EVALUATION OF AIRBORNE INERTIAL NAVIGATIONAL ACCURACY USING PC-BASED KALMAN FILTER TECHNOLOGY

Airborne LASERNAV II with usage options in external NAVAID type and frequency of fixes

by Thomas Kerr

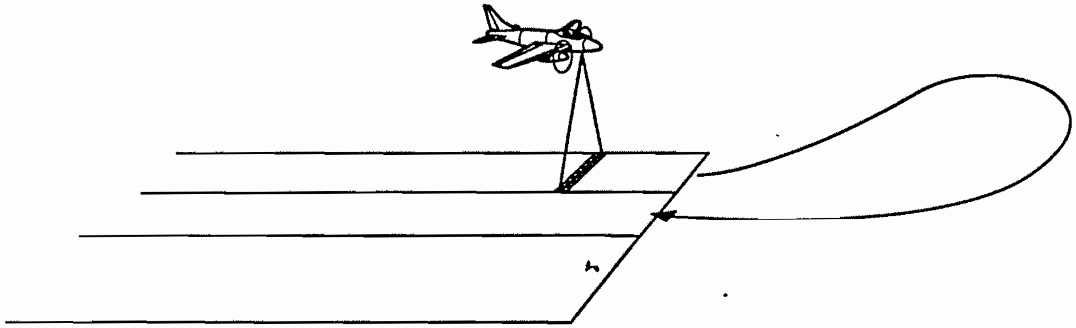
31 October 1991

TOPICS COVERED

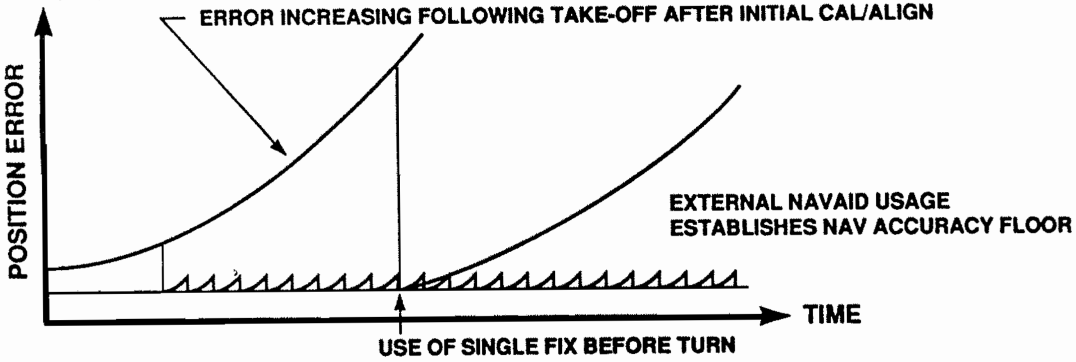
- STATEMENT OF THE PROBLEM
- AN INTRODUCTION TO THE SIMPLE KALMAN FILTER (KF)
- A PC-BASED KALMAN FILTER (KF) SOFTWARE IMPLEMENTATION (expanded and enhanced to satisfy our needs)
- CLOSED-FORM TEST CASES OF KNOWN SOLUTION USED TO VALIDATE/CALIBRATE OUR SOFTWARE
- SYSTEM MODELS REPRESENTING AN AIRBORNE RING-LASER INS AND NAVAIDS
- PREDICTING SYSTEM NAVIGATION ACCURACY VIA KF COVARIANCE ANALYSIS
- SPECIFYING TYPE AND FREQUENCY OF EXTERNAL NAVAID FIXES
- RECOMMENDED SOLUTION

STATEMENT OF THE PROBLEM

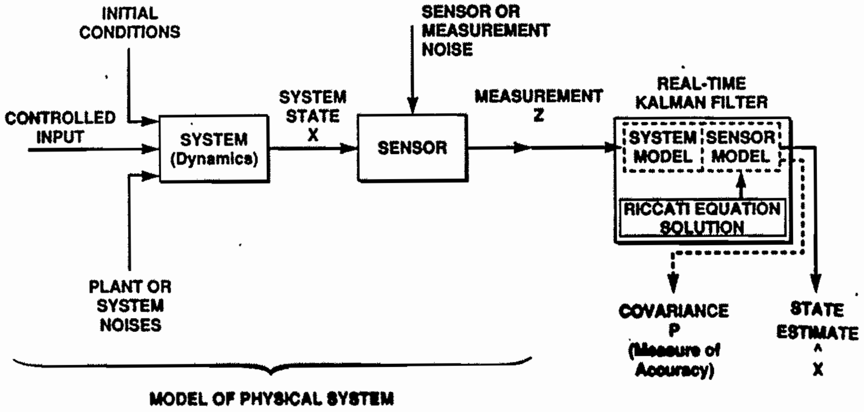
AIRBORNE DATA COLLECTION FOR REALISTIC ELECTRONIC TERRAIN BOARD DATA BASE



FFECT OF GYRO DRIFT-RATE ON ACCURACY BEHAVIOR OF INS



BLOCK DIAGRAM OF STANDARD KALMAN FILTER



- Investigate use of navigation information to expidite collection of test range data so that measured strips from sensor swath reasonably DOVETAIL with previous pass (to avoid unneccessary overlap or gaps between rows).

GOALS: Specification of

- TYPE of external navaids (and/or mixes) to use for position corrections;
- RATE of external navaid use;
- LASERNAV II model STRUCTURE, PARAMETERS, and UNITS;
- MODEL for each navaid (especially for fixes from surveyed retroreflector);
- Whether absolute geodetic position info should be stored on mag tape of sensor record (any benefits ?);
- Whether INS-derived tilts or ATTITUDE info can be used for sensor MOTION COMPENSATION;
- How LASERNAV II WAYPOINTS can be used for flight trajectory and MISSION PLANNING.

