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ALGORITHMS AND LOGIC FOR INCORPORATING MLS BACK AZIMUTH INFORMATION INTO THE NASA TCV B-737 AIRPLANE AREA NAVIGATION SYSTEM

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16 Abstract

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SUMMARY

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INTRODUCTION

The NASA TCV B-737 airplane has demonstrated the ability to navigate along a curved path approach to landing with an on-board navigation system utilizing position information from the time referenced scanning beam (TRSB) microwave landing system (MLS). While operating in the MLS environment, azimuth and vertical information was obtained from two scanning beams and distance information was provided by a precision MLS DME for use in the on-board navigation and autoland systems. The TRSB MLS provided azimuth information 60 degrees either side of the runway centerline, vertical information from the surface to 20 degrees elevation, and precision DME information 5 to 7 n.mi. from the MLS antenna.

Missed approach navigation capability was recently added to the MLS system in the form of back azimuth and DME information. Hence, to fully utilize the TRSB MLS, it became necessary to incorporate the use of back azimuth information into the NASA TCV B-737 airplane navigation computer for use in generating missed approach guidance.

The purpose of this report is to describe the equations and logic used to generate a navigation position estimate in the MLS back azimuth signal environment. The equations used to calculate position error components derived from 1) MLS back azimuth angular position measurements and randomly located DME range measurements and, 2) only MLS back azimuth angular position measurements are described. A summary of the NASA TCV B-737 airplane's estimate process will also be described so that the total navigation process may be shown.

SYMBOLS

A	-	distance between the DME and MLS back azimuth antenna - m
a	-	East component of A - m
b	-	North component of A - m
D	-	DME corrected for slant range - n.mi.
D'	-	DME slant range - n.mi.
DME	-	distance measuring equipment
$\overline{DP}$	-	position difference vector
$\overline{DP}_{\perp}$	-	component of the position difference vector, $\overline{DP}$, perpendicular to the runway centerline.
$DP_{\perp}$	-	magnitude of vector $\overline{DP}_{\perp}$ - n.mi.
dt	-	cycle interaction time of navigation computer - sec
F	-	ellipticity constant, 0.003367

$H_{a/c}$ - altitude of aircraft above mean sea level - m

H_{DME} - altitude of DME antenna above mean sea level - m

H_0 - altitude of MLS back azimuth antenna above mean sea level - m

$\hat{i}, \hat{j}$ - unit coordinate vectors

IBD - navigation update mode; inertial velocity, back azimuth & DME

IBX - navigation update mode; inertial velocity & back azimuth

K_1 - position update gain

K_2 - velocity update gain

L - outer radial limit of back azimuth volumetric check - n.mi.

M - inner radial limit of back azimuth volumetric check - m

N,E - axes of orthogonal coordinate system oriented towards True North

P - angle formed by the vector $\bar{Z}_m$ and a line between the airplane and DME antenna - deg

R_E - Earth radius - m

R_M - Meridianal radius of curvature - m

R_N - Normal radius of curvature - m

$\hat{u}$ - unit vector perpendicular to the runway centerline

V_N, V_E - North & East components of system velocity estimate - KTS

$\hat{V}_N$, $\hat{V}_E$ - North & East components of inertial ground speed - KTS

X', Y' - axes of orthogonal coordinate system oriented along the runway centerline

X'_e, Y'_e - coordinates of vector $\bar{Z}_e$ transformed into the X', Y' coordinate system

$\bar{Z}_e$ - airplane's estimated position vector

Z_e - magnitude of $\bar{Z}_e$ the airplane's estimated position vector - n.mi.

Z_{eN}, Z_{eE} - North & East component of $\bar{Z}_e$ the airplane's estimate position vector - n.mi.

