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NRL Report 6199

Design Equations for Rainbow Optical Landing Aid

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Washington, D.C.

CONTENTS

ABSTRACT

The Rainbow Optical Landing Aid is a carrier-based landing display system which enables the pilot to control the rate of descent of his aircraft to a high level of accuracy. The system is purely optical-geometrical and requires no electronics. The command signal is presented as a color-coded array of lights, which is achieved by mounting color transparencies of exponential curves on a revolving transparent drum and by projecting the resultant pattern into space.

This report is concerned with the color pattern on the revolving drum of the Rainbow optical landing display, including both the basic mathematical aspects of this pattern and its color coding.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

NRL Problem Y02-21
Project RS-11-50-016/652-1/F012-06-02

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DESIGN EQUATIONS FOR RAINBOW OPTICAL LANDING AID

INTRODUCTION

Rainbow is a carrier-based landing display which enables the pilot to control the rate of descent of his aircraft to a high level of accuracy. The pilot matches his rate of descent to the command of the system and is brought to the desired glidepath. The command signal is a colored light which the pilot sees by looking directly at a projector lens which is located on the carrier deck. In this "backward projector" technique, the lens appears to be only one color at a time even though the projected image is composed of an array of differently colored lights. The pilot's position in space determines the apparent color of the lens at any given instant (see Fig. 1).

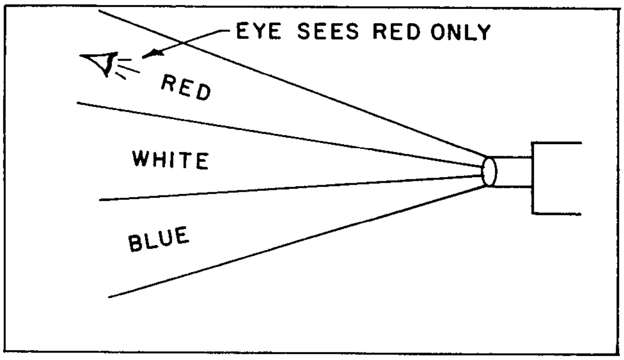


Fig. 1 - The backward projector method is used to present an array of colored lights to aid in safe aircraft landing

If the array of lights consists of three colors (red, white, blue) such that the pilot sees a sequence of blue, white, red if his rate of descent is too large and red, white, blue if his rate of descent is too small, and if these colors are moving so that by following any one of them he will be able to approach the ideal glidepath exponentially, then the command signal is based upon both position information and rate information.*

The array of lights, which combine with the spatial geometry to develop this command to the pilot, is achieved by mounting color transparencies of exponential curves on a revolving drum and by projecting the pattern into space (Fig. 2).

DRUM DESIGN

The pattern on the drum consists of (1) the glidepath, (2) exponential curves, (3) warning flashes (Fig. 3).

*See Perry, B. L., "The Rainbow Optical Landing Aid," NRL Report 6184, 1964, for a detailed description of the mode of operation of the Rainbow system.

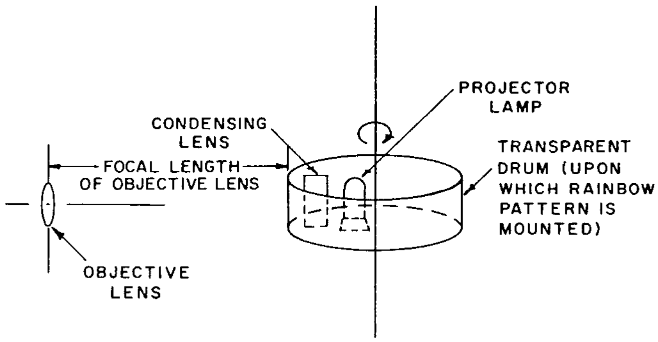
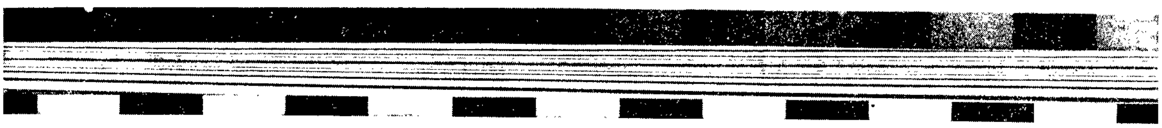
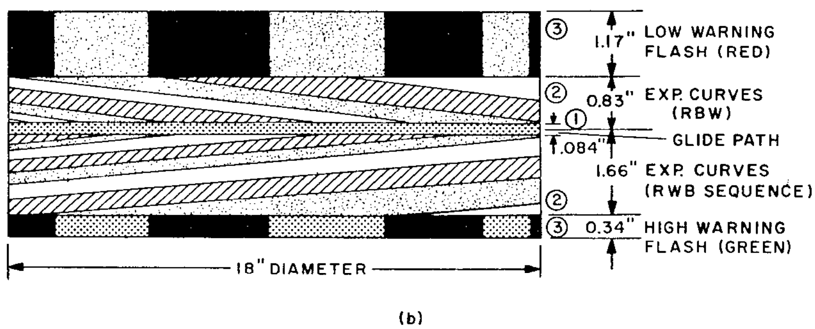