METHODOLOGY: Kalman filtering technology used for NAV accuracy predictions

KALMAN FILTER RESEARCH THRUSTS TO SUPPORT AIRCRAFT DATA BASE COLLECTION

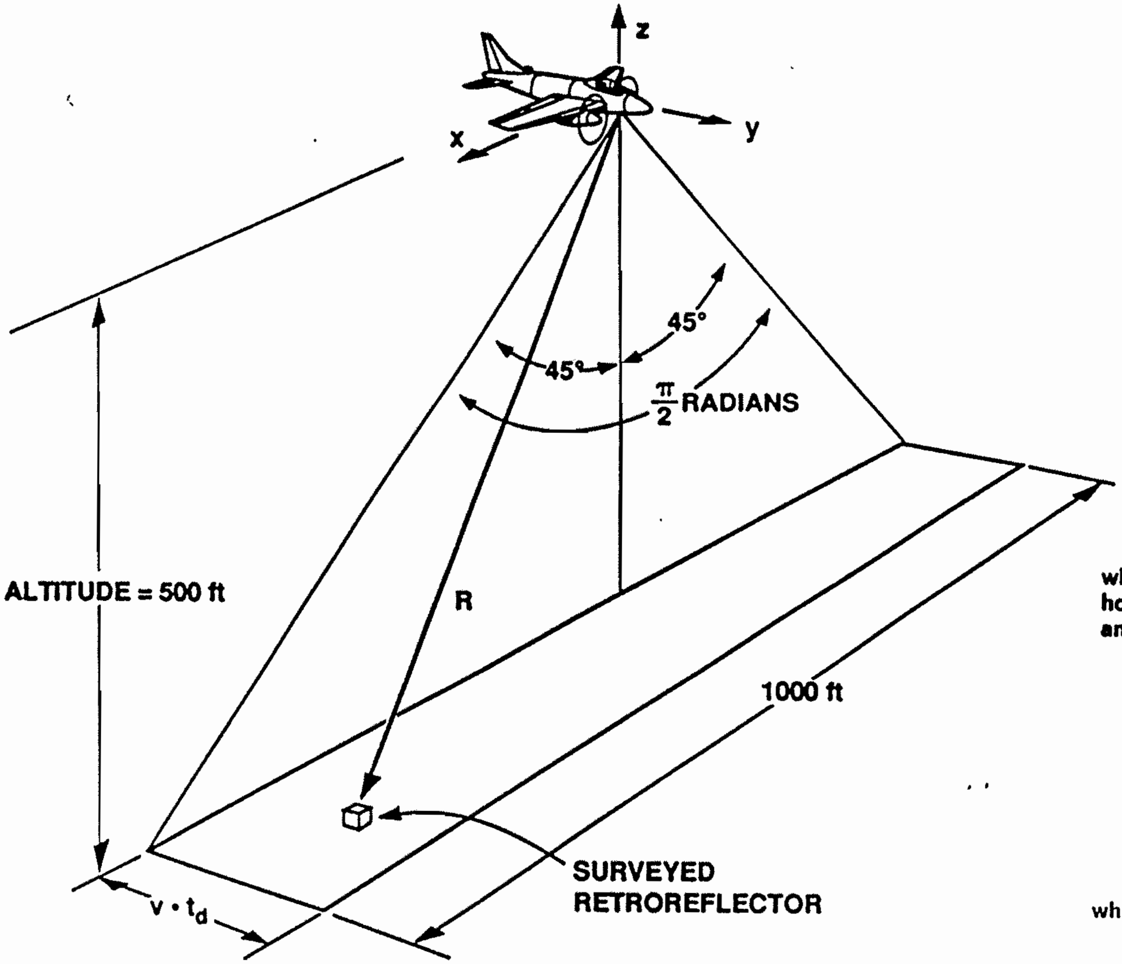
- **PROBLEM STATEMENT:** Investigate use of navigation information to expidite collection of test range data by allowing next row scan to reasonably dovetail to the last to avoid recording excessive overlap of redundant pixel data available from previous pass. Investigate use of INS WAYPOINTS for mission planning and in deciding what NAV info should be recorded on mission tapes.

- INS (*with its own internal Kalman filter*) nominally provides 3-D position and velocity but accuracy drifts off with time.

- PC-based Kalman filter software can be used to evaluate accuracy potential provided by these different design options:
  - INS only with initialization on take-off;
  - INS with some other radio navaid (*e.g., VOR/DME*) for updates/resets in transit and on station;
  - INS with periodic visual updates (*via GaAs Line Scanner*) of retroreflectors (*of known surveyed location*).

- To do the above evaluations, need good models for each system and need to use validated (*trustworthy*) software.
  - Validated software with low-dimensional test problems of known solution;
  - Enhanced software to offer additional capabilities that we needed.

SING SURVEYED RETROREFLECTOR POSITION IXES IN RETURNS FROM GaAs LINE-SCANNER



$$R = f(h,\theta,\phi) = h \csc(\phi) ,$$

where ϕ is the depression angle (measured at the aircraft from the horizontal down), h is altitude, and explicit dependence on polar projection angle θ is absent.

$$\begin{aligned} \sigma_R^2 &\approx |\frac{\partial f(\cdot)}{\partial h}|^2 \sigma_h^2 + |\frac{\partial f(\cdot)}{\partial \phi}|^2 \sigma_\phi^2 \\ &= (\csc(\phi))^2 \left[\sigma_h^2 + h^2(\cot(\phi))^2 \sigma_\phi^2\right] , \end{aligned}$$

where

- $\sigma_h = 20$ ft (as availed from the uncertainty of a typical baro-altimeter)
- $\sigma_\phi = 1$ milliradian angular uncertainty (angular resolution)

