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DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.
STATISTICAL THEORY OF NAVIGATION EMPLOYING INDEPENDENT INERTIAL AND VELOCITY MEASUREMENTS: MINIMUM RMS ERROR IN COMPUTED POSITION

P. Swerling
E. Reich

RM-1321

17 August 1954

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Correction to RM-1321: Statistical Theory of Navigation Employing Independent Inertial and Velocity Measurements; Minimum RMS Error in Computed Position

by P. Swerling and E. Reich

The fourth line of Eq. (II.5), p. 4, should read:

\[ \Delta = L_{11} - L_{12}^2 \]
SUMMARY

Analysis of navigation systems employing independent inertial and velocity measurements, begun in Ref. 1, is continued. Explicit formulas are given for minimum rms error in computed position as a function of time of flight. Curves based on these formulas are presented, showing the results for a number of illustrative cases.
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# List of Symbols

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<td>( x(t) )</td>
<td>vehicle position at time ( t )</td>
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<tr>
<td>( \hat{x}(t;T) )</td>
<td>optimum computer's estimate of ( x(t) ) based on all the dial readings up to time ( T )</td>
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<td>( \hat{x}(T;T) )</td>
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<td>( T )</td>
<td>elapsed time since beginning of flight</td>
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<tr>
<td>( \gamma_1, \gamma_2, \gamma_3, \gamma_4 )</td>
<td>parameters describing instrument error statistics</td>
<td>1, 2, 5, 16</td>
</tr>
<tr>
<td>( a_2, \beta_2, a_1, \beta_1 )</td>
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<tr>
<td>( \xi_2(t;T) )</td>
<td>( \hat{x}(t;T) - x(t) )</td>
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<tr>
<td>( \xi_3(T) )</td>
<td>( \hat{x}(T;T) - x(T) )</td>
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<tr>
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<tr>
<td>( \eta_{ij} )</td>
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<td>15</td>
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<tr>
<td>( g_B(s,t) )</td>
<td>accelerometer error autocorrelation function</td>
<td>1</td>
</tr>
<tr>
<td>( g_V(s,t) )</td>
<td>velocity dial error autocorrelation function</td>
<td>1</td>
</tr>
<tr>
<td>( \Omega )</td>
<td>frequency of earth's radius pendulum</td>
<td>3</td>
</tr>
<tr>
<td>( \mu )</td>
<td>defined by Eq. (II.4)</td>
<td>4</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

This report is an extension of the work begun in Ref. 1. This is not a self-contained report; rather, a reading of Ref. 1 is a necessary basis for the understanding of the following material. Repetition of expository material and results obtained in Ref. 1 will be kept to a minimum.

The major results of Ref. 1 were obtained for two cases, viz:

Case 1
\[ \varphi_3(s,t) = \gamma_1 \]

Case 2
\[ \varphi_v(s,t) = \gamma_2 \]

where \( \varphi_3(s,t) \) and \( \varphi_v(s,t) \) are the autocorrelation functions of the accelerometer dial error and the velocity dial error, respectively. Formulas were derived for the optimum method of position computation in each case; also, formulas were given by means of which the rms error in computed position as a function of time of flight could be derived.

In the following pages, the actual formulas for rms error in computed position will be given; also, computations based on these formulas will be given for a number of illustrative cases.

As in Ref. 1, let, for \( 0 < t < T \),

\[ x(t) = \text{true position at time } t \]

\[ \hat{x}(t;T) = \text{optimum computer's estimate of } x(t), \text{ based on all the dial readings up to time } T. \]

Denote \( \hat{x}(T;T) \) simply by \( \hat{x}(T) \).
Also let

\[ \xi_{X}(t;T) = \mathcal{X}(t;T) - x(t) \]

(I.1)

\[ \xi_{x}(T) = \mathcal{X}(T;T) = \mathcal{X}(T) - x(T) \]

and

\[ \overline{\xi^{2}_{X}(t;T)} = \frac{1}{T} \int_{t}^{T} \xi^{2}_{X}(t) \, dt \]

(I.2)

the mean being taken over an ensemble of flights.

