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PRELIMINARY ANALYSIS OF SEVERAL MICROWAVE LANDING SYSTEM FLARE ELEVATION CONFIGURATIONS

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Abstract

Four configurations of MLS Flare Elevation Systems (El_2) that can be considered reasonable and practical in actual implementation are identified. Each of these are analyzed and compared with respect to (a) computational requirement, (b) required coverage, and (c) accuracy including altitude and sink-rate estimation error performance.

I. Configurations

The four (4) configurations are based on the coordinates (conical or planar) and the orientation of the beam center (conventional or nonconventional; parallel or perpendicular to the runway center line, respectively).

(i) Conical/conventional (the most likely U.S. candidate)
(ii) Conical/nonconventional
(iii) Planar/conventional
(iv) Planar/nonconventional (ALI; Australian candidate).

II. Computational (or Algorithm) Requirements

By the computational requirement is meant the difficulty or the simplicity of obtaining the altitude from El_2, DME and Azimuth information.

The following notations are used.

r	= DME slant range
ψ	= Azimuth Angle
ε	= El_2 flare elevation angle
x,y,z	= Runway referenced rectangular coordinates of the aircraft
XAZ, ZAZ	= Az/DME (colocated) antenna site.
XEl_2, YEl_2, ZEl_2	= El_2 antenna site

(A) MLS Equations from x,y and z

The range (DME) and the azimuth (conical) equations are the same regardless of the configurations:

DME Equation:

(1) $$r = [(x-XAZ)^2 + y^2 + (z-ZAZ)^2]^{1/2}$$

(2) Az Equation:

$$\psi = SIN^{-1} \left(\frac{y}{r}\right)$$

The El_2 equations are not the same for the various configurations. They are given next for each configuration.

(i) Conical/conventional

(3) $$\varepsilon = -\tan^{-1}\left\{\frac{z-ZEl_2}{[(x-XEl_2)^2 + (y-YEl_2)^2 + (z-ZEl_2)^2]^{1/2}}\right\}$$

(ii) Conical/nonconventional

Same as (3)

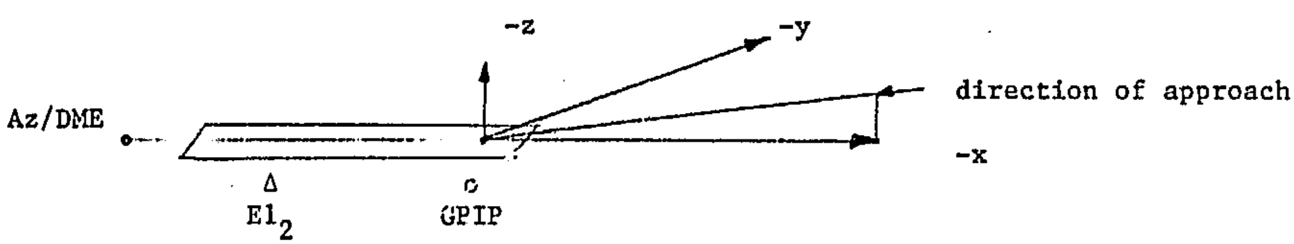
(iii) Planar/conventional

(4) $$\varepsilon = \tan^{-1}\left\{\frac{z - ZEl_2}{x - XEl_2}\right\}$$

(iv) Planar/nonconventional

(5) $$\varepsilon = \tan^{-1}\left\{\frac{z - ZEl_2}{y - YEl_2}\right\}$$

NOTE: x, y, z are expressed in the runway center line coordinate system shown below:



(B) Altitude Equation from MLS

(i) Conical/conventional

For this configuration Equations (1, 2, and 3) must be used to determine the altitude precisely. The solution involves a quadratic equation:

(6) $$z = ZEl_2 - \left\{\frac{\tan^2\varepsilon}{1-\tan^2\varepsilon}\,[(x-XEl_2)^2 + (y-YEl_2)^2]\right\}^{1/2},$$

where

(7) $$y = r \sin \psi$$

and x is a solution of a quadratic equation

(8) $$Ax^2 + Bx + C = 0$$

with

$$A = \frac{1}{1- \tan^2 \varepsilon}$$

(9) $$B = -2 \cdot \{XAZ + XEl_2 \cdot \frac{\tan^2 \varepsilon}{1-\tan^2 \varepsilon}\}$$

$$C = -r^2\cos^2\psi + XAZ + \frac{\tan^2 \varepsilon}{1-\tan^2 \varepsilon}\{XEl_2^2 + [r \ SIN \ \psi - YEl_2]^2\}$$

Equations (6) through (9) are exact solutions in the sense that there is no approximation involved except the antenna heig! was assumed the same.