which implies that $\csc(\phi_o) \sim \sqrt{2}$ and $\cot(\phi_o) \sim 1$, hence

$$\sigma_R^2 \approx 2\,\sigma_h^2 ,$$

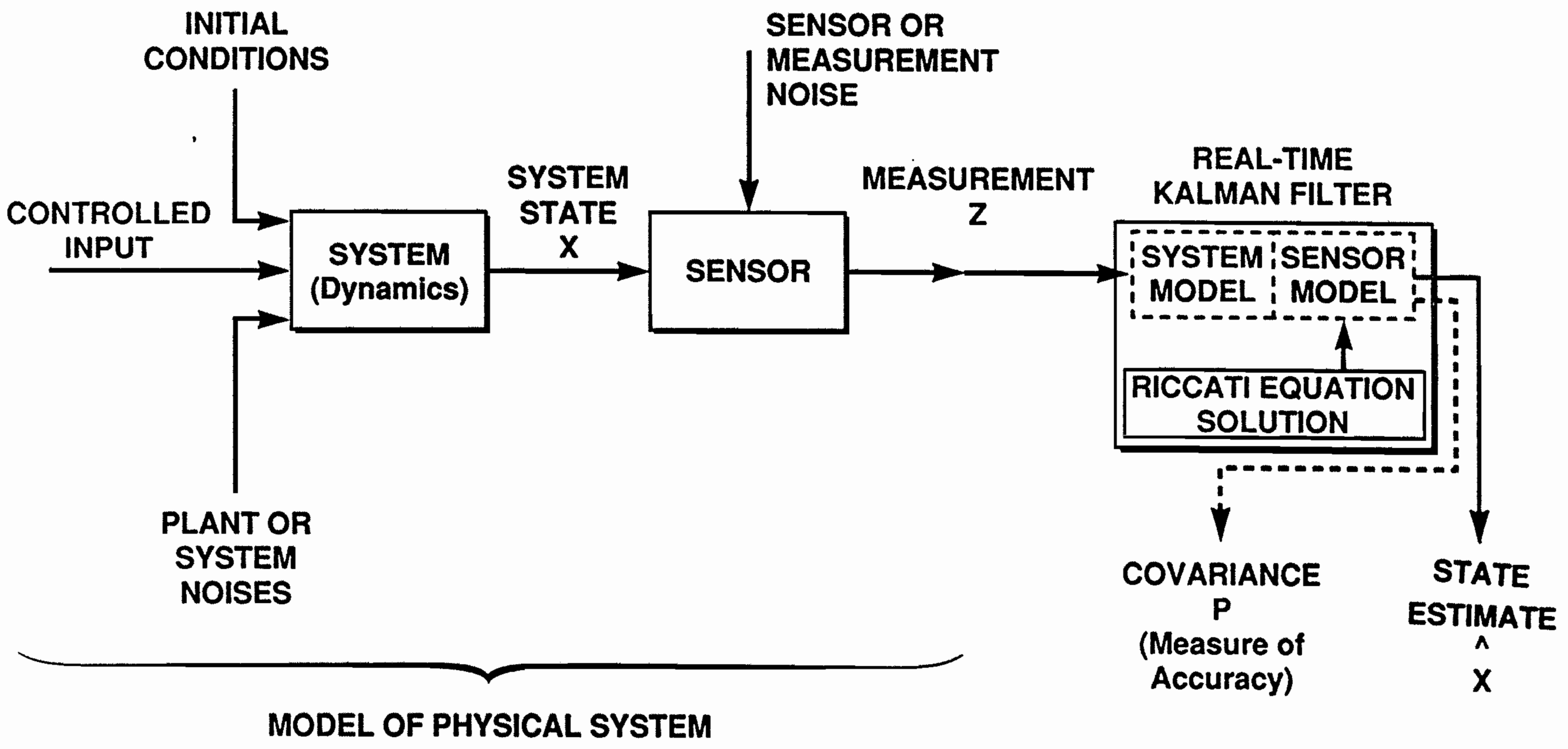
RETROREFLECTOR FIXES

Accounting for Wind-Induced Departures from Level Flight

- Undergoing pitch, roll, and yaw while maintaining nominal angle-of-attack prevents aircraft from being “perfectly level”.
- Retroreflector angle-sighting (*on GaAs Line Scanner terminal screen*) is with respect to aircraft body orientation.
- Body orientation can be referenced back to onboard INS (*LASERNAV II*), where its effect can be removed but only to the degree of fundamental tilt errors present in the INS used in the unraveling.
- Angle (*tilt*) errors can be decomposed into two components:
    - Due to inherent angle error in using Line Scanner (*with respect to*) aircraft body axes;
    - Due to angle error in body-axes-to-onboard-INS unraveling;
    - Since both above components are independent, RSSing both yields total “effective” tilt error.

Evaluations that follow use final “effective” composite value of “worse case” tilts experienced over 4 hr mission time.

BLOCK DIAGRAM OF STANDARD KALMAN FILTER



143842-9,A

FORM OF UNDERLYING MODEL FOR SYSTEM

Linear ODE's with Additive Gaussian White Noises

For systems having a truth model of the following form:

$$\underline{x}(k+1) = \Phi(k+1, k)\, \underline{x}(k) + \underline{w}(k)$$

$$\underline{z}(k) = H(k)\, \underline{x}(k) + \underline{v}(k)$$

where

$$\underline{w}(\cdot),\ \underline{v}(\cdot)$$

are zero mean, independent, Gaussian white noise

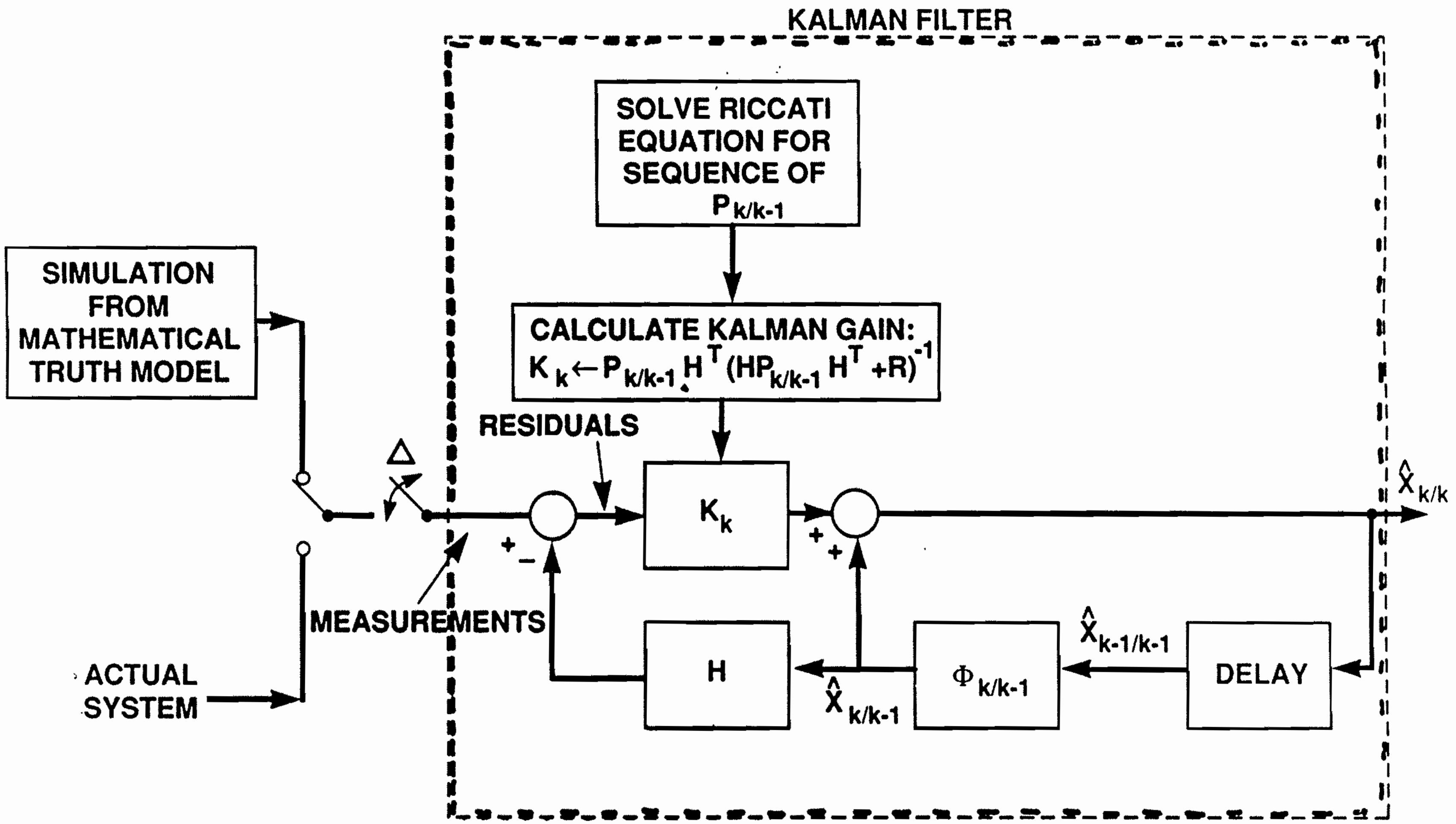
$$\underline{x}(0) \sim N[\underline{x}_0,\ P_0]$$

and

$\underline{x}(0)$ is independent of $\underline{w}(\cdot)$ and $\underline{v}(\cdot)$

UNCLASSIFIED

STANDARD DISCRETE-TIME KALMAN FILTER MECHANIZATION



143842-4

KALMAN FILTER APPLICATIONS

- Used in Navigation (in conjunction with gyros/accelerometers/GPS satellites) in:
    - ICBMs/SLBMs
    - Aircraft, RPVs, cruise missiles
    - Ships, submarines
    - tanks (that can shoot-on-the-move)
- Breakthrough use in automobiles (in conjunction with GPS and digital map technology);
- Used in radar for target tracking (Air Traffic Control, National Defense).

Kalman Filtering opportunities are unlimited! Look for opportunities in your applications.

Software Modifications Made to Better Accommodate Needs of the ETB Application

- Undeclared array XINIT, which defaulted (under BASIC) to a value of 10 (preventing use of the code on systems higher than 10) has now been declared as XINIT(N).