Fig. 2 - Rainbow projection scheme



(a) Photograph of drum pattern



(b) Schematic of drum pattern geometry

Fig. 3 - Detail of Rainbow drum

The glidepath will be designated by a steady green signal. This portion of the pattern subtends an angle of 0.2° in space. Thus, if the pilot is on the glidepath at one mile from the carrier, for example, he is holding his ideal altitude to within ±9 feet.

Warning flashes will indicate to the pilot that he is extremely high (green flash) or that he is extremely low (red flash). They will indicate that he should circle around and try his landing again. These warning signals flash approximately four times per second on a 50-50 duty cycle. (See Appendix A for details.)

The rate of descent command is generated by a series of colored exponential curves. The exponential curves on the lower half of the drum subtend twice as much angle in space as the curves on the upper portion of the drum. Since the lens inverts the image, this means that the pilot is allowed a greater altitude error for elevations above the glidepath than for below it.

If the pilot is above glidepath and maintaining the angular error, he will see a red-white-blue light sequence. As he increases his rate of descent, this sequence will move more slowly. If he overcorrects, he will see a blue-white-red sequence, commanding a decrease in his rate of descent even though he is still above glidepath. Conversely, if he is below glidepath and not correcting sufficiently, he will see a blue-white-red sequence; if he overcorrects, a red-white-blue sequence. In all cases, if he corrects his rate of descent properly, the color sequence rate will go to zero and, within a few seconds, he will see the steady green "on glidepath" indication. Should he drift off glidepath more than 0.1°, he will again receive the necessary color sequencing to bring him back on glidepath.

SYMBOLS AND THEIR MEANINGS

f = focal length of lens system (in inches)

Ω = total angle subtended in space by glidepath stripe

x = height of glidepath pattern on drum (in inches)*

L = decay constant of exponential curve (in inches)*

τ = projected time constant of exponential curve (in seconds)

D = diameter of drum (in inches)

m = an integer to be determined (m is the number of sets of 3 colors on the drum)

H = maximum height of exponential curve (in inches)*

ζ = number of inches along drum circumference measured from beginning of exponential curve*

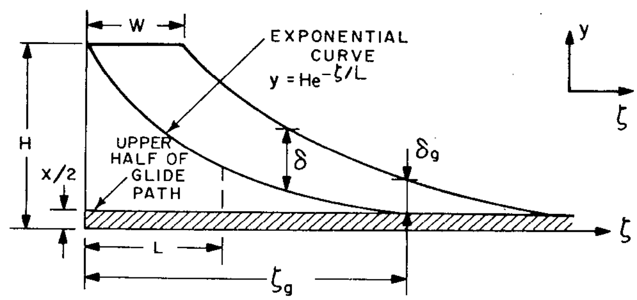


Fig. 4 - Geometry of glidepath stripe and of one of the exponential colored stripes used on the rotating drum of the Rainbow system

*See Fig. 4.

ζ_g = number of inches along drum circumference measured from beginning of curve to intersection with glidepath strip*

t_g = time it takes drum to revolve from the beginning of an exponential curve to its intersection with glidepath (in seconds)

W = horizontal width of exponential curve (in inches)*

γ = flash rate (the number of colors per second which cross a given point in space)

δ = vertical height of colors as a function of ζ*

δ_g = vertical height of curve at the point where the curve intercepts the glidepath ($\zeta = \zeta_g$).*

EQUATIONS

The following are the basic equations used in the design of the Rainbow pattern. These equations are derived in Appendix B.