$\bar{Z}_M$	-	airplane's measured position vector
Z_M	-	magnitude of $\bar{Z}_M$ - n.mi.
Z_{MN}, Z_{ME}	-	North & East components of $\bar{Z}_M$
$\bar{Z}_R$	-	vector of airplane's position estimated radially along the measured azimuth angle
Z_R	-	magnitude of position vector Z_R - n.mi.
Z_{RN}, Z_{RE}	-	North & East components of position vector $\bar{Z}_R$
α	-	angle formed by the DME antenna, origin, and measured airplane position - degrees
ΔP_N, ΔP_E	-	North & East component of position estimate error - n.mi.
ΔV_N, ΔV_E	-	North & East components of system velocity update - KTS
$\Delta\phi$, $\Delta\lambda$	-	latitude and longitude update estimate
η	-	back azimuth angle relative to the runway centerline - deg
μ	-	relative angle between the DME & MLS back azimuth antenna - deg
π	-	pi - 3.1416
ϕ_e, λ_e	-	latitude and longitude of airplane position estimate - deg
ϕ_{DME} λ_{DME}	-	latitude, longitude of back azimuth antenna location - deg
ϕ_o, λ_o	-	latitude, longitude of DME antenna location - deg
ψ_R	-	runway heading to true North - deg
Ω	-	vertical angular limit of back azimuth volumetric check - deg
ω	-	lateral angular limit of back azimuth volumetric check - deg

DISCUSSION

NAVIGATION POSITION ESTIMATE DESCRIPTION

Position Error

The TCV B-737 navigation computer is software controlled to select and tune two appropriate DME and/or VOR stations in the vicinity of the airplane. The distance and/or azimuth information received from these stations is used to determine a position error from the previous position estimate. This position error is divided into North and East error components to be used in determining a new position estimate.

Other sources of navigation information may also be used to determine position errors. While operating in the MLS back azimuth environment, these position error components are calculated with back azimuth and DME information. This estimate mode is shown on the pilot's electronic map display as IBD (inertial, back azimuth, DME). If no DME is available, the estimate mode is IBX.

Position Estimate

In the TCV B-737 airplane's navigation system, the position estimate calculations are used regardless of the manner in which the position error is determined. The first step in the position estimate process is to develop a system velocity update from the position error

$$\Delta V_N = \Delta V_N + K_2\ \Delta P_N$$

$$\Delta V_E = \Delta V_E + K_2\ \Delta P_E.$$

A system velocity estimate is obtained by summing the system velocity update with ground speed obtained from the inertial navigation system.

$$V_N = \Delta V_N + \hat{V}_N$$

$$V_E = \Delta V_E + \hat{V}_E$$

A position update, in terms of latitude and longitude is obtained using the system velocity and the position error as follows:

$$\Delta\phi = (V_N dt + K_1 \ \Delta P_N)/R_M$$

$$\Delta\lambda = (V_E dt + K_1 \ \Delta P_E)/R_N.$$

This position update is based on an oblate spheroid earth model (ref. 1) by using appropriate radii of curvature in the North/South and East/West directions.

$$R_M = H_{a/c} + R_E(1 - 2F + 3F \sin^2 \phi_e) \qquad \text{(North/South)}$$

$$R_N = H_{a/c} + R_E(1 + f \sin^2 \phi) \ \cos \phi_e \qquad \text{(East/West)}$$

The updated position estimate is found by summing the old previous position with the position update terms.

$$\phi_e = \phi_e + \Delta\phi$$

$$\lambda_e = \lambda_e + \Delta\lambda$$

BACK AZIMUTH/DME (IBD) POSITION ESTIMATE

General Solution

Figure 1 shows the geometry of the MLS back azimuth antenna, the DME antenna, the airplane's position estimate and its position as measured with back azimuth and DME information, and the runway with an extended centerline. An orthogonal coordinate system, with its origin placed on the back azimuth antenna, is oriented in a True North direction. Since the DME may be either randomly or manually selected, it is not required to be co-located with the back azimuth antenna.

By determining the relative geometry between the back azimuth antenna and the DME and the airplane's position measured with the back azimuth and DME information, the vector between the origin and the airplane's measured position, $\overline{Z}_M$, may be found. The vector between the origin and the airplane's previously estimated position, $\overline{Z}_e$, may be found directly from their known latitudes and longitudes. The desired position error used to form a new position estimate may then be found by subtracting $\overline{Z}_e$ from $\overline{Z}_M$.