As in Ref. 1, the following notation is used for description of the dial error statistics:

- \( \xi_{B}(t) \) = accelerometer dial error
- \( \xi_{V}(t) \) = velocity dial error
- \( \xi_{X_{o}} \) = independent initial position dial error
- \( \xi_{X_{v}} \) = independent initial velocity dial error

The ensemble means of all these errors are zero; also

\[ \overline{\xi^{2}_{X_{0}}} = \gamma_{3}, \quad \overline{\xi^{2}_{X_{v}}} = \gamma_{4} \]

(I.3)

and

\[ \phi_{B}(s,t) = \overline{\xi_{B}^{2}(s) \xi_{B}(t)} \]

(I.4)

\[ \phi_{V}(s,t) = \overline{\xi_{V}^{2}(s) \xi_{V}(t)} \]

(All averages are taken over an ensemble of flights.)
II. CASE 1: $A_b(s,t) = \gamma_1$

Let $0 = t_0 < t_1 \cdots < t_{n-1} = T$ be $n$ equally spaced time points in the interval $(0,T)$. Let

$$
\begin{align*}
(II.1) & \quad \left[ \xi_{ij} \right] = \left[ \phi_v(t_i, t_j) \right]^{-1} \quad \text{(matrix inverse)} \\
& \quad \text{Also let} \\
& \quad \left[ A_{11} \right]_n = \sum_{i,j=0}^{n-1} \xi_{ij} \sin \Omega t_i \sin \Omega t_j \\
& \quad \left[ A_{12} \right]_n = \sum_{i,j=0}^{n-1} \xi_{ij} \sin \Omega t_i \cos \Omega t_j \\
& \quad \left[ A_{22} \right]_n = \sum_{i,j=0}^{n-1} \xi_{ij} \cos \Omega t_i \cos \Omega t_j \\
& \quad \text{and} \\
& \quad A_{11} = \lim_{n \to \infty} \left[ A_{11} \right]_n \\
& \quad A_{12} = \lim_{n \to \infty} \left[ A_{12} \right]_n \\
& \quad A_{22} = \lim_{n \to \infty} \left[ A_{22} \right]_n \\
& \quad \text{The quantities } A_{11}, A_{12}, A_{22} \text{ are functions of } T.
\end{align*}
$$
Reference I gave formulas (Eqs. III.16, III.17, III.20 of Ref. I) from which could be derived the formula for $\varepsilon_2^{(2)}(t; T)$. The result can be expressed as follows:

Let

\[(\text{II.4}) \quad \nu = \frac{\gamma_3}{\Omega + \gamma_3} \]

and

\[(\text{II.5}) \quad \begin{align*}
L_{11} &= A_{11} + \frac{1}{\frac{\gamma_3}{\Omega} + \gamma_3} \\
L_{12} &= A_{12} \\
L_{22} &= A_{22} + \frac{1}{\gamma_4} \\
\Delta &= L_{11} L_{12} - L_{12}^2
\end{align*} \]

Then, for $0 \leq t \leq T$,

\[(\text{II.6}) \quad \varepsilon_2^{(2)}(t; T) = \nu + \frac{1}{\delta} \left\{ \begin{array}{c}
L_{22} \left( \cos \Omega t - \frac{\nu}{\gamma_3} \right)^2 \\
+ 2L_{12} \left( \cos \Omega t - \frac{\nu}{\gamma_3} \right) \sin \Omega t \\
+ L_{11} \frac{\sin^2 \Omega t}{\Omega^2} \end{array} \right\} \]
The quantity $\frac{\epsilon^2}{x(T)} = \left[ x(T) - x(T') \right]^2$ is equal to $\frac{\epsilon^2}{x(T)}$, Thus

\begin{equation}
\frac{\epsilon^2}{x(T)} = \frac{1}{3} \left\{ L_{22} \left( \cos \omega T - \frac{H}{\gamma} \right)^2 \right. \\
+ 2L_{12} \left( \cos \omega T - \frac{H}{\gamma} \right) \frac{\sin \omega T}{\gamma} \right. \\
+ L_{11} \frac{\sin^2 \omega T}{\gamma^2} \right\}
\end{equation}

These formulas hold for any $\varphi_v(s,t)$.