For the same order of exactness the following recursive (or iterative) algorithm can be used:

(10)
Step (i) Assume an estimate of altitude, Z^+.
Step (ii) Obtain $y = r \sin \psi$
Step (iii) Using Z^+ & y, obtain x from Equation (1).
Step (iv) Using Z^+ & y & x and ε, obtain z from Equation (6).
Step (v) Use z as the estimate and go back to step (ii) and repeat.

NOTE: This recursive algorithm has been evaluated for the computation of altitude from DME, Az and El_1 on the glide-slope, and it converged rapidly.

Algorithm (10) still involves considerable computation, therefore the planar approximation

(11) $$Z = ZEl_2 - (r - XDIST) \tan \varepsilon$$

is used, where
XDIST = distance between DME and El_2.

As will be shown later, this approximation turns out to be surprisingly good in spite of its simplicity.

(ii) Conical/nonconventional

In order to determine altitude with this configuration, either Equations (6) through (9) or the recursive algorithm (10) must be solved. The planar approximation would not yield good results, since the distance to the aircraft is much shorter.

(iii) Planar/conventional

The exact solution is given by:

(12) $$Z = ZEl_2 + (x - XEl_2) \cdot \tan \varepsilon$$

where

(13) $$y = r \sin \psi$$

and x is a solution of

(14) $$Ax^2 + Bx + C = o,$$

(15) $$\begin{cases} A = 1 + \tan^2 \varepsilon \\ B = -2\ [XAZ - XEl_2 \cdot \tan^2 \varepsilon] \\ C = XAZ^2 + XEl_2^2 \tan - r^2 \cos^2 \psi \end{cases}$$

The recursive algorithm corresponding to (10) can be derived for this case also; however, the computation savings is nil. Similar to Equation (11), we can obtain an approximation:

(16) $$Z = ZEl_2 - (r - XDIST).\ \tan \varepsilon$$

This approximation (using DME directly instead of computed as in (12)) should yield excellent accuracy.

(iv) Planar/nonconventional

For this configuration the exact solution is the easiest and is given by:

(17) $$Z = ZEl_2 - (r \cdot \mathrm{Sin}\ \psi - YEl_2) \cdot \tan \varepsilon,$$

If the aircraft is assumed on the extended runway centerline the equation simplifies to:

(18) $$Z = ZEl_2 - YEl_2 \cdot \tan \varepsilon,$$

since $\psi = 0$.

Conclusions for Section II

(1) For conical coordinates (Conf. (i) & (ii)) the exact altitude determination is very involved. This can be simplified somewhat using recursive formulation with very good accuracy; however, the algorithm is still involved. For configuration (i) the planar approximation can be used with satisfactory results.

III. Required Coverage

The El_2 coverage requirements are specified by RTCA DO-148 (page 8). The Flare signal must be available near the runway surface throughout the touchdown zone and shall extend to a range of 0.5 nm from the threshold. For a 3° glideslope a nominal flare initiation altitude of 50 feet at 200 feet/second landing speed, the above requirement gives 100 feet (approximately 10 seconds) of margin to acquire and settle the filter prior to initiating the flare maneuver. (From the coverage point of view, the portion from 150 ft. ∿ 50 ft. altitude is the only advantage the MLS derived flare has over radio altimeter since the latter may not be reliable ahead of the threshold due to irregular terrain at some airfields.)

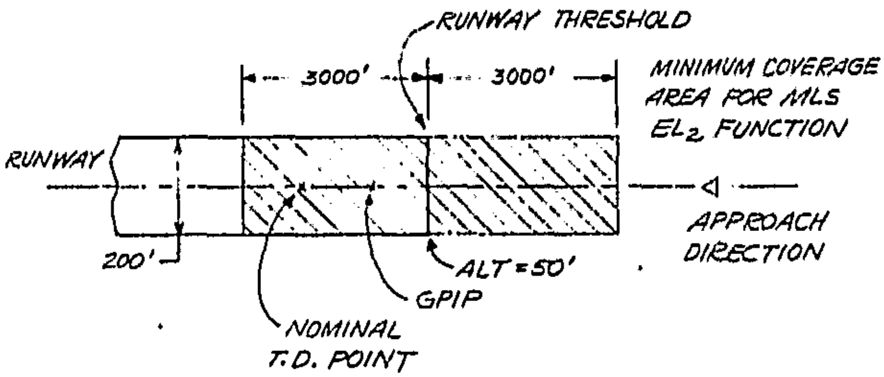


Fig. 1. Minimum Coverage Area for Flare Function

(A) <u>Configuration (i)</u>

Assuming the flare antenna is 2500' behind the GPIP toward the runway stop-end and offset 450' laterally from the runway centerline, the coverage for configuration (i) is given by (see Figure 2)

$$\text{lateral coverage} = \tan^{-1}\left(\frac{450' + 100'}{500'}\right) = 47.7°$$

$$\text{vertical coverage} = \tan^{-1}\left(\frac{150'}{3000' + 3500'}\right) = 1.4°$$

NOTE: The 1.4° vertical coverage is substantially less than specified in DO-148 (page IIIA-11).