Calculation of the Airplane Position Vector $\overline{Z}_M$

Figure 1 shows that $\overline{Z}_M$ is one side of the triangle formed between the origin (back azimuth antenna), the airplane's measured position, and the DME antenna. Known quantities used to determine $\overline{Z}_M$ in this triangle include the runway heading, ψ_R; the slant range of the DME, D'; the back azimuth angle relative to the runway centerline, η; and the latitudes and longitudes of the DME antenna, ϕ_{DME}, λ_{DME}; and the back azimuth antenna location ϕ_o, λ_o.

Figure 2 shows the angular geometry and distance between the origin and DME antenna, A. The length A and the relative angle between the DME antenna from the North axis, μ, remains constant and is calculated only once. If a new DME is tuned, then A and μ are recalculated.

The length of A is determined by vectorially summing its components a and b.

$$a = (\lambda_{DME} - \lambda_o)(60)\cos \frac{\phi_o + \phi_{DME}}{2} \qquad \text{n.mi.}$$

$$b = (\phi_{DME} - \phi_o)(60) \qquad \text{n.mi.}$$

$$A = \sqrt{a^2 + b^2} \qquad \text{n.mi}$$

The angle μ is found by

$$\mu = \tan^{-1}\left[{}^{a}/_{b}\right]$$

The angle α, formed by side A and vector $\overline{Z}_M$, may continuously vary and is calculated 20 times per second. Angle α is found by taking the absolute value of the sum of the azimuth deviation angle, and the angle μ, and the difference of the runway heading.

$$\alpha = \left|\mu - (\psi_R - \eta)\right|$$

If the absolute value of α is greater than Π, then:

$$\alpha = 2\Pi - \alpha$$

The magnitude of the DME reading as measured in the airplane, D', is the slant range distance between the ground-based DME antenna and the airplane. This distance was slant-range-corrected to determine the ground distance, D, between the airplane and DME

$$D = D' \sin \cos^{-1} \frac{H_{a/c} - H_{DME}}{D'}.$$

Angle P is formed by the vector $\overline{Z}_M$ and side D. This angle may continuously vary and is calculated 20 times per second. Knowing the relation

$$\frac{P}{\sin P} = \frac{D}{\sin\alpha},$$

angle P is determined by

$$P = \sin^{-1} \left[\frac{A}{D} \sin\alpha\right].$$

It must be determined if angle P is an oblique or an acute angle. This is accomplished by comparing the square of side A with the sum of the square of side D and the square of the magnitude of the estimated airplane position vector, $\bar{Z}_e$. If

$A^2 > D^2 + Z_e^2$, then P is oblique and set equal to

$P = \pi - P$. Otherwise, $P = P$.

The magnitude of $\bar{Z}_e$ is used as an approximation for $\bar{Z}_M$. The magnitude of $\bar{Z}_e$ is:

$$Z_e = \sqrt{Z_{eN}^2 + Z_{eE}^2}$$

in which

$$Z_{eN} = (\phi_e - \phi_o)(60)$$

$$Z_{eE} = (\lambda_e - \lambda_o)(60) \cos \frac{\phi_o + \phi_e}{2}$$

The magnitude of $\bar{Z}_M$ is found by

$$Z_M = A \cos(\alpha) + D \cos(P).$$

The North and East components of $\bar{Z}_M$ are found knowing the angle, $(\psi_R - \eta)$, between the North axis and $\bar{Z}_M$.

$$Z_{MN} = Z_M \cos(\psi_R - \eta)$$

$$Z_{ME} = Z_M \sin(\psi_R - \eta)$$

Calculation of the Desired Position Error in North & East Components: ΔP_N, ΔP_E-IBD Update Mode

The desired position error, in North and East components, is now found by subtracting the North component of $\bar{Z}_e$ from the North component of $\bar{Z}_M$ and the East component of $\bar{Z}_e$ from the East component of $\bar{Z}_M$.

$$\Delta P_N = Z_{eN} - Z_{MN}$$

$$\Delta P_E = Z_{eE} - Z_{ME}$$

These position error components are then used directly in the navigation position estimate algorithms.

