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SUMMARY OF ERROR PROPAGATION IN AN INERTIAL SYSTEM

by
Janusz Sciegienny

August 1963

MIT INSTRUMENTATION LABORATORY
CAMBRIDGE 39, MASSACHUSETTS

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SUMMARY OF ERROR PROPAGATION IN AN INERTIAL SYSTEM

ABSTRACT

This report contains the summary of analytical studies of error propagation in an inertial system during the orbital and during the suborbital flights. The error is caused by the initial condition errors and accelerometers' bias. The analysis is based on the linearization of the equations of error propagation and the analytical results were confirmed by computer simulation.

The tabulated results may be used to determine the propagation of position and velocity errors in the inertial system (1) with no external corrections during the orbits around a planet, (2) with no external corrections during the suborbital flight above a planet, or (3) with an altimeter during the suborbital flight above a planet.

by Janusz Sciegienny
August, 1963

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SUMMARY OF ERROR PROPAGATION IN AN INERTIAL SYSTEM

The derivation of the equations of error propagation in an inertial system is given in References 1, 2, and 3. The analytical results presented in the tables in this report were confirmed by computer simulations. The flight starts at $t = 0$. The angular orbital frequency is

$$\omega_o = \sqrt{\frac{K}{(R + h)^3}}$$

For $h \ll R$,

$$\omega_o = \sqrt{\frac{K}{R^3}} \left(1 - \frac{3h}{2R}\right)$$

where

K is the product of the universal gravitational constant and the mass of the planet.

R is the mean radius of the planet.

h is the mean vehicle altitude above the surface of the planet.

K, R, and ω_o are tabulated for the Solar System planets, the Sun, and the Moon in Table I.

TABLE I

PLANETARY CONSTANTS

Planet	K $[km^3/sec^2]$	R [km]	ω_o [rad/sec]
Mercury	2.164×10^4	2,500	1.77×10^{-3}
Venus	3.243×10^5	6,200	1.167×10^{-3}
Earth	3.98603×10^5	6,371	1.2415×10^{-3}
Mars	4.305×10^5	3,310	1.090×10^{-3}
Jupiter	1.269×10^8	69,880	0.610×10^{-3}
Saturn	3.799×10^7	57,520	0.447×10^{-3}
Uranus	5.812×10^6	25,500	0.592×10^{-3}
Neptune	6.880×10^6	25,000	0.302×10^{-3}
Sun	1.325×10^{11}	696,500	0.6263×10^{-3}
Moon	4.8938×10^3	1,738	0.9655×10^{-3}

During a suborbital flight, the angular velocity of the vehicle with respect to the non-rotating planet is

$$\omega_1 = V/(R + h)$$

where V is the horizontal component of the vehicle velocity.

The errors are defined as the differences between the computed values and the true values. The tabulated errors are the altitude error, the range error, the track error and the velocity errors along the altitude, the range and the track.

The track errors are independent of the altitude and range errors. The effect of altitude error on the error in velocity along range and the range error on the velocity along the altitude are included in the tabulation.

Table II contains the summary of the propagation of initial condition errors in the altitude, the range, the velocity along altitude and the velocity along range in the inertial system during a near circular orbit.

Table III contains the summary of error propagation caused by the accelerometers' bias during a near circular orbit. The accelerometers are oriented either along the altitude and range or remain fixed in the inertial space with angle ϕ from the local vertical at time $t = 0$. The positive sense of direction of the accelerometers' bias is shown in Figure 1.

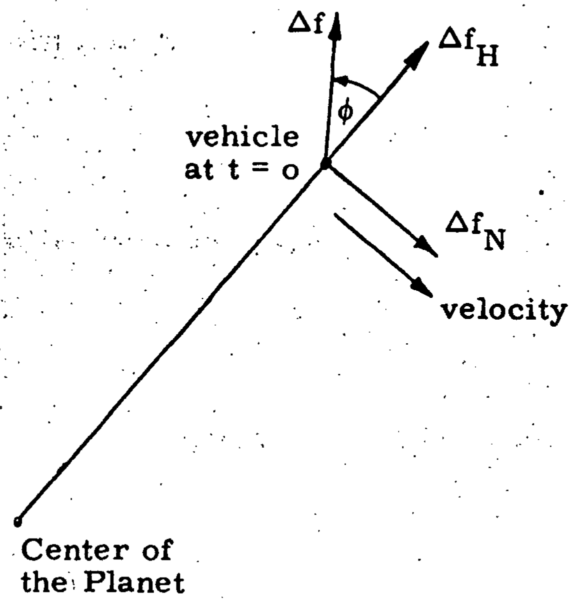

Fig. 1 Sign Definition of Accelerometers' Bias During Near Circular Orbit

Table IV contains the summary of the propagation of initial condition errors in the altitude, the range, the velocity along altitude and the velocity along range in the inertial system, with no external corrections, during a suborbital flight.

