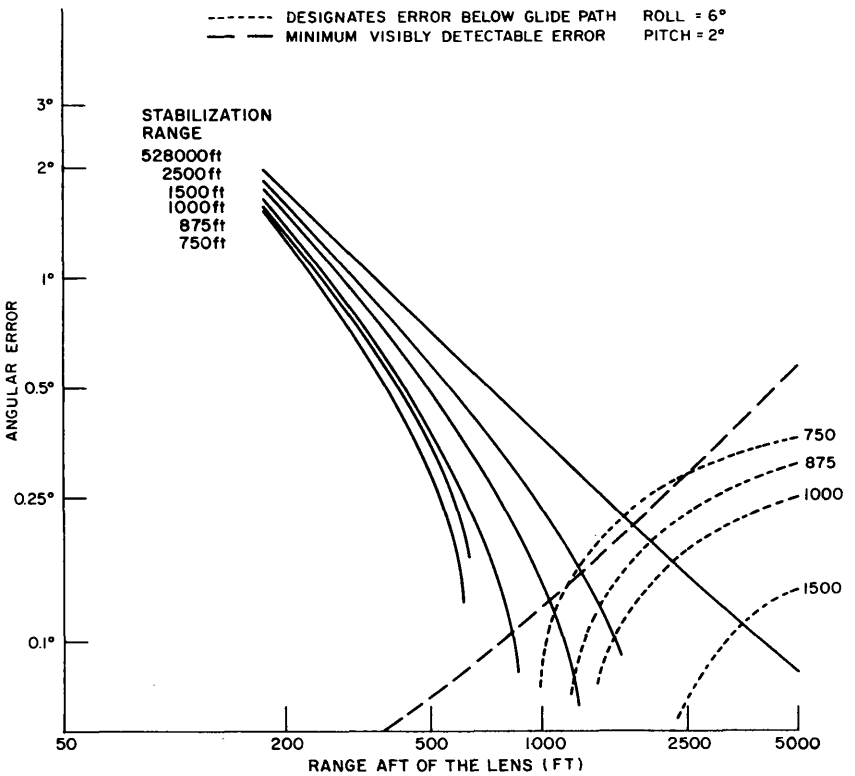


Fig. 9 - Plot of the absolute value of glide-path error due to ship roll and pitch versus range

The fact that an error is below glide path becomes particularly critical at close ranges, where, if it is large enough, a ramp strike will result. The means of data plotting adopted for this study provides a simple method for comparing the magnitude of the deviation, as well as for indicating the sign of the error.

The errors due to visual limitations were determined as follows. On the basis of Ref. 9, it was determined that the pilot can discriminate a displacement of the meatball from the datum lights under conditions of good visibility when the displacement between the center of the meatball and the lateral axis of the datum lights subtends an angle of approximately one minute at the eye. The resulting amount of meatball displacement that the pilot can resolve was calculated for various ranges. The calculated range at which he can just resolve a full-scale displacement of the meatball as positive or negative agreed closely with verbal reports by pilots.* The minimum discriminable error from the indicated path at the selected range was then computed by using the discriminable displacements with their respective ranges in the geometry of the problem. The minimum discriminable error was then plotted with the stabilization errors for ease of comparison.

The effect of aircraft dynamics on the selection of the optimum stabilization point is to limit the gross error which the approaching aircraft may safely incur. Obviously,

*The full-scale displacement of the meatball in the Fresnel lens system for which these calculations were made was 22 in. Any changes in this dimension will result in a similar change in the range at which the pilot can resolve a full-scale displacement.

any error beyond the ability of the pilot-aircraft system to correct in the time remaining to the wave-off point is not tolerable.

Reduction of the stabilization error below the smallest discriminable error was deemed unprofitable. With no beam error, the pilot can unknowingly have an error as large as the minimum discriminable angle. If the beam is allowed under severe conditions to vary approximately this same amount from the ideal height, he can have a true error approximately twice as large as that due to his visual limitations, and yet believe he is at the correct height. His true error at any given moment will also depend upon the nature of his correction and the point in time of the ship's roll and pitch cycle. Theoretically, then, the pilot will be able to maintain a true error within twice his visual tolerance, which is within the limitation imposed by aircraft dynamics.

As shown by Fig. 9, under the most severe conditions, the maximum error from the proper glide path with the beam stabilized at 1000 ft is nearly as large as, and no larger than, the error due to visual limitations. Stabilization at 1000 ft will afford the pilot a relatively constant increase in accuracy from the gross tolerable error to a minimum error near the point where he is last able to make any significant correction or maneuver. Stabilization at 1000 ft will also provide greater accuracy at closer ranges than will stabilization at the then current range of 2500 ft. It was for these reasons that we judged the optimum point for stabilization to lie approximately 1000 ft aft of the lens.

NEW CONCEPTS IN DISPLAY DESIGN

A constant theme underlying all the specific problems and individual developments of this project is the pressing need for greater system accuracy. The need for increased precision of certain flight parameters at the moment of touchdown has been demonstrated on a statistical basis. Clearly, the same discussion could apply to any of a number of parameters. However, it is our very strong feeling that greater accuracy of control is necessary not only at touchdown but also during the entire approach. The advantages of "getting set up early" can hardly be overemphasized. The pilot who is on glide path with the proper rate of descent, proper angle of attack, and proper airspeed has to combat only external disturbances to his flight path during the final seconds prior to touchdown. If the phugoid oscillation excited by the initial control efforts to acquire the glide path is already settled out, all the pilot's control efforts can be utilized to compensate for gust inputs or to guide the aircraft over the "rooster tail," as the characteristic turbulence aft of the carrier is known.

Getting set up early requires longer acquisition ranges for the display, to allow the pilot sufficient time to acquire and maintain the proper flight conditions before the most critical moments of the approach. The matter of increased display range is accordingly considered to be of primary importance, and is, in fact, one characteristic of every system embodying the new error-signal-encoding concepts.

Closely associated with the need for increased range is the need for increased precision. This is to be interpreted as smaller tolerances in the "on-glide-path" indication. If greater precision is required throughout the approach, greater precision can reasonably be expected at the time of touchdown, i.e., at the termination of the approach. The on-glide-path or zero-error indication of the FLOLS is about 0.3 degree (this angle represents the dimension of the center cell, and a meatball in the center cell usually represents an acceptable condition to the pilot). The zero-error indication on the majority of the newly developed NRL systems is ±0.1 degree. The capacity for even greater precision is inherent to the systems, however. Of course, with this smaller "zero-error" condition, the pilot will be controlling his aircraft with greatly improved accuracy, and resulting increased safety.

Still another characteristic common to the new systems is simplicity of construction and maintenance, provided to ensure greater reliability and lower costs. The effects of temperature variations are minimal, for example.

In answer to the problems of insufficient gain and lack of derivative information in the present error-display signal, as revealed by the analytical work, the new displays have been, without exception, designed to exhibit increased error sensitivity, or gain. Further, each produces an error signal which either is a direct display of the necessary rate information, or is a position signal with higher gain and less optical noise or interference, so as to permit the more accurate extraction of the necessary rate information by the pilot. These two display characteristics are emphasized repeatedly, because they are the crux of the present problem as well as of the optimal solution.

At this point, it is desirable to digress a bit — to discuss in general terms a principle of physics which is the basis of the instrumentation of the new landing systems. This principle is called "backward projection." It is a simple concept, seldom exploited, but it has great potential in the long-range projection of extremely precise information.

Consider an ordinary slide projector containing a multicolored slide focused at some arbitrary distance. To the person standing in the image plane looking directly at the projection lens, the entire lens appears to be of a single color. The apparent color of the lens is a function of the position of the viewer's eye in the image plane.

In order to illustrate more specifically, let us take the projection of a two-color slide, the top half of which is red, and the lower half green (Fig. 10). It is seen that if a projection screen were erected in the image plane, the area of the screen around point E_1 would be red, since all the light illuminating this area originates from the red portion of the slide. Furthermore, because only red light strikes this point, to the person with his eye located at E_1 the entire lens will appear red. Likewise, the person whose eye is at point E_2 will see the lens as green, since all the light reaching this point is coming from the green sector of the slide. If the eye is very near to the boundary between the two colors, it has to be moved only a short distance for the entire lens to appear to change color. If the focus is truly at optical infinity, the viewer's range from the projector has nothing to do with the phenomenon described. At a range of ten or twenty miles, with the projector focused at "optical infinity," he still need move his eye only a few inches to observe a total and instantaneous color change of the projector light. The utilization of the backward-projector principle eliminates the necessity for electronic or mechanical sensing or computing of craft position or movement, because the signal received by the pilot is inherently a function of his angular position and movement relative to the projected beam.

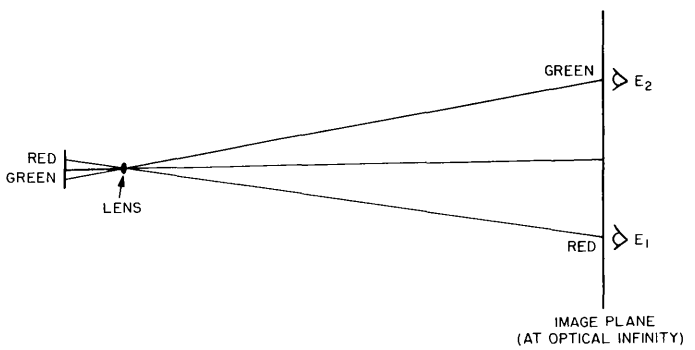


Fig. 10 - Ray diagram of projection of two-color slide

HIGH-GAIN DISPLAYS OF SINK-RATE-ERROR INFORMATION

The Rainbow Optical Landing System

The Rainbow Optical Landing System was designed to present to a pilot highly sensitive information regarding his error in rate of approach to glide path. The system, which is located adjacent to the desired point of touchdown, projects a dynamic beam of multicolored light toward approaching aircraft. A pilot flies his aircraft into the beam, and receives a visual signal which is a function of the interaction of the aircraft motion with the moving beam. This beam pattern consists of very many sets of beams of three colors which sweep vertically through the sky to converge about the glide path. The pilot observes the sets of colored beams as the cyclic time-sequencing of the color of a single light source. He interprets the order of the sequencing as an indication of the polarity of an error in rate of descent, and the rate of the sequencing as an approximate measure of the size of his sink-rate error.

Color sequencing has several characteristics in its favor as a means of error encoding. In the first place, color-sequence encoding can replace displacement coding (i.e., a signal which indicates error as a function of the displacement between two lights, such as in the FLOLS). We have said that the displacement-coded signal is range limited because the angle subtended at the viewer's eye by a given displacement on the system varies as an inverse function of range, and the eye, of course, has a minimum discriminable angle. It follows that the visual signal which is not dependent on displacement coding can have a far greater maximum operating range. Further, reducing the size of the color-sequence-coded display mechanism does not bring about an attendant loss of error sensitivity.

The second advantage of color sequencing as a means of signal coding lies in the repetitive changing or sequencing of the light. It is a well-known fact that gazing at a single-colored light for a while causes the color saturation to appear to fade as the eye adapts to the color of the light. It is therefore difficult to determine if a red light is gradually becoming pink, for example, or if one's eye is merely adapting. This characteristic often limits the value of color coding of a light, where color gradation is significant in error indication. However, the sequencing of the colors, which amounts to the frequent provision of a color reference for each color of the sequence, prevents any significant adaptation by the eye. Also, in the Rainbow system, the three colors were deliberately and painstakingly selected to be as far separated from each other in hue as possible. Subtle color changes or blending are therefore not used to convey information.

The advantages of a color-sequenced light to provide guidance information are, then, the increase in usable range and decrease in unit size, together with the possible long-term detection of color. Its disadvantages, or limitations, which led to further system improvements, become apparent after a detailed description of the Rainbow system.

Flying the Rainbow — Instructions given to a pilot "flying the Rainbow" are as follows: "The Rainbow system tells you how to modify sink rate so as to acquire and maintain glide path. When you see the indicator light change from red to white to blue, you are not descending rapidly enough. As you increase your sink rate, the color sequencing will slow down. If you over-correct, that is, begin to sink too rapidly, the sequence will reverse — blue to white to red. When your sink rate is appropriate, the sequencing will stop, so you will see a steady color — red or white or blue — which eventually will become green as you are brought onto glide path. As long as you are within some fixed tolerance of glide path, a steady green will be visible. The flashing red and flashing green mean that you are at the outer limits of the beam pattern. Whether you are above or below glide path, blue-white-red consistently means 'decrease sink rate,' and red-white-blue calls for an increase in sink rate. You slow down or stop the sequencing by adjusting your sink rate according to the command of the changing colors."

Commands Generated by Rainbow Beam Pattern — The beam geometry of the Rainbow Optical Landing System is pictured in Fig. 11, which of necessity represents the dynamic pattern at only a single instant in time. In the drawing, U represents the unit located on the carrier deck. The pilot flying the system never sees at one time the complete array of lights, of course, but a single-color point of light on the indicator. Since the system utilized the backward-projector principle, the color of the light which he sees depends on the position of his eye in the beam pattern. A pilot whose eye is situated within a red beam, for instance, will observe that the display appears red. If the aircraft position is such that his eye is within a blue beam, the indication will appear blue.

The colored Rainbow beams converge upon the green beam, each beam sweeping toward the green at a rate which is proportional to its instantaneous angular displacement from the glide path (that is, at an exponential rate). As each beam approaches the

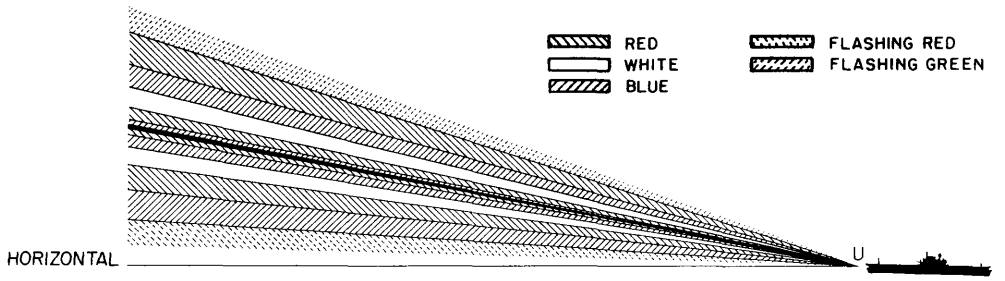


Fig. 11 - Beam geometry of the Rainblow Optical Landing System

glide path, it grows thinner until it eventually vanishes into the green beam. If the pilot whose aircraft is initially above glide path, for example, observes the red-white-blue sequence, his aircraft is approaching the glide path more slowly than are the beams, for, in effect, the beams are passing him by. If he increases his sink rate in accordance with this sequence command, and if the color sequencing appears to slow down, then his rate of approach to the glide path is more nearly equal to that of the beams and, therefore, to that which is commanded by the Rainbow system, but it is still not great enough. On the other hand, if the color sequencing reverses direction, becoming blue-white-red, when he increases sink rate, he has overcorrected and is approaching the glide path more rapidly than are the colors. He is receiving, therefore, the command to decrease his sink rate, even though he is still high, lest he pass through the glide path. When a constant color is observed on the indicator, the pilot is maintaining a sink rate equal to the rate at which the beams move toward the green beam, which means that the aircraft is being brought optimally onto the glide path.

As another example, consider the pilot who, upon turning his aircraft on the final leg of his approach to a landing, is below the glide path and maintains, for a moment, straight and level flight. The dynamic beams will sweep past his eye in the order of blue-white-red as they move up toward the glide-path beam. This sequence is commanding the pilot to decrease his sink rate or, in an extreme case, to climb! If the pilot begins to climb too rapidly, so that his rate of approach to glide path exceeds that of the beam rate, the order in which the colored beams pass his eye will reverse, and he will observe, therefore, while still low, the red-white-blue command to increase sink rate, or decrease his climb rate, as the case may be.

It is seen, from such examples, that the red-white-blue sequence is consistently a command to increase sink rate, and the blue-white-red sequence a command to decrease sink rate, regardless of whether the pilot is, at the given moment, above or below the glide path. A slowing of the sequence indicates that an appropriate correction was made; a speeding up of the sequence means that the wrong correction was made; a sequence reversal indicates overcorrection; and a constant color (or zeroed sequence) indicates that the proper correction of sink rate has been made to bring the aircraft along a non-oscillatory, optimal approach to glide path.

It is important to note that the programming of the beam sweep determines the path of approach to glide path which is commanded by the Rainbow system. The exponential nature of the beam dynamics was selected because it provides a sink-rate command which is always appropriate to the present position of the aircraft; that is, a larger sink rate is commanded when the aircraft is far from the glide path, while a smaller, more gentle sink rate is commanded when the aircraft is nearer to the glide path.

The nature of the Rainbow's command is made more explicit by the following equation, which expresses the instantaneous rate of change of beam color at the pilot's eye, $\dot{C}_e$, as a function of two beam characteristics, ΔT and τ, and two characteristics of aircraft position and motion, β_e and $\dot{\beta}_a$:

$$\dot{C}_e = \frac{1}{\Delta T}\left(\frac{\beta_e - \tau\dot{\beta}_a}{|\beta_e|}\right) \tag{4}$$

where ΔT is the length of time (in seconds) required for an entire color to move past any fixed point within the pattern, τ is the exponential time constant of the beams, and is roughly equal to the time required for any point within the beam to cover about 63 percent of the angular distance remaining to the glide path, β_e represents the angular error of the aircraft from the glide path, and $\dot{\beta}_a$ is aircraft angular rate (with reference to the horizontal) within the beam.*

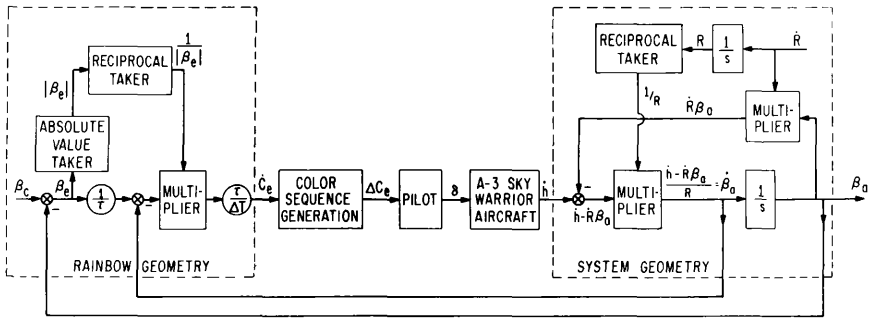
From this general expression, it is apparent that for the pilot flying directly toward the indicator ($\dot{\beta}_a = 0$) the instantaneous color rate is equal to the reciprocal of the time duration; that is, $\dot{C}_e = \pm 1/\Delta T$. If he continues to fly in this direction for a long enough period of time, he will see the indicator colors sequence at a rate of $\Delta C_e = \pm 1/\Delta T$ per sec. If the aircraft is either above or below glide path ($\beta_e \neq 0$), but its angular position is being corrected at the commanded rate ($\dot{\beta}_a = \beta_e/\tau$), then $\dot{C}_e = 0$ and the pilot observes a zero color-sequence rate, or constant color. If the aircraft is not flying directly toward the indicator ($\dot{\beta}_a \neq 0$) but passes through the glide path ($\beta_e = 0$), the expression for $\dot{C}_e$ indicates that the pilot observes an infinite color rate. In practice, however, this event does not occur, for the green on-glide-path beam has a finite width, so that the exponential beams never actually become infinitely thin. For this reason, the maximum color rate which can be observed is a function not only of the aircraft's angular error rate in the beam, but also of the angular width of the green beam.