The height x of the glidepath pattern is

$$x = 2f \tan\left(\frac{\Omega}{2}\right).$$

The flash rate γ is defined as the number of colored exponential curves which pass a given point in space per second. We have determined that a flash rate of the order of 1.5 per second is ideal. The actual flash rate will be determined by the speed of the drum (RPM) and the value of the integer m such that

$$\gamma = m\,(\mathrm{RPM})/20\ ;$$

γ is selected so that it is as close to 1.5 as possible while allowing m to be an integer.

Curve width W is given by the expression

$$W = \pi D/(3m)\ .$$

The projected time constant τ is selected arbitrarily (τ is defined as the time required for the drum to revolve a distance L). A good value for τ is found to be 4 seconds, as determined by flight tests. Once τ is determined, L is given by the expression

$$L = (\gamma\tau)\,W\ .$$

Other equations pertinent to the Rainbow display pattern are

$$\zeta_g = L \ln\left(\frac{2H}{x}\right)$$

$$t_g = \tau\left(\frac{\zeta_g}{L}\right)$$

$$\delta_g = \frac{x}{2}\left(e^{1/\gamma\tau} - 1\right)\ .$$

*See Fig. 4.

The focal length of the lens is 24 inches, thus the glidepath pattern must be 0.084 inch high so that an angle of 0.2° is subtended in space. For a 33-1/3 rpm drum which is 18" in diameter, for example, we find that $\gamma = 1.67$ colors per second if m (the number of sets of color) is 1. Other figures for this drum speed are

$$W = 18.85 \text{ inches}$$

$$L = 125.66 \text{ inches}$$

$$\tau = 4 \text{ seconds}$$

$$\zeta_g = \begin{cases} 375.5 \text{ inches on upper half of drum} \\ 463 \text{ inches on lower half} \end{cases}$$

$$t_g = \begin{cases} 11.93 \text{ seconds} \\ 14.70 \text{ seconds} \end{cases}$$

$$\delta_g = 0.0068 \text{ inches.}$$

Note that δ_g is very small. The practical problems encountered in producing an exponential "tail" of such extraordinary fineness forced us to make the slope of the curves constant starting approximately 0.3° above the center of the glidepath. Figure 5 illustrates this point; the equation for the linearized tail may be found in Appendix C.

A set of points for the exponential curves with "tails" linearized 0.3° above the center of the glidepath is given in Table 1.* The data in this table furnish points for one of the three colored curve patterns, as typified by Fig. 5. By producing a mirror image of the pattern and using this in conjunction with the original pattern, we obtain a complete set of curves for the red pattern on both upper and lower halves of the drum. (Figure 6a illustrates this point using curves which have greatly exaggerated slopes.) By producing

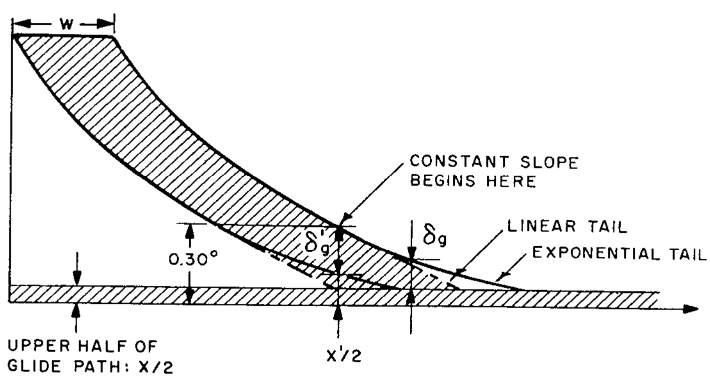
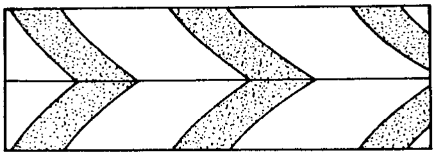


Fig. 5 - The vertical distance between the two exponential curves at the value of ζ for which the slope of the upper curve becomes constant is δ_g'. Having defined δ_g', we can then define x' as the height of the imaginary glidepath which would be necessary if δ_g' were the height of the colored exponential curve at the point where the curve intersects this glidepath.

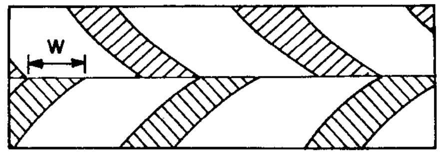
*The data are for a drum revolution rate of 33-1/3 rpm.