BACK AZIMUTH ONLY (IBX) POSITION ESTIMATE

General Solution

In the event that a DME can not be tuned, the navigation computer will utilize the back azimuth signal and inertial velocity to determine a position estimate. Figure 3 shows the geometry of the back azimuth antenna, the airplane's position estimate and its estimated position on a measured back azimuth angle, and the runway with an extended centerline. An orthogonal coordinate system, with its origin placed on the back azimuth antenna, is oriented in a True North direction.

Since no DME information is available, no radio position errors can be developed in a radial direction from the back azimuth antenna. However, inertial velocity is still utilized in the radial direction and will supply inputs for a new position estimate in the position estimate algorithms. Radio position error in the IBX update mode is limited to a direction perpendicular to the runway centerline.

North and East position estimates are found in the following manner. A position difference vector, $\overline{DP}$, is found by subtracting the estimated position vector, $\overline{Z}_e$, from the estimated position vector on the measured back azimuth angle, $\overline{Z}_R$. The component of $\overline{DP}$ perpendicular to the runway is found and broken into North and East components. These components are used in the navigation position estimate algorithms. This process is repeated 20 times per second.

Calculation of $\overline{DP}$

To determine $\overline{DP}$ it is necessary to calculate the position estimate vector, $\overline{Z}_e$, in North and East components from the latitudes and longitudes of the last position estimate and the back azimuth antenna location.

$$Z_{eN} = (60)\ (\phi_e - \phi_o)$$

$$Z_{eE} = (60)\ (\lambda_e - \lambda_o)\ \cos \frac{\phi_e + \phi_o}{2}$$

$$\overline{Z}_e = Z_{eE}\ \hat{i} + Z_{eN}\ \hat{j}$$

A vector $\overline{Z}_R$, of the airplane's estimated position along a measured back azimuth angle is determined in the following manner. Since no radio updates can be obtained in a radial direction from the back azimuth antenna, it will be assumed that the estimated radial distance from the origin is correct. Hence, the vector length of $\overline{Z}_R$ and $\overline{Z}_e$ will be the same (directions may differ to obtain $\overline{DP}$).

The length of $\overline{Z}_R$ and $\overline{Z}_e$ is:

$$Z_R = Z_e = \sqrt{Z_{eN}^2 + Z_{eE}^2}$$

The North and East components of $\overline{Z}_R$ are found knowing the angle, $(\psi_R - \eta)$, between the vector $\overline{Z}_R$ and the North axis.

$$Z_{RN} = Z_R \cos\ (\psi_R - \eta)$$

$$Z_{RE} = Z_R \sin\ (\psi_R - \eta)$$

$$\overline{Z}_R = Z_{RE}\ \hat{i} + Z_{RN}\ \hat{j}$$

$\overline{DP}$ is found vectorially

$$\overline{DP} = \overline{Z}_R - \overline{Z}_e$$

Calculation of the Desired Position Error: ΔP_N, ΔP_E - IBX Update mode

The magnitude of the component of $\overline{DP}$ perpendicular to the runway centerline is obtained by the vector dot product of $\overline{DP}$ with a unit vector, $\hat{u}$, perpendicular to the runway centerline. This results in the magnitude of the desired position error. This magnitude is then multiplied times the unit vector to obtain the desired position error in North and East components. These components are then used directly in the navigation position estimate algorithms.

The unit vector, $\hat{u}$, shown in figure 3, is:

$$\hat{u} = -\cos(\psi_R)\,\hat{i} + \sin(\psi_R)\,\hat{j}$$

The magnitude of the component of $\overline{DP}$ perpendicular to the runway centerline is:

$$DP_{\perp} = \overline{DP} \cdot \hat{u}$$

$$DP_{\perp} = -(Z_{RE} - Z_{eE}) \cos(\psi_R) + (Z_{RN} - Z_{eN}) \sin(\psi_R)$$

The North and East components of the desired position error are:

$$\Delta P_N = DP_{\perp} \sin(\psi_R)$$

$$\Delta P_E = -DP_{\perp} \cos(\psi_R).$$

These position error components are then used directly in the navigation position estimate algorithms.