- Performed minor re-adjustment (in several subroutines) of row and column spacing in echo of matrix input so that the VDT can now accommodate a 12-dimensional state variable model.

- Double occurrence of XINIT for specification of initial conditions in both AVBSIM.BAS and in AVBFILTR.BAS now distinguished by renaming one version to be XINITT.

- Inputting and outputting of application related system matrices, covariances, etc., converted from previous format of "XXX.XXXX" to current scientific notation "+X.XXE+XX".

- Miserable graphics originally supplied with the Kalman filter software package now augmented using EASYPLOT^{TM}.

- The transition matrix calculation for converting continuous-time n-state model description to discrete-time, originally adaptively tailored the number of terms to be retained in the Taylor series by using a coarse norm. Now use tighter bound derived from column-sum and row-sum norms instead and set a limit on total number of terms to use in calculation so it can't run away.

- Keyboard entry of all $12 \times 12 = 144$ elements of the initial covariance, previously required, is now avoided.

- Modifying AVBFILTR.BAS to output a file for EASYPLOT that depicts the characteristic sawtooth covariance familiar in navigation applications (instead of currently outputting just its best case lower envelop).

MOTIVATION FOR USING THIS PC-BASED SOFTWARE: Menu-driven, easy to use, portable, well thought out, validated with test problems of known solution, can be easily personalized. DEMO AVAILABLE

CLOSED-FORM TEST CASES OF KNOWN SOLUTION USED TO VALIDATE OUR SOFTWARE

EXPLOITING PROPERTIES OF IDEMPOTENT MATRICES: $F^2 = F$

BENEFITS: Offers closed-form expression for the transition matrix:

$$\begin{aligned} e^{F\,\Delta} &= I + F\,\Delta + \frac{1}{2!}F^2\,\Delta^2 + \frac{1}{3!}F^3\,\Delta^3 + \cdots \quad \text{(Answer Not Closed — Form)}, \\ &= I + F\,\Delta + \frac{1}{2!}F\,\Delta^2 + \frac{1}{3!}F\,\Delta^3 + \cdots, \\ &= I + F\{\Delta + \frac{1}{2!}\,\Delta^2 + \frac{1}{3!}\,\Delta^3 + \cdots\}, \\ &= I + F\{e^{\Delta} - 1\} \qquad \text{(Closed — Form Answer)} \end{aligned}$$

and closed-form expression for exact numerical calculation of discrete-time process noise covariance intensity matrix:

$$Q_d = e^{F\,\Delta}\left[\int_0^{\Delta} e^{-F\,\tau} Q_c e^{-F^T\,\tau}\, d\tau\right] e^{F^T\,\Delta}$$

that can both be used to confirm computations from general purpose software under the same test conditions.

EXPLOITING PROPERTIES OF IDEMPOTENT MATRICES: $F^2 = F$

EXAMPLES OF IDEMPOTENT MATRICES:

$$\begin{bmatrix} \frac{4}{5} & -\frac{2}{5} \\ -\frac{2}{5} & \frac{1}{5} \end{bmatrix} ; \begin{bmatrix} \frac{1}{3} & -\frac{1}{3} & \frac{1}{3} \\ -\frac{1}{3} & \frac{1}{3} & -\frac{1}{3} \\ \frac{1}{3} & -\frac{1}{3} & \frac{1}{3} \end{bmatrix}$$

Can provide such non-diagonal test matrices of any dimension as needed. (Alternative testing with only diagonal matrices fails to uncover possible software problems with computation of off-diagonal components.)

Kerr, T. H., "Use of Idempotent Matrices to Validate Systems Software," IEEE Vol. AES-26, No. 6, March 1990.

FURTHER EXPLOITING PROPERTIES OF IDEMPOTENT MATRICES: $F^2 = F$

OBSERVABILITY/CONTROLLABILITY TESTS SUCH AS THE FOLLOWING NECESSARY CHECK:

$$\text{rank}\left[G|FG|F^2G|\cdots|F^{(n-1)}G\right] = n$$

NOW SIMPLIFY INTO JUST CHECKING THE FOLLOWING:

$$\text{rank}\,[G|FG] = n$$

AS A LOWER COMPUTATIONAL BURDEN.

CAN CONCATENATE SMALL TEST PROBLEMS INTO LARGER ONES (AS NEEDED) IN SUCH A WAY THAT OBSERVERABILITY/CONTROLLABILITY PROPERTIES CONTINUE TO HOLD FOR THE FINAL AGGREGATE SYSTEM USED FOR THE TEST. (RESULT WOULD BE USELESS IF PROPERTIES DIDN'T CARRY OVER!)

AUGMENT/ADJOIN LOW-ORDER MODEL/SOLUTIONS TO GET HIGHER ORDER ONES

For 3-state test problem of known solution:

$$\overset{(3\times 1)}{x} = \begin{bmatrix} \text{position} \\ \text{velocity} \\ \text{acceleration} \end{bmatrix},$$

with

$$\begin{aligned} \dot{x} &= F_1 x + G_1 u, \quad u \sim \mathcal{N}(0, Q_1), \\ y &= H_1 x + v, \quad v \sim \mathcal{N}(0, R_1), \end{aligned}$$

and assumed to be already satisfying Kalman's "controllability and observability" rank test criteria, respectively, as

$$\begin{aligned} rank[G_1 \vdots F_1 G_1 \vdots F_1^2 G_1] &= n_1 = 3, \\ rank[H_1^T \vdots F_1^T H_1^T \vdots (F_1^T)^2 H_1^T] &= n_1 = 3. \end{aligned}$$

Now the augmented system of the form

$$x = \begin{bmatrix} \text{position} \\ \text{velocity} \\ \text{acceleration} \\ \cdots \\ \text{position} \\ \text{velocity} \\ \text{acceleration} \end{bmatrix},$$

with

$$\dot{x} = \begin{bmatrix} F_1 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & F_1 \end{bmatrix} x + \begin{bmatrix} G_1 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & G_1 \end{bmatrix} \begin{bmatrix} u \\ \cdots \\ u \end{bmatrix}$$

$$y = \begin{bmatrix} H_1 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & H_1 \end{bmatrix} x + \begin{bmatrix} I & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & I \end{bmatrix} \begin{bmatrix} v \\ \cdots \\ v \end{bmatrix}$$

has system, process noise gain, and observation matrices, respectively, of the form

$$F_2 = \begin{bmatrix} F_1 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & F_1 \end{bmatrix},$$

$$G_2 = \begin{bmatrix} G_1 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & G_1 \end{bmatrix},$$

$$H_2 = \begin{bmatrix} H_1 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & H_1 \end{bmatrix}.$$