In Ref. 1, explicit expressions were obtained for $A_{11}, A_{12}, A_{22}$ for the case:

\begin{equation}
\varphi_v(s,t) = \gamma_2 + \beta_2 e^{-\alpha_2 |s-t|}
\end{equation}

The results were

\begin{equation}
A_{11} = \frac{\epsilon^2}{2p_2^2} \left\{ \frac{a_2^2 T}{2} \left( 1 + \frac{\epsilon^2}{a_2^2} \right) - \frac{a_2^2}{4} \left( 1 - \frac{\epsilon^2}{a_2^2} \right) \sin 2 \omega T \right. \\
+ \left. \sin^2 \omega T \left[ \frac{\epsilon^2(1 - \cos \omega T) + \sin \omega T}{2 + \alpha_2 + \frac{2p_2^2}{\gamma^2}} \right]^2 \right\}
\end{equation}
\[ a_{12} = \frac{a_2}{2p_2^2} \left( 1 - \frac{1}{a_2^2} \right) \sin^2 \frac{\pi}{T} + \frac{1}{2} \sin 2 \pi T \]

\[ \left[ \frac{a_2}{\gamma_2} (1 - \cos \pi T) + \sin \frac{\pi}{T} \right] \left[ \frac{a_2}{\gamma_2} \sin \frac{\pi}{T} + 1 + \cos \frac{\pi}{T} \right] \]

\[ \frac{2 + a_2 T + \frac{2p_2}{\gamma_2}}{2 + a_2 T + \frac{2p_2}{\gamma_2}} \]

\[ (11.311) \]

\[ a_{22} = \frac{1}{2p_2^2} \left( \frac{a_2}{\gamma_2} \left( 1 + \frac{2}{a_2^2} \right) + \frac{a_2}{\gamma_2} \left( 1 - \frac{2}{a_2^2} \right) \sin \frac{\pi}{T} + 1 + \cos \frac{\pi}{T} \right) \]

\[ \left[ \frac{a_2}{\gamma_2} \sin \frac{\pi}{T} + 1 + \cos \frac{\pi}{T} \right] \]

\[ \frac{2 + a_2 T + \frac{2p_2}{\gamma_2}}{2 + a_2 T + \frac{2p_2}{\gamma_2}} \]

In Figs. 1-7 are shown curves of the quantity \[ \left[ \frac{a_2}{\gamma_2} \left( 1 \pm a \right) \right]^{1/2} \] as a function of \( T \) for \( \beta(s, t) = \gamma_2 + \beta_2 e^{-a_2 s - t} \). Each curve is determined by specification of the six statistical parameters \( \gamma_1, \gamma_2, \gamma_3, \gamma_4, \alpha_2, \beta_2 \).

The following table gives the parameter values associated with each curve.

One word of explanation about the table is in order: an interesting case is the case in which the velocity dial error contains a "white noise" component. This can be obtained by letting \( a_2 \to \infty \) and \( \frac{\beta_2}{a_2} \to \gamma_2 \) in Eq. (II.7). The exponential component of the velocity dial error then approaches white noise with spectral density \( \gamma_2 \) per cycle.
In the following table, the units for the various parameters are as follows:

\[
\begin{align*}
\gamma_1 & : \text{(nautical miles)}^2 \cdot (\text{hours})^{-4} \\
\gamma_2 & : \text{(nautical miles)}^2 \cdot (\text{hours})^{-2} \\
\gamma_3 & : \text{(nautical miles)}^2 \\
\gamma_4 & : \text{(nautical miles)}^2 \cdot (\text{hours})^{-2} \\
\alpha_2 & : \text{(hours)}^{-1} \\
\beta_2 & : \text{(nautical miles)}^2 \cdot (\text{hours})^{-2}
\end{align*}
\]

The individual curves in Figs. 1-7 are identified by circled numbers.