BACK AZIMUTH/AIRPLANE POSITION VALIDITY CHECK

Since random DME selection, automatic frequency tunning, and other means of automatic software control will be utilized in the navigation computer, a check must be made to ensure that the navigation computer is using the appropriate navigation data for the area in which the airplane is flying. Obviously, if improper navigation data is being utilized, position estimates based on that data must be inhibited.

To preclude the possibility of using the wrong MLS back azimuth navigation data, a volumetric geometry check is made to determine if the airplane's position estimate is within the MLS back azimuth boundaries. If the airplane is not within these boundaries then MLS updating is inhibited. These boundaries include lateral, radial, and vertical limits of coverage as shown in figure 4. The lateral limit of the back azimuth angle of coverage is $\pm\omega$ from the back azimuth antenna. Radial limits require that the airplane be within L n.mi. of the back azimuth antenna, but not closer than M meters.

A new orthogonal coordinate system, with its origin located at the back azimuth antenna and x' axis parallel to the runway centerline, was used to make the geometric checks. To make the checks, the North and East components of the estimated position vector $\overline{Z}_e$, are transformed into the new x', y' coordinate system as follows:

$$X'_e = Z_{eN} \cos(\psi_R) + Z_{eE} \sin(\psi_R)$$

$$Y'_e = Z_{eN} \sin(\psi_R) - Z_{eE} \cos(\psi_R).$$

The lateral azimuth check is then

$$-X'_e \tan \omega \leq Y'_e \leq X'_e \tan \omega.$$

The radial check is

$$M \text{ meters} \leq X'_e \leq L \text{ n.mi.}$$

The vertical check is

$$H_{a/c} \leq H_o + X'_e \tan \Omega.$$

CONCLUDING REMARKS

Area navigation systems may use various radio inputs to calculate a position estimate for course guidance. Flight tests of the NASA TCV B-737 airplane using the Time Referenced Scanning Beam microwave landing system have shown that an area navigation system may utilize front course signals to provide guidance for curved path approaches to landing.

MLS back azimuth signal coverage has been added to the microwave landing system to provide guidance during missed approaches. These back azimuth signals are utilized on the TCV B-737 airplane by algorithms that generate position error information to be used in the area navigations system. These algorithms are designed so that they may be added to an existing area navigation system (ARINC Characteristic 582 and the more sophisticated systems under ARINC Characteristics 583) with minimun software modification.