Equation 4 is of interest because it illustrates the interrelationship of beam geometry with aircraft flight-path geometry to produce the signal viewed by the pilot. Both the equation and the Rainbow-pilot-aircraft-geometry system block diagram (Fig. 12) help to clarify some of the advantages of the Rainbow design to overall system performance. For instance, it is apparent that the sensitivity of the signal received by the pilot is indeed completely independent of his viewing range. This fact is, of course, due to the replacement of displacement coding with color-sequence coding. If the light can be detected at all, the gain on the displayed signal, that is, on the color sequence, is constant for all ranges. For this reason, the usable range of the system is limited only by the intensity of the light source and by visibility conditions, not by the physical size of the indicator. (It should be pointed out that the angular error signal as developed by the system is dependent on range, that is, is always appropriate for the aircraft's present range. Only the display gain on the error signal is independent of range.) For purposes of comparing Eq. 4 with similar expressions for the FLOLS, Eq. 3 should be converted to angular sensitivity; that is, since $\bar{h} = \beta_e/R$ and $\phi_{\text{FLOLS}} = 150\bar{h}/R^2$,

$$DS_{\text{FL}_{\text{ANG}}} = \frac{\phi_{\text{FLOLS}}}{\beta_e} = \frac{150}{R} .$$

Even more beneficial than the increase in display gain, however, is the provision by the Rainbow display to the pilot of information concerning his error in rate of descent rather than in altitude. In servo terminology, then, the Rainbow system incorporates into the display a lead, or quickening term, which substantially reduces the complexity of the control function required of the pilot (see Refs. 1 and 5). It can also be seen from

*Reference 10 includes a complete derivation of Eq. 4.



β_c = COMMAND GLIDE PATH ANGLE
β_a = ACTUAL ANGULAR POSITION OF AIRCRAFT
β_e = ANGULAR ERROR OF AIRCRAFT
h = AIRCRAFT ALTITUDE
R = RANGE TO TOUCHDOWN
δ = CONTROL
τ = EXPONENTIAL TIME CONSTANT OF COLORED BEAMS
ΔT = TIME DURATION OF EACH COLORED BEAM
$\dot{C}_e$ = INSTANTANEOUS COLORED BEAM RATE
ΔC_e = COLOR SEQUENCE

Fig. 12 - Block diagram of Rainbow pilot-aircraft-geometry control loop

Fig. 12 that as the pilot approaches the glide path, thereby reducing β_e, the forward loop gain, and thus display sensitivity to error in $\dot{\beta}_a$, is increased. Again in servo terminology, system damping increases as error decreases, which implies that error correction is more rapid when errors are larger and that more precise control develops as the aircraft comes closer to the glide path. Comparison of the diagram of Fig. 12 with that of the pilot-aircraft-geometry-FLOLS display system of Fig. 5 emphasizes the system improvements which result from the introduction of the Rainbow display into the system.

Rainbow Display Equipment Design Principles — The equipment designed to produce the dynamic array of the Rainbow display system is essentially an optical system requiring no electronic or mechanical sensing or computing of system parameters, either aboard the aircraft or at the location of the display. The utilization of the backward-projector principle, discussed previously, obviates the need for any sensors (other than the pilot's eye) or any (but the visual) data links between aircraft and display, because, of course, the characteristics of the error signal, as developed and observed, are a function of the geometrical relationships inherent in the system.

The exponentially moving beam pattern of the Rainbow system is provided by a dynamic multicolored slide. A patterned color transparency is superimposed upon a transparent cylindrical drum. The drum rotates about a high-intensity light source and condensing lens so that the transparency moves in the focal plane of the projection lens (Fig. 13). The pattern superimposed on the drum consists mainly of a continuous cycle of red, white, and blue stripes which approach the center green stripe exponentially, and which generate the rate-error information. The glide-path portion of the pattern subtends an angle of ±0.1 degree in space. A horizontal, alternating red-and-black stripe around the top of the drum and a horizontal, alternating green-and-black stripe around the bottom of the drum provide the flashing boundary beams. Two versions of the experimental units are illustrated in Fig. 14.

The Rainbow pattern design equations are derived as a function of both drum parameters and two parameters of the dynamics of the projected pattern. The primary drum parameters are rotation speed, the horizontal distance along the drum circumference of each exponential band, and the exponential decay constant of these bands. These parameters interact to determine the two main parameters of the light pattern in space: (a) the sequence rate seen by a pilot maintaining a constant angular error from glide path

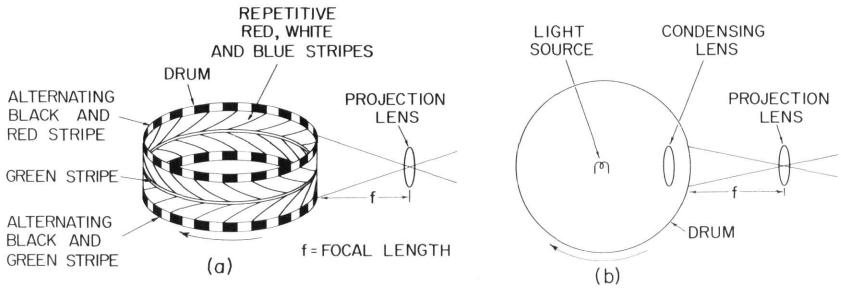
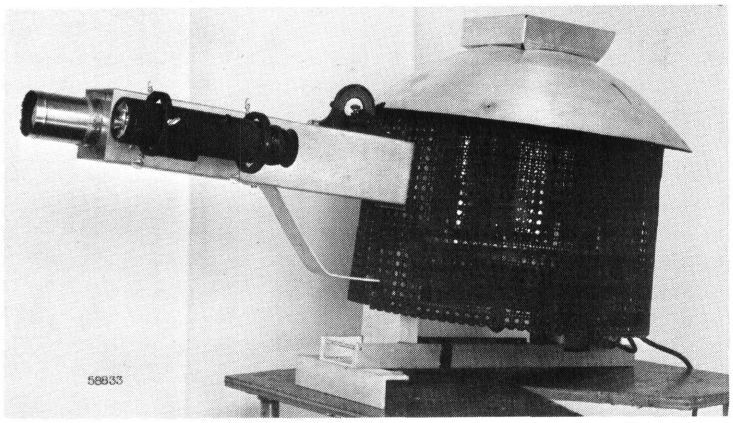


Fig. 13 - Schematic representation of the rotating drum and lens system: (a) side view, (b) top view



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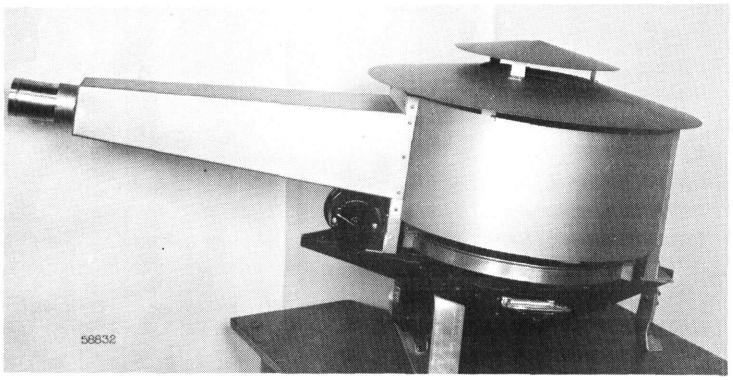

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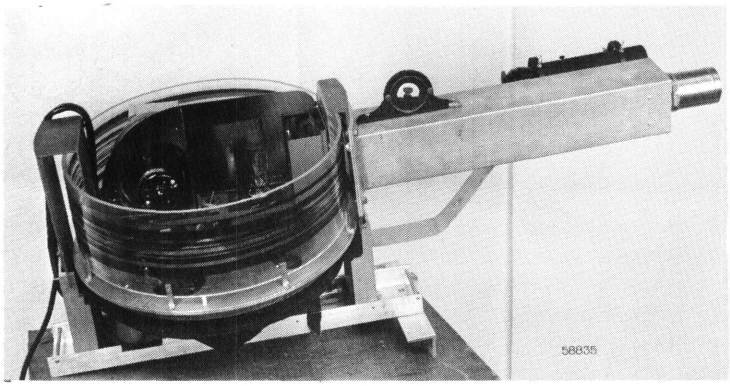


c

Fig. 14 - Rainbow Optical Landing System experimental units. (a) Preliminary experimental unit, with a telescope mounted on the casing for ground observation of aircraft deviations from the ideal glide path. (b) Modified experimental unit. (c) Preliminary experimental unit, with casing removed to reveal color-patterned, transparent, rotating drum which revolves about the light source and condensing lens. In this unit an ordinary Delineascope was used.

(basic sequence rate), and (b) the time constant of the motion of the color beams toward the glide path. Figure 15 depicts the geometry of the exponential curves of the drum pattern. Parameters are defined as in Ref. 11, where $x/2$ is the height of half of the glide-path pattern on the drum, L is the decay constant of an exponential curve, τ is the projected time constant of an exponential curve, H is the maximum height of an exponential curve, W is the horizontal width of an exponential curve, ζ is the number of inches along the drum circumference measured from the beginning of an exponential curve, δ is the vertical height of a curve as a function of ζ, δ_g is the vertical height of a curve at the point where it intercepts the glide path, and ζ_g is the number of inches along the drum circumference measured from the beginning of a curve to its first intersection with the glide path.

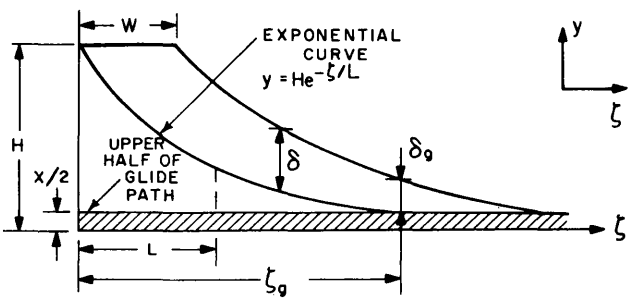


Fig. 15 - Geometry of glide-path stripe and of one of the exponential colored stripes used on the rotating drum of the Rainbow system

Note that δ_g is very small. Because of the practical problems encountered in producing an exponential "tail" of such extraordinary fineness, the slope of the curves was made constant, starting approximately 0.3 degree above the center of the glide path. Figure 16 illustrates this point; the equation for the linearized tail may be found in Ref. 11.

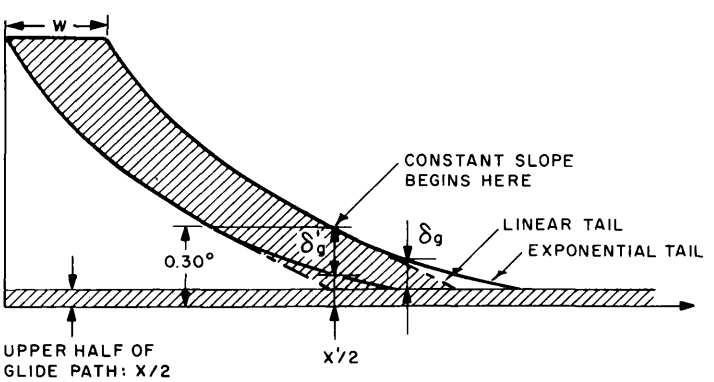
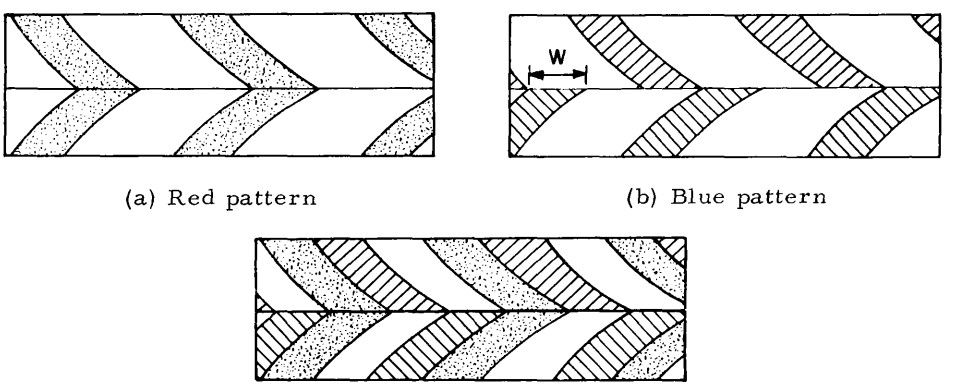


Fig. 16 - Geometry of glide-path stripe and of one of the exponential colored stripes having a linear tail

The equations and drawings of the preceding discussion are presented here as background information in order to give the reader an understanding of some of the practical problems encountered in the fabrication of the Rainbow drum pattern. The problems fell into two basic categories: (a) achieving the needed accuracy on the drum pattern to generate the precision required of the projected light pattern, and (b) determining and subsequently obtaining the best possible colors on the transparency.

With respect to the first of these categories, the approximation of the linear tail was a device introduced at an early stage, in order to obtain the required accuracy. The true exponential tail, resulting from the intersection of a straight line (top of the glide path) and an exponential curve, would approach zero width as a limit and would clearly be impossible to construct except under theoretically ideal circumstances.

Multilayer Pattern — The first effort to obtain a drum pattern was centered around the superposition of multiple layers of transparent ozalid which can be processed with any pattern in one color. Since all the curves are identical, one layer, printed in red, would contain one third of the exponential curves; the second layer, printed in blue, would contain another third of the same exponential curves, shifted to the right (with respect to the red pattern) by the amount W. Superposition of these two layers (Fig. 17) would produce the desired pattern. Although theoretically sound, this method of pattern drawing led to "crossover" and "gaps" in the critical area near the glide path, due to very tiny errors in the original plotting of the exponential curves. Dimensional tolerances of the order of a few thousandths of an inch are required on the drum pattern because of the enlargement occurring through the projection system. The seriousness of these errors was multiplied by the fact that they occurred close to glide path, the area of maximum sensitivity of the system to aircraft variations in sink rate, or to beam-rate error, and also in the area where precise control is most necessary. The ozalid Rainbow pattern was clearly unusable because of these problems, yet even in its inaccurate state, the potential merits of the Rainbow system in the precise control of aircraft were indicated.



(a) Red pattern

(b) Blue pattern

(c) Overall rainbow display pattern

Fig. 17 - Red, blue, and composite patterns of exponential stripes (with greatly exaggerated slopes)

The Ektachrome-X Pattern — The search then began for a material on which all three colors of the Rainbow pattern could be produced. If the entire exponential pattern of adjacent colored bands could be constructed on one piece of material, it might contain the same size errors, but it would not suffer from the crossover or gaps which make the color sequence indiscernible.

The drum-pattern parameters were selcted so that a total of 30 bands would appear around the drum, or ten sets of the three-color series (corresponding to a drum-rotation

speed of 3 rpm). Since all the exponential curves are identical, the pattern was repetitive ten times around the drum. The drawing, then, needed to be only one tenth of the entire pattern. It was drawn on a greatly enlarged scale in order to reduce the relative size of any errors. The actual enlargement factor, 8:1, was determined by the limits of cameras and frames available. The pattern segment was drawn with a ten-percent extension at the right end for later use in aligning and matching the photographed segments. The drawing was then photographed successively and reduced to 1/8th its original size in two stages. Alignment was accomplished on a large sheet of glass, using ten pattern segments of actual size. The pieced-together pattern was then fitted into a specially made frame for contact printing, and another photograph was made to produce a one-piece pattern which could be easily wrapped around the drum.

This procedure obviously calls for several photographic steps, a process which is generally considered impossible in color photography if preservation of color purity is of interest. Usually, repeated exposures result in washed-out colors. However, a technique was evolved to permit multiple exposure without this characteristic degradation of color. It was only the development of this technique which permitted the use of the so-called "enlargement-reduction" process to obtain the necessary pattern accuracy.

Once again, in order to discuss the photographic techniques involved, some basic information about the color film used is required. The drum pattern was photographed on Kodak Ektachrome MS Aerographic Film (Estar Base), which is of medium speed, and was available on a stable base in 100-ft rolls. (Since drum diameter D = 18 in., the finished drum pattern must be 56.55 in. long. Stable-base film was required to minimize distortion due to heat emanating from the projector source.) Ektachrome was selected because of the spectral characteristics of its three component layers of emulsion and its unusual capability of faithfully reproducing blue shades.

Ektachrome-X film is made up of three layers of emulsion: a magenta-dye-forming layer, a yellow-dye-forming layer, and a cyan-dye-forming layer. The developed transparency appears green when the magenta-forming emulsion is clear, leaving only the yellow-plus cyan-dye layers. The magenta-dye-forming emulsion is sensitive to, and therefore is cleared by exposure to, green light. Similarly the yellow-dye-forming emulsion is cleared by exposure to blue light, leaving the magenta- and cyan-dyes which, combined, appear blue. Red is obtained on the transparency by preventing the formation of cyan dye (by exposure to red light) and leaving the magenta- plus the yellow dye layers. Yellow light striking the film results in exposure of both the red- and green-sensitive layers and the elimination of cyan or magenta dyes. Only the yellow dye remains in the processed transparency. Exposure to white light results in elimination of all colors, since all the wavelengths to which the three emulsions are sensitive are contained in white light. The sensitivity curves of a Kodak Ektachrome film are shown in Fig. 18.

If the maximum capability of the film is to be realized, exposure of each emulsion should be with light of a wavelength which is very close to that to which the emulsion is most sensitive. To ensure this, filters were selected which had transmission peaks occurring at the maximum sensitivity peaks of the three emulsions respectively, and further which had skirts such that a minimum of unwanted exposure of the other emulsions would occur (Fig. 19).

Paints of red, green, and blue were selected to be maximally compatible with their respective filters and maximally rejectable by other filters. Figure 20a shows the spectral characteristics of the paints finally selected. Figure 20b illustrates, using blue as an example, the manner of selection. Figure 21 represents the transmission characteristics of the paints of Fig. 20a in combination with or as viewed through the filters of Fig. 19.

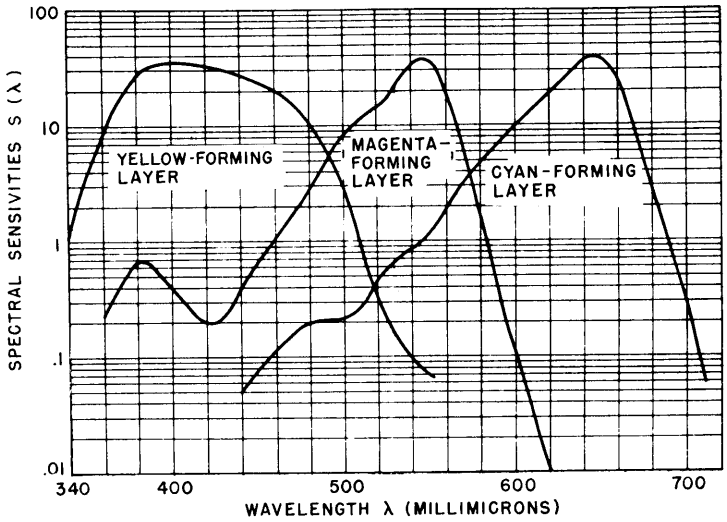


Fig. 18 - Sensitivity curves of Kodak Ektrachrome MS Aerographic Film, showing the relative spectral response to Taylor-Kerr daylight transmitted by an average camera lens, normalized so that the integrated responses of the individual layers are equal. This figure is reproduced by courtesy of Eastman Kodak Co., Rochester, N.Y. "The properties of individual emulsions may exhibit variations from these curves. Continuous efforts are made to improve these products and the curves may become obsolete as a result of changes in manufacturing technique. Before using data for purposes other than general information, additional inquiries should be addressed to Eastman Kodak Company."

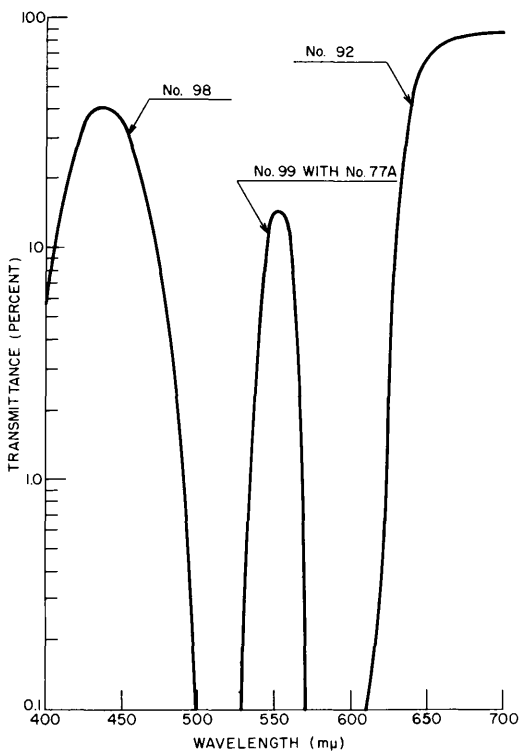


Fig. 19 - Transmittance curves of the Kodak Wratten filters used for photographing the Rainbow drum pattern. Data for calculating and plotting these curves were obtained from Kodak Wratten Filters, Kodak Publication No. B-3, Eastman Kodak Co., 1962 (also 1960).