(B) <u>Configuration (iv)</u>

For Configuration (iv) the lateral as well as the vertical coverage are more sensitive to the offset distance since (see Figure 3)

$$\text{lateral coverage} = \tan^{-1}\left(\frac{3000'}{\text{D offset} - 100'}\right)$$

$$\text{vertical coverage} = \tan^{-1}\left(\frac{150'}{\text{D offset} - 100'}\right)$$

where

D offset = Flare antenna lateral offset distance from the runway centerline.

FIGURE 2 COVERAGE FOR CONF. (i)

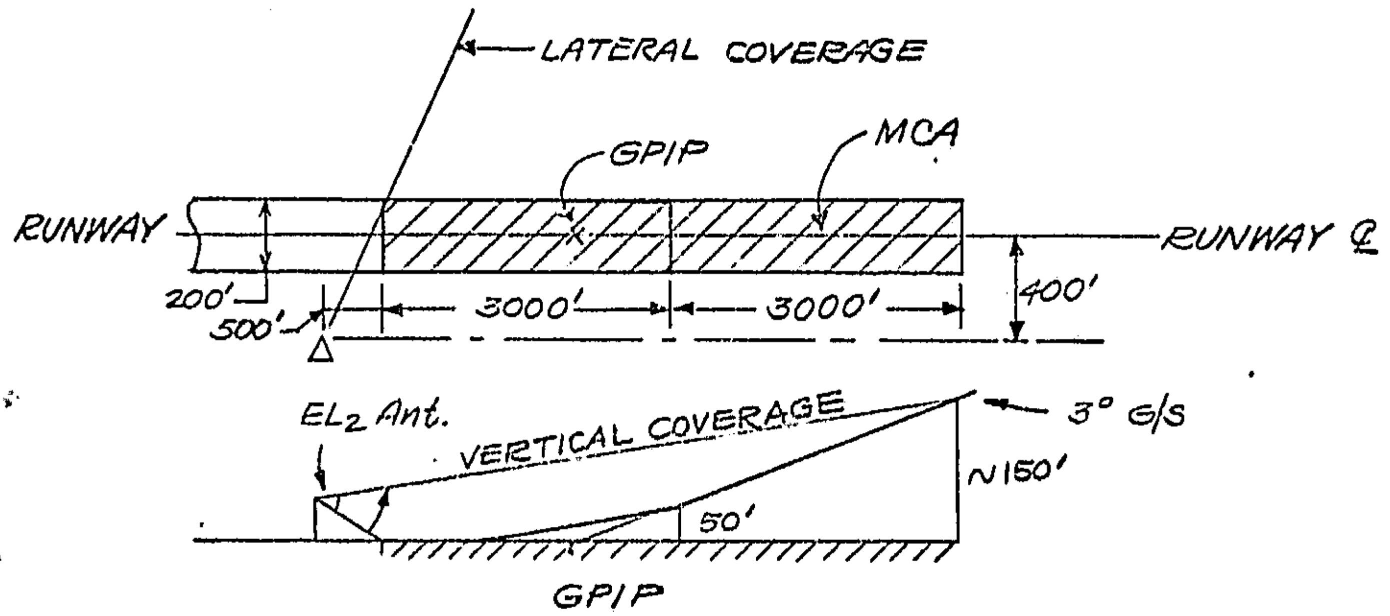
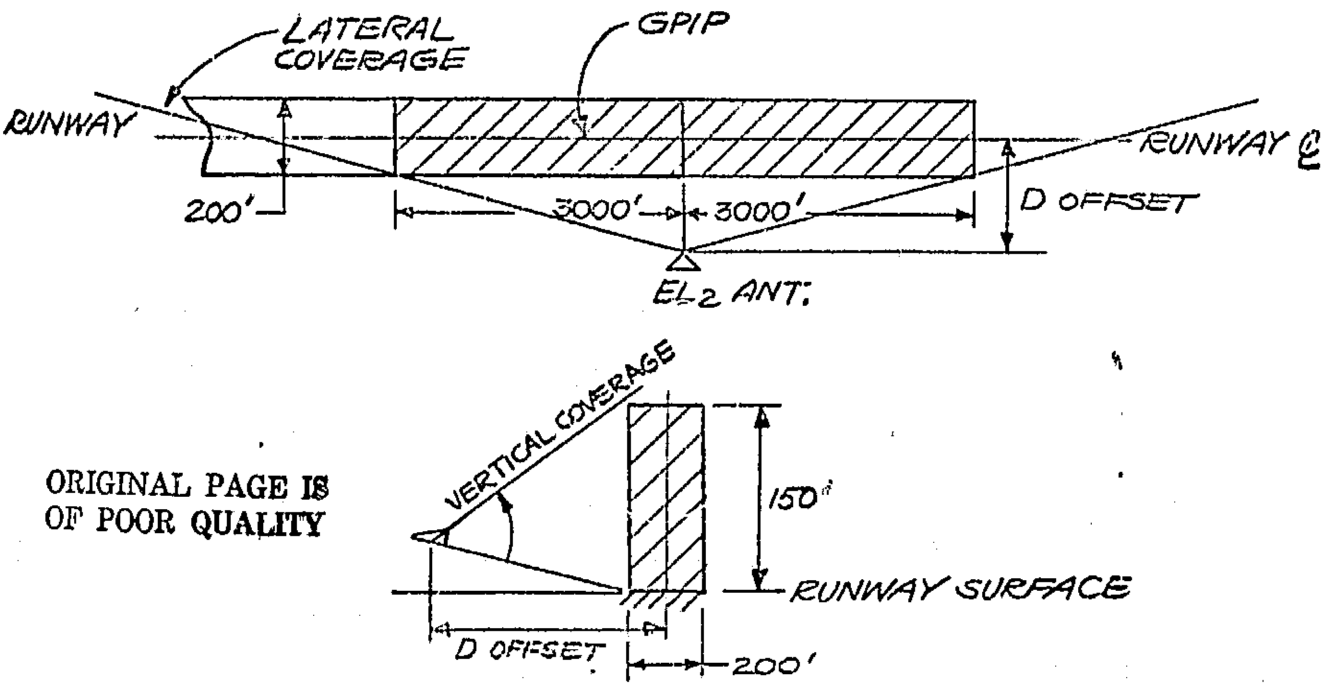