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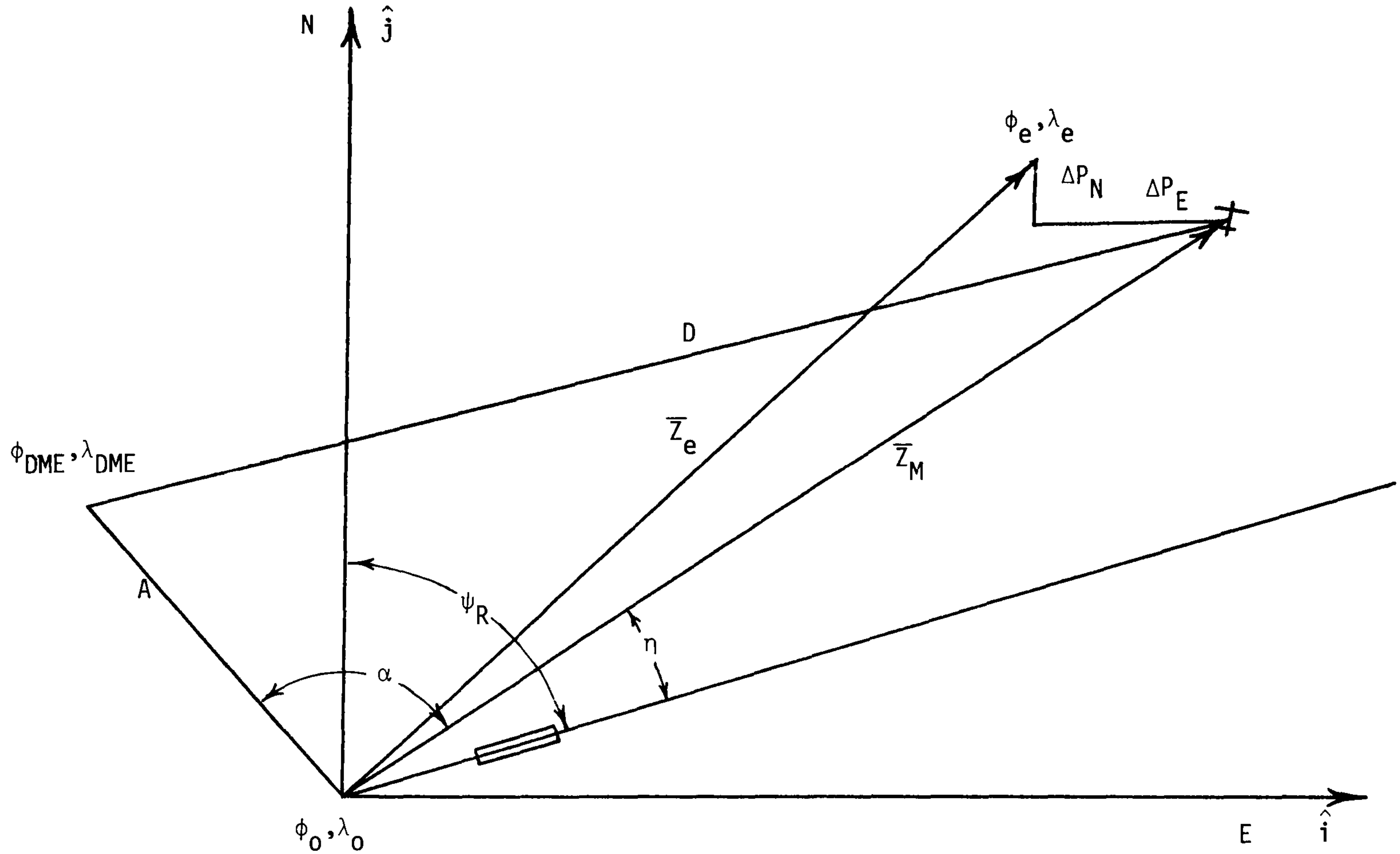

Figure 1.- Back azimuth, DME, airplane estimated and measured positions, and runway with an extended centerline geometry - IBD update mode.