Each photographic stage consisted of three successive exposures, using each filter sequentially. For example, when the film is exposed through filter 92, red light strikes the film, clearing the cyan-forming layer in all locations which correspond to the areas of the painting which reflect red or yellow light. Next, exposure through filter 98, which transmits only blue light, results in clearing of the yellow-forming layer in the areas corresponding to the blue-painted area, leaving the magenta and cyan-forming layers. The third step exposes the film through the combined filters 99 and 77A. This light clears the magenta-forming layer in the areas corresponding to both the green- and yellow-painted areas, without affecting the yellow- and cyan-forming layers. Clearance of the magenta- and cyan-forming layers by exposure to first the red and then the green light leaves only the yellow-forming layer in the area corresponding to the yellow portions of the painting.*

The selection of the yellow paint was perhaps more critical than that of any of the others. This is because its characteristics had to be such that the light reflected from it would pass through both filter 98 and the 99-77A combination to clear both the magenta- and cyan-forming layers in the proper areas, but would not contain an excess of stray frequencies which would cause undesirable clearing of the blue-sensitive or yellow-forming layer.

Various experimentally selected exposure times, ranging from underexposure to overexposure, were used. The necessity of using different exposure times can be understood by consideration of the following relationships. The product of the reflectance from a paint (at a given wavelength) and the transmittance of a filter (at the same wavelength) determines the energy passing through the filter. This figure multiplied by the number

*The rationale for any yellow areas in the painting will be discussed later in a more relevant context.

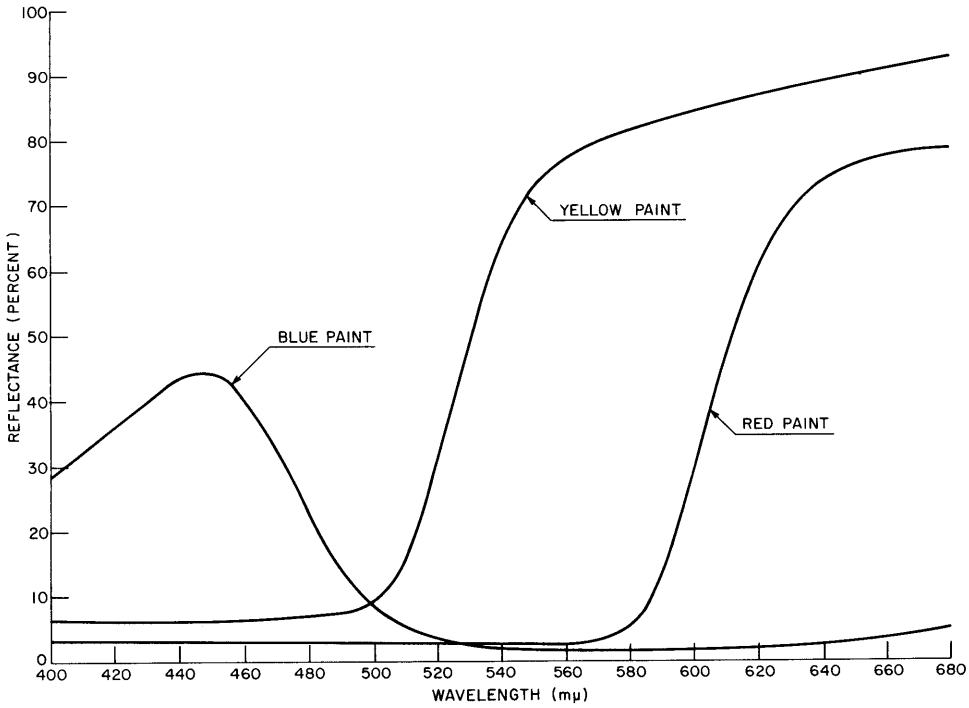


Fig. 20a - Tracings of reflectance curves, obtained by using a Beckman photospectrometer, of the red, yellow, and blue paints used for the original painting of the Rainbow pattern. Such a reflectance curve is not shown for the green paint, because a fluorescent paint was ultimately selected, and the spectrometer measurements do not accurately represent the actual reflectance of this paint when illuminated by white light. The green paint was chosen on the basis of its apparent color when viewed through the filters.

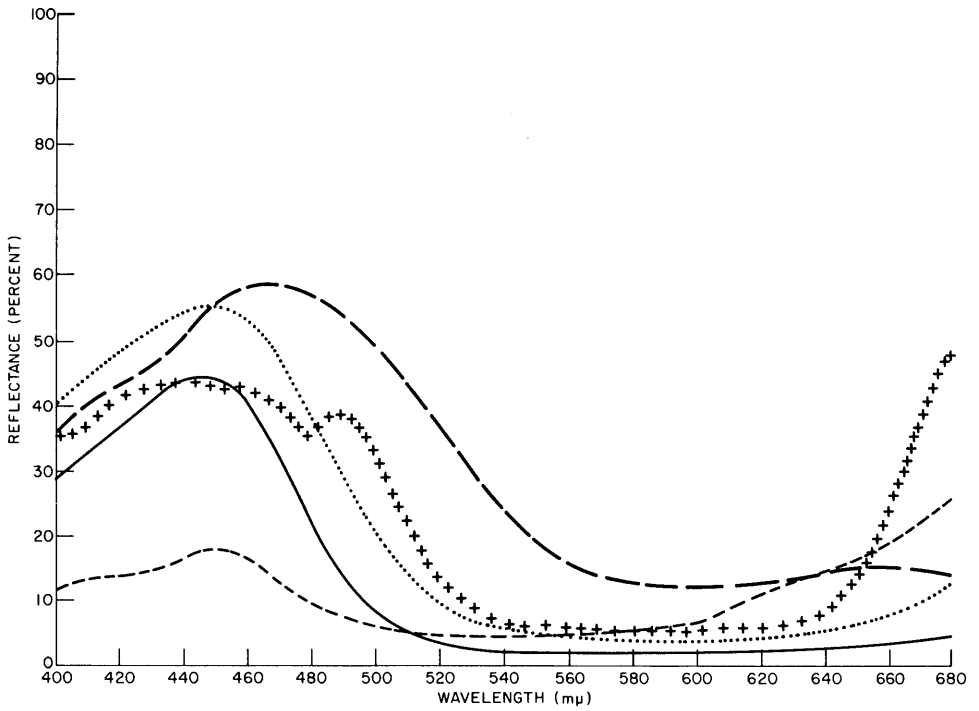


Fig. 20b - Reflectance curves of several blue paints from which the final selection was made. The paint represented by the solid line was chosen on the basis of its peak reflectance in the blue portion of the spectrum, together with its minimal reflectance in the remainder of the spectrum. Note that the paint represented by the dotted line exhibits a higher reflectance of blue, but also of the unwanted green. Further, the paint represented by the x-ed line exhibits a higher reflectance of red than of blue, even though it appears blue to the eye.

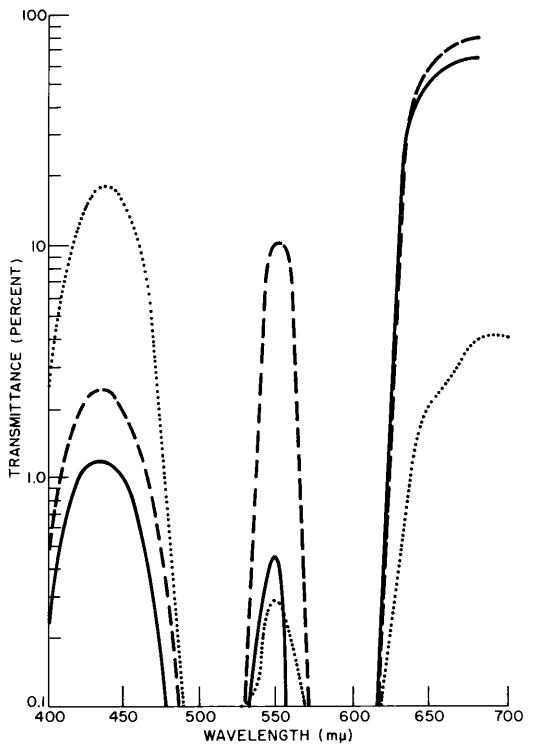


Fig. 21 - Paints of Fig. 20a as seen through filters of Fig. 19. The dotted line represents blue paint, the dashed line yellow paint, and the solid line red paint. Curves for green paint are not shown. The curves to the extreme left represent transmission through filter 98, those in center represent the transmission through filter 99 with filter 77A, and those on the extreme right represent transmission through filter 92.

of exposure units represents the amount of energy of a given wavelength available to activate the film emulsion. The three sensitive emulsions do not, however, respond equally to the energy available at a given wavelength. Therefore, in order to get comparable responses from all three layers, different exposure times are required. Also, throughout the successive photographic stages the transmission losses resulting from successive filtering were compensated for by increased exposure times. Much experimentation was required in order to select the optimum combination of exposure times. The films obtained at this stage were very carefully aligned for contact printing. A master transparency of the drum pattern was then made, using the same filters and various exposure times. From this master any number of further contact prints could be made.

The spectral characteristics of the light source must also be taken into account, because the source must emit light of a given frequency before that frequency can be projected through a transparency. From the beginning of the project blue presented very severe problems. The transmission of blue was quite low with respect to that of the other colors, as can be seen in the spectrographs. However, the Ektachrome-X was the best film found for transmitting blue. Part of this problem lay in the incandescent light source, which was deficient in the blue frequencies. Color temperature is a critical factor in determining the component frequencies emitted by a given source. It was determined that a color temperature of between 5000°K and 6000°K was necessary if the radiant flux in blue is to be comparable to that in red. The color temperature of the bulb used in the Rainbow system, however, was only 3375°K. Part of the blue trouble was therefore attributed to the source. Some consideration was given to using a Xenon lamp, which has a color temperature of about 6000°K, but the practical power problems associated with the starting and running of this source were prohibitive. It was concluded, however, that it is indeed feasible to improve the characteristics of the projected colors, such as by making their peak transmission levels comparable, through the introduction of more compatible sources. The pattern was certainly usable, however, as it was, and therefore further efforts to enhance the blue were not considered necessary at the present stage of development.

One further consideration played a part in the selection of the colors of the Rainbow drum pattern — the spectral characteristics of the human eye. Equal amounts of radiant flux of different wavelengths do not evoke visual sensations of equal brightness. For example, under daylight conditions the index of sensitivity (from the Standard Luminosity Curve, Fig. 22) for red is 0.83, for yellow and green is 1.00, for blue is 0.67 and for violet is 0.19. It is all too apparent that the blue problems, at least in daylight, were being intensified by the characteristics of the eye.

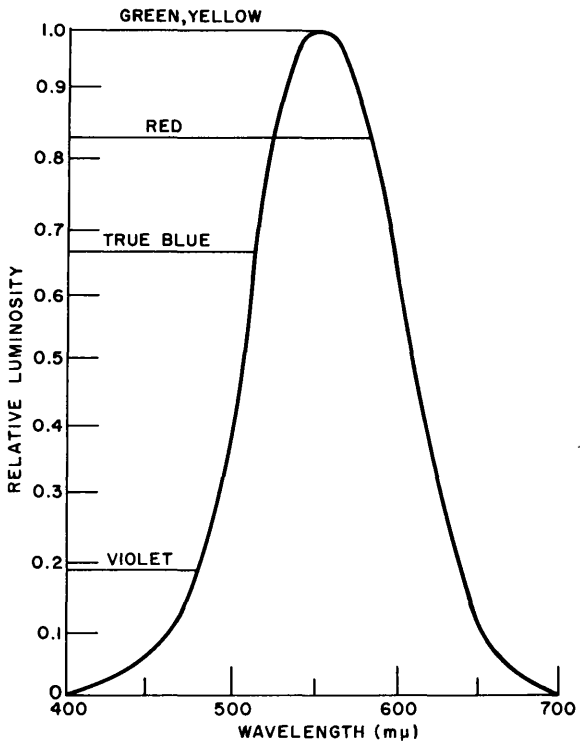


Fig. 22 - The standard luminosity curve

A partial solution of the problems of the blue consisted of replacing the "white" of the pattern with yellow. Yellow is essentially white light with those frequencies at the blue end of the spectrum removed. Blue and yellow therefore are much more different, spectrally, from one another than blue and white, and are therefore more distinguishable. The yellow did not appear other than white when projected, and therefore the discussions about and directions for flying the system were left unchanged. This paragraph explains the references to yellow paint appearing previously in this section.

Naval Oceanographic Office Pattern — In a concurrent attempt to obtain an ideal drum pattern, a project was arranged with the Naval Ocenographic Office. Their approach to the problem was to scribe the exponential pattern onto a stable material and color this pattern by hand with colors whose characteristics would be supplied by NRL. The scribing was accomplished by means of a computer-driver tool; the accuracy of these curves was outstanding. The pattern, when projected, appeared to move regularly and evenly, and the one joint was very precise. (This drum pattern was designed for a rotation speed of 33-1/3 rpm, and the entire drum circumference was taken up by one set of three colored bands, so the pattern was not repetitive.)

The problems once again centered about obtaining the desired colors, as specified spectrally. Finally, some translucent inks were found which could be applied to the pattern material and whose color characteristics satisfactorily matched the ideals. Applying the color required unprecedented accuracy, for there could be no black lines separating adjacent colors (which would, when projected, appear as dark areas of no information). These colors must be made to butt perfectly. NOO surmounted this problem (12). Unfortunately, the translucent inks caused scattering of the light from the condensing lens. This scattering greatly reduced the light level at the projection lens, and produced a loss of image clarity; the color changed gradually rather than abruptly as the eye was moved from one portion of the beam to another. Such an effect is unacceptable, because the distinctive aspect of the color sequencing is lost.

The preceding discussions of the development of the Rainbow drum pattern are included to document the technological breakthrough which made the multiple-stage photographing of the Ektrachrome-X drum possible, and because a large portion of the NRL

effort on the landing problem was devoted at this time to research on color characteristics, photographic techniques, and optical systems in general. The work done by NOO in the development of the inked pattern, while ultimately unsatisfactory due to the inks used, represented much successful effort and the development of precision techniques.

Approach Path Study — In the effort to obtain the optimum drum pattern, determination of the ideal exponential time constant was based on a mathematical consideration of beam characteristics and aircraft limitations and was validated by experimental flights, as discussed subsequently. The optimum projected pattern was defined in terms of the "programmed flight path," which is the theoretical path an aircraft would follow with respect to the carrier or desired landing point if the pilot were to maintain a zero sink-rate error at all times, after he began to fly the Rainbow. Such a path is determined by the dynamic characteristics of the projected beam and the location of the aircraft when the pilot begins to fly the system.

The optimum programmed flight path is one which is asymptotic to the glide path, the vertical rates experienced by an aircraft flying this path are not excessive for aircraft structural limitations, and the time (or distance) until acquisition of the glide path is minimized. The mathematical study was oriented toward determining the effects on the programmed flight path of varying the value of the time constant of the projected pattern. The exponential pattern produced a programmed flight path asymptotic to the glide path. The vertical rates and the glide-path intercept time depend on the value of the exponential time constant. For instance, a shorter time constant produces a shortened time to glide-path interception, but greater vertical rate. However, a longer time constant increases system damping and hence the ease of acquiring and maintaining glide path. There is, then, some trade-off in the selection of the proper time constant, as based on vertical rates, intercept time, and system damping.

There is one other determining factor in the selection of the time constant. This factor, known as the "potential reversal," refers to the possibility of the color sequence reversing direction due to overcorrection of a sink-rate error. Clearly, if the beam rate exceeds the maximum acceptable vertical rates for the aircraft, the pilot will never observe a color reversal (if he adheres to the rate restrictions on his craft). In order to realize the full potential of the Rainbow system, it is necessary to design for potential reversal and at the same time to maintain sufficient beam rate to produce an acceptable glide-path intercept time.

Although this study was intended for the design of the optimum projected pattern on the basis of the preceding criteria, a serendipitous aspect was the determination of the effect of airspeed on the programmed flight path. Since various classes of aircraft have different landing speeds, and since landing speed for a given aircraft is a function of gross weight, the effects of airspeed on the programmed flight path influence the feasibility of several craft using the system simultaneously and determine the criticality of airspeed to the design of the projected pattern.

Consideration of the geometrical properties of the entire system — i.e., Rainbow unit, projected pattern, and aircraft in the beam — permits expression of the programmed flight path as a function of the design parameters of the beam pattern, the initial position of the aircraft in the beam, and the range rate of the aircraft. Optimization of the programmed flight path for various initial positions of the aircraft leads to selection of the best value for the pattern time constant. Further, the effects of airspeed on the programmed flight path can be illustrated by using two values of range rate. In this study, range rate is assumed constant for any given approach and also is assumed to differ from airspeed only by a constant. This approximation is a reasonable one, since standard operating procedure calls for an attempt to be made to maintain a fixed wind speed along the deck and also because of the small angles involved.

In Fig. 23, the configuration to the right of the lens, which is considered as the origin, represents the projected beam pattern through which the aircraft flies. The aircraft is located at some altitude h and at some range R from the desired point of touchdown. Its angular position in the beam is represented by $\beta_a(t)$; β_c denotes commanded (glide-path) angle and $\beta_e(t)$ the angular error of the aircraft from the glide path. It should be noted that, due to the way in which the angles are defined, $\beta_e(t) < 0$ when the aircraft is above the glide path. This sign convention is consistent with general block-diagram terminology, which defines error as the difference between input and output, or as commanded angle minus actual angle; i.e., $\beta_e(t) \equiv \beta_c - \beta_a(t)$.

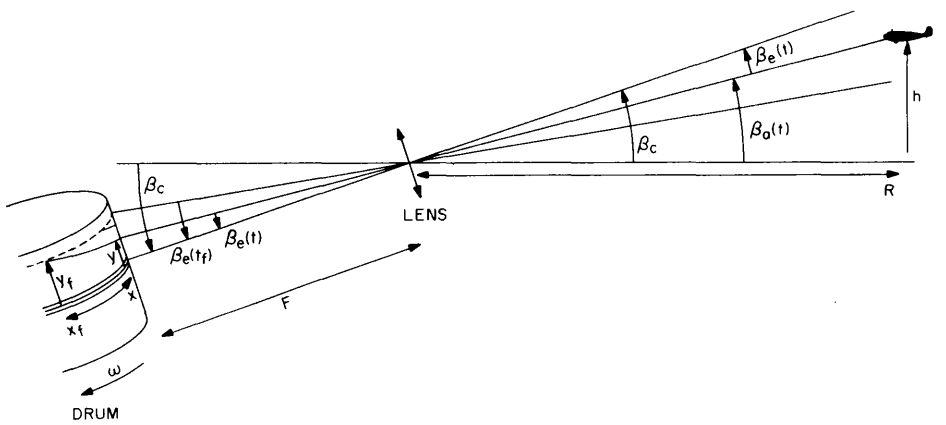


Fig. 23 - Geometry of the Rainbow pattern projection

The configuration to the left of the origin is a schematic representation of the rotating drum with the pattern superimposed upon it. Since the projected image must be focused at optical infinity, the distance between the lens and the drum must equal the focal length F of the lens. (Because the drum is to the left of the origin, F is assumed to have a negative value.) The drum-lens system is tilted at an angle β_c with respect to the horizontal.