The parameter values associated with each curve are as follows:

<table>
<thead>
<tr>
<th>Curve No.</th>
<th>( \gamma_1 )</th>
<th>( \gamma_2 )</th>
<th>( \gamma_3 )</th>
<th>( \gamma_4 )</th>
<th>( \alpha_2 )</th>
<th>( \beta_2 )</th>
<th>( \lim \frac{P_0}{P_0} )</th>
</tr>
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<td>1</td>
<td>50.0</td>
<td>1.0</td>
<td>0.0010</td>
<td>9.0</td>
<td>( \rightarrow \infty )</td>
<td>( \rightarrow \infty )</td>
<td>0.00010</td>
</tr>
<tr>
<td>2</td>
<td>50.0</td>
<td>1.0</td>
<td>0.0010</td>
<td>( \infty )</td>
<td>( \rightarrow \infty )</td>
<td>( \rightarrow \infty )</td>
<td>0.0010</td>
</tr>
<tr>
<td>3</td>
<td>50.0</td>
<td>1.0</td>
<td>0.10</td>
<td>9.0</td>
<td>( \rightarrow \infty )</td>
<td>( \rightarrow \infty )</td>
<td>0.0010</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>1.0</td>
<td>0.10</td>
<td>9.0</td>
<td>( \rightarrow \infty )</td>
<td>( \rightarrow \infty )</td>
<td>0.0010</td>
</tr>
<tr>
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<td>( \rightarrow \infty )</td>
<td>0.10</td>
</tr>
<tr>
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<td>10.0</td>
<td>1.0</td>
<td>0.010</td>
<td>1.0</td>
<td>( \rightarrow \infty )</td>
<td>( \rightarrow \infty )</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
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<td>1.0</td>
<td>0.10</td>
<td>1.0</td>
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<td>( \rightarrow \infty )</td>
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</tr>
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<td>0.60</td>
<td>2000</td>
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<tr>
<td>9</td>
<td>50.0</td>
<td>200</td>
<td>1.0</td>
<td>25.0</td>
<td>0.60</td>
<td>800</td>
<td></td>
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<tr>
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<td>200</td>
<td>1.0</td>
<td>25.0</td>
<td>1.80</td>
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<td></td>
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<td>( \infty )</td>
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<td>800</td>
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<td>1000</td>
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Case 1

\[ \sigma(T) = \left[ \frac{F}{X(T)} \right]^{1/2} \] in nautical miles

Figure 1
\[ \sigma(T) = \left( \frac{\rho}{k(T)} \right)^{1/2} \text{ in nautical miles} \]
Case 2: $\gamma_v(n,t) = \gamma_2$

As in Case 1, let $0 = t_0 < t_1 \cdots < t_{n-1} = T$ be $n$ equally spaced time points in $(0,T)$.

Let

\[(III.1) \quad \begin{pmatrix} \eta_{ij} \end{pmatrix} = \left[ \begin{pmatrix} \delta_B(t_i, t_j) \end{pmatrix} \right]^{-1} \quad \text{(matrix inverse)}\]

Also let

\[(III.2) \quad \begin{pmatrix} A_{11} \\ A_{12} \\ A_{22} \end{pmatrix}_n = \bigg( \sum_{i,j=1}^{n-1} \eta_{ij} t_i \bigg) \bigg( \sum_{i,j=1}^{n-1} \eta_{ij} t_i \bigg) \]

and

\[(III.3) \quad A_{11} = \lim_{n \to \infty} \begin{pmatrix} A_{11} \end{pmatrix}_n \quad A_{12} = \lim_{n \to \infty} \begin{pmatrix} A_{12} \end{pmatrix}_n \quad A_{22} = \lim_{n \to \infty} \begin{pmatrix} A_{22} \end{pmatrix}_n \]

The quantities $A_{11}, A_{12}, A_{22}$ are functions of $T$. 