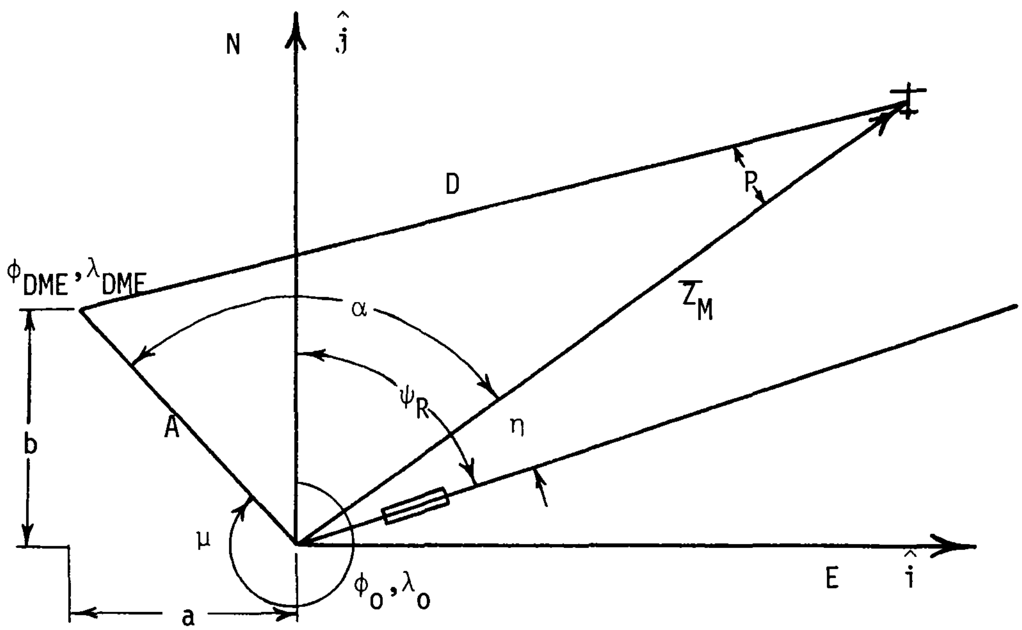

Figure 2.- Vector $\bar{Z}_M$ triangle components - IBD update mode.

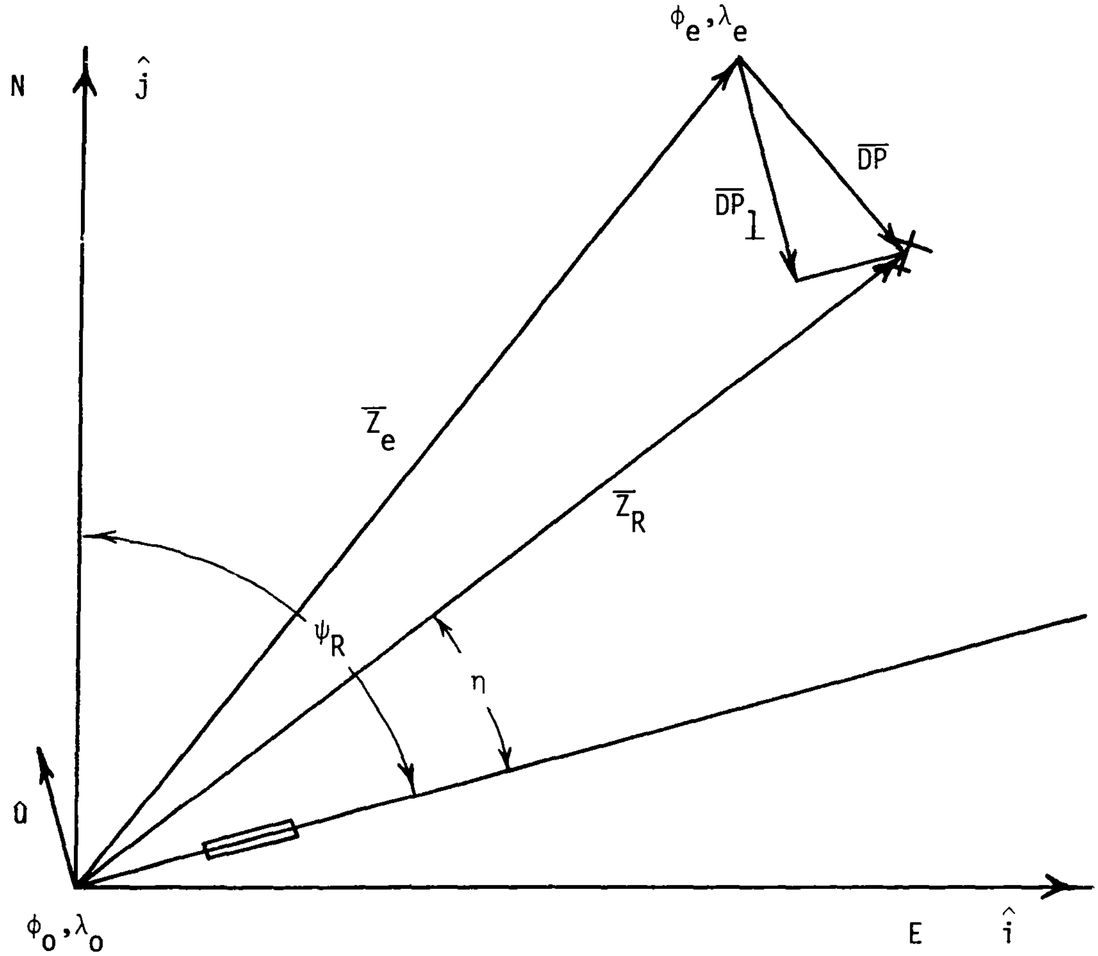

Figure 3.- Back azimuth, airplane estimated and measured azimuth positions, and runway with extended centerline geometry - IBX update mode.