Table V contains the summary of the propagation of initial condition errors, during a suborbital flight, in a system consisting of an inertial system and a perfect altimeter. The altimeter is used to compute the precise magnitude of the distance from the center of the planet to the vehicle, $R + h$. This distance is used to compute the components of the gravitational acceleration acting on the vehicle.

Table VI contains the summary of the error propagation in the altitude, the range, the velocity along altitude and the velocity along the range, during a suborbital flight, in a system consisting of an inertial system and an altimeter. The errors are caused by the bias in the accelerometers fixed in inertial space (Fig. 2) and by the altimeter bias.

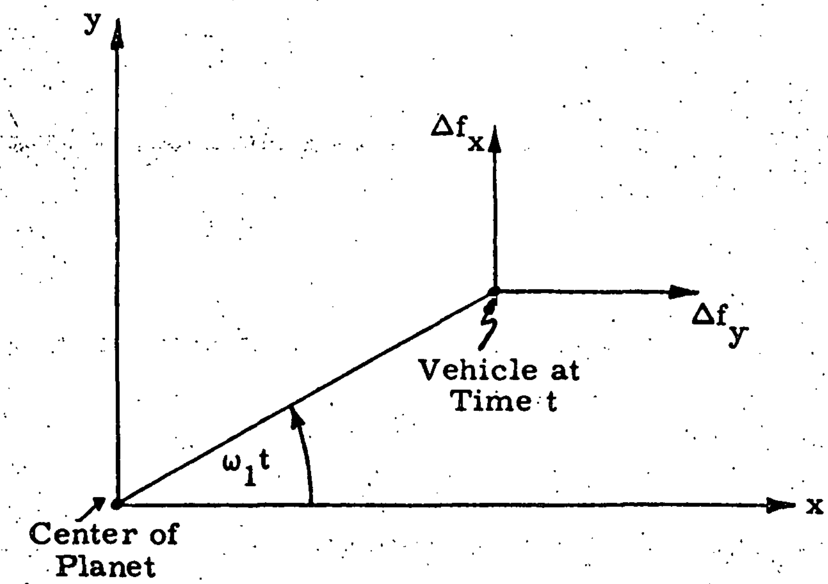

Fig. 2 Sign Definition of Accelerometers' Bias During Suborbital Flight

Table VII contains the summary of error propagation in the track and in the velocity along the track in an inertial system during the orbital or during the suborbital flights. The errors are caused by the initial condition errors in the track, the velocity along the track and by the accelerometer bias along the track direction. The track errors are independent of the altitude and the range errors.

TABLE II

PROPAGATION OF INITIAL CONDITION ERRORS IN INERTIAL SYSTEM DURING NEAR CIRCULAR ORBIT

PROPAGATED ERRORS IN	INITIAL CONDITION ERROR IN: ALTITUDE ΔR_H	RANGE ΔR_N	VELOCITY ALONG ALTITUDE ΔV_H	VELOCITY ALONG RANGE ΔV_N
ALTITUDE $R_{HE}(t)$	$\Delta R_H(2-\cos\omega_o t)$	$\Delta R_N \sin\omega_o t$	$\frac{\Delta V_H}{\omega_o}\sin\omega_o t$	$\frac{2\Delta V_N}{\omega_o}(1-\cos\omega_o t)$
RANGE $R_{NE}(t)$	$\Delta R_H(2\sin\omega_o t-3\omega_o t)$	$\Delta R_N(2\cos\omega_o t-1)$	$\frac{2\Delta V_H}{\omega_o}(\cos\omega_o t-1)$	$\frac{\Delta V_N}{\omega_o}(4\sin\omega_o t-3\omega_o t)$
VELOCITY ALONG ALTITUDE $V_{HE}(t)$	$\Delta R_H\omega_o(3\omega_o t-\sin\omega_o t)$	$\Delta R_N\omega_o(1-\cos\omega_o t)$	$\Delta V_H(2-\cos\omega_o t)$	$\Delta V_N(3\omega_o t-2\sin\omega_o t)$
VELOCITY ALONG RANGE $V_{NE}(t)$	$\Delta R_H\omega_o(\cos\omega_o t-1)$	$-\Delta R_N\omega_o\sin\omega_o t$	$-\Delta V_H\sin\omega_o t$	$\Delta V_N(2\cos\omega_o t-1)$

$$\omega_o\left[\text{rad/sec}\right] \approx 0.966 \times 10^{-3} \text{ on lunar surface}$$
$$\approx 1.242 \times 10^{-3} \text{ on earth surface}$$