From Fig. 23, a general equation $h = h(t)$, describing the position of the aircraft as a function of time, can be developed. The general equation for the pattern on the drum can also be written, and finally the altitude and altitude rate of the aircraft can be expressed in terms of the critical parameters of the beam pattern, with range as the independent variable, since aircraft and beam altitude will always be equal after beam acquisition.

The drum rotation and pattern projection are continuous and repetitive. An aircraft can intercept and begin to fly a beam at any time after the system begins to operate, and at any range and altitude within the beam pattern. The aircraft path depends on the initial position of the aircraft when it intercepts a beam and on the dynamic characteristics of the beam, but not on the size of the pattern itself.

The equations for $h = h(R)$ and also $\dot{h} = \dot{h}(R)$, obtained by differentiation, are:

$$h = R\left[\beta_c - \beta_e(0)\ e^{(R_0 - R)/\dot{R}\tau}\right] \tag{5}$$

$$\dot{h} = \left(\frac{R}{\tau} - \dot{R}\right)\beta_e(0)\, e^{(R_0 - R)/\dot{R}\tau} + \dot{R}\beta_c \,. \tag{6}$$

Reference 13 contains a complete derivation of these equations and a table of calculations of h and $\dot{h}$ for the selected value of τ.

The above expressions fully define the programmed flight path of an aircraft having a range rate $\dot{R}$ (defined as negative) and flying toward a glide path of angle β_c from an initial angular error $\beta_e(0)$ at range R_0; the time constant of the projected beam is τ.

Figure 24 shows the programmed flight path $h = h(R)$ of an aircraft flying each of four different projected beam patterns. A glide path ±0.1 degree wide, set at an angle of 3.5 degrees, is indicated by the cross-hatched area. The aircraft's rate of approach to the carrier is 120 knots. The initial range at which the pilot begins to fly the system is two miles. Initial errors of 0.5 degree high and 1.0 degree low are considered. The time constant τ of the projected beams is shown for values of 2, 4, 6, and 8 sec. This graph is plotted on a 1:1 scale in order to present a realistic picture of the landing approach.

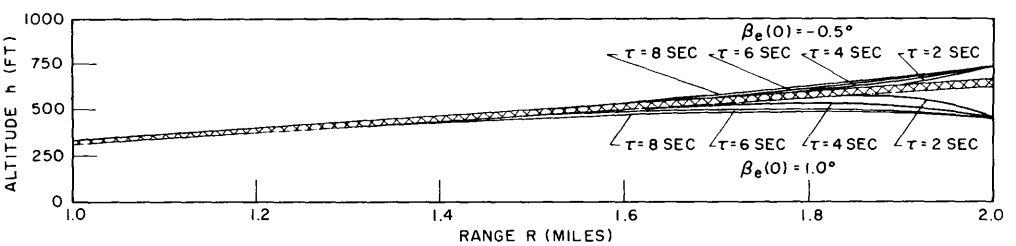


Fig. 24 - Programmed flight path $h = h(R)$. Graph has approximate 1:1 scale for realistic presentation of the landing situation. $\dot{R}$ = -120 knots, R_0 = 2 mi, τ = 2,4,6,8 sec.

Figure 25 presents the same information, but on an expanded (5:1) vertical scale for more accurate interpretation. It is evident that the programmed flight paths do not differ by great amounts for various values of τ. The glide-path intercept range R_G is between 1.3 and 1.9 mi for all values of τ. Range R_G decreases as the time constant increases, i.e., the longer the time constant, the longer the time until the aircraft enters the glide-path band.

Figure 26 is a plot of $\dot{h} = \dot{h}(R)$ for the same set of conditions illustrated in Figs. 24 and 25. The cross-hatched area defines glide-path sink rates. This graph clearly indicates that a short intercept time (large R_G) is achieved only at the cost of increased vertical rates. For instance, this graph shows that to correct an error of only 0.5 degree above glide path at two miles from touchdown, the pilot flying the τ = 2 sec pattern would be commanded to subject his craft to vertical rates in excess of 3000 ft/min. Of course the vertical rates become more tolerable as the time constant is increased. At the other extreme are the climb rates commanded by the τ = 8 sec pattern, which are seen to be less than 1000 ft/min for the initial errors shown.

Final selection of the optimum time constant involves trade-off between minimizing vertical rates and maximizing glide-path intercept range. The τ = 8 sec pattern was rejected because of the slow approach to glide path and the fine detail required in the drum pattern. The τ = 6 sec pattern was selected as the best overall compromise. This

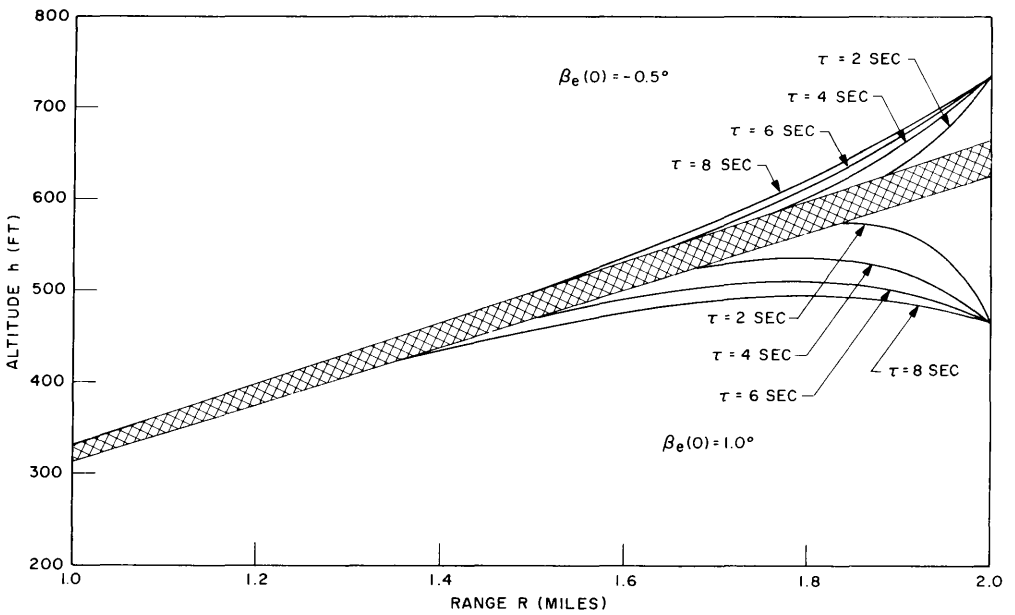


Fig. 25 - Programmed flight path $h = h(R)$, with expanded vertical scale of 5:1; $\dot{R}$ = -120 knots, R_0 = 2 mi, τ = 2,4,6,8 sec.

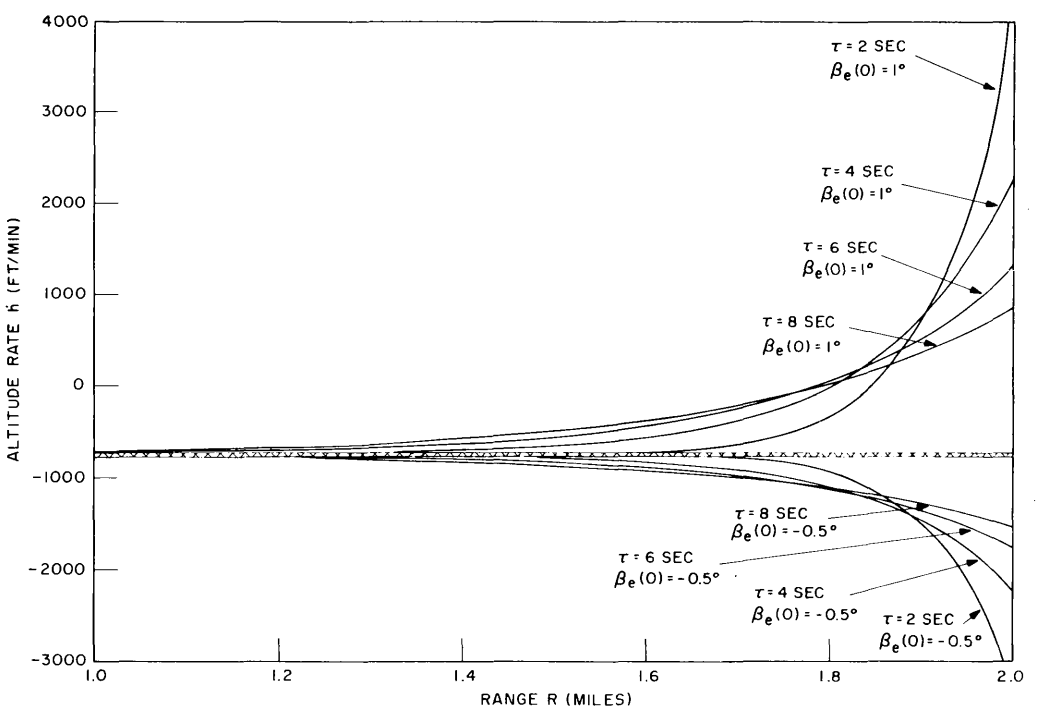


Fig. 26 - Vertical rate $\dot{h} = \dot{h}(R)$ of the programmed flight path. $\dot{R}$ = -120 knots, R_0 = 2 mi, τ = 2,4,6,8 sec.

beam pattern produced a programmed flight path characterized by an intercept range of about 1.65 mi after an initial error of 0.5 degree high, with rates never exceeding 1800 ft/min, and an intercept range of about 1.5 mi from an initial error of 1.0 degree low, with the climb rates never exceeding 1300 ft/min.

Figure 27 (on a 5:1 scale) illustrates the effects of airspeed on the programmed flight path. Again, the glide path is set at 3.5 degrees; the initial range is two miles; the initial errors considered are 0.5 and 2.0 degrees high and 1.0 and 1.5 degrees low. Two values for the rate of approach to the carrier are considered: 120 knots, represented by the solid lines, and 60 knots, represented by the dashed lines. The τ = 6 sec pattern is used for all these curves.

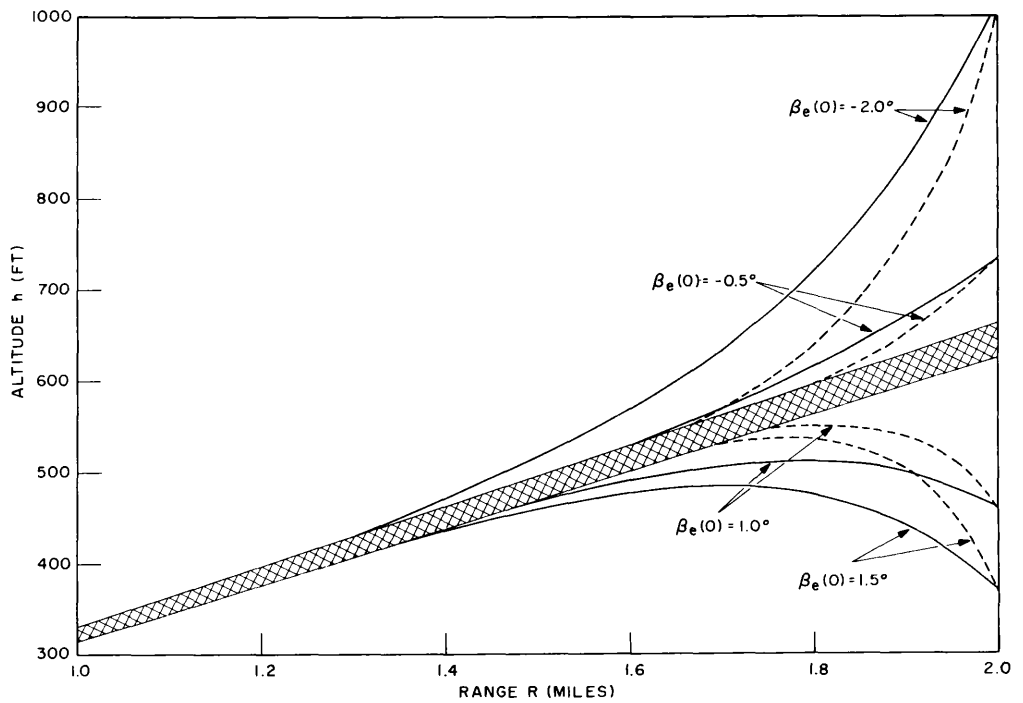


Fig. 27 - Programmed flight path $h = h(R)$ (expanded vertical scale of 5:1); $\dot{R}$ = -120 knots (solid line), -60 knots (dashed line); R_0 = 2 mi; τ = 6 sec

It can be seen that for an initial range of two miles and an initial error of 1.0 degree low, the glide-path intercept ranges will change from 1.46 to 1.74 mi as a result of halving the approach rate of the aircraft to the carrier. It can be shown that the vertical rates experienced in flying the pattern are slightly greater for the slower approach speed. On the basis of such curves, where approach rate is varied between 60 and 120 knots, it was decided that approach-rate variations of about five to ten knots would initiate negligible variations in the programmed flight path and associated vertical rates. As a result, one projected pattern is appropriate to guide aircraft of various classes with various landing speeds to the glide path.

Early Experimental and Demonstration Flights — Flights were made at intervals to evaluate performance or to optimize various parameters of the Rainbow system experimentally. These flights were made in light aircraft, piloted by the project engineer and

another NRL scientist at Maryland Airport, Pomonkey, Md. The first successful flight test was made on March 25, 1964, using the Rainbow system with the original multiple-layer ozalid drum pattern. The color confusion near glide path resulting from the previously discussed problems of crossover and gaps was quite evident. However, the flight substantiated the hypothesis that precise, up-to-date error information on rate of descent could contribute greatly to the accuracy of an approach. Further, these early flights demonstrated the usability of a three-color sequence to encode sink-rate-error information. Although it was found that concentration and some training were required, facile determination of the sequence and interpretation of its control information were feasible. It was also quite evident that a better pattern would be required.

A large number of flights were made to validate the analytical work of color selection for both the Ektachrome-X pattern and the NOO pattern. Segments of the drum were covered with various samples of color film or other transparent material. No guidance information was placed on these test drums, which were used solely to evaluate the colors in flight at variable ranges during the day and at night. Such flights were necessary because it was proved at an early date that the colors do not appear the same when viewed from the air as when viewed in a dark laboratory. Further, a color does not even appear the same when viewed outside, on the same day, from the same range, from the ground and from the air. These differences were attributed to atmospheric effects and to the color and lighting of the viewing background. Also noticeable was the effect of heat waves rising from very near the ground. The color selections eventually made were based both on consideration of the spectral characteristics of paint, filters, film, and the eye, and on atmospheric effects at varying ranges and under various weather conditions.

Another parameter which was checked out experimentally was the exponential time constant of the colors of the projected beam. Originally established at four seconds, this value was later increased to six seconds on the basis of the analytical study discussed above. The experimental unit has a vertical field of view of four degrees above glide path and two degrees below glide path and a lateral field of ±5 degrees.

The selection of the basic sequence rate ($1/\Delta T$) was originally made in the laboratory. The value of 1.5 colors per second was established as being well below the highest discriminable rate under idealized conditions. Factors to be considered in selection of this constant are (a) discriminability of sequence, and (b) the desired basic sensitivity of the system, which is directly proportional to $1/\Delta T$. This gain was later decreased in conjunction with increasing the time constant, and it was found that either value was acceptable. It should be recalled that we are discussing basic sequence rate, which is the rate of passage of a color past any fixed point within the pattern. The observed rate, of course, may be much faster or much slower, depending on the sink rate of the aircraft. The basic rate must be chosen so that it does not become indistinguishably fast when the aircraft is in the most sensitive area of the pattern and develops a minor rate error or, on the other hand, so slow that it cannot provide useful information to the aircraft at all times.

Generally, the Rainbow system was considered from the point of view of flyability and its general effectiveness in increasing the overall accuracy of the approach and landing. Throughout the tests, it became increasingly easy to distinguish, interpret, and respond to the color-sequence commands. It was also apparent, however, that some degree of training was required to achieve the full benefits of the system. Even with minimal practice, however, pilots were generally able to acquire the green glide path smoothly and remain within it for about 80 to 90 percent of the approach. This glide-path beam was therefore reduced from an original size of ±0.3 degree to only ±0.1 degree, which indicates that a pilot seeing the green at a range of about one mile is flying to an accuracy of ±8 ft from glide path. Pilots were still able to maintain the green for the major part of the approach.

This accuracy was reinforced by extremely long acquisition ranges. The system could be sensed and flown from a distance of greater than three miles on a bright, sunny day and, in an extreme test, was acquired out beyond 20 miles at night. Such figures do not suggest that such long acquisition ranges are desirable, but rather that the usable system range is, for all practical purposes, unlimited. An acquisition range of about four miles means that the pilot flying his aircraft at 150 knots gets useful control information for about 1-1/4 minutes before touchdown, which is ample time to get well set up on glide path.

Movie films were taken from the aircraft of the runway and the Rainbow system and simultaneously, from the ground, adjacent to the display, of the approaching aircraft. The former show the color-sequencing light as the pilot receives error information regarding his rate of descent and makes the indicated corrections. The latter show the very small amounts of deviation of the flight path once the green indication is achieved.*

Modifications Proposed to the Basic Rainbow System —

Linear System — At one time, consideration was given to a linear, rather than exponential, drum pattern. The advantages of such a pattern would be in preventing the development of commands for excessive vertical rates even at positions of large error from glide path, and also preventing the system from becoming overly sensitive to rate changes at positions very close to the glide path. Clearly, a linear pattern would be decidedly easier to create than an exponential one, since the vertical dimension as well as the horizontal dimension of each color would remain constant in all areas of the pattern. The tolerances would therefore not be continually decreasing close to glide path.

A linear pattern was fabricated for an experimental flight, but it was found to be unsatisfactory because the time elapsing between beam acquisition and glide-path interception was excessive. The exponential pattern may command greater vertical rates than the pilot is willing to let develop, but it provides for glide-path acquisition in minimal time, limited only by aircraft restrictions. A linear pattern, on the other hand, develops rate commands that are much too small to correct large errors or else are so large even at small errors that overshoot becomes inevitable.

The linear pattern was also evaluated in the analytical study. It resulted in a programmed flight path which was not asymptotic and which had an acceptable glide-path intercept time only when the vertical rates became excessive, exactly as observed during flight. Without further study, this type pattern was discarded.

Two-Color System — A question which had frequently been raised regarding the Rainbow system concerned the necessity of having three colors in the sequence. It was pointed out that one two-color sequence, such as blue-white, above the green glide path, and a different two-color sequence, such as red-white, below glide path, would have several distinct advantages over the three-color system.

Instructions to a pilot flying such a two-color system would be as follows: "If the color sequence contains blue, you are high. If the sequence contains red, you are low. Sequencing colors indicate a sink-rate error. A steady color (other than green) indicates an appropriate correction of sink rate." Note the similarity of these commands to those used by the pilot flying the three-color system. The drum pattern for such a two-color system would vary from that of the three-color system only in the coloring of the exponential bands.

*Qualified requesters may receive copies of these films. Address inquiries to the Director, Naval Research Laboratory, Washington, D.C. 20390.

Several advantages of a two-color system over a three-color system are apparent. One is the greater ease with which the pilot might learn to interpret the commands of the display. A second, concerned with installation aboard a carrier, is minimal color confusion due to the beam movement introduced by ship motion. The third and perhaps most important advantage, however, is the provision of high-low information to the pilot.

Not to be overlooked is the feasibility of manufacturing the drum pattern selected. Clearly, a two-color transparency would be less complicated to produce than would a three-color one, since a line negative printed in a single color for the top half and a different color for the bottom half would provide the two-color projected pattern (with none of the multiple layer alignments which are so difficult to achieve accurately).

On the other hand, there are also several problems associated with a two-color system. The primary one concerns the fact that two alternating colors contain no direction information. For example, a pilot turning final in a descent, and seeing the alternating red and white indication, could not know whether his sink rate was too great or not great enough. Another concerns the potential for "color-sequence reversals," which are the indication to the pilot of an overcorrection of sink-rate error. A color reversal is, of course, discernible only when the color sequence contains more than two colors, since one cannot distinguish when the red-white-red-white sequence reverses to white-red-white-red. The pilot flying a two-color system with a time constant of six or eight seconds who overcorrected his sink-rate error would at best notice only that the color sequencing had speeded up. But this is also precisely the indication of improper correction, or correction in the wrong direction. This ambiguity could clearly lead to serious trouble.