FIGURE 3 COVERAGE FOR CONF. (iv)



The following table summarizes the coverages for different values of D offset.

D offset (ft)	Lateral Coverage (deg)	Lateral Coverage (deg)
500	82.4	20.6
750	77.8	13.0
1000	73.3	9.5
1250	69.1	7.5

Table 1. Lateral & Vertical Coverage for Configuration (iv)

IV. Accuracy and Filtering Performance of Configuration (i) and (iv)

In this section the following cases are examined for a nominal exponential flare at 200 ft/sec landing speed and 3° glide slope. (See Figure 4.)

(1) Configuration (i)

(1.a) Planar approximation (conicity) altitude error
(1.b) Altitude and sink-rate estimation errors with complementary filter with planar approximation.
(1.c) Same as (1.b) except with noncomplementary filter (i.e., no acceleration information.)

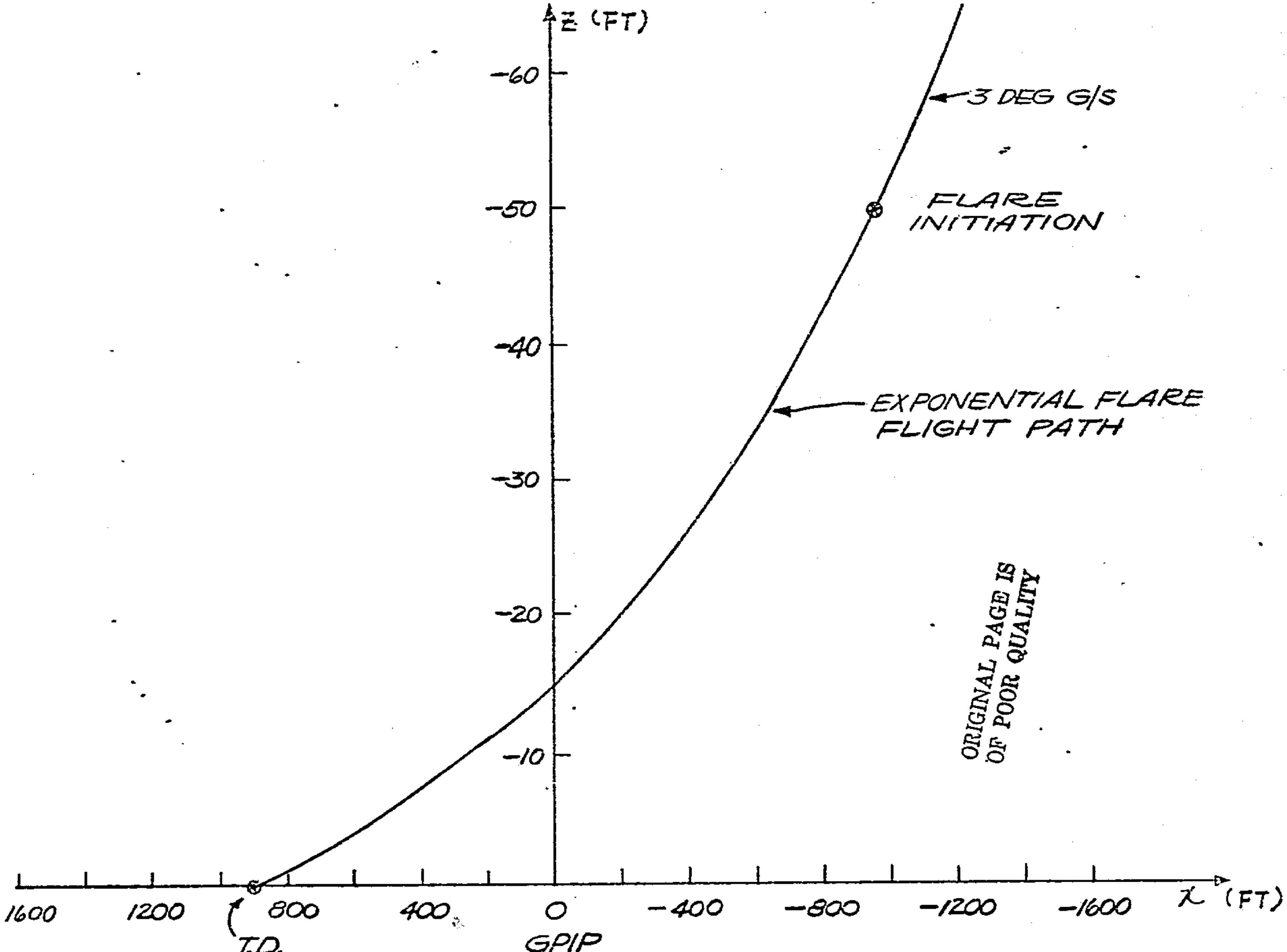
(2) Configuration (iv)