In testing for controllability of this augmented system, form

$$rank[G_2 \vdots F_2G_2 \vdots F_2^2G_2 \vdots F_2^3G_2 \vdots F_2^4G_2 \vdots F_2^5G_2] =$$

$$\text{rank} \begin{bmatrix} G_1 & \vdots & 0 & \vdots & F_1G_1 & \vdots & 0 & \vdots & F_1^2G_1 & \vdots & 0 & \vdots & \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\text{other stuff} \\ 0 & \vdots & G_1 & \vdots & 0 & \vdots & F_1G_1 & \vdots & 0 & \vdots & F_1^2G_1 & \vdots & \end{bmatrix} =$$

$$\text{rank} \begin{bmatrix} G_1 & \vdots & F_1G_1 & \vdots & F_1^2G_1 & \vdots & 0 & \vdots & 0 & \vdots & 0 & \vdots & \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\text{other stuff} \\ 0 & \vdots & 0 & \vdots & 0 & \vdots & G_1 & \vdots & F_1G_1 & \vdots & F_1^2G_1 & \vdots & \end{bmatrix}$$

$$= 3 + 3 = 6 .$$

The corresponding augmented system covariances are:

$$R_2 = \begin{bmatrix} R_1 & \vdots & R_1 \\ \cdots & \cdots & \cdots \\ R_1 & \vdots & R_1 \end{bmatrix}.$$

However, this is a situation of "singular measurement noise"! Instead use

$$R_2 = \begin{bmatrix} R_1 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & R_1 \end{bmatrix},$$

$$Q_2 = \begin{bmatrix} Q_1 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & Q_1 \end{bmatrix},$$

$$P_2(0) = \begin{bmatrix} P_1(0) & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & P_1(0) \end{bmatrix}.$$

STANDARDIZATION OF MODEL CASES FOR SIMULATION TESTING

Case No.	Test Case 1	Test Case 2	Test Case 3	Test Case 4
Step Size DEL (Δ)	0.405	0.5	0.5	1
System Matrix F	$\begin{bmatrix}1/3 & -1/3 & 1/3\\ -1/3 & 1/3 & -1/3\\ 1/3 & -1/3 & 1/3\end{bmatrix}$	$\begin{bmatrix}-5 & -1\\ 6 & 0\end{bmatrix}$	$\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}$	—
Transition Matrix $e^{F\Delta}$	$\begin{bmatrix}1.16\overline{6} & -0.16\overline{6} & 0.16\overline{6}\\ -0.16\overline{6} & 1.16\overline{6} & -0.16\overline{6}\\ 0.16\overline{6} & -0.166 & 1.16\overline{6}\end{bmatrix}$ as calculated	$\begin{bmatrix}-0.0664 & -0.1447\\ 0.8685 & 0.6574\end{bmatrix}$ as calculated	$\begin{bmatrix}1 & 0.5\\ 0 & 1\end{bmatrix}$ as calculated	$\begin{bmatrix}0.34-j0.22 & -0.75\\ 0.65 & 0.55\end{bmatrix}^{*}$ as entered
NDIM	NDIM = 3	NDIM = 2	NDIM = 2	NDIM = 2
MDIM	MDIM = 2	MDIM = 2	MDIM = 2	MDIM = 2
Process Noise Covariance Intensity Matrix Q	continuous time version $\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}$	continuous time version $\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$	continuous time version $\begin{bmatrix}10^{-\text{[illegible]}} & 0\\ 0 & 10^{-\text{[illegible]}}\end{bmatrix}$	Discrete time version $\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$
Observation Matrix H	$\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\end{bmatrix}$	$\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$	$\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$	$\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$
Measurement Noise Covariance Intensity Matrix R	$\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$	$\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$	$\begin{bmatrix}10^{-\text{[illegible]}} & 0\\ 0 & 10^{-\text{[illegible]}}\end{bmatrix}$	$\begin{bmatrix}10^{-\text{[illegible]}} & 0\\ 0 & 10^{-\text{[illegible]}}\end{bmatrix}$
Initial mean $\overline{X}_o$	$\begin{bmatrix}0 & 0 & 0\end{bmatrix}^T$	$\begin{bmatrix}0 & 0\end{bmatrix}^T$	$\begin{bmatrix}10 & 4\end{bmatrix}^T$	$\begin{bmatrix}0 & 0\end{bmatrix}^T$
Initial Covariance P_o	$\begin{bmatrix}6 & 2 & 1\\ 2 & 8 & 3\\ 1 & 3 & 12\end{bmatrix}$	$\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$	$\begin{bmatrix}10^{-\text{[illegible]}} & 0\\ 0 & 10^{-\text{[illegible]}}\end{bmatrix}$	$\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$

*Put capability into simulation program to read this in directly without calculating it.

Kerr, T. H., Lincoln Laboratory Tech. Report No. PA-512, 22 Dec. 1989.

TESTABILITY COVERAGE MATRIX

FUNCTION	CASE 1	CASE 2	CASE 3	CASE 4
Transition Matrix Computation: Pade (Ward's Algorithm)	✓	✓		
Transition Matrix Computation: Pade (Kleinman's Algorithm)	✓	✓		
Q_d Computation: Discrete-Time Equivalent of Continuous-Time White Noise	✓	✓		
Steady-State Computation of Initial Condition Mean		✓		
Steady-State Computation of Initial Condition Covariance (Lyapunov Equation Solution)		✓		
Verification of SVD-based Positive Definiteness Test for Nondiagonal Matrices	✓			
Verification of Abbreviated Positive Definiteness Test for Diagonal Matrices	✓	✓	✓	✓
Checked Process Noise Calculations as Output from Random Number Generator	✓	✓		
Checked Measurement Noise Calculations as Output from Random Number Generator	✓	✓		
Checked Recursive Calculation of all Constituent Components of Entire Random Process Over Several Iterations	✓	✓		
Checked Proper Handling of PRN Seed	✓	✓		
Verification of Stable Sample Functions Indicative of Stationary Process		✓		✓
Verification of Unstable Sample Functions Indicative of Nonstationary Process	✓		✓	
Obvious Aggregate High Level At-A-Glance Confirmation From Output that all Functions Work Properly in Concert			✓	
Confirmation of Identical Results When Complex Version of Software Enabled	✓	✓	✓	
Eventual Confirmation of Proper Sample Function Statistics from Downstream Spectral Estimation Software Module Outputs		✓		✓

BOVE TEST PROBLEMS USED TO PINPOINT FAULTS IN COMMERCIAL KF SOFTWARE
ND VERIFY OUR CORRECTIONS AND MODIFICATIONS/EXTENSIONS

SYSTEM MODELS REPRESENTING AN AIRBORNE RING-LASER INS AND NAVAIDS

NAV SUPPORT OF REALISTIC DATA BASE COLLECTION FOR ELECTONIC TERRAIN BOARD

LINEARIZED ERROR MODEL

- Simplified linearized error model to represent Honeywell's LASERNAV II, as exercised in a Kalman filter covariance analysis to predict expected navigation accuracy attainable during ETB data collection missions.