In order to eliminate the possibility of overcorrection over a major portion of the approach envelope, the time constant could be decreased until beam rate generally exceeded the vertical rates of an aircraft whose pilot adhered to the structural limitations of his aircraft. As a result, overcorrection could very rarely occur, so color-sequence acceleration would consistently indicate improper correction. The time constant would have to be decreased to about two seconds to minimize the possibility of overcorrection. However, as shown earlier, decreasing the time constant to this small value simultaneously decreases the gain on the rate-feedback term and thus decreases system damping, or nullifies the main advantages of the Rainbow system, because it leads to a less stable landing approach.

The advantages to be gained with a short-time-constant, two-color system are considered not to outweigh the accompanying loss of system damping. For this reason, the three-color system was chosen for experimental work. This discussion of a two-color system is included merely to describe one alternative method of color-sequence encoding of rate-error information in conjunction with binary position information where low system damping is tolerable.

Flashing Lower-Half Pattern — Yet another modification suggested was to flash the lower half of the pattern, in an effort to provide high-low information as well as sink-rate-error information. A pattern was modified by superimposing strips of opaque tape on the lower half of the pattern, spaced so as to produce a noticeably different frequency from that of the basic rate of the sequencing colors. When flown, this system resulted in utter confusion and was therefore dropped.

Integrated Fresnel-Rainbow Optical Landing System — This system, as conceived, consists of the unique and precise combination of the Rainbow and the Fresnel lens systems in such a way as to produce more complete guidance information than is inherent in either system alone.

The IFROLS, as its name suggests, is essentially a combination of a standard Rainbow unit and two modified Fresnel lens units.* The FLOLS has been criticized because of the lack of any rate information or of a signal suitable to pilot derivation of the necessary information. The Rainbow, on the other hand, while its rate-error information is based on and therefore always appropriate to position error, has been equally criticized for its failure to provide a distinct display of position information to the pilot. The previous discussions recount some of the efforts to incorporate this information into the Rainbow system.

The IFROLS represents another attempt to supply the missing high-low indication by the addition of two Fresnel lens units, with modified optics, on either side of the Rainbow, adjusted so that their horizontal centerlines are exactly aligned with the Rainbow's green glide-path beam. The optics would be modified (by altering either the focal length of the Fresnel lens or the distance from the light source to the lens) so as to convert the virtual image to a real image. The practical effect of this modification, of course, is to reverse the direction in which the image moves in response to vertical motion of the pilot's eye. The Fresnel units thus become the "datum arms" of the IFROLS with which the relative position of the Rainbow meatball is compared. Although the image movement is actually in the Fresnel units, thus producing moving datum arms, the system gives the illusion of the standard FLOLS, with a "high meatball" for error above glide path (actually displayed by low datum lights and stationary meatball, Fig. 28a), and a "low meatball" for error below glide path (displayed by high reference lights and stationary meatball, Fig. 28b).

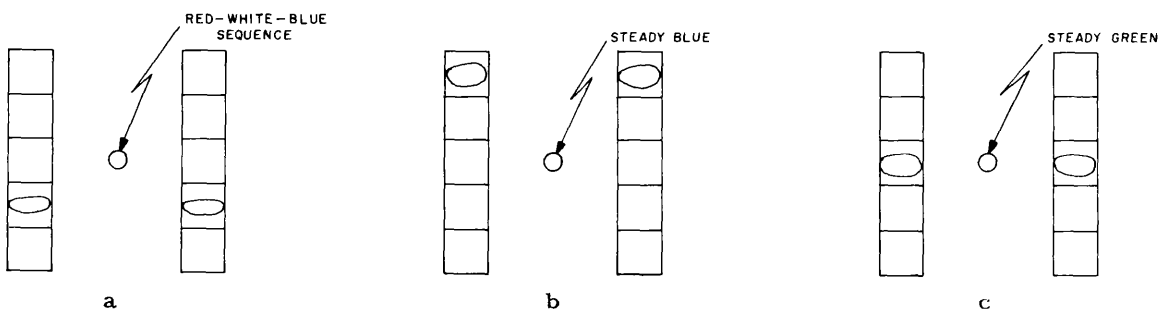


Fig. 28 - The Integrated Fresnel-Rainbow Optical Landing System

a. Indication of "high" and "insufficient rate of descent"
b. Indication of "low" and "proper rate of correction"
c. Indication of "on-glide-path" and "proper sink rate"

Simultaneously, the Rainbow meatball is projecting its sequencing colors to inform the pilot of any discrepancies in his rate of descent for acquiring the glide path. The color sequence indicating insufficient rate of descent when the aircraft is high is also shown in Fig. 28a. A steady blue color is shown in Fig. 28b, indicating that the aircraft is low but that the pilot has adjusted rate of descent for optimal acquisition of glide path. Figure 28c shows a green, "Roger meatball" as both components indicate that the aircraft is on the correct glide path.

*The IFROLS was conceived prior to the invention of two other point-source-type landing displays discussed later in this report. The discussion on the IFROLS is equally applicable, however, to such a system incorporating any point-source display as the "meatball."

The IFROLS was fabricated for a test flight using greatly simplified but optically equivalent units in place of the Fresnel units. As long as the pilot responded to the color-sequenced rate commands of the Rainbow indication, he was unable to detect any relative motion of the Rainbow meatball and the datum arms. At very long range, for instance, it is predictable that the size and dimensions of the "datum arm" units (identical to those of the FLOLS) preclude discrimination of error indications. By following the color-sequenced rate commands, the pilot decreases error from glide path as range decreases. As a result, by the time the aircraft is within the useful range of the datum arms (about one mile) there is unlikely to be sufficiently large deviation from the glide path as to be observable by meatball displacement.

This result is due, of course, to the sensitivities inherent in the two component systems. The on-glide-path indication of the Rainbow system is ±0.1 degree, which corresponds to the center two thirds of the center cell of the FLOLS, an area smaller than the apparent size of the image at most ranges. The FLOLS can be made more sensitive in order to exhibit more image movement only by increasing its size, which would be undesirable for shipboard operation, or by decreasing its total angular field, which would further limit its utility when the aircraft is far from the glide path. Although experimentation once again resulted in rejection of efforts to add position-error information to the Rainbow signal, it served a useful purpose, for it demonstrated that the accuracy which is achieved with the narrow-glide-path Rainbow system results in error below the sensitivity threshold in the FLOLS, in most circumstances.

Experimental Evaluation of the Rainbow System — On May 3, 1965, NAVAIRSYSCOM initiated a Problem Assignment (14) to the Naval Air Test Center, Patuxent River, Maryland, "to evaluate the concept of the rainbow optical landing aid (color-sequence-coded signals)" in general and in detail, "utilizing standard carrier approach patterns: (1) evaluate the concept of this system, (2) evaluate the feasibility of using this system aboard aircraft carriers and/or shore stations as a primary optical landing system, (3) evaluate the feasibility of using this system aboard aircraft carriers and/or shore stations in conjunction with the Fresnel lens optical landing system."

At an early stage in the evaluation, the pilots reported that they considered the glide path to be unnecessarily fine, the lateral field too narrow, and the system overly sensitive in the regions close to the glide path. Halving the focal length of the projection lens would produce changes in the projected pattern in the directions indicated by the pilot's suggestions. For example, the dimensions of the field of view, both vertical and horizontal, would be doubled (and parts of the vertical field could be blocked out if desired), the glide-path beam would be twice as large (±0.2 degree), and the sensitivity near glide path cut in half (color size would be doubled, but basic sequence rate would remain unchanged). Accordingly this modification was made to the system, and the remainder of the evaluation was conducted with the modified system.

Upon completion of the evaluation, two primary objections to the system were voiced. The first of these was that the system required excessive concentration for signal interpretation. This long-scan-time requirement was attributed to (a) "similarity of the basic error codes" of red-white-blue and blue-white-red, which made recognition of reversals difficult; (b) "incompatibility of color-sequencing dynamics with the pilot's ability to discriminate the order of color sequence," which prevented the use of the error-trend information presented; and (c) "use of a point light source" which was inconspicuous against the cluttered daylight landing background. The greater portion of the evaluation was conducted at night, "where the usable range was approximately 3 to 4 miles" (15).

The second objection to the Rainbow system was in the absence of position information in relationship to the glide path. The report concludes "A dynamic situation display, which indicates to the pilot exactly where he is, which way he is going and how fast, is a mandatory requirement for any landing aid. Systems which lack or degrade even one of these three parameters are unsatisfactory." (16).

Since we believed the Rainbow to be theoretically sound and the objections to be primarily to the manner of error-signal encoding, we next conceived a system which would be similar to the Rainbow in some respects but different in others.

Altitude Rate Command (ARC) System

The ARC system is quite similar to the Rainbow, both in design and in the fact that each presents error information regarding rate of descent to the pilot. The primary differences between the two are the improved form of error-signal encoding employed in the ARC system, and the additional information provided. The sequencing colors of the Rainbow have been replaced by a sequencing of different levels of intensity in the ARC system. Intensity-sequence encoding, like color-sequence encoding, can be projected from as small a display unit as is practicable. Since there is no displacement coding involved, the size of the display will not affect the sensitivity of the error signal. The intensity-sequenced signal is also, of course, range independent.

There are two primary advantages of intensity sequencing over color sequencing for encoding error. The first of these concerns a built-in redundancy feature. Suppose, for the sake of illustration, that an intensity sequence contains three light levels, i.e., bright (B), medium (M), and dark (D), which are analogous to the red, white, and blue of the Rainbow. Suppose that the intensity is in the increasing mode, i.e., D, M, B, D, M, B. The step from dark to medium is qualitatively the same as the subsequent step from medium to bright. Therefore, in the span of each cycle of the sequence, the same bit of information is presented twice. The color sequencing of the Rainbow system, on the other hand, does not have this feature, but depends rather on the qualitative differences between the three colors. As a result, there is much less to learn and remember in order to decode the meaning of an intensity sequence than of a color sequence. This fact should reduce the attention required of the pilot, and the training time as well. A practical advantage of an intensity-sequenced system is that no longer is it necessary to achieve the complex color pattern on the transparency which was at the heart of so many of the early practical difficulties with the Rainbow system. Finally, the replacement of color sequencing with intensity sequencing as the primary signal encoding, releases the use of color for a type of secondary signal encoding — the desired high-low information.

Flying the ARC System — Pilots are told to interpret the intensity sequencing of the ARC system as follows: "When the light gradually becomes brighter, in a cyclic or repetitive manner, add power so as to decrease sink rate (corresponding to the blue-white-red Rainbow sequence); when the reverse sequence appears, that is, when the light grows gradually dimmer in a cyclic or repetitive manner, reduce power so as to increase rate of descent (corresponding to the red-white-blue Rainbow sequence). Slowing of the sequence indicates that the proper type correction is being made. A steady light of constant intensity, a zeroed sequence, denotes the optimum sink-rate correction. Sequence reversal indicates overcorrection, and sequence acceleration warns of correction of the wrong polarity. Sink-rate-error information then is presented in the form of a repetitive, sequential ordering of increasing or decreasing levels of intensity."

There is an element of naturalness in these interpretations of the intensity sequence direction. A decreasing light calls for decreased power to cause more rapid descent; conversely, an increasing light commands increased power to reduce descent rate.

Since color is no longer needed in the beam pattern to provide sink-rate-error information, it becomes available for encoding high-low information. The ARC glide path is indicated by an amber beam. The portion of the projected pattern below glide path is red, and that above it is green. (It has been found that the intensity sequencing of both red and green light is equally as noticeable and distinguishable as that of white light.)

To summarize, then, the pilots receive from the ARC system color-coded high-low information, together with rate-of-descent error information, which is intensity-sequence coded.

Generation of ARC Commands — Figure 29 shows a beam pattern which will generate ARC error signals for incoming pilots. This schematic shows the projected pattern at a single instant in time. Actually the pattern is continually changing as the bands of light converge about the glide path. The apparent intensity and color of the light which the pilot sees at any moment depends, as with the Rainbow system, on the position of his eye relative to the beam. In Fig. 29, the narrow-glide-path beam is amber, the area above the glide path is green, and that below it is red. Note that the pattern as described has four levels of intensity labeled, for convenience of discussion, bright (B), medium bright (MB), medium dark (MD), and dark (D).

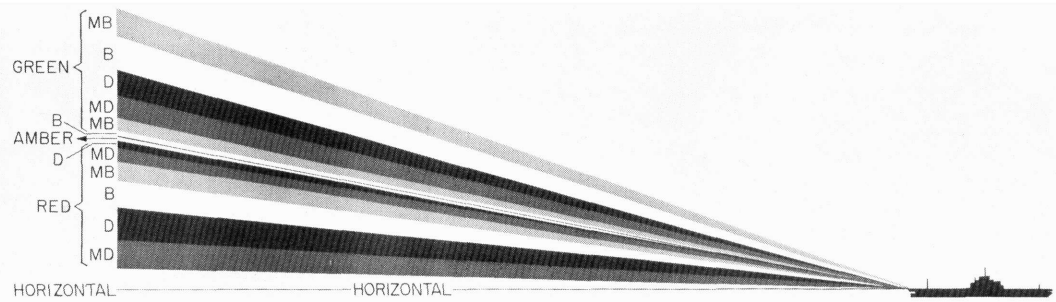


Fig. 29 - The ARC system profile

If a pilot is in straight and level flight above the glide path, these bands move down past his eye. The resulting sequence which he sees then is B, MB, MD, D, etc. This decreasing sequence repeats until he follows the command to decrease power so as to increase sink rate. As his aircraft begins to sink more rapidly, he will observe that the sequencing slows down, and, if he makes exactly the right correction, stops altogether, so that he sees a green light of constant intensity. If he overcorrects, however, and begins to descent too rapidly, he flies down through the moving bands and sees an apparent reversal of the sequence, although the light remains green. The increasing light sequence D, MD, MB, B, etc., tells him to add power so as to reduce his sink rate. It becomes apparent that a pilot can see a green light, telling him he is above glide path, which is sequencing so as to tell him to add power to decrease his rate of descent to avoid overshooting the glide path. If overshoot should occur, however, the light will become amber as the aircraft intercepts the glide-path beam, and will turn to red as the aircraft goes below. At the same time, the intensity sequencing will resume, to provide information appropriate to setting up the correct rate of descent (or climb, as the case may be) to reacquire and maintain the glide path.

The movement of the beams toward the glide path is exponential, as in the Rainbow system, which means that beam rate at any given angular position is always proportional to the angular distance remaining to the glide path. The aircraft flying within any single intensity band, then, must make large sink-rate corrections when far from glide path and smaller ones as it nears the glide path. When the aircraft intercepts the amber beam from along such an approach, its rate of descent is appropriate to maintain glide path.

Experimental Unit Design — The ARC system uses essentially the same equipment to project its beam pattern as does the Rainbow. The primary difference between the two is in the transparency through which the pattern is projected into space. Figure 30 is an idealized representation of an ARC drum, showing the bands of four levels of intensity which converge exponentially about the glide-path band. These bands can be defined in terms of their transmission characteristics. In the first experimental unit, the bright band is 100 percent transmissive, the medium bright band is 50 percent transmissive, the medium dark band is 25 percent transmissive, and the dark band is 12.5 percent transmissive. Early tests indicated that these 50-percent attenuations between successive bands, resulting in an eight-to-one difference between the greatest and the least, would result in a sequence with easily sensed steps and obvious bounds.

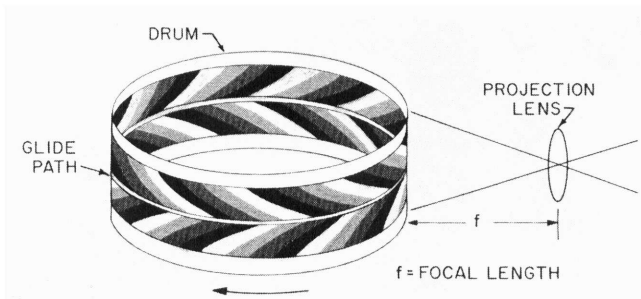


Fig. 30 - Artist's conception of an ARC drum pattern

The information rate of the ARC system is higher than that of the Rainbow, but the basic sequence repetition rate is the same. This is to say that the four levels of brightness will pass any stationary point within the pattern in the same amount of time as would three Rainbow colors. The direction, or order, of the sequence is therefore established sooner, permitting the pilot to initiate corrective actions more readily than he can with the Rainbow system. Also, because of its redundancy feature the intensity sequencing is more readable than the color sequencing at high sequence rates, such as when the aircraft has an error in rate very close to the glide path. Higher basic sequence rates can therefore be tolerated in the ARC system. Because of this increased readability of the signal, and also on the basis of the approach-path study described earlier (and which is equally applicable to the ARC system), longer time constants and more reasonable rate changes are feasible. A time constant of ten seconds has been selected for the experimental ARC system. (For a complete discussion of this system see Ref. 17.)

A drum pattern for an experimental ARC unit was designed according to the equations used for the Rainbow (11). Once again the enlargement-reduction photographic process and the approximation of the linear tail were employed to achieve the necessary pattern accuracy.

Several ways of producing the required transmission levels are feasible. For instance, neutral-density filters of the desired density could be cut to the proper shape and aligned on a sheet of clear plastic to be colored subsequently. However, this method would undoubtedly again create problems of crossover and gaps.

A pattern could be painted, as was done for the Rainbow, in carefully selected shades of gray for photographing. This method would require great accuracy, not only on the part of the person mixing and applying the paint (more than for the Rainbow pattern where pure, unmixed colors were applied full strength), but also on the part of the

photographer in very rigid control of exposure time, development time, and developer chemical composition. Also, duplication would become a severe problem.

An alternative method was used which restricted the precision requirements to the calculating and drawing stage of the pattern. The method is essentially a "screening" technique. The exponential stripes consist of alternate opaque and transparent vertical stripes. When these rotate past the projection lens the observer sees an apparent attenuation of brightness, the amount of attenuation depending on the relative width of clear to opaque in each cycle. The spacing and size of the stripes is such that the resulting flicker frequency remains constant, well above the maximum frequency detectable by the eye. A portion of the actual drum pattern before coloring (true size) is shown in Fig. 31. The flicker frequency arising from the rotation of this pattern at 3 rpm is 50 cps, high enough to be unnoticed. Vertical stripes have been added at the outer edges of the pattern to produce warning flashes (of a frequency different from that of the intensity sequence). This pattern was photographed on line film which, of course, prints only black or white but has fine resolution. The only critical photographic parameter is the camera focus, which can be controlled precisely. After photographic reduction and final alignment, the pattern is printed in a single piece. It is then hand-colored with aniline dyes.

Experimental and Demonstration Flights — Experimental flights were made to check out the operating characteristics of the display. The ARC system appeared to be quite flyable and to contribute substantially to an optimal approach to landing. The intensity sequencing provided useful information for setting up the proper rates to acquire the amber beam along an ideal path. The color coding was helpful in the quick recovery of glide path following a gust disturbance or a gradual drifting from the amber area. The glide-path beam of ±0.15 degree can be maintained over a large percentage of the approach by most pilots, with only a minimum of practice.

After the experimental checkout of the system, demonstration flights were made for NAVAIRSYSCOM representatives and other interested naval officers. (These demonstrations are reported in CSR's: 1966: 5120-28, -29, -30, -31, -32, -34, -35, -37, of Ref. 1). The consensus of opinion was that there is indeed a pressing need for the provision of a good rate-of-descent signal to the pilot and that the ARC system has definite merit in this respect. Also it was agreed that the ARC system provides real improvement over the Rainbow in its form of rate-error signal encoding and also in its provision of the desired high-low information. There was also general agreement that the intensity-sequenced signal needs to be made more conspicuous than it presently is. However, it was felt that the system should be sent to NATC Patuxent River without delay for a preliminary evaluation of the principles inherent in the system. Accordingly, on Dec. 6, 1966, a Problem Assignment (18) was sent by NAVAIRSYSCOM to NATC to conduct initial shore-based evaluation of the ARC system with a unit furnished by NRL. This evaluation has been initiated.