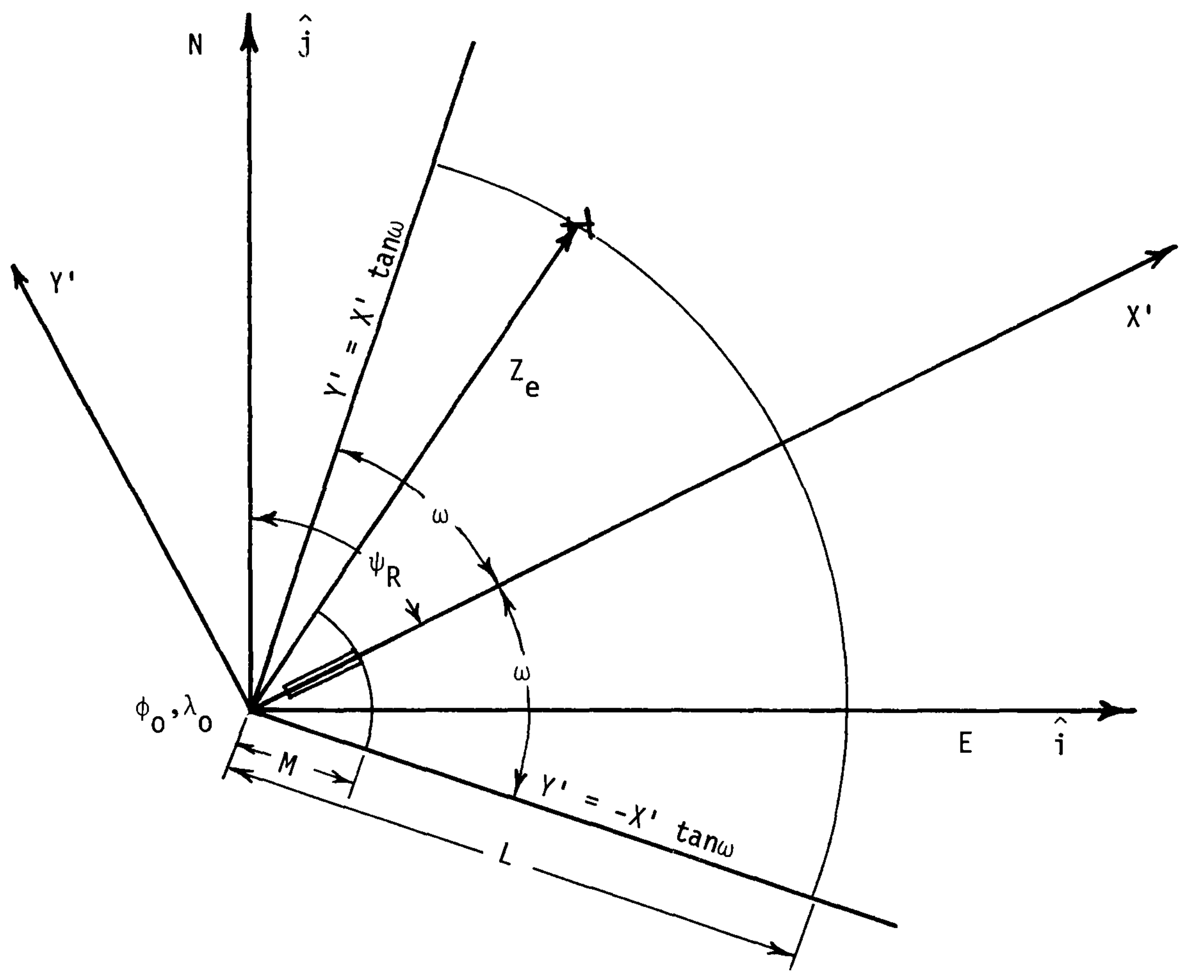

Figure 4.- Lateral and radial MLS back azimuth geometry limits.

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