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Reference 1 gave formulas (eqs. IV.14, IV.15, IV.17 of Ref. 1) from which could be derived the formula for $\tilde{C}_x(t;\Gamma)$. The result can be expressed as follows:

Let

\[
\begin{align*}
K_{11} &= A_{11} + \frac{1}{\gamma_3} \\
K_{12} &= A_{12} \\
K_{22} &= A_{22} + \frac{1}{\gamma_2} + \frac{1}{\gamma_4} \\
\Delta &= K_{11} K_{22} - K_{12}^2
\end{align*}
\]

Then, for $0 \leq t \leq T$,

\[
(III.5) \quad \tilde{C}_x^2(t;\Gamma) = \frac{1}{8} \left\{ K_{22} - 2K_{12} t + K_{11} t^2 \right\}
\]

and therefore

\[
(III.5') \quad \frac{\tilde{C}_x^2(t;\Gamma)}{\Delta} = \frac{1}{3} \left\{ K_{22} - 2K_{12} T + K_{11} T^2 \right\}
\]

These formulas hold for any $\phi_\Delta(s,t)$.

In Ref. 1, explicit expressions were obtained for $A_{11}, A_{12}, A_{22}$ for the case

\[
(III.6) \quad \phi_\Delta(s,t) = \gamma_1 + \beta_1 e^{-\beta_1 |s-t|}
\]
The results were

\begin{align*}
A_{11} &= \frac{\Omega^2 (2+\alpha_1 T)}{2\beta_1} \left[ 1 - \frac{1}{2\beta_1} \frac{1}{1 + \gamma_1 (2+\alpha_1 T)} \right] \\
A_{12} &= \frac{\Omega^2 (2+\alpha_1 T) T}{4\beta_1} \left[ 1 - \frac{1}{2\beta_1} \frac{1}{1 + \gamma_1 (2+\alpha_1 T)} \right] \\
A_{22} &= \frac{\Omega^2 T^2}{2\beta_1} \left[ 1 + \frac{\alpha_1 T}{3 - \alpha_1 T} \frac{1}{1 + \frac{1}{2\beta_1}} \frac{1}{1 + \gamma_1 (2+\alpha_1 T)} \right]
\end{align*}

In Figs. 8-10 are shown curves of \( \left[ \frac{C^2}{X(T)} \right]^{1/2} \) as a function of \( T \) for \( a_1 |a-t| \). Each curve is determined by specification of the six statistical parameters \( \gamma_1, \gamma_2, \gamma_3, \gamma_4, \alpha_1, \beta_1 \).

An interesting case is the case in which the accelerometer dial error contains a "white noise" component. This can be obtained by letting \( a_1 \to \infty \) and \( \frac{\beta_1}{\alpha_1} \to \kappa_1 \) in Eq. (III.6). The exponential component of the accelerometer dial error then approaches white noise with spectral density \( \kappa_1 \) per cycle.
In the following table, the units for the various parameters are as follows:

\[ \begin{align*}
\gamma_1 & : (\text{nautical miles})^2 (\text{hours})^{-1} \\
\gamma_2 & : (\text{nautical miles})^2 (\text{hours})^{-2} \\
\gamma_3 & : (\text{nautical miles})^2 \\
\gamma_4 & : (\text{nautical miles})^2 (\text{hours})^{-2} \\
a_1 & : (\text{hours})^{-1} \\
\beta_1 & : (\text{nautical miles})^2 (\text{hours})^{-4}
\end{align*} \]

The parameter values associated with each curve in Figs. 8-10 are as follows:

<table>
<thead>
<tr>
<th>Curve No.</th>
<th>(\gamma_1)</th>
<th>(\gamma_2)</th>
<th>(\gamma_3)</th>
<th>(\gamma_4)</th>
<th>(a_1)</th>
<th>(\beta_1)</th>
<th>(\lim_{t \to \infty} \frac{\beta_1}{a_1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>→ ∞</td>
<td>→ ∞</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>1.0</td>
<td>0.10</td>
<td>9.0</td>
<td>→ ∞</td>
<td>→ ∞</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>1.0</td>
<td>0.10</td>
<td>6.0</td>
<td>10</td>
<td>800</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>50.0</td>
<td>1.0</td>
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REFERENCES