Basic Study for Optimization of ARC Signal — Although the original unit had already been delivered to NATC for evaluation, a basic study was undertaken to determine the characteristics of an optimum intensity sequence, because of the interest and encouragement of several Navy officers who are cognizant of the current carrier landing problems and of the NRL developments. Increasing the conspicuity of the signal by varying the nature of the drum-pattern design is the purpose of the study.

A number of parameters of the intensity sequence are determining factors of general signal conspicuity. These are (a) the number of levels in the sequence, (b) the relative time duration of the levels, (c) the mathematical nature of the attenuation of intensity between adjacent levels, (d) the basic sequence rate (not to be confused with the flicker frequency generated by the screening technique for brightness attenuation), and (e) the the ratio of the highest and lowest intensities of the sequence, hereafter referred to as signal range, or SR.

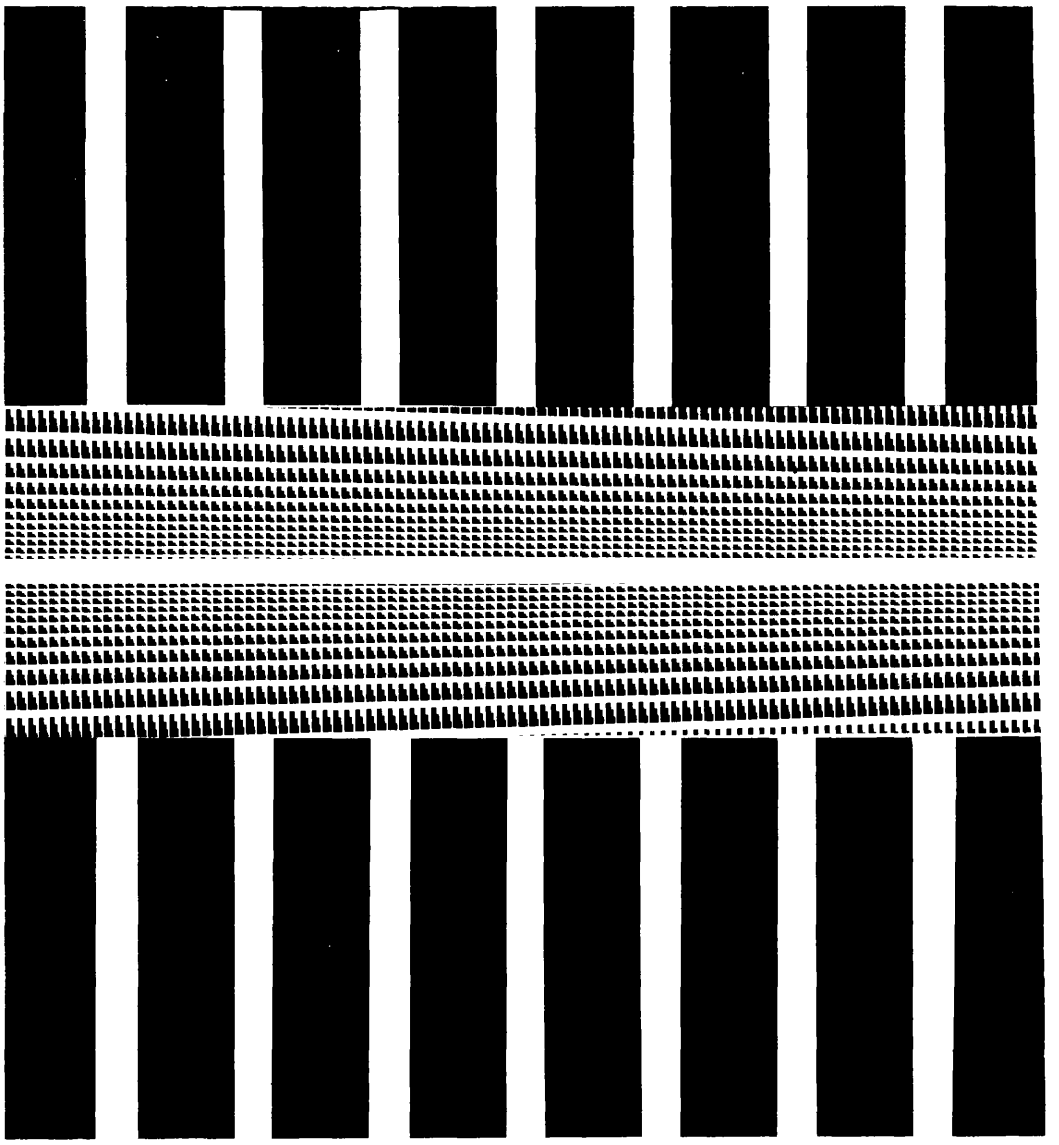


Fig. 31 - Portion of ARC pattern (shown in actual size)

Test sequences have been designed and fabricated for use in a laboratory selection of the optimally conspicuous sequence. These test patterns contain no guidance information, but merely simulate a given sequence which changes intensity at a constant rate independent of any motion of the viewer's eye in the beam. In the operational system, actual observed sequence rate varies, of course, as a result of aircraft motion in the beam. For this reason the basic programmed rate must be a compromise, so that for all likely aircraft motion beam rate becomes neither too fast nor too slow.

The method of fabricating the test sequences for the laboratory study consists of applying constant-width opaque tape onto clear ozalid, with spacing such that the ratio of clear to opaque is equal to the desired transmission characteristic. The test pattern is then attached to the rotating drum. The flicker frequencies resulting from this screening method are variable, but always above that detectable by the eye (the lowest being about 50 cps), and the variation is therefore insignificant.

For the first stage of this study, at least, two of the five possible parameters were not varied. These are (d) the basic sequence rate, and (e) the ratio of the highest level of intensity to the lowest, which was maintained at 8 to 1. The sequence frequency selected was about 1/2 cps. This frequency was used successfully in the original ARC system. The 8-to-1 signal range, while selected rather arbitrarily, proved satisfactory in the early ARC flights and studies. The ratio must be easily distinguishable without the lowest level ever becoming so low as to be lost at long viewing range; also, the highest level must not become so bright relative to the lowest level as to blind the viewer.

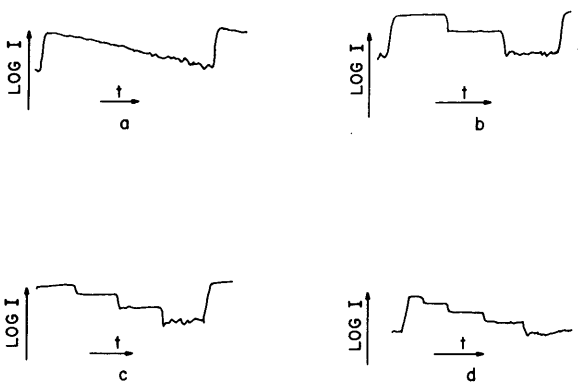


Fig. 32 - Recordings taken from test-pattern sequences (using a photocell with logarithmic response characteristics)

a. One-level sequence, which varies approximately logarithmically from a minimum intensity of 6.25 percent to a maximum of 50 percent (and projected with twice as bright a light source for comparison with sequences having a maximum intensity of 100 percent)
b. Three-level sequence, with levels of equal duration and the logarithmically attenuated intensities of 100, 35, and 12.5 percent
c. Four-level sequence, with levels of equal duration and the logarithmically attenuated intensities of 100, 50, 25, and 12.5 percent, "controldrum:" similar to original ARC pattern sequence
d. Five-level sequence, with levels of slightly unequal duration and the logarithmically attenuated intensities of 100, 60, 35, 21, and 12.5 percent

The parameters which are varied in the study are (a) the number of levels, (b) the duration of the levels, and (c) the nature of the intensity changes between consecutive levels. In the first category, test patterns have been made of three, four, and five levels, and as an extreme case, a continually changing one (an infinite number of levels). Figure 32 shows recordings made with a logarithmic photocell of test-pattern sequences containing each of these. Note that Fig. 32c is a sequence designed in accordance with that used in the original ARC pattern. A one-level sequence can be considered the limiting case at both extremes, since it is theoretically an infinite number of levels or a single level, depending on the point of view. Two-level sequences were not considered because of the impossibility of detecting direction from an alternating sequence (this point was discussed previously with reference to a two-color sequence). Of note is the fact that slow sequence rates (resulting from fewer intensity levels) may be a positive factor in sequence discrimination; however, error-information rate is directly proportional to sequence rate. There may, therefore, be some tradeoff necessary to achieve a signal which is both usable and useful. The basis of selection of the proper number of levels is whether the sequence is made more conspicuous by more levels and therefore less attenuation between levels, or by fewer levels marked by greater intensity changes.

In the second category, level duration, test patterns were made in which the various levels have equal duration, and several in which they have "inversely proportional duration." In those having inversely proportional duration, the highest-intensity levels are of the shortest duration, and the lowest levels of the longest duration. Figure 33 shows examples of equal and of inversely proportional duration levels. The idea is to equalize approximately the light flux reaching the eye from each level of the sequence. The original ARC system has equal durations. The point in question here is whether flux or time is the critical item in the recognition of the various steps.

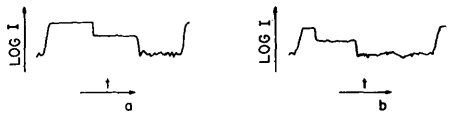


Fig. 33 - Recordings taken from test-pattern sequences of three levels, logarithmically attenuated intensities of 100, 35, and 12.5 percent

a. Equal durations of 33-1/2 percent each
b. Inversely proportional durations of 12.5, 30, and 57.5 percent. All measurements were made with a logarithmic photocell.

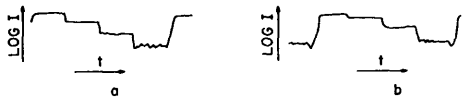


Fig. 34 - Recordings taken from test-pattern sequences of four levels of equal duration

a. Logarithmically attenuated intensities of 100, 50, 25, and 12.5 percent
b. Nonlogarithmically attenuated intensities of 100, 70, 35, and 12.5 percent. Measurements were made with a logarithmic photocell.

The third category deals with the nature of the intensity attenuations between consecutive levels. Logarithmic reduction means that, for a four-level sequence, the intensity is halved between consecutive levels (reduction factor between adjacent levels is $(SR)^{-1/(N-1)}$, where N = number of levels). For a three-level drum, the reduction factor is $8^{-1/2}$, and for a five-level drum $8^{-1/4}$. Here, of course, the relative change between levels should be constant, in keeping with the Weber principle (19), which indicates that logarithmically equal reductions in brightness might be expected to be equally apparent at any brightness level. The other type of reduction considered is nonlogarithmic; the absolute change in intensity between consecutive levels is more nearly equalized in an effort to increase the absolute size of the differences between the lower levels. Examples of both type attenuation are seen in Fig. 34.

One other class of test sequences is included in the study. These sequences, known as "bouncers," are designed with equal durations, logarithmic reductions, and three, four, or five "levels." The bounce characteristic is achieved by varying the intensity within each level by plus or minus a fixed percentage of the average intensity of that level. The purpose of bouncing levels is to increase the differences between adjacent levels so as to make sequence steps more obvious, while simultaneously providing that the internal variation of the level be both small and gradual enough to be unnoticeable. For example, if the average intensities are 100 percent, 50 percent, 25 percent, and 12.5 percent, the corresponding bouncer might have a bounce percentage of ±20 percent of the average intensity and therefore level intensities of 100 percent, 40 to 60 percent, 20 to 30 percent, and 10 to 15 percent. Several bouncers are shown in Fig. 35.

Selection of the most useful of these test-pattern sequences could be based on a number of criteria. For instance, one method might be that of paired comparisons to optimize conspicuity (on a judgment basis). Other possible measures are reaction time, maximum detection distance from the light source, background illumination, etc. Most of these, however, weight different types of patterns differently.

The method used in the NRL study is to have the subject manipulate a control to set the signal-range SR at the minimum level at which the sequence direction is conspicuous. Varying range in such a way amounts to compressing or expanding the ratio between the highest and the lowest levels of intensity while preserving the internal relationships, in effect varying display sensitivity. The selection criterion is threshold conspicuity. Figure 36 is a recording of a test sequence, showing two values of signal range. There are several advantages attendant with this choice of criterion: a quantitative score is available

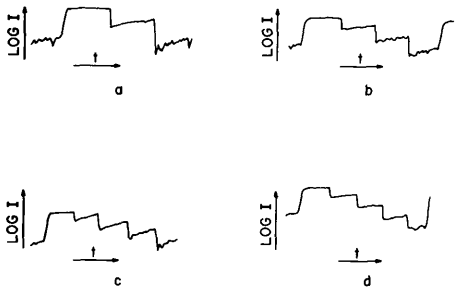


Fig. 35 - Recordings taken from test-pattern "bouncing" sequences, with "levels" of equal duration, and logarithmically attenuated intensities. All measurements were made with logarithmic photocell.

a. Three-level bouncer, with bounce of ±27 percent of average value of each level
b. Four-level bouncer, with bounce of ±20 percent of average value of each level
c. Five-level bouncer, with bounce of ±27 percent of average value of each level
d. Five-level bouncer, with bounce of ±16 percent of average value of each level.

for each pattern, permitting determination not only of which sequence is best but by how much it is superior to any other. Such a measure is important because it permits theoretical assessment of potential improvement to be realized by the introduction of a new pattern.

The study to determine the most conspicuous test pattern has been initiated. Its results will largely influence the eventual specifications for the characteristics of the optimum intensity sequence for use in a system such as the ARC. Other determining factors which must be considered, however, are time required to discern sequence direction at established signal range (as opposed to threshold signal range), probability of mistaking sequence direction, and information rate.

Depending on the results of this determination, and the level of improvement indicated over the original sequence, together with the status of the NATC evaluation at that time, a decision will be made as to whether a new drum pattern based on the optimized sequence characteristics should be fabricated.

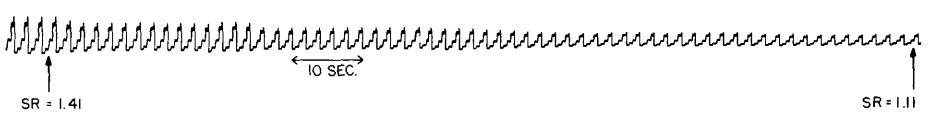


Fig. 36 - Recording of a test-pattern four-level sequence, showing the effects of different signal range settings, from a maximum of 1.41 to a minimum of 1.11, which represents a change of about 4 to 1 in brightness modulation level

HIGH-GAIN DISPLAYS OF POSITION-ERROR INFORMATION

The discussion of new system concepts and techniques has, up to this point, dealt only with displays which provide directly, in one form or another, error information regarding rate of descent. It was precisely this characteristic of rate information which was shown by the analytical work to be necessary for the accurate control of an aircraft during the landing approach. However, there are at least two ways of providing a rate signal at a given point in this man-machine system. The first, of course, is to develop the necessary signal within a display for direct presentation to the pilot, as described previously. The other consists of providing on a display an error signal of such a type that the pilot can operate on the displayed information to derive the required rate information. A number of the latter type displays were also developed as possible solutions to the carrier-landing safety problem.

In order for the pilot to process such displayed position-error information accurately, high-gain, low-noise displays are required. Various types of encoding are used, and various levels of error information are provided, ranging from binary to precise, quantitative indications.

The position-error display, as opposed to the rate-error display, has one highly desirable characteristic with respect to shipboard installation. This characteristic concerns the accuracy requirement of beam stabilization to counteract the effects of deck motion due to pitch, roll, and heave of the ship. While stabilization of one type or another is required for any shipboard display to within various tolerances, maximum accuracy, or minimum beam movement, is required for a rate display. This fact results because of the inherent nature of a derivative function and the fact that differentiation is by nature a high-bandpass process. Therefore, any noise (high frequency) originating within a differentiator is amplified, whereas the same noise originating within a low-bandpass element or even an amplifier will not be amplified to the same extent. This merely says that "noise" or any stray high-frequency inputs arising from deck disturbances will be much more serious a problem when amplified by a rate display than when they are not so emphasized by a position-error display.

With this drawback to rate-type systems for shipboard use in mind, NRL conceived a number of high-gain position-error systems and fabricated two of these for experimental validation.

Ten-Fold FLOLS

One solution to the problem of the FLOLS' insufficient display gain immediately suggested itself. If ten individual cells were vertically spaced such that the total distance between top and bottom cell were ten times that of the FLOLS and the focal length adjusted so that the angular field were unchanged, meatball displacement for a given error would be increased by a factor of ten. Just as immediate as this suggested solution are the problems which would result. In the first place, increasing meatball displacement for a given altitude error by a factor of ten serves to extend the range at which the system is sensitive to a given error by a factor of only $10^{1/2}$. Secondly, the practical problems alone would make such a system infeasible, for it would be so large that it could not be located on the left side of the deck, but would doubtless have to be mounted along the superstructure. Finally, the maintenance problems would be increased substantially, and the sensors and computers for stabilization corrections would be greatly complicated. Because of the many engineering problems associated with, at best, a slight improvement in sensitivity, implementation of this idea was never seriously considered.

Laterally Compounded FLOLS

The next display system conceived was entitled the Laterally Compounded Fresnel Lens Optical Landing System (this system was first revealed in an unpublished technical note to BuWeps on Mar. 19, 1964). This system, as first conceived, would incorporate three Fresnel lens units. On one unit, unchanged except for the removal of the datum arms, the pilot would observe the standard virtual image moving up and down as he moved his eye up and down in the projected beam. The optics of the additional two units would be modified (either by decreasing the focal length of the lens or by adjusting the distance of the light source to the lens) to convert the virtual image to a real image.

Further, since the present FLOLS has the five cells angled by 18 to 20 minutes in order that the images from all of its cells converge 150 ft behind the lens, the cells of the auxiliary units would have to be angled by the same amount, but in the opposite

direction, so that the images from all of its cells would converge 150 ft before the lens. This modification would not only move the image to the other side of the lens but also would cause it to move in the opposite direction to the viewer's eye movement.

If the aircraft is on glide path, the pilot would see all three meatballs in alignment across the center of the display (Fig. 37a). If the aircraft should move above glide path, however, the inner meatball would move up and the outer two meatballs down (Fig. 37b), and conversely, if the aircraft should sink below glide path the inner meatball would move down and the outer meatballs up (Fig. 37c). Comparison of the error indication presented by such a display with that presented for the same error by the standard FLOLS makes immediately obvious the increased sensitivity of the LCFOLS. The apparent displacement between the center LCFLOLS meatball and its adjacent reference lights, i.e., the outer meatballs, is twice that generated in the FLOLS between the meatball and the stationary datum arms. The qualitative difference in the tasks presented to the pilot by the two systems is the change from a pursuit tracking task to a compensatory tracking task.

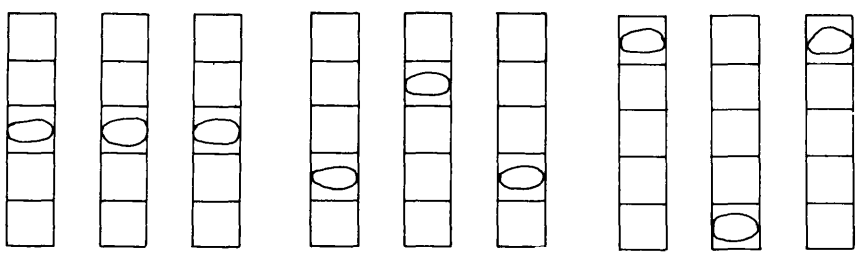


Fig. 37 - Laterally Compounded Fresnel Lens Optical Landing System indications:

a. "on glide path"
b. "Slightly high"
c. "Very low"

Equation 3 stated that display sensitivity of the FLOLS is inversely proportional to the square of the viewing range, or $DS_{\mathrm{FLOLS}} = 150/R^2$. By doubling the displacement resulting from a given altitude error, the display sensitivity of the LCFLOLS can be shown to be $DS_{\mathrm{LCFLOLS}} = 300/R^2$. Comparison of these equations shows that $DS_{\mathrm{LCFLOLS}} = 2\,DS_{\mathrm{FLOLS}}$, which says that, for any given range R, the sensitivity was doubled by the addition of the auxiliary units.