(2.a) Altitude and sink-rate estimation error with complementary filter and zero lateral (y) deviations
(2.b) Same as (2.a) except with noncomplementary filter.

Computer runs were made with the conditions and equations shown below. (Only one run was made for each set of conditions; however, the same noise sequence was used for each configuration so that comparitive results were obtained.)

Constant lateral (y) deviations were employed to approximate the effects of aircraft lateral errors on measurement performance and to simulate the coupling between the aircraft lateral and vertical motions. The magniture of the aircraft high frequency lateral motion is generally small and hence the induced high frequency vertical errors will also be small; however, the low frequency lateral motion induces a slowly varying vertical path following error which cannot be filtered effectively. This coupling effect will be most pronounced with configuration (iv) with the simplified altitude computation; however, the problem is substantially reduced if the exact altitude computation is utilized.

FIGURE 4. NOMINAL EXPONENTIAL FLARE FLIGHT PATH
@ SPEED=200 FT/SEC AND 3 DEG GLIDE SLOPE



Following conditions were used.

°El_2 Ant. site for Conf. (i)

XEl_2 = 2500', YEl_2 = 400', ZEl_2 = -10'.

°El_2 Ant. Site for Conf. (iv)

XEl_2 = 0. YEl_2 = 500', ZEl_2 = -10'.

°El_2 Errors **

bias = 0.015, 0., - 0.015° ($\pm$ 1σ)

· Noise = 0.016° (1σ)

°DME Error

bias = 0

Noise = 20 ft. (1σ)

Equations

° Nominal Exponential Flare Flight-path

$$x_{n+1} = x_n + \dot{x}\,\Delta$$

$$y_{n+1} = y_n = \text{const} = -30,\ 0,\ 30'$$

$$Z_{n+1} = Z_n + \dot{Z}_n\,\Delta \quad (\dot{Z}_n = \text{const for } 3° \text{ glide slope portion of flight path})$$

$$\left.\begin{aligned} Z_{n+1} &= \tau\,[\dot{Z}_{T.D.} - \dot{Z}_n] \\ \dot{Z}_{n+1} &= \exp(-\Delta/\tau)\cdot \dot{Z}n \\ \ddot{Z}_{n+1} &= -\dot{Z}_{n+1}/\tau \end{aligned}\right\} \text{Exponential Flare Flight-path portion}$$

$$\tau \equiv Z_{INT}/(\dot{Z}_{TD} - \dot{Z}_{INT})$$

x_o = -1431 ft, $\dot{x}$ = 200 ft/sec, Z_o = -75 ft, $\dot{Z}_o$ = 10.5 ft/sec,

Z_{INT} = - 50 ft, $\dot{Z}_{INT}$ = 10.5 ft/sec, $\dot{Z}_{TD}$ = 2.3 ft/sec,

τ = 6.05 sec.

**Note that since the El-2 antenna location for configuration (iv) is closer to the touchdown point than for configuration (i), the configuration (iv) angular error can be two to three times larger for the same linear altitude error.