Table 1
Typical Values Used to Plot One of the Colored Exponential Stripes Used in the Rainbow Display System

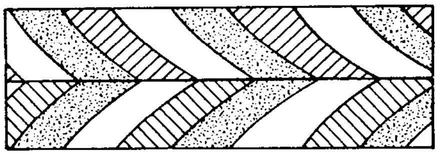
Points for Curve $y_{\#2}$								
Horizontal (ζ) (in.)	Vertical (y) (in.)							
0.00	1.66	1.23	0.783	0.499	0.319	0.202	0.130	0.074
6.28	1.66	1.17	0.746	0.477	0.304	0.194	0.123	0.068
12.57	1.66	1.11	0.710	0.453	0.289	0.184	0.117	0.061
18.85	1.66	1.06	0.675	0.430	0.274	0.174	0.110	0.055
25.13	1.58	1.007	0.642	0.410	0.261	0.166	0.104	0.049
31.42	1.50	0.957	0.611	0.390	0.249	0.158	0.098	0.043
37.70	1.43	0.912	0.582	0.370	0.236	0.151	0.092	0.042
43.98	1.36	0.866	0.552	0.352	0.224	0.143	0.086	0.042
50.26	1.29	0.825	0.527	0.335	0.214	0.136	0.080	0.042
56.55	1.23	0.783	0.499	0.319	0.202	0.130	0.074	0.042
Points for Curve $y_{\#1}$								
Horizontal (ζ) (in.)	Vertical (y) (in.)							
0.00	1.66	1.06	0.675	0.430	0.274	0.174	0.110	0.055
6.28	1.58	1.007	0.642	0.410	0.261	0.166	0.104	0.049
12.57	1.50	0.957	0.611	0.390	0.249	0.158	0.098	0.043
18.85	1.43	0.912	0.582	0.370	0.236	0.151	0.092	0.042
25.13	1.36	0.866	0.552	0.352	0.224	0.143	0.086	0.042
31.42	1.29	0.825	0.527	0.335	0.214	0.136	0.080	0.042
37.70	1.23	0.783	0.499	0.319	0.202	0.130	0.074	0.042
43.98	1.17	0.746	0.477	0.304	0.194	0.123	0.068	0.042
50.26	1.11	0.710	0.453	0.289	0.184	0.117	0.061	0.042
56.55	1.06	0.675	0.430	0.274	0.174	0.110	0.055	0.042



(a) Red pattern



(b) Blue pattern



(c) Overall Rainbow display pattern

Fig. 6 - Exponential colored stripes, with greatly exaggerated slopes, used in the Rainbow display system

a mirror image of the pattern and then shifting it to the right by an amount W with respect to the original pattern, we obtain a complete set of curves for the blue pattern (Fig. 6b).

The red and blue patterns are printed on transparent film in such a manner that the red, white, and blue pattern of the Rainbow emerges (Fig. 6c).

ACKNOWLEDGMENTS

The author wishes to express appreciation to Mr. Fred Smith who checked the equations in Appendix B by deriving them independently of the author, and to Mr. A. W. Baldwin, Mr. Henry P. Birmingham, Miss Barbour Lee Perry, and Mrs. Ruth H. Shields for their helpful suggestions and criticisms.

Appendix A

WARNING-SIGNAL FLASH RATES

The warning signals are designed to flash four times per second. This rate was chosen because the human operator can easily recognize the flash characteristic of the signal in a short time. The flash effect is obtained by using the scheme: color-blank-color-blank, etc. This is illustrated in Fig. 3 of the text.

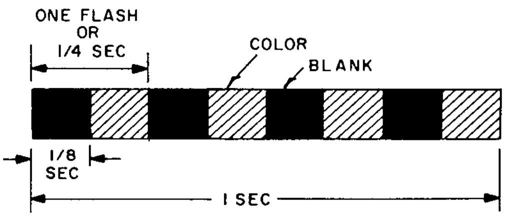


Fig. A1 - Warning-signal flash pattern used in Rainbow display system

Consider Fig. A1 wherein a flash pattern is to pass a given point in space in one second. The question, of course, is how long must each space be (in inches) if it is to last 1/8 second. The answer is very simple; the proportional equation is