While this modification has doubled the display sensitivity to a given error for a given range, from another viewpoint it can be said that the workable range of the system has been increased. It is possible to determine at what range R_m the modified system will exhibit the same sensitivity as the standard unit exhibits at range R.

If $DS_{\mathrm{LCFLOLS}} = DS_{\mathrm{FLOLS}}$, then

$$\frac{300}{(R_m)^2} = \frac{150}{R^2} \quad \text{and} \quad R_m = \sqrt{2}\,R = 1.4R\,.$$

The above equation states that the LCFLOLS will exhibit at a 40-percent greater range the same display sensitivity as the standard FLOLS.

There is another significant comparison which can be made between the two systems. A given angular error of the aircraft in the beam will be represented by twice the error indication on the LCFLOLS as on the standard unit. This is to say that the same angle is subtended at the eye when the pilot using the modified display is twice as far from touchdown as the pilot using the standard display. If this angle is the minimum discriminable angle, for example, this comparison states that, for a given angular error, the modified system would be discriminable at twice as great a range as the standard, although the altitude error from glide path is twice as great in this situation.

To summarize, the proposed modification to the standard FLOLS would double the display gain of the system. This increased gain may be described in terms of improvement over the standard unit. The benefits to be achieved by such a modification would be:

1. For a given range R, the sensitivity of the standard unit would be doubled.

2. The modified unit would exhibit at a 40-percent greater range the same display sensitivity to a given error as the standard unit.

3. For a given angular error of the aircraft in the beam, the same angle would be subtended at the pilot's eye by the modified unit at twice the range at which the standard unit subtends this angle.

In spite of these improvements which would result, the costly operation of modifying two FLOLS units (and then tripling the total system cost due to the additional two units) did not appear to be warranted.

Shadow Box Optical Landing System

The Shadow Box system is a simple indicator designed to exhibit effectively the same optical properties as the FLOLS, but by means of an extremely simplified design and construction. The Shadow Box Optical Landing System (SBOLS) was conceived and built at NRL as an experimental tool for use in the empirical evaluation of various modifications suggested from time to time for the FLOLS.

The SBOLS simulates the FLOLS by means of a shadow-box type of projection system which projects a beam pattern without the use of lenses. This projection is accomplished by means of a bulb plate on which are mounted a number of thin-filament bulbs, effectively point sources of light, and a slot plate, both mounted in a rigid housing (Fig. 38). Baffling should be included in the unit to insure that the rays from each light can pass only through its corresponding slot. Such a unit behaves as a backward projection system, because the light source which the pilot sees is a function of the position of his eye in the beam pattern. He will see the seventh light, for instance, when and only when his eye is in alignment with the seventh light and the seventh slot. If his eye is in a higher position, so as to be aligned with the third slot and third bulb, he will see that source. (Since each slot is slightly wider than the bulb filaments, each "beam" has a finite angular width). Because of the dimensions of the display unit, a pilot is not aware of observing different sources as he moves up or down in the beam pattern; for it appears that a single light is moving up or down on the face of the slot plate, just as it appears when he watches the meatball move on the FLOLS in response to his movement above or below glide path.

The apparent movement of the SBOLS meatball can be made to correspond, or, if desired, to be opposite, to the vertical motion of the aircraft. A unit in which meatball motion is in the same direction as aircraft vertical motion (similar to the FLOLS) exhibits a virtual image to the pilot and is called the "forward unit;" conversely, a unit on which the meatball reacts in the opposite direction to aircraft motion exhibits a real

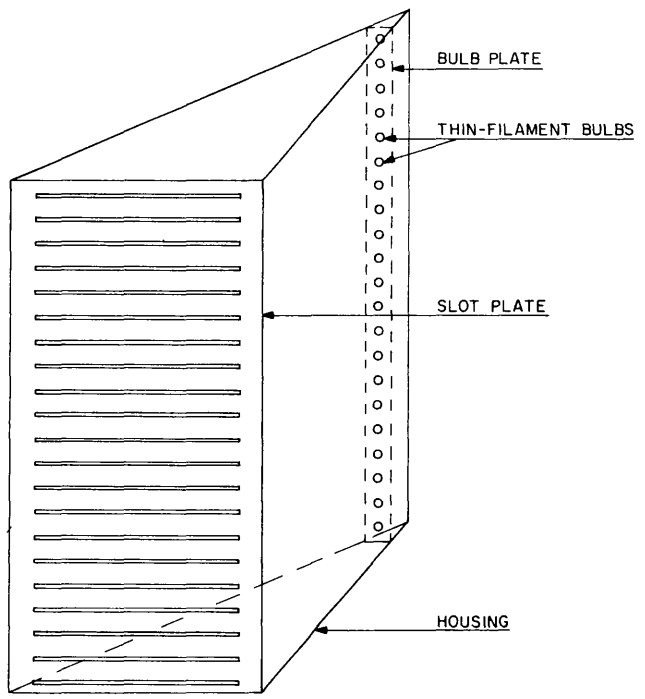


Fig. 38 - The Shadow Box Optical Landing System

image to the pilot and is called the "backward unit." The forwardness or backwardness of an SBOLS unit is determined by the relative spacing of the slots on the slot plate. The bulb mountings are the same for both types of units. For the forward unit, each slot is placed slightly farther from the center-line reference than is its associated bulb. For the backward unit, the reverse is true; i.e., each slot is located slightly closer to the centerline reference than is its partner lamp. (Reference 20 contains design equations and schematic drawings of the configurations for both forward and backward units).

Because the "beams" originating from each bulb-slot combination are slightly divergent, the viewer's eye will generally be within more than one beam, which means that he will see more than one source. However, due to the close proximity of the slots to each other and the relatively long viewing range, when several adjacent slots are illuminated with respect to the pilot's eye, the multiple images will blend together and appear as one slightly elongated meatball. The experimental forward unit was constructed so that the pilot's eye can never be within more than four beams simultaneously. This means that the maximum number of lights visible, even at maximum range, is four. As range decreases, this number also decreases. Conversely, for the backward unit, as long as the aircraft is beyond the focal point, the pilot will always see at least four lights, and at increasingly close range the size of the meatball will grow as more and more lights become visible. When the meatball becomes noticeably larger, as it does at very close range, within 200 to 300 ft, the pilot can treat the center of the image as the zero reference point for true meatball indication. In early flights, as expected, the variable apparent size of the meatball did not prove to be a problem, even for the backward unit.

The first experimental unit was built to correspond roughly to the dimensions of the standard FLOLS. It has a total angular field of ±0.75 degree and a vertical display height of four feet. Its focal length is therefore 150 ft. There are 21 light sources mounted on

the bulb plate. Initial flights with the experimental unit verified its functional similarity in appearance to the FLOLS. This fact, together with its low cost, portability, and simplified design, which readily permits parametric variation, suggest the worth of the system as a substitute for the operational system in experimentation. As a matter of fact, the experimental consideration and ultimate rejection of the IFROLS, without costly modification to actual FLOLS units and further costly evaluation, was made feasible by the development of the SBOLS. The principle of the LCFLOLS was also verified by test flights with a simulated unit made up of SBOLS units.

In these preliminary evaluation flights, the performance of the SBOLS unit appeared to be quite satisfactory, in that its general appearance and optical characteristics are very similar to those of the FLOLS. It is greatly simplified, however, in construction and maintainability, since, for example, its design characteristics do not place rigorous demands on temperature control, and also since operating power requirements are greatly reduced. As an example, the light sources used in the experimental unit were standard automotive stoplight bulbs. After the initial flights, with the experimental SBOLS verifying its apparent optical similarities to the FLOLS, it was suggested (17) and is repeated here that the new system could also be utilized at various naval air fields to provide carrier pilots with a model of the operational system to use as a training and/or field practice aid. The simplicity and low cost of the SBOLS would make it feasible to install one on every runway of many airfields, so that even routine landings might be made with a system such as is used aboard ship.

Audio System

The Audio system is another display designed to provide information regarding position error from glide path. It does so by means of the Rainbow and ARC mechanism and a unique pattern. This drum pattern consists of a number of horizontal bands of vertical black lines, which are so placed within the horizontal bands as to interrupt the source light with frequencies in the audio spectrum. A photocell is required in the aircraft to receive this signal, which is amplified electronically. A number of sound tracks are superimposed on the drum, the message of each track to depend on its angular displacement from the ideal glide slope. The message which the pilot receives is therefore a function of his angular location in the beam.

This system was contemplated but never fabricated, for the reason that it was considered undesirable to introduce the necessary sensors into the aircraft, particularly in view of the fact that position-error information can be provided, at least under visual flight conditions, equally well or better by a strictly optical system to be discussed later in this report.

Phi-Flash System

The Phi-Flash system is another use of the Rainbow-ARC mechanism to provide the pilot with information concerning his altitude error in a light-beam pattern. It consists of two flashing lights aligned vertically but separated by a rather large distance. On a carrier, for example, one might be located at the base of the island and the other at the top. The flash frequency of the lights is such that if the aircraft were on the proper glide slope the pilot would see the two lights flash simultaneously. If it were above glide slope, he would see the upper light flash before the lower, and conversely, if below glide path, he would see the lower light flash first. The amount of time between the flashes of the two lights is a function of the size of his altitude error.

According to the well-known psychological phi phenomenon, such flashing lights give the appearance of one moving light. That is, if below glide slope the pilot would see not

two flashing lights, but one light, which would appear to move up, directing him to bring the aircraft up to the glide path.

The timing of the flashes is accomplished by the backward projector and the rotating drum of the Rainbow-ARC system and a pattern, shown in Fig. 39, to cause projected light flashes at a constant rate as the drum rotates. This element of the system is located at the lower of the two positions specified. At the higher position is the second light. The geometry for the system is seen in Fig. 40. Note that the projector has been rotated 90 degrees, so that the axis of the drum is horizontal.

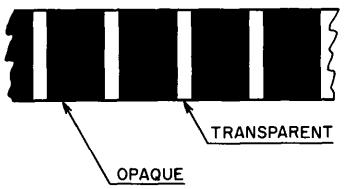


Fig. 39 - Drum pattern for the Phi flash system

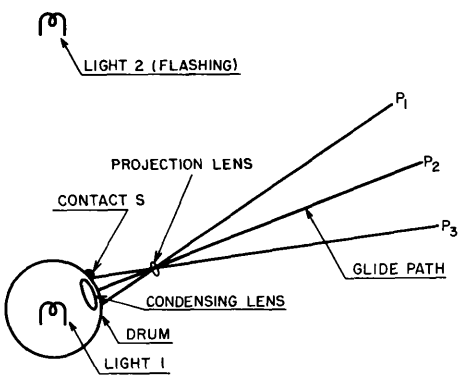


Fig. 40 - The geometry of the Phi flash system

As the drum rotates, the slot moves in the image plane from top to bottom. S is a stationary electrical contact mounted at an angle above the horizontal equal to the desired glide path. Every time a slot passes this contact the second light is illuminated. It remains on for the length of time required for the slot to pass the contact. Thus, if the aircraft is on glide slope (position P2), the pilot sees the upper light flash at the instant that the light from a successive slot hits his eye. If, however, the aircraft is above glide path (position P1), the slot passes S and causes light 2 to come on before the slot is oriented so that the projected light hits the pilot's eye. The reverse occurs when he is below glide slope, at position P3.

The system calls for a pair of flashing lights to indicate to the pilot whether he is above, on, or below glide path. The direction of the apparent motion attributed to the phi phenomenon would indicate whether the aircraft is high or low. The length of the time interval between two flashes, i.e., between the beginning and end of the movement, would indicate the size of his error. It should be pointed out, however, that estimation of time intervals is a task which the human is ill-fitted to perform accurately.

There is an element of displacement coding in this system, since the two component sources must be widely separated in order to produce the phi effect. Display gain is therefore a function of this displacement. However, the displacement is not in itself

used to encode information. It remains constant, and therefore the display sensitivity does not vary inversely as the square of the viewing range. The Phi Flash system has many of the same advantages as most of the other systems here reported. However, like the ten-fold FLOLS, it introduces a problem because of its necessarily large size. Further, as was true of the Audio system, it was felt that better position-error information could be provided by a simpler, more compact projection system; accordingly the Phi Flash system was never fabricated.

Depth of Flash Optical Landing System

Depth of Flash is another unique means of encoding a projected colored light beam to provide guidance information to pilots of approaching vehicles. This type of encoding consists of a constant-frequency flashing light. The depth of its flash can be defined as the ratio of the intensity change within a flash cycle to the maximum intensity of that cycle.

One very common example of depth of flash is found in an ordinary automobile taillight bulb and turn-signal indicator. Consider the taillight already illuminated and the additive flashing component superimposed by the turn indicator on the constant intensity of the taillight. This type of flashing light is quite an obvious signal as far as attracting attention and being easily discriminable. Since the steady taillight is generally three candle power and the turn indicator 21 candlepower, a flash depth of 87.5 percent is produced. In Fig. 41, which provides a graphic representation of the concept of depth of flash, the turn-indicator contribution is analogous to the flashing component, indicated by arrow B, and that of the taillight to the intensity level, indicated by arrow A.

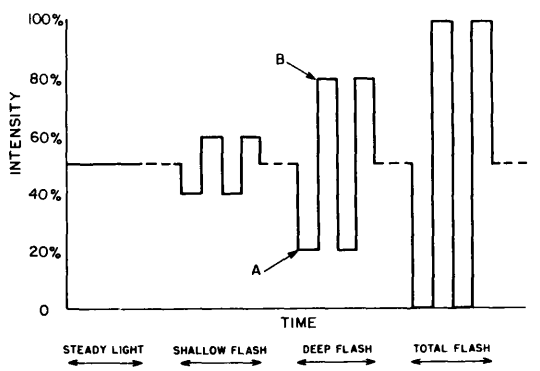


Fig. 41 - Plot showing various degrees of depth of flash. Note that both average intensity and flash rate remain constant throughout. Point A represents the constant portion of the light, and point B represents the signal with the additive flash component.

This plot represents four levels of depth of flash, varying from zero to 100 percent. A zero depth of flash is obviously a nonflashing, constant-intensity light, whereas a 100-percent depth of flash implies total flashing, possible only when the intensity of the base light level is zero. The value of the second level of flash depth is

$$\frac{60\% - 40\%}{60\%} = 33\text{-}1/3\%$$

and that of the third level is

$$\frac{80\% - 20\%}{80\%} = 75\%.$$

Basic work indicated the potential of depth of flash as a means of display signal encoding (21) and located the minimum discriminable depth of flash at about five percent. Various means of implementation of a depth-of-flash encoding principle into a display of error from glide path were considered. All of these have in common the interpretation of the flashing light into useful control information.

Flying Depth-of-Flash Displays — Instructions given to a pilot flying a Depth-of-Flash system are as follows. "This display provides you with information concerning the size of your angular error from glide path. The light is color coded to inform you of the nature of an error, that is, above or below glide path, and depth-of-flash coded to indicate the approximate angular size of the error. If you see a steady amber light, you are within the fixed tolerance of the glide path. When you are above glide path, the light appears green. If you are only slightly high, this green light appears of constant intensity. However, if your error increases, the steady green light begins to take on a flashing quality which becomes gradually more and more pronounced the farther you are from the glide path. At the very extreme of the beam pattern, the flash is total, the light alternating from on to off. Similarly, on the low side, signified by a red light, a total flash indicates a large angular error from glide path. As you correct this error and come near to the amber beam, the flashing characteristic gradually becomes less noticeable and eventually dies away completely, to leave a steady red light, the indication of slightly low. Throughout the pattern, the depth of the flashing characteristic of the light is indicative of the size of your error, while the color of light represents the direction of the error." Several possible implementations of the system generally described above will be discussed.

Fresnel Depth-of-Flash System — The first potential application of depth of flash, conceived very early in this program, called for a large, transparent cylinder positioned so as to rotate, on a vertical axis, about the five cells of the FLOLS (Fig. 42a), to supplement but not interfere with the normal displacement information of that system. Superimposed upon the cylinder would be a neutral-density graded filter, generally appearing as in Fig. 42b. The filter would also be color coded, as indicated on the drawing. Rotation of this cylinder about the FLOLS would not affect the light projected through the clear portion of the filter and from the vertical center of the FLOLS. This amber light, of course, represents the "Roger meatball," or on-glide-path indication. Immediately on either side of the amber band, it is seen that the filter density in both lateral portions C and D is the same. Here are produced the steady red and steady green signals, indicating small errors below or above glide path respectively. Slightly farther from the glide path, the shading of these portions is oppositely graduated, the C portion of the cylinder becoming continually more dense until it is opaque at the outer edge, and the D portion becoming continually less dense until it is totally clear at the outer edge.

Each rotation of this cylinder produces one flash, with a duty cycle of 50 percent. Quite clearly, if the viewer's eye is in or near the central portion of the beam, he will see a steady nonflashing light of amber, green, or red. Slightly larger errors result in a slight interruption or fluctuation of the light intensity. This fluctuation becomes more pronounced the farther the aircraft is from the glide path.

Discussion of this display concept and implementation with the NAVAIRSYSCOM representatives resulted in a decision not to fabricate the system. The factors of this decision were two-fold: (a) the equipment or ultimate display design was thought to be infeasible to implement and to stabilize, due to its bulk, (b) the optical characteristics of the FLOLS are such that the proposed Fresnel Depth of Flash System would not be expected to perform satisfactorily at longer ranges, and (c) this concept of encoding position error, proposed simultaneously with the color-sequenced encoding of rate error, was considered to have far less potential for increasing system accuracy.

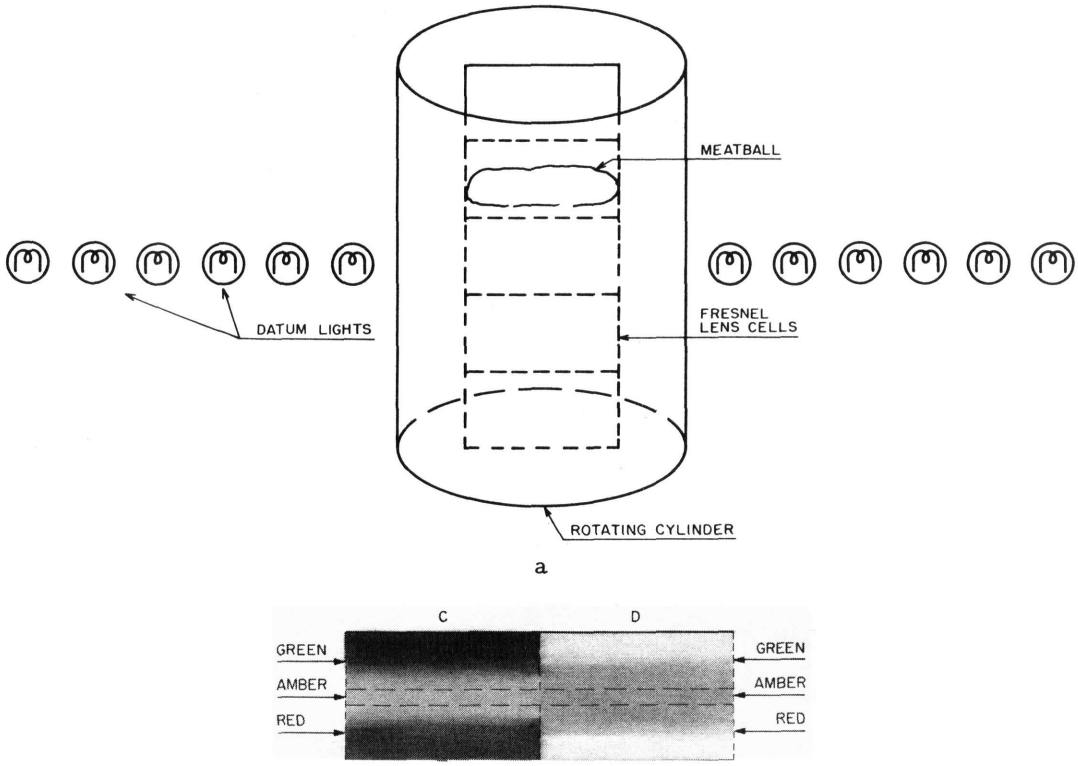


Fig. 42 - Schematic drawings of a possible modification to the FLOLS to include depth-of-flash coding

a. FLOLS and transparent rotating cylinder
b. Graded filter pattern to be superimposed on cylinder

Nevertheless, the very simplicity of learning and consequently interpreting the depth-of-flash signal encouraged consideration of other implementations of a system which would be acceptable on the basis of size and complexity.