- The strong coupling between the gyro drift errors, accelerometer bias errors, and platform tilts or misalignments (contained or captured in the linear error model representation of the INS) allows mere navaid fixes of position to propagate or translate into corrections of *position, velocity, and tilt.*

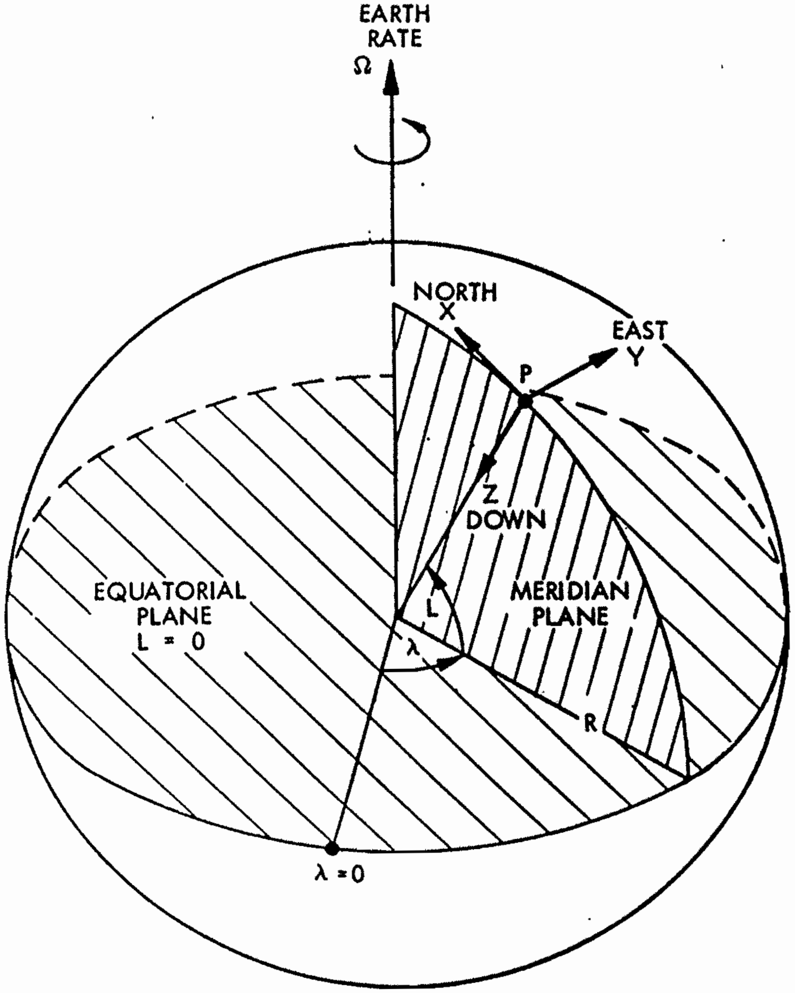
- Tying in to established 25+ year old tradition for properly handling such situations to expedite obtaining of evaluation/prediction results.

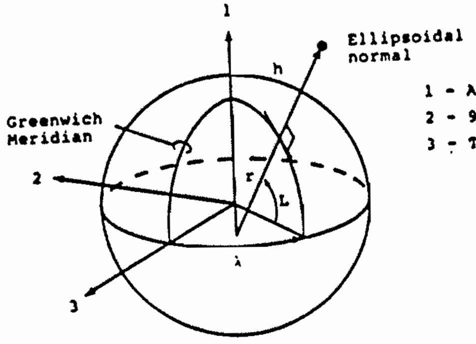
- The conventions and error models that account for the behavior of the gyros and accelerometers were developed by others and have been independently cross-checked and streamlined for this ETB application.

- Several ~ 19 to 25 state error models exist for airborne INS. Our model was whittled down to 12 states. Numbers in the matrices were checked and cross-checked. Numbers came from gyro and accelerometer specs and accuracies of fix source.

- Proper scaling and units to use were established as input to the software in order to obtain the output answers in the units that we want.

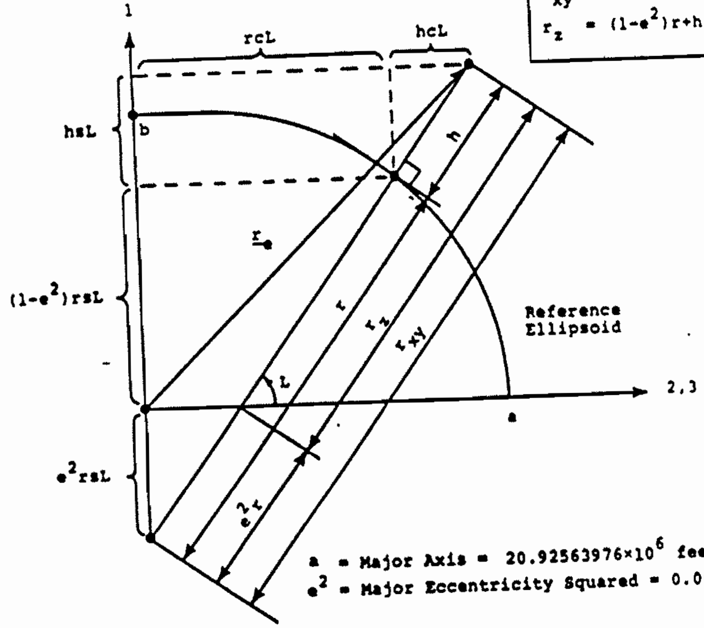
CONVENTION IN COORDINATE SYSTEM USED





1 - Along Polar Axis
2 - 90° West of Greenwich ($\lambda = -90°$)
3 - Through Greenwich ($\lambda = 0°$)

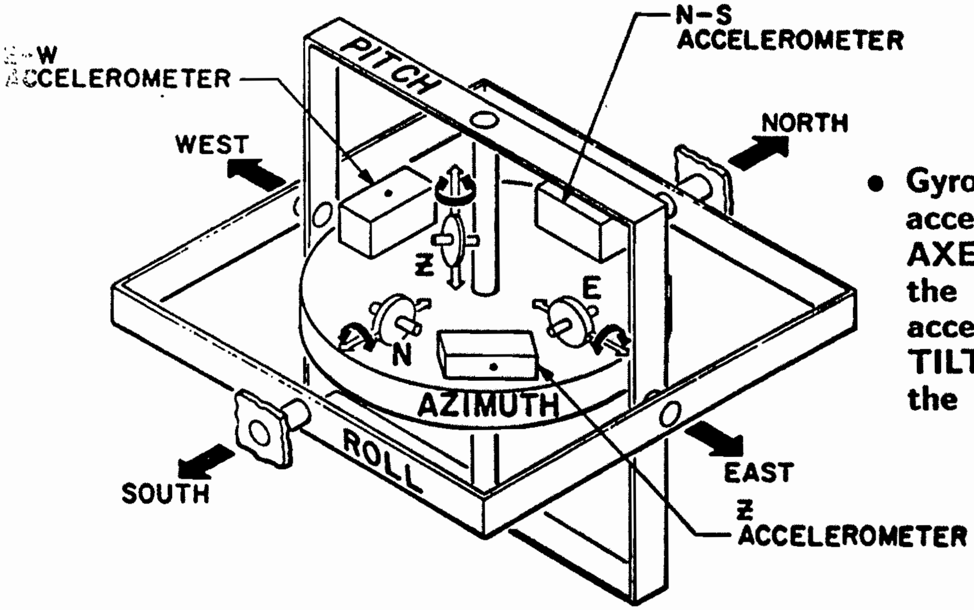
$r = a/\sqrt{1-e^2 sL^2}$
$x_{u3} = (r+h)cL\,c\lambda$
$x_{u2} = -(r+h)cL\,s\lambda$
$x_{u1} = \left[(1-e^2)r+h\right]sL$
$r_{xy} = r+h$
$r_z = (1-e^2)r+h$



a = Major Axis = 20.92563976×10^6 feet
e^2 = Major Eccentricity Squared = 0.00669431778