- Altitude computation for Conf. (i); see Equation (11) § II

$$Z'_n \simeq ZEl_2 - (r_n - 11355.0) \quad \tan \varepsilon_n$$

- Altitude computation for conf. (iv), see Equation (18), § V

$$Z'_n \simeq ZEl_2 - YEl_2 \cdot \tan \varepsilon_n$$

where r_n is the DME measurement and ε_n is the El_2 measurement. Both contain the errors given previously.

Filter Equations

Complementary and noncomplementary filters were implemented in sequential versions, since the sequential format is much simpler with a digital computer.

(a) Complementary Filter

$$\begin{bmatrix} Z^P_{n+1} \\ \dot{Z}^P_{n+1} \end{bmatrix} = \begin{bmatrix} 1 & \Delta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{Z}_n \\ \hat{\dot{Z}}_n \end{bmatrix} + \begin{bmatrix} \frac{\Delta^2}{2} \\ \Delta \end{bmatrix} \ddot{Z}_n$$

Acceleration Complementation Term

$$\begin{bmatrix} \hat{Z}_{n+1} \\ \hat{\dot{Z}}_{n+1} \end{bmatrix} = \begin{bmatrix} Z^P_{n+1} \\ \dot{Z}^P_{n+1} \end{bmatrix} + \begin{bmatrix} g_{c1} \\ g_{c1} \end{bmatrix} [Z'_{n+1} - Z^P_{n+1}]$$

(b) Noncomplementary Filter

$$\begin{bmatrix} Z^P_{n+1} \\ \dot{Z}^P_{n+1} \end{bmatrix} = \begin{bmatrix} 1 & \Delta \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \hat{Z}_n \\ \hat{\dot{Z}}_n \end{bmatrix}$$

$$\begin{bmatrix} \hat{Z}_{n+1} \\ \hat{\dot{Z}}_{n+1} \end{bmatrix} = \begin{bmatrix} Z^P_{n+1} \\ \dot{Z}^P_{n+1} \end{bmatrix} + \begin{bmatrix} g_{n1} \\ g_{n2} \end{bmatrix} [Z'_{n+1} - Z^P_{n+1}]$$

$(\ )^P_n$ = a-priori estimate, $\hat{(\ )}_n$ = a-posterrori estimate,

$(\ )'_n$ = observed or measured value at time n.

$g_{c1} = 0.081$, $g_{c2} = 0.017$, $gn_1 = 0.156$, $gn_2 = 0.066$

Results

The results of computer runs are summarized below. The heading numbers correspond to the cases itemized at the beginning of this section.

(1) Configuration (i); Conical/Conventional (See Tables 2a and b)

(1.a) The planar (Equation 11) approximation was found to be surprisingly accurate. Along the nominal exponential flight-path and on the azimuth ℄ the computed altitude error was between -0.34 feet at 75' altitude to +0.34 feet at T.D. Since this configuration (and the approximation) is insensitive to lateral y-deviations, the result will hold for reasonable y-deviations, say within ± 30 feet.

(1.b) The maximum altitude estimation error was less than 1.6 feet (1σ) and the sink-rate estimation error was less than 0.3 ft/sec (1σ). The estimates were very smooth. The bias in El_2 was the major source of error. Even though not shown, DME noise of 20 ft (1σ) contributed very little error. The apparent touch down distance (where the filter indicates the aircraft touched down as opposed to where it actually touched down were nicely clustered. No noticeable y-deviation effects were observed.

(1.c) The performance for the noncomplementary filter was decidedly inferior compared to the complementary filter case. The maximum altitude error was ≈ 2.5 ft. (1σ) and the maximum sink-rate error ≈ 2.6 ft/sec. The estimates were very noisy. This is to be expected since the filter's band-width is eight (8) times that of the complementary filter, and thus allows more MLS noise to pass through. (However, the band-width may not be reduced arbitrarily, since the dynamic delay error will begin to dominate.) The apparent touch down distances were more dispersed and the bias in El_2 measurements had more prominent affect on the errors.

(2) Configuration (iv); Planar/nonconventional (See Tables 3a and b)

(2.a) The maximum altitude estimation error was less than 3.3 ft. and the sink-rate error less than 0.5 ft/sec. with complementary filtering. The estimates were very smooth. The apparent touch down points were scattered compared to (1.b). The bias and the noise of El_2 had much less affect than in (1.b), since linear errors due to El_2 error are much smaller due to shorter distance to the aircraft. The major source of error was due to the neglected lateral y-deviation.