Rainbow Depth-of-Flash System — At this time, the Rainbow mechanism was under development, and of course the possibility of using this instrument to fabricate a depth-of-flash system was immediately obvious. A drum pattern consisting of a number of graded filters would readily produce the depth-of-flash coded beam pattern. The graded filters making up such a drum pattern should be similar to the one of Fig. 42b, with continual gradation from light to dark. Note that this filter arrangement provides for a constant average intensity regardless of error from glide path.

Difficulty was encountered in obtaining filters of the necessary optical quality and precision for use on this drum pattern. As an alternative, some experimental photographic work was undertaken to produce filters of the desired transmission characteristics. However, these too proved to be marginal.

Another drum pattern which utilizes the attenuation process of the ARC system, namely high flicker frequency — variable duty cycle, is probably the most suitable depth-of-flash configuration for fleet use. In such a configuration, the nature of the change of flash depth as a function of angular error from glide path can be made to conform to any theoretically determined optimum. Such precise control of flash-depth characteristics is somewhat restricted in other mechanizations of a depth of flash system.

Dual-Projector Depth-of-Flash System -- Eventually another entirely different mechanism for obtaining a depth-of-flash system was suggested. This system was originally an independent development by three members of the Engineering Psychology Branch. Because it is inherently less precise than some of the other systems discussed and indeed less than some of the previously considered implementations of depth of flash, the system was intended only as a simple and inexpensive glide-path indicator and acquisition aid for use at small, general aviation airports (22).

The system utilizes dual projectors located closely adjacent to one another. One of the resultant overlapping images is a steady light pattern, and the other is flashing at constant frequency. The depth of flash thus produced is additive rather than alternating. Depth of flash as originally defined is here produced as the ratio of the light from the flashing projector to the summed light from both projectors.

This signal is projected by a unit (Fig. 43) which consists primarily of two slide projectors, two stationary slides, and a rotating sector disk placed in the light path of one of the projectors (B), permitting that slide to be projected only 25 percent of the time. Since the two projectors are located in close proximity to one another, they appear as a single light source to the approaching pilot, for the light from the separate beams is summed at his eye. The projectors are firmly affixed to a common chassis, the angle of which can be adjusted to provide any desired glide-path angle. They contain identical slides which project green to the upper field, red to the lower field, and amber to indicate glide path (Fig. 44).

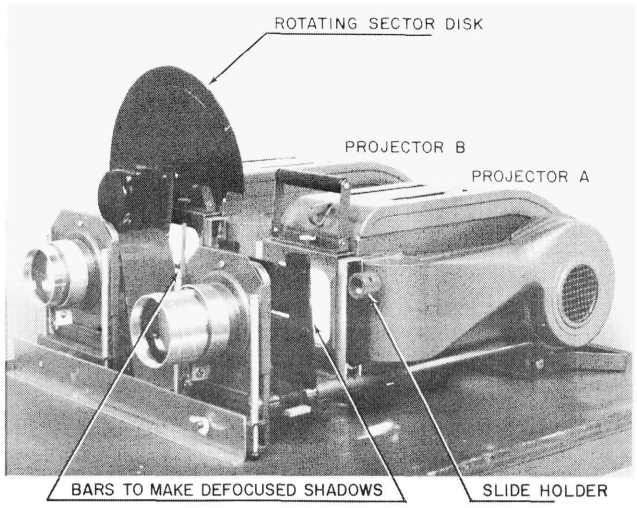


Fig. 43 - Dual-projector Depth of Flash unit

The constant-intensity light of the amber glide path and the steady red and green just below and above it originate entirely from projector A, which projects at full intensity near glide path. In order to prevent the undesired addition of any light in these areas from projector B, its slide has the center portion blacked out by an opaque bar inserted between the slide and the projection lens. The flashing projector B, then, intermittently adds its intensity to that of projector A only in the areas considerably above or below the ideal approach path. However, light from projector A is undesired in these areas far from the glide path, and is likewise prevented by the insertion of two opaque bars between the slide and the projection lens. The desired beam pattern required in

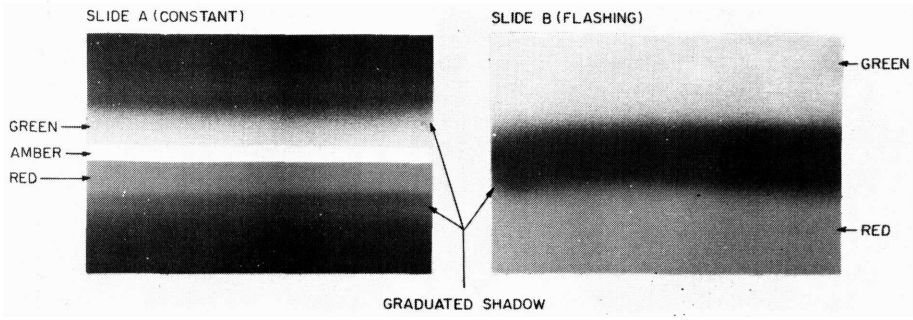


Fig. 44 - Images projected by dual-projector Depth of Flash Unit

the projected images from both projectors is thus accomplished very simply by the use of these opaque bars. Intensity gradation results from defocusing the bars slightly so that they fully obscure the light from certain areas and provide a generally lessening shadow effect into areas where full transmission is desired.* The effect of the defocusing is illustrated in Fig. 44, which shows the projected images from each projector. It is seen that as the intensity of projector A decreases with error, the intensity of flashing projector B increases; i.e., projector B adds more and more as projector A provides less and less, thereby producing the complete on-off flashes at high and low extremes. The transmissiveness of the two slides must be regulated in this manner so that the combined signal source will present an approximately uniform brilliance at all vertical points within the pattern.

The defocused shadow-bar method provides a large range of variability of the depth of flash. Theoretically, a constant rate of change from near glide path to maximum error could be programmed. However, experimentation and flight testing determined that the optimum pattern placed the largest variation near the glide path. This pattern is characterized by greater sensitivity where accuracy is most critical, which enables the pilot to adjust his rate of descent appropriately, so as to avoid overshooting the glide path with the resultant oscillatory corrections.

Projection lamps of 1000 watts are used in daytime in this unit, providing an acquisition range of about 3.5 miles. In nighttime operations, the range can be increased to more than 20 miles; 500-watt projection lamps provide a usable signal for these conditions. The flash rate is constant at two per second for the selected duty cycle.

A Depth of Flash system exhibits most of the same advantages attributed earlier to the Rainbow and ARC systems. No electronic or mechanical sensors are required in the aircraft, and the only data link necessary between the pilot and the ground is a visual one. Further, it should be noted that the coding of the depth-of-flash signal causes interpretation of its guidance commands to be relatively independent of range to touchdown. At any range from which the signal can be detected, it can be categorized as to its color and flashing or nonflashing quality. The usable range of the system then is limited only by the intensity of the light source and by conditions of visibility.

*It is interesting to consider the feasibility of utilizing the defocusing technique in conjunction with the Rainbow mechanism to produce a depth-of-flash pattern. Strips of opaque tape can be superimposed on a drum, alternating with clear areas, which when the lens is defocused will cast graduated shadows. This implementation does not have the feature, however, of constant average intensity throughout the beam pattern which both the ARC Depth of Flash and the dual-projector Depth of Flash have.

In some respects this dual-projector Depth of Flash Optical Landing System far exceeded expectations. In the first place, the signal appeared quite conspicuous, and observers could readily distinguish it, from the totally flashing light through the decreasing depth of flash to the steady light which signified that the aircraft was very near to glide path. Secondly, this type of encoding is perhaps the simplest to understand and easiest to remember of all those considered or tested. Finally, the concentration of the sensitivity in the critical areas near glide path made it possible for the pilot to extract there the needed rate information from the displayed indication of position error.

These characteristics and the outstanding performance of the experimental unit resulted in its being brought to the attention of the Air Systems Command and the Naval Support Forces Antarctica. The latter communicated their need for a visual landing aid for use in a unique Polar weather condition called "whiteout," which occurs when extreme diffusion of light upon the totally white terrain blots out all shadow definition. Both surface and horizon become obscured, causing pilots to experience a dangerous loss of depth perception.

Among the available landing aids considered to fill this need were the Mirror or Fresnel Lens Optical Landing System, now in use aboard carriers, and the Rainbow Optical Landing System. Particular emphasis was placed upon the requirement for simplicity of operation and ease of interpretation of the signal provided. Another requirement is simplified error-signal encoding, because many pilots will arrive and fly the system for the first time, receiving instructions only over the aircraft radio as they make their first landing. The Rainbow system developers at NRL, contacted for advice on the problem, suggested that the dual-projector Depth of Flash Optical Landing System might be applicable to these special needs. Subsequently, the NAVAIRSYSCOM, at the request of Naval Support Forces, Antarctica, sponsored the building of a weatherproofed experimental unit for testing at Williams Field, McMurdo Station, Antarctica.

The unit was shipped to Project Deepfreeze in November 1965 for use during their summer season. Subsequently, an evaluation report, dated July 18, 1966 (23), suggested modifications to the unit (wider beam angle and longer-life bulbs), but recommended further evaluation, particularly under twilight and diffused light conditions. A positive comment referred to the simplicity of the system. The need for assurance that an aircraft is across the threshold prior to touchdown was again emphasized. A former Deepfreeze officer who had worked closely with the system reported informally that maximum viewing range was several miles, even in daylight. He explained, however, that narrow beam width is a severe problem because of the great width of the skiway. The wide displacement of the unit from the centerline results in the pilots' losing a narrow beam at short range or not intercepting it at long range. Widening of the beam width would bring about an accompanying decrease of intensity. It would seem therefore that future efforts to improve a Deepfreeze Depth of Flash unit should begin with improved bulbs.

The NAVAIRSYSCOM requested that a second unit be built for tests and evaluation by the Naval Air Test Center, Patuxent River, Maryland, particularly concerning its potential for fleet use aboard carriers. The result of these preliminary tests was a recommendation that the system undergo sea trials. It was stated that the "DFOLS use as primary aid was precluded by lack of precise position indicator," but that the system "aids FLOLS approach by providing earlier glide slope acquisition and adequate coarse glide slope control from 10 mi range until FLOLS usable range (3/4 mi)." Shorebased trials would continue to determine the optimum intensity and location of the DFOLS relative to the FLOLS (24).

CONCLUSIONS

The problem of reducing the night accident rate of aircraft landings aboard ship has been consistently treated by NRL as a task to increase the overall landing accuracy and precision of a pilot-aircraft-display system. This approach to the problem evolved from a statistical consideration of the nature of accidents and a determination that many of those attributed to "pilot error" should instead be blamed on inadequacies of the system.

Mathematical analysis located the origin of these inadequacies in the presently used display system, which was shown to be highly insensitive to aircraft errors, particularly at long range. However, there was a strong feeling that successful landings required longer glide-path acquisition ranges and more time to get set up on glide path before turbulence or stack gases excited the natural modes of the aircraft. The range-squared dependence of the display caused by the inherent nature of its displacement encoding of an error signal was considered a large part of the problem. This fact, together with the requirement to introduce no additional equipment into the aircraft, strongly indicated the need for improved error-signal-encoding techniques of a projected light source.

The concepts and designs of the newly developed displays can generally be categorized as two main types — those which display rate-error information directly, and those which display position-error information, from which the pilot can derive the necessary rate information. The specific systems of both of these classes all exhibit high gain, or increased sensitivity.

Among all of the systems described, perhaps two, one from each general category, stand out as exhibiting the greatest potential for increasing landing accuracy. These two displays, the ARC system and the Depth of Flash system, have a number of characteristics in common: (a) display gain or sensitivity is independent of range, (b) maximum viewing range is of the order of 3.5 miles in daylight and over 20 miles at night, (c) maximum useful range is limited only by maximum viewing range, (d) no electronic sensors or computers in the aircraft or on the ground are required, as well as no electronic data link between aircraft and ground, (e) the signal viewed by the pilot is a function of the interaction of beam characteristics with flight-path characteristics, thus making it feasible for several aircraft to fly the system simultaneously, (f) color is used to encode high-low information.

The differences between the two systems are not so numerous but are perhaps more critical, for they will doubtless be the key factor in the selection of the optimum system. The ARC system utilizes repetitive, cyclic changes in (more than two) levels of intensity to encode the error-rate information required to direct the aircraft along an asymptotic approach to the glide path.

The Depth of Flash, with its alternating changes of intensity in varying depths as a function of error from glide path, has the advantage of a simpler encoding system — easier to learn and easier to interpret. The ARC system is theoretically superior to the Depth of Flash in its provision of sink-rate commands, which provide a high degree of accuracy and tolerate a minimum of glide-path overshoot or oscillation. While these error-rate commands are generated on the basis of the present position of the aircraft, the only display of position error from glide path is of a binary nature. On the other hand, the Depth of Flash indicates the size of the error from glide path, by means of a highly sensitive signal, thus enabling the pilot to extract the needed rate information.

One further advantage of the DFOLS is its greater tolerance of beam fluctuations resulting from ship motion. Beam errors, as explained earlier, are less crucial for a position display than for a rate display which by its nature amplifies such disturbances. Either system, of course, would require some compensation for ship motion.

The ultimate selection between these two systems can only be made experimentally, because of the many relevant factors. "Flyability" must be considered, together with training time and effort, and operations in periods of stress. Critically required are measurements of the overall landing accuracy achievable with both systems. Without them, almost any evaluation is meaningless.

ACKNOWLEDGMENTS

The project scientists would like to express their appreciation to and recognize the outstanding contributions to work on carrier landing safety by the following persons:

Mr. Robert H. Mathes, of the NRL Sound Division, who volunteered to pilot a second aircraft during many of the night experimental and demonstration flights involving Rainbow, Depth of Flash, and ARC systems and thereby materially reduced the length and number of night flight operations necessary.

Capt. Charles Meshier, OP-93, CNO, whose interest and encouragement are largely responsible for the decision to develop the ARC system and who undertook to provide liaison between NRL scientists and interested, high-level naval personnel.

Mrs. Carol A. Roberts, who derived the Rainbow drum pattern design equations and who was responsible for most of the analytical work and data recording required in the selection of paints and filters for development of the Ektachrome-X pattern and from whose unpublished research notes much of the material on color selection used in this report was taken.

Miss Nancy A. Monacelli, of the NRL Technical Information Division, who supplied helpful advice and the numerous paint and dye samples used in the spectroscopic selection of paints for the Rainbow pattern, and who colored all ARC system patterns by hand.

Mr. Vernon P. Robey, Mr. John F. Otto, Mr. John N. Langford, and Mr. Frederick Tyrell, whose ingenuity in photographic technology and energy in performing experimental work finally led to the achievement of the Rainbow and ARC patterns.

Mr. John J. Lister and Mr. William H. McAda of the NRL Public Affairs Office, for their aid in communicating system concepts and details to interested non-NRL scientists.

LCDR. Clyde Stallings, Jr., for providing liaison between project scientists and interested naval personnel, and also for his effective scheduling of flight operations.

Miss Anna B. Mays of the NRL Research Computation Center, who programmed the equations which were used in the approach path study for the NAREC.

Mr. D. D. Choha, Naval Oceanographic Office, for his development of one of the experimental Rainbow patterns.

Mr. Stanley Kozloski, who did precision drafting work on the exponential patterns for both the Rainbow and the ARC systems.

Eastman Kodak Company and particularly Mr. Howard C. Colton, for the provision of the data on Kodak Ektachrome Film spectral sensitivity characteristics, vital to the development of the Rainbow drum pattern, and also for permission to use these data in this report; as well as for cooperation and helpful suggestions pertaining to the description of the photographic work.

Mr. Robert E. Clark, of the NRL Technical Information Division, for his technical editing services and his helpful contributions to the preparation for publication of this report and several prior reports on this project.

Mr. Russell Hartz, Code AIR 5375, NAVAIRSYSCOM, who actively encouraged the initiation of the program and provided continuing advice with respect to program implementation.

Particular appreciation is expressed to Mr. Jack Crawford for extending use of the airstrip and facilities at Maryland Airport, at no cost to the government, during the extensive flight testing of the experimental units and demonstrations of the Rainbow, Depth of Flash, and ARC system capabilities.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP --

3. REPORT TITLE

OPTICAL GUIDANCE SYSTEMS: ANALYSIS, DESIGN, AND DEVELOPMENT
A Summary Report of NRL Research on Night Carrier Landing

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

A final report on the problem; work is completed.

5. AUTHOR(S) *(First name, middle initial, last name)*

Barbour Lee Perry

6. REPORT DATE July 20, 1967	7a. TOTAL NO. OF PAGES 72	7b. NO. OF REFS 24

8a. CONTRACT OR GRANT NO. NRL Problem Y02-21 b. PROJECT NO. A34-537/016/652-1/F012-06-02 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6581 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Naval Air Systems Command Washington, D.C.

13. ABSTRACT

Increased safety and reduction of the accident rate in carrier landing are of prime importance to the Navy. Believing that these objectives could be achieved only by a general increase in total system precision, NRL analyzed the landing configuration to locate the sources of present system inaccuracy. Insufficient display gain (sensitivity) and the accompanying lack of necessary derivative signals were found to be primary causes of system imprecision.

To alleviate such problems, many new display schemes were accordingly conceived, developed, and experimentally tested. These include the Rainbow Optical Landing System and the Altitude Rate Command (ARC) System, which are high-gain direct displays of rate error information; and the Depth of Flash Optical Landing System, a highly sensitive display of error information presented so that the pilot can accurately extract rate or predictive information. Additional displays covered are the Laterally Compounded Fresnel Lens Optical Landing System, the Ten-fold Fresnel Lens Optical Landing System, the Shadow Box Optical Landing System, the Integrated Fresnel Rainbow Optical Landing System, the Audio system, the Phi Flash system, and several variations of a Depth of Flash system.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Aircraft landings						
Carrier landings						
Optical landing systems						
Color-coded landing aids						
Carrier landings — Equipment						
Projected color display						
Vehicular guidance system						
Rate of descent — Control						
Control systems — Quickened						
Error sensitivity						
Research tools						
Rainbow Optical Landing System (ROLS)						
Shadow Box Optical Landing System (SBOLS)						
Fresnel Lens Optical Landing System (FLOLS)						
Depth of Flash Optical Landing System (DFOLS)						
Altitude Rate Command (ARC) system						
Backward projection						
Landing approach paths						
Determination of near-optimum stabilization point for FLOLS						
Color sequence coded error signal						
Intensity sequence coded error signal						
Depth of flash coded error signal						
Lensless projection system						
Photographic techniques						
Multistage color photography						

The bases of the new displays are unique concepts in error-signal encoding of a projected light beam, designed for compatibility with human eye characteristics: color sequencing, intensity sequencing, and depth of flash. Implementation of the display concepts required development of unique mechanisms. The colored transparency, heart of the Rainbow system evoked development of techniques to preserve color characteristics through multistage photography. The ARC beam pattern, requiring different, precise levels of light attenuation in specific areas, is achieved by the moving drum pattern of opaque bars, the attenuation level being determined by the duty cycle of the screening bars. Continuous gradation of intensity, basic to the Depth of Flash system, is produced by means of defocused shadow bars.