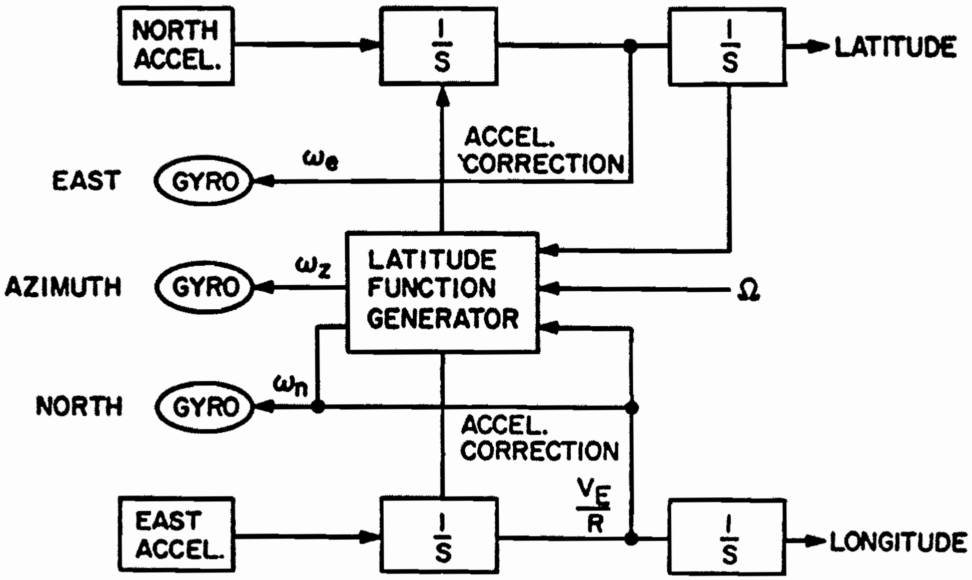
Angular velocity and acceleration are vectors consistent with right-hand-rule
(*i.e., direction of thumb as fingers curl along the spin direction of angle*)

Platform and Structure of a Typical Conventional Airborne Local Level INS Mechanization

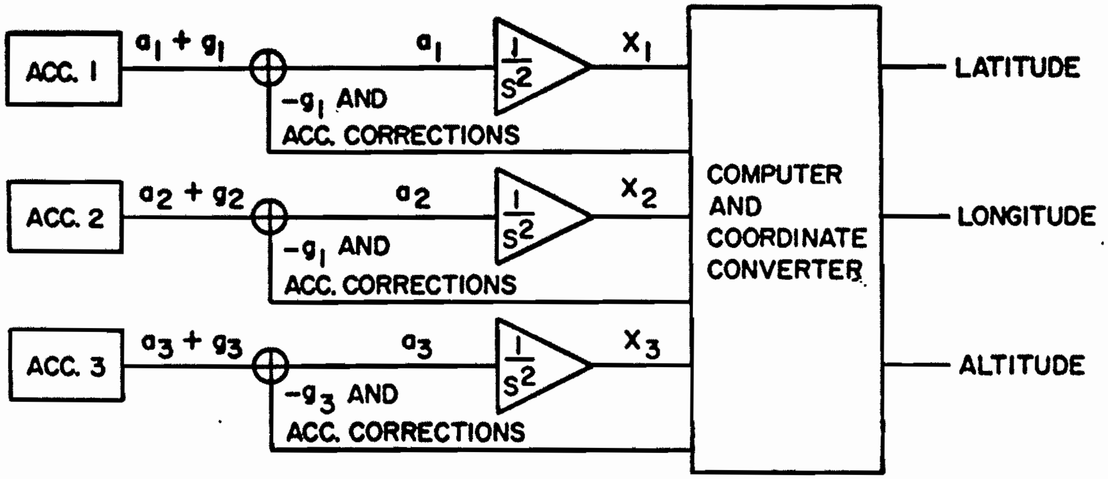


- Gyros establish the stable platform upon which the triad of accelerometers are mounted as the motion sensing elements. INPUT AXES of the GYROS affects the orientation of the INPUT AXES of the ACCELEROMETERS used to sense and measure platform accelerations which affects the COMPUTED gyro-induced platform TILTS, which affects the positioning of the sensitive INPUT AXES o the GYROS. (round-robin!)

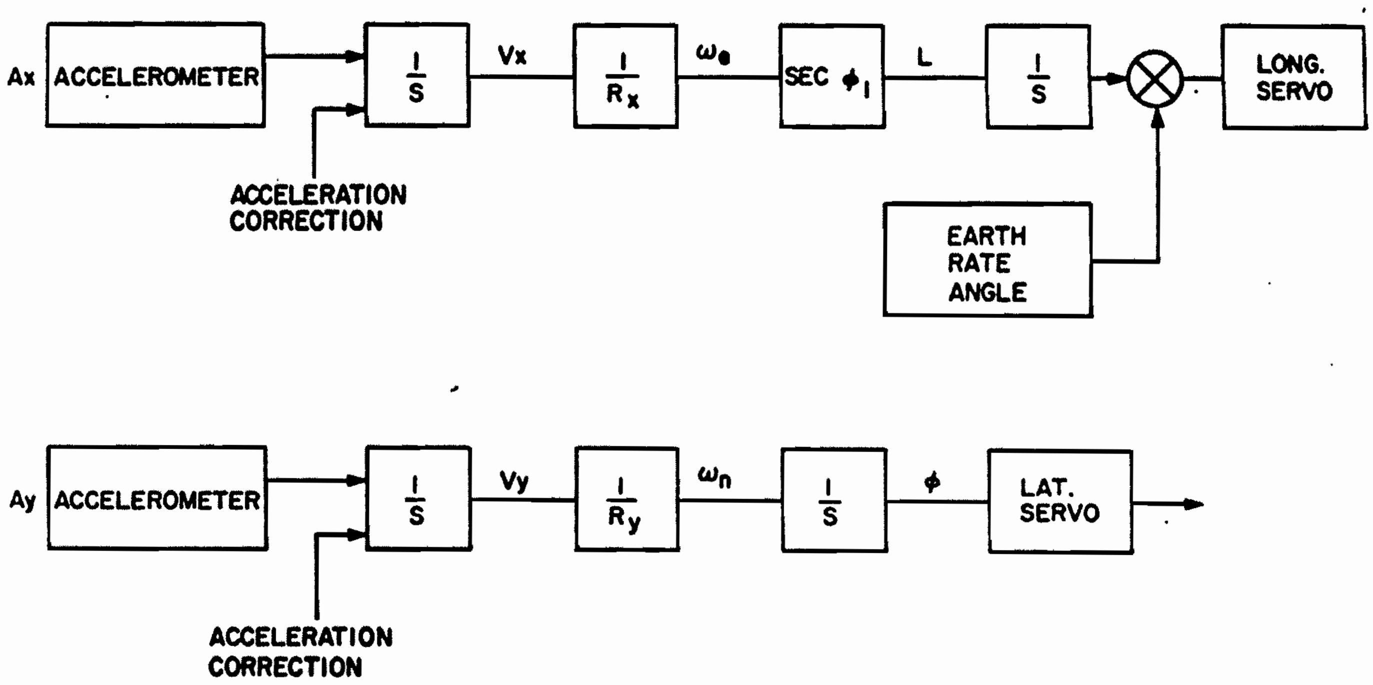
Simplified View of Inputs and Outputs of an INS