(2.b) Without complementary filtering the maximum altitude estimation error was less than 2.7 ft. and the sink-rate error less than 1.63 ft/sec. The estimates were somewhat noisier than the (2.a) case, but smoother than the (1.c) case. This is because the errors in El_2 do not contribute greatly to the altitude computation. The apparent touch down points were similar to the (2.a) case. The largest errors occurred at or immediately after the flare initiation, since this is where the vertical acceleration is largest and hence the most severe maneuver dynamics effect takes place. Soon after the filter's performance approaches that of (2.a). The affect of y deviation on vertical error was essentially the same as shown in (2.a).

y- dev. (feet)	E12 bias (deg)	(0) Alt. Error @ 50' (ft)	(1) Max Alt. Est. Error (ft)	(2) Max Sink rate error (ft/sec)	(3) Apparent T.D.* (ft. from GPIP)
30	0.0	0.8	0.5	0.08	946
0	0.00	0.8	0.5	0.04	946
-30	0.0	0.7	0.6	0.09	946
30	0.015	1.7	1.1	0.16	986
0	0.015	1.7	1.0	0.16	986
-30	0.015	1.7	0.9	0.15	976
30	-0.015	-1.1	1.5	0.21	906
0	-0.015	0.1	1.5	0.22	906
-30	-0.015	-0.2	1.6	0.22	906

(0) Alt Error at 50' = Alt_{act} Alt_{comp} at 50' Alt
(1) Maximum estimated altitude error = $Alt_{act} - Alt_{est}$ during flare
(2) Maximum estimated sink-rate error = $(\dot{Alt})_{est}$ during flare
(3) Apparent longitudinal T.D. point - where the filter thinks the a/c T.D.ed, i.e., where tha Alt est = 0.0

Table 2.a) Conical/Conventional with Complementary filter (τ = 2.36 sec) & Planar Approximation

*Nominal value for T.D. = 946'

y-dev. (feet)	El2 bias (deg)	(0) Alt Error @ 50' (ft)	(1) Max. Alt. Est. Error (ft)	(2) Max. Sink Rate Est. Error (ft/sec)	(3) Apparent T.D.* (ft from GPIP)
30	0.0	0.8	1.5	2.45	936
0	0.0	0.8	1.5	2.52	936
-30	0.0	0.7	1.6	2.51	946
30	0.015	1.7	2.1	2.56	1006
0	0.015	1.7	2.1	2.57	1006
-30	0.015	1.7	2.0	2.57	1016
30	-0.015	-1.1	2.4	2.47	926
0	-0.015	0.1	2.4	2.46	926
-30	-0.015	-0.2	2.4	2.46	926

(0) Alt. Error at 50' Alt. = $\text{Alt}_{\text{act}} - \text{Alt}_{\text{comp}}$ at 50' Alt.

(1) Maximum estimated altitude error = $\text{Alt}_{\text{act}} - \text{Alt}_{\text{est}}$ during flare

(2) Maximum estimated sink-rate error = $(\dot{\text{Alt}})_{\text{act}} - (\dot{\text{Alt}})_{\text{est}}$ during flare

(3) Apparent longitudinal T.D. point = where the filter thinks the a/c T.D. 'ed, i.e., where the Alt est = 0.0

Table 2.b) Conical/Conventional with Non-Complementary filter (τ = 0.295 sec) & Planar Approximation

*Nominal value for T.D. = 946'

y-dev. feet	E12 bias (deg)	(0) Alt Error @ 50' (ft)	(1) Max. Alt. Est. Error (ft)	(2) Max. Sink Rate Est. Error (ft/sec)	(3) Apparent T.D.* (ft from GPIP)
30	0.0	-2.3	2.8	0.2	1006
0	0.0	0.0	0.1	0.03	946
-30	0.0	2.5	3.1	0.48	886
30	0.015	-2.2	2.7	0.38	1026
0	0.015	0.2	0.2	0.03	946
-30	0.015	2.8	3.3	0.5	886
30	-0.015	-2.4	3.0	0.42	986
0	-0.015	-0.1	0.2	0.04	926
-30	-0.015	2.3	3.0	0.45	846

(0) Alt Error at 50' Alt = $\text{Alt}_{act} - \text{Alt}_{comp}$ at 50' Alt.

(1) Maximum estimated altitude error = $\text{Alt}_{act} - \text{Alt}_{est}$ during flare

(2) Maximum estimated sink-rate error = $(\dot{\text{Alt}})_{act} - (\dot{\text{Alt}})_{est}$ during flare

(3) Apparent longitudinal T.D. point = where the filter thinks the a/c T.D. ed, i.e., where the $\text{Alt}_{est} = 0.0$

Table 3.a) Planar/Non-conventional with Complementary filter (τ - 2.3 sec)

*Nominal value for T. D. = 946'

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y-dev. (feet)	E12 bias (deg)	(0) Alt Error @ 50' (ft)	(1) Max. Alt. Est. Error (ft)	(2) Max Sink Rate Est. Error (ft/sec)	(3) Apparent T.D.* (ft frin GPIP)
30	0.0	-2.3	2.3	0.57	1006
0	0.0	0.0	0.3	1.01	926
-30	0.0	2.5	2.5	1.63	886
30	0.015	-2.2	2.2	0.57	1026
0	0.015	0.2	0.2	1.01	926
-30	0.015	2.8	2.7	1.63	906
30	-0.015	-2.4	2.5	0.57	986
0	-0.015	-0.1	0.4	2.0	926
-30	-0.015	2.3	2.4	1.63	886