TABLE III

PROPAGATION OF ERROR CAUSED BY ACCELEROMETERS' BIAS IN INERTIAL SYSTEM DURING NEAR CIRCULAR ORBIT

PROPAGATED ERRORS IN	ACCELEROMETERS BIAS: ACCELEROMETERS ORIENTED ALONG ALTITUDE Δf_H	ACCELEROMETERS ORIENTED ALONG RANGE Δf_N	ACCELEROMETER FIXED IN INERTIAL SPACE AT ANGLE Φ FROM LOCAL VERTICAL AT $t=0$ Δf
ALTITUDE $R_{HE}(t)$	$\frac{\Delta f_H}{\omega_0^2}(1-\cos\omega_0 t)$	$\frac{2\Delta f_N}{\omega_0^2}(\omega_0 t-\sin\omega_0 t)$	$\frac{\Delta f}{\omega_0^2}\left\{\left[\frac{3}{2}\omega_0 t\sin\omega_0 t+2(\cos\omega_0 t-1)\right]\cos\Phi+\frac{3}{2}\left[\omega_0 t\cos\omega_0 t-\sin\omega_0 t\right]\sin\Phi\right\}$
RANGE $R_{NE}(t)$	$\frac{2\Delta f_H}{\omega_0^2}(\sin\omega_0 t-\omega_0 t)$	$\frac{\Delta f_N}{\omega_0^2}\left[4(1-\cos\omega_0 t)-\frac{3}{2}\omega_0^2 t^2\right]$	$\frac{\Delta f}{\omega_0^2}\left\{3\left[\omega_0 t(1+\cos\omega_0 t)-2\sin\omega_0 t\right]\cos\Phi-\left[3\omega_0 t\sin\omega_0 t+5(\cos\omega_0 t-1)\right]\sin\Phi\right\}$
VELOCITY ALONG ALTITUDE $V_{HE}(t)$	$\frac{\Delta f_H}{\omega_0}(2\omega_0 t-\sin\omega_0 t)$	$\frac{3\Delta f_N}{\omega_0}\left(\frac{\omega_0^2 t^2}{2}-1+\cos\omega_0 t\right)$	$\frac{\Delta f}{\omega_0}\left\{\left[-\frac{3}{2}\omega_0 t(2+\cos\omega_0 t)+\frac{11}{2}\sin\omega_0 t\right]\cos\Phi+\left[\frac{3}{2}\omega_0 t\sin\omega_0 t-5(1-\cos\omega_0 t)\right]\sin\Phi\right\}$
VELOCITY ALONG RANGE $V_{NE}(t)$	$\frac{\Delta f_H}{\omega_0}(\cos\omega_0 t-1)$	$\frac{\Delta f_N}{\omega_0}(2\sin\omega_0 t-\omega_0 t)$	$\frac{\Delta f}{\omega_0}\left\{\left[-\frac{3}{2}\omega_0 t\sin\omega_0 t+1-\cos\omega_0 t\right]\cos\Phi+\frac{1}{2}\left[-3\omega_0 t\cos\omega_0 t+\sin\omega_0 t\right]\sin\Phi\right\}$

$\omega_0\left[\text{rad/sec}\right] \approx 0.966 \times 10^{-3}$ on lunar surface