$$\frac{\text{seconds per revolution}}{\text{inches per revolution (drum circumference)}} = \frac{1/8 \text{ second}}{\text{length of space to last } 1/8 \text{ second}}$$

$$\frac{\left(\dfrac{60 \text{ sec/min}}{\text{RPM}}\right)}{\pi D} = \frac{1/8 \text{ sec}}{d}$$

$$d = \frac{1}{8}\left[\frac{\pi D \text{ RPM}}{60}\right] .$$

For the drum in our example ($D = 18''$, $\text{RPM} = 33\text{-}1/3$), it follows that $d = 3.92$ inches. However, the pattern must be repetitive as the drum rotates. Thus, $\pi D/d$ must be an even number.

$$\frac{\pi D}{d} = 2n .$$

Therefore,

$$d = \frac{\pi D}{2n} \cong \frac{1}{8}\left[(\pi D)\left(\frac{\text{RPM}}{60}\right)\right] .$$

That is, d cannot be exactly 3.92 inches (which would give a flash rate of exactly four per second). We must choose d as close to this figure as possible while fulfilling the condition $d \cong \pi D/2n$. If $n = 7$, $d = 4.03''$ and actual flash rate is 3.9 per second.

Appendix B

DERIVATION OF RAINBOW DESIGN EQUATIONS

HEIGHT OF GLIDEPATH

From simple trigonometry we obtain the equation for the height x of the glidepath pattern as

$$\frac{\left(\frac{x}{2}\right)}{f} = \tan\frac{\Omega}{2} ,$$

or (1)

$$x = 2f \tan\left(\frac{\Omega}{2}\right) .$$

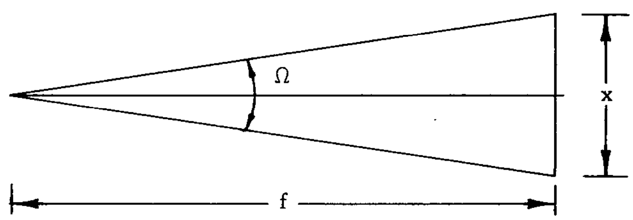


Fig. B1 - Sketch of relationship between total glidepath angle Ω, lens system focal length f, and glidepath pattern height x on drum

EQUATIONS FOR EXPONENTIAL CURVES

Figure 4 is reproduced in Fig. B2, with the two curves defining the bounds of one exponential stripe being labeled as shown.

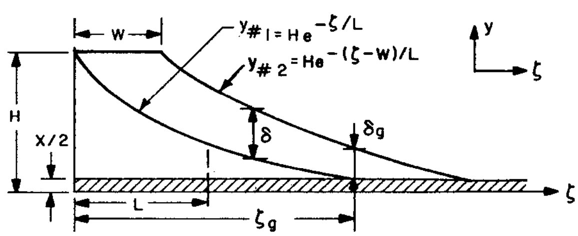


Fig. B2 - Geometry of glidepath stripe and of one of the exponential colored stripes used on the rotating drum of the Rainbow system

The curve whose value is H at $\zeta = 0$ has the equation

$$y_{\#1} = He^{-\zeta/L}. \tag{2}$$

From the figure note that

$$y_{\#1}\Big|_{\zeta=\zeta_g} = He^{-\zeta_g/L} = x/2. \tag{3}$$

Therefore,

$$\zeta_g = L \ln\left(\frac{2H}{x}\right). \tag{4}$$

The curve which is shifted to the right of the origin by $\zeta = W$ has the equation

$$y_{\#2} = He^{-(\zeta-W)/L}. \tag{5}$$

The vertical distance between the two exponential curves (δ) is simply $y_2 - y_1$, i.e.,

$$\begin{aligned} \delta &= y_2 - y_1 = H\left[e^{-(\zeta-W)/L} - e^{-\zeta/L}\right] \\ &= He^{-\zeta/L}\left[e^{W/L} - 1\right]. \end{aligned} \tag{6}$$

We would now like to obtain an expression for W/L. We begin by considering the equation for the projected time constant τ:

$$\begin{aligned} \tau &= L \times \left(\frac{60 \text{ sec/min}}{\text{RPM}}\right) \times \left(\frac{1}{\text{inches per revolution}}\right) \\ &= L \times \left(\frac{60}{\pi D \text{ RPM}}\right). \end{aligned} \tag{7}$$