(0) Alt Error at 50' Alt = $\text{Alt}_{act} - \text{Alt}_{comp}$ at 50' Alt

(1) Maximum estimated altitude error = $\text{Alt}_{act} - \text{Alt}_{est}$ during flare

(2) Maximum estimated sink-rate error = $(\dot{\text{Alt}})_{act} - (\dot{\text{Alt}})_{est}$ during flare

(3) Apparent longitudinal T.D. point = where the filter thinks the a/c T.D. ed, i.e., where the $\text{Alt}_{est} = 0.0$

Table 3.b) Planar/Non-conventional with Non-Complementary filter (τ - 0.295 sec)

* Nominal T.D. = 946'

V. Conclusions

It was found that computationally configuration (iv) was simplest in concept. However, its severe sensitivity to the lateral y-deviation requires that this deviation be accounted for in precision usages of this configuration (Equation 17). A possible simplification is to use the average distance over the touchdown zone in conjunction with the azimuth measurement.

On the other hand, configuration (i) proved to be the most cumbersome from a computational point of view. However, computing altitude from El_2 and DME measurements only via the planar approximation of (Equation 11), proved to be very accurate (within ∿ 1/3 ft). Therefore, there is no difference computationally if configuration (i) is used with the planar approximation and configuration (iv) with lateral y-deviation compensation using DME and Azimuth information.

Configuration (iii) should yield similar or better results than configuration (i) if the same computation is used, since DME is used directly instead of the computed x distance.

The nonconventional configurations require approximately twice the horizontal coverage as the conventional configurations. Furthermore, these configurations are constrained to place the antenna near the threshold. The nonconventional configurations require more than an order of magnitude greater vertical coverage compared to the conventional configurations.

From the estimation point of view the combination of configuration (i) with the planar approximation and complementary filtering was best. (Therefore, configuration (iii) with the same filter should yield compatible or better results.) When configuration (iv) (Planar/nonconventional) was used with the y-deviation = 0 assumption and the complementary filtering, the results were not very favorable compared to the above case. However, when the lateral y-deviation is properly accounted for the estimation performance should be comparable with the above case.

The noncomplementary (no acceleration aiding) filter for both cases was inferior in performance. The estimation errors were noisier due to the wider filter band-width compared to the complementary filter.

Even though 20 ft (1σ) of DME noise did not show much affect in configuration (i) with either filter, we cannot give an acceptable DME noise value at this time. Neither can we give any conclusions on the impact of using the noncomplementary filter in a closed-loop (with the aircraft) flare auto-pilot. This point must be resolved with a more elaborate simulation of a controlled aircraft.

The results are summarized in Table 4 below.

Comparing configuration (i) to (iv) essentially results in a draw. There is little difference in computational requirements (for the (i) planar approximation and the (iv) exact equations). Configuration (i) requires considerably less coverage than (iv); however, better altitude and sink-rate estimates are available without complementary filtering with configuration (iv).

Table 4. Summary Table for El_2 Analysis

Configuration	Computational Requirements	Coverage		Altitude & Sink-Rate Estimation		Comments
		Horizontal	Vertical	with complementary filter	with non-complementary filter	
(i) Conical/ Conventional	*Complex with exact (DME, Az, El_2) *Simple with planar approx. (DME, El_2)	47.7°	1.4°	*Good smooth Estimates *El_2 bias large affect *Fairly insensitive to DME noise	*Inferior and noiser *Sensitive to El_2 bias *Fairly insensitive to DME noise	*Planar approx. good to within 1/3 ft *Flexible in cpverage
(ii) Conical/ Non-conventional	*Complex with exact (DME, Az, El_2) *No simple approx. suitable	± 82.4° (500′ offset)	20.6° (500′ offset)			*Not very practical
(iii) Planar/ Conventional	*Complex with exact (DME, Az, El_2) *Simple with approx. (DME, El_2)	47.7°	1.4°	*Should be approximately the same as (i)	*Approximately the same as (i)	*Should be comparable with (i)
(iv) Planar/ Non-Conventional	*Simple with exact (DME, Az, El_2) *None with approx. (El_2 only)	± 82.4° (500′ offset)	20.6° (500′ offset)	*Fairly good, smooth estimates *y-dev. effect too large with approx. *El_2 bias & noise nil	*Better than (i) *y-dev. effect too large with approximation	*Inflexible in coverage *Simple approx. too sensitive to y-dev. *If y-dev. accounted for, comparable to (i)