$\approx 1.242 \times 10^{-3}$ on earth surface

TABLE IV

PROPAGATION OF INITIAL CONDITION ERRORS IN INERTIAL SYSTEM DURING SUBORBITAL FLIGHT

Propagated errors in	Initial condition error in: Altitude, ΔR_H	Range, ΔR_N	Velocity along altitude, ΔV_H	Velocity along range, ΔV_N
Altitude $R_{HE}(t)$	$\Delta R_H \operatorname{Cosh}(\sqrt{2}\,\omega_o t)\operatorname{Cos}\omega_1 t$	$\Delta R_N \operatorname{Cos}\omega_o t \operatorname{Sin}\omega_1 t$	$\frac{\Delta V_H}{\sqrt{2}\,\omega_o}\operatorname{Sinh}(\sqrt{2}\,\omega_o t)\operatorname{Cos}\omega_1 t$	$\frac{\Delta V_N}{\omega_o}\operatorname{Sin}\omega_o t \operatorname{Sin}\omega_1 t$
Range $R_{NE}(t)$	$-\Delta R_H \operatorname{Cosh}(\sqrt{2}\,\omega_o t)\operatorname{Sin}\omega_1 t$	$\Delta R_N \operatorname{Cos}\omega_o t \operatorname{Cos}\omega_1 t$	$\frac{-\Delta V_H}{\sqrt{2}\,\omega_o}\operatorname{Sinh}(\sqrt{2}\,\omega_o t)\operatorname{Sin}\omega_1 t$	$\frac{\Delta V_N}{\omega_o}\operatorname{Sin}\omega_o t \operatorname{Cos}\omega_1 t$
Velocity along altitude $V_{HE}(t)$	$\Delta R_H \sqrt{2}\,\omega_o \operatorname{Sinh}(\sqrt{2}\,\omega_o t)\operatorname{Cos}\omega_1 t$	$-\Delta R_N \omega_o \operatorname{Sin}\omega_o t \operatorname{Sin}\omega_1 t$	$\Delta V_H \operatorname{Cosh}(\sqrt{2}\,\omega_o t)\operatorname{Cos}\omega_1 t$	$\Delta V_N \operatorname{Cos}\omega_o t \operatorname{Sin}\omega_1 t$
Velocity along range $V_{NE}(t)$	$-\Delta R_H \sqrt{2}\,\omega_o \operatorname{Sinh}(\sqrt{2}\,\omega_o t)\operatorname{Sin}\omega_1 t$	$-\Delta R_N \omega_o \operatorname{Sin}\omega_o t \operatorname{Cos}\omega_1 t$	$-\Delta V_H \operatorname{Cosh}(\sqrt{2}\,\omega_o t)\operatorname{Sin}\omega_1 t$	$\Delta V_N \operatorname{Cos}\omega_o t \operatorname{Cos}\omega_1 t$

$\omega_o \left[\text{rad/sec}\right] \approx 0.966 \times 10^{-3}$ on lunar surface

$\approx 1.242 \times 10^{-3}$ on earth surface

$\omega_1 = V/R \left[\text{rad/sec}\right]$

$R\left[\text{km}\right] \approx 1738$ (Moon)

≈ 6371 (Earth)

V = average horizontal velocity

TABLE V

PROPAGATION OF INITIAL CONDITION ERRORS IN INERTIAL SYSTEM WITH PERFECT ALTIMETER DURING SUBORBITAL FLIGHT

PROPAGATED ERROR IN	INITIAL CONDITION ERRORS IN: ALTITUDE ΔR_H	RANGE ΔR_N	VELOCITY ALONG ALTITUDE ΔV_H	VELOCITY ALONG RANGE ΔV_N
ALTITUDE $R_{HE}(t)$	$\Delta R_H \cos\omega_0 t \cos\omega_1 t$	$\Delta R_N \cos\omega_0 t \sin\omega_1 t$	$\frac{\Delta V_H}{\omega_0} \sin\omega_0 t \cos\omega_1 t$	$\frac{\Delta V_N}{\omega_0} \sin\omega_0 t \sin\omega_1 t$
RANGE $R_{NE}(t)$	$-\Delta R_H \cos\omega_0 t \sin\omega_1 t$	$\Delta R_N \cos\omega_0 t \cos\omega_1 t$	$-\frac{\Delta V_H}{\omega_0} \sin\omega_0 t \sin\omega_1 t$	$\frac{\Delta V_N}{\omega_0} \sin\omega_0 t \cos\omega_1 t$
VELOCITY ALONG ALTITUDE $V_{HE}(t)$	$-\Delta R_H \omega_0 \sin\omega_0 t \cos\omega_1 t$	$-\Delta R_N \omega_0 \sin\omega_0 t \sin\omega_1 t$	$\Delta V_H \cos\omega_0 t \cos\omega_1 t$	$\Delta V_N \cos\omega_0 t \sin\omega_1 t$
VELOCITY ALONG RANGE $V_{NE}(t)$	$\Delta R_H \omega_0 \sin\omega_0 t \sin\omega_1 t$	$-\Delta R_N \omega_0 \sin\omega_0 t \cos\omega_1 t$	$-\Delta V_H \cos\omega_0 t \sin\omega_1 t$	$\Delta V_N \cos\omega_0 t \cos\omega_1 t$