Thus,

$$\frac{L}{\tau} = \frac{\pi D \text{ (RPM)}}{60}. \tag{8}$$

The next step is to find an expression for γ :

$$\begin{aligned} \gamma &= \left(\frac{\text{RPM}}{60 \text{ sec/min}}\right) \times (\text{inches per rev.}) \times \left(\frac{1}{\text{curve thickness}}\right) \\ &= \left(\frac{\text{RPM}}{60}\right)\left(\frac{\pi D}{W}\right). \end{aligned} \tag{9}$$

Solving for γW we find that

$$\gamma W = \frac{\pi D \text{ (RPM)}}{60}. \tag{10}$$

But this is equal to L/τ. Therefore,

$$\frac{W}{L} = \frac{1}{\gamma\tau} . \tag{11}$$

We can now rewrite the expression for δ, using Eqs. (6) and (11), as

$$\delta = He^{-\zeta/L}(e^{W/L} - 1) = He^{-\zeta/L}(e^{1/\gamma\tau} - 1) . \tag{12}$$

Then, the height of the exponential curve at its intersection with the glidepath (δ_g) is found by using Eqs. (3) and (12) to be

$$\delta_g = He^{-\zeta_g/L}(e^{1/\gamma\tau} - 1) = \frac{x}{2}(e^{1/\gamma\tau} - 1) . \tag{13}$$

By using simple proportion, we find that

$$t_g = \left(\frac{\zeta_g}{L}\right)\tau . \tag{14}$$

In order for the colored exponential curves to be continuous when the pattern is wrapped around the drum, the total number of colored curves ($3m$) times the width of one color (W) must equal the circumference of the drum, or

$$3mW = \pi D ;$$

Thus

$$W = \frac{\pi D}{3m} . \tag{15}$$

We now have all the basic equations; with a little more manipulation we shall obtain the equations presented in the text.

From Eq. (9) we obtain

$$\gamma = \frac{\pi D \text{ (RPM)}}{60 \ W} ,$$

and Eq. (15) gives

$$W = \frac{\pi D}{3m} .$$

It follows that

$$\gamma = \frac{3m \text{ (RPM)}}{60} = \frac{m \text{ (RPM)}}{20} .$$

Rearranging Eq. (11), we find that

$$L = (\gamma\tau) W .$$

Appendix C

EQUATION OF THE LINEAR TAIL

In order to derive the equation for y_{top} (Fig. C1), we first shall define an imaginary glidepath height (x') such that the slope of the curves is constant beginning with a distance δ_g' above this imaginary glidepath (Fig. 5 of text).

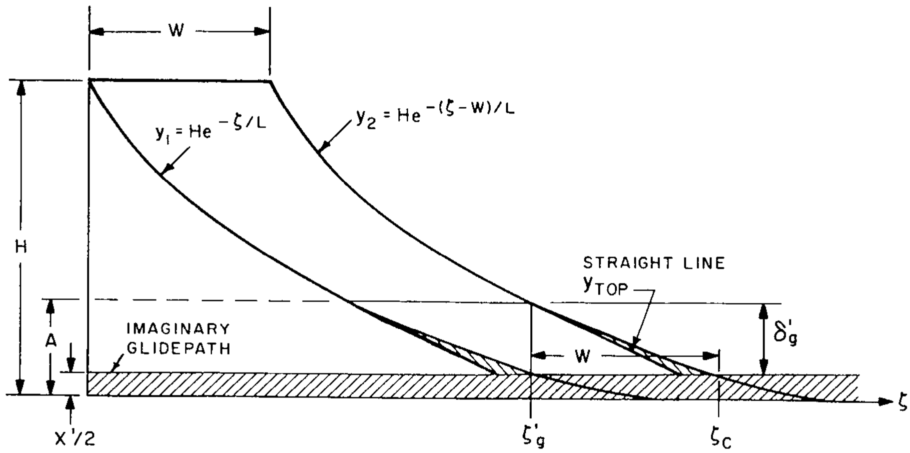


Fig. C1 - Imaginary glidepath geometry used to derive equations for the "linearized" exponential tails

To find δ_g' and x', let A be defined as the vertical distance on the drum which, when projected into space, subtends a half-angle of 0.3°. Then

$$A = \delta_g' + \frac{x'}{2} = f \tan 0.3° . \tag{1}$$

We have previously derived the relationship

$$\delta_g = \frac{x}{2}(e^{1/\gamma\tau} - 1) .$$

Since δ_g and δ_g' are defined in the same manner,

$$\delta_g' = \frac{x'}{2}(e^{1/\gamma\tau} - 1) . \tag{2}$$

Solving (1) and (2) simultaneously, we obtain

$$x' = 2A\, e^{-1/\gamma\tau} = 2f \tan 0.3°\, e^{-1/\gamma\tau} \tag{3}$$

$$\delta_g' = A(1 - e^{-1/\gamma\tau}) . \tag{4}$$

Referring to Fig. C1, ζ_g' corresponds to δ_g'.