ω_o [rad/sec] $\approx 0.966 \times 10^{-3}$ on lunar surface

$\approx 1.242 \times 10^{-3}$ on earth surface

$\omega_1 = V/R$ [rad/sec]

R[km] $\approx$ 1738 (Moon)

$\approx$ 6371 (Earth)

V = average horizontal velocity

TABLE VI

PROPAGATION OF ERRORS CAUSED BY ACCELEROMETERS' BIAS AND ALTIMETER BIAS IN INERTIAL SYSTEM WITH ALTIMETER DURING SUBORBITAL FLIGHT (X-Y AXIS SYSTEM FIXED IN INERTIAL SPACE WITH X-AXIS ALONG ALTITUDE AND Y-AXIS ALONG RANGE AT t=0)

PROPAGATED ERROR IN	SOURCE OF ERROR: ACCELEROMETER BIAS ALONG X-AXIS Δf_x	SOURCE OF ERROR: ACCELEROMETER BIAS ALONG Y-AXIS Δf_y	SOURCE OF ERROR: ALTIMETER BIAS ΔR
ALTITUDE $R_{HE}(t)$	$\frac{\Delta f_x}{\omega_0^2}(1-\cos\omega_0 t)\cos\omega_1 t$	$\frac{\Delta f_y}{\omega_0^2}(1-\cos\omega_0 t)\sin\omega_1 t$	$\frac{3\Delta R}{1-(\omega_1/\omega_0)^2}\left[1-\frac{\omega_1}{\omega_0}\sin\omega_0 t\sin\omega_1 t-\cos\omega_0 t\cos\omega_1 t\right]$
RANGE $R_{NE}(t)$	$-\frac{\Delta f_x}{\omega_0^2}(1-\cos\omega_0 t)\sin\omega_1 t$	$\frac{\Delta f_y}{\omega_0^2}(1-\cos\omega_0 t)\cos\omega_1 t$	$\frac{3\Delta R}{1-(\omega_1/\omega_0)^2}\left[\cos\omega_0 t\sin\omega_1 t-\frac{\omega_1}{\omega_0}\sin\omega_0 t\cos\omega_1 t\right]$
VELOCITY ALONG ALTITUDE $V_{HE}(t)$	$\frac{\Delta f_x}{\omega_0}\sin\omega_0 t\cos\omega_1 t$	$\frac{\Delta f_y}{\omega_0}\sin\omega_0 t\sin\omega_1 t$	$\frac{3\Delta R}{1-(\omega_1/\omega_0)^2}\left[\omega_1\cos\omega_0 t\sin\omega_1 t+\omega_0\sin\omega_0 t\cos\omega_1 t\right]$
VELOCITY ALONG RANGE $V_{NE}(t)$	$-\frac{\Delta f_x}{\omega_0}\sin\omega_0 t\sin\omega_1 t$	$\frac{\Delta f_y}{\omega_0}\sin\omega_0 t\cos\omega_1 t$	$\frac{-3\Delta R}{1-(\omega_1/\omega_0)^2}\left[\omega_0\sin\omega_0 t\sin\omega_1 t+\omega_1\cos\omega_0 t\cos\omega_1 t\right]$

ω_0 [rad/sec] $\approx 0.966 \times 10^{-3}$ on lunar surface

$\omega_1 = V/R$ [rad/sec]

V = average horizontal velocity

R[km] $\approx$ 1738 (Moon)

$\approx$ 6371 (Earth)

TABLE VII

PROPAGATION OF TRACK ERRORS IN INERTIAL SYSTEM

		INITIAL CONDITION ERROR IN		ACCELEROMETER BIAS ALONG TRACK Δf_M
		TRACK ΔR_M	VELOCITY ALONG TRACK ΔV_M	
PROPAGATED ERRORS IN	TRACK $R_{ME}(t)$	$\Delta R_M \cos \omega_o t$	$\frac{\Delta V_M}{\omega_o} \sin \omega_o t$	$\frac{\Delta f_M}{\omega_o^2}(1-\cos \omega_o t)$
	VELOCITY ALONG TRACK $V_{ME}(t)$	$-\Delta R_M \omega_o \sin \omega_o t$	$\Delta V_M \cos \omega_o t$	$\frac{\Delta f_M}{\omega_o} \sin \omega_o t$

$$\omega_o \left[\text{rad/sec}\right] \approx 0.966 \times 10^{-3} \text{ on lunar surface}$$
$$\approx 1.242 \times 10^{-3} \text{ on earth surface}$$

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