The slope of the linear tail is simply the derivative of curve y_2 evaluated at ζ_g':

$$y_2 = He^{-(\zeta - W)/L}$$

so

$$\left.\frac{dy_2}{d\zeta}\right|_{\zeta_g'} = -\frac{H}{L}\, e^{-(\zeta_g' - W)/L} = -\frac{x'}{2L}\, e^{1/\gamma\tau}\,. \tag{5}$$

The equation of a straight line is $y = mx + b$, where m is the slope of the line and b is the y intercept. If y_{top} is the equation of the upper straight line of the tail, then

$$y_{top} = \left(-\frac{x'}{2L}\, e^{1/\gamma\tau}\right) \zeta + b\,. \tag{6}$$

The y intercept is determined as follows (refer to Fig. C1):

$$\left. y_{top}\right|_{\zeta_g'} = A = -\frac{x'}{2L}\, e^{1/\gamma\tau}\, \zeta_g' + b\,, \tag{7}$$

and

$$b = A + \frac{x'}{2L}\, e^{1/\gamma\tau}\, \zeta_g' \tag{8}$$

Therefore,

$$y_{top} = -\frac{x'}{2L}\, e^{1/\gamma\tau}\, (\zeta - \zeta_g') + A\,. \tag{9}$$

We know that

$$\left. y_1\right|_{\zeta_g'} = \frac{x'}{2} = He^{-\zeta_g'/L}\,.$$

Therefore,

$$\frac{\zeta_g'}{L} = \ln\left(\frac{2H}{x'}\right). \tag{10}$$

From (3) and (10)

$$\begin{aligned} \frac{\zeta_g'}{L} &= \ln\left(\frac{2H}{2f \tan 0.3^\circ e^{-1/\gamma\tau}}\right) \\ &= \ln\left(\frac{H}{f \tan 0.3^\circ}\right) + \frac{1}{\gamma\tau}\,. \end{aligned} \tag{11}$$

Thus, (9) becomes

$$y_{top} = f \tan 0.3^\circ \left[1 - \frac{\zeta}{L} + \ln\left(\frac{H}{f \tan 0.3^\circ}\right) + \frac{1}{\gamma\tau}\right] \tag{12}$$

$$y_{top} = B\zeta + C, \tag{13}$$

where

$$B = -f \tan 0.3°/L \tag{14}$$

$$C = f \tan 0.3° \left[1 + \ln\left(\frac{H}{f \tan 0.3°}\right) + \frac{1}{\gamma\tau}\right]. \tag{15}$$

The equation for the lower straight line of the linear tail is

$$y_{bottom} = B(\zeta + W) + C. \tag{16}$$

(It should be noted here that Table 1 contains values for a linearized tail based on 0.294° above center rather than 0.30°. This was done so that ζ_g' fell on the closest of the ten values of ζ given in the table.)

* * *

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5. AUTHOR(S) *(Last name, first name, initial)*

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13. ABSTRACT

The Rainbow Optical Landing Aid is a carrier-based landing display system which enables the pilot to control the rate of descent of his aircraft to a high level of accuracy. The system is purely optical-geometrical and requires no electronics. The command signal is presented as a color-coded array of lights, which is achieved by mounting color transparencies of exponential curves on a revolving transparent drum and by projecting the resultant pattern into space.

This report is concerned with the color pattern on the revolving drum of the Rainbow optical landing display, including both the basic mathematical aspects of this pattern and its color coding.

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Landing aids — Color coded Landing aids — Optical Carrier landings — Equipment Projected color display Aircraft landings Vehicular guidance system Rate of descent — Control Control system — Quickened Error sensitivity — Range independence Error sensitivity — Inverse-actual-error dependence						

INSTRUCTIONS

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