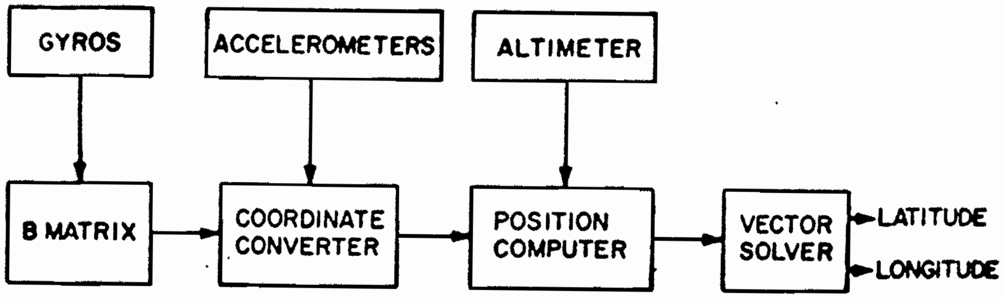
Simplified Block Diagram of Conventional Airborne Local-Level INS



FUNCTIONAL DIAGRAM OF AN INS



SIMPLIFIED OVERVIEW OF A STRAP-DOWN INS



Strapdown Mechanized INS (vs. Conventional Gimballed INS)

- Absence of gimball mounted reference table (*gyros and accelerometers bolted directly to vehicle frame*);

- Gyros provide angular rates directly to the B-Matrix, which converts to direction cosines;

- Signals used to specify vehicular attitude with respect to inertially ideal reference frame (*e.g., the "fixed stars"*);

- Position computer accepts raw acceleration and altitude readings as input and outputs velocity and position in inertial space;

- Vector Solver converts position outputs to aircraft Latitude and Longitude;

- Required fast sampling rates and processing speeds (only achievable within last 12 years) needed to accommodate various specific forces experienced by maneuvering aircraft buffeted by winds are "orders-of-magnitude" more taxing than those of gimballed INS;

- Accuracy achievable by any INS ultimately depends on quality of component accelerometers and gyros (*biases, scale factor error, drift-rate biases and random component*) and quality of it's external NAVAID's (*and rate of fix taking*). Our accuracy analysis performed for conventional local-level mechanized INS to avoid otherwise exorbitant computational burden of instantaneous exact Strapdown calculations.

STRUCTURE OF THE MODEL FROM FIRST PRINCIPLES-AT AGGREGATE HIGH LEVEL

$$\begin{aligned} \dot{v} + (\bar{\Omega} + \omega) \times v &= \nabla - (\Psi \times f) + \Delta g \, , \\ \dot{r} + (\rho \times r) &= v \, , \\ \dot{\Psi} + (\omega \times \Psi) &= \epsilon \, , \end{aligned}$$

$$\bar{\Omega} = \begin{bmatrix} \Omega \cos(L) \\ 0 \\ -\Omega \sin(L) \end{bmatrix} ,$$

where L is the local latitude. The vector ω is computed as follows:

$$\omega = \bar{\Omega} + \rho \, ,$$

where

$$\rho = \begin{bmatrix} \dot{\lambda} \cos(L) \\ -\dot{L} \\ -\dot{\lambda} \sin(L) \end{bmatrix} ,$$

where λ represents longitude and $\dot{\lambda}$ represents the rate-of-change in aircraft longitude.

STRUCTURE OF THE MODEL FROM FIRST PRINCIPLES

Specifics

$$\begin{aligned}
\dot{\lambda} &= \frac{V_N}{(R_o + h)} \,, \\
\dot{\phi} &= \frac{V_{GE}}{(R_o + h)\cos(\lambda)} \,, \\
\dot{V}_N &= A_N - (\omega_A + \Omega \sin(\lambda)) V_{GE} - E_N - g\,\psi_E + A_E\,\psi_A \,, \\
\dot{V}_{GE} &= A_E - (\omega_A + \Omega \sin(\lambda)) V_N - E_E + g\,\psi_N - A_N\,\psi_A \,,
\end{aligned}$$

where $g = 32.095\ \mathrm{ft/sec^2} = 9.78049\ \mathrm{m/sec^2}$ is the acceleration of gravity and

$$\begin{aligned}
\omega_E &\equiv \frac{-V_N}{(R_o + h)} \,, \\
\omega_N &\equiv \Omega \cos(\lambda) + \frac{V_{GE}}{(R_o + h)} \,, \\
\omega_A &\equiv \omega_N \tan(\lambda) \,,
\end{aligned}$$

where the magnitude of the velocity (i.e., speed) is

$$V = \sqrt{V_N^2 + V_{GE}^2} \,,$$

and $\Omega = \frac{2\pi \text{ radians}}{24 \text{ hrs}} = 0.2617$ rad/hr $= 0.2506844773^o$/min $=$ $7.292115856 \times 10^{-5}$ rad/sec is the earth rotation rate and $R_o = 6378.145$ km $= 2.092567257 \times 10^7$ ft ($= 3963.195563$ mi) is the mean radius of the earth and $h=$ altitude of the aircraft above the surface of the earth. The time-varying dynamics of gyro misalignment are further characterized by three differential equations describing the time evolution of the three coupled ψ-angles (*as expressed in terms of the true gyro frame to computer frame (i.e., computed) misalignments*):

$$\begin{aligned} \dot{\psi}_E &= D_E - \omega_N \psi_A + \omega_A \psi_N + T_E - \omega_E \,, \\ \dot{\psi}_N &= D_N - \omega_A \psi_E + \omega_E \psi_A + T_N - \omega_N \,, \\ \dot{\psi}_A &= D_A + \omega_N \psi_E - \omega_E \psi_N + T_A - \omega_A \,, \end{aligned}$$

where the T_i's are the "effective gyro torquing rates."

$$\dot{D}_E = \dot{D}_N = \dot{D}_A = \dot{E}_E = \dot{E}_N = 0 \,.$$

OVERVIEW OF PRIOR FILTER MODELS FOR AIRBORNE NAVIGATION USING ALTERNATIVE NAVAIDS: GPS, GPS/INS, JTIDS/INS, JTIDS, and GPS/JTIDS/INS

FILTER STATE DESIGNATIONS	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11		No. 12	
	GPS (Unaided) Draper 1978	GPS Aided by IMU Draper 1978	GPS Aided by INS Kriegsman & Stonestreet	GPS Aided by INS Widnall Gobbini 1980	JTIDS Rome Stenbaugh Kleinman	JTIDS/INS Draper & Kriegsman & Stonestreet	JTIDS/INS ADM Singer Kearfott	JTIDS/INS MIT Hughes	JTIDS/INS Widnall & Gobbini	JTIDS Unaided* Fried	GPS/JTIDS/INS		GPS/JTIDS/INS TRW MFBARS	
											Widnall & Gobbini	Draper Kriegsman Stonestreet		
Position			Error 3	Error 3		Error 2	Whole Value 2	Error 2	Error 2	Error 3	Error 3	Error 3	3	
Velocity Errors	3	3	3	3		2	2	2	2	3	3	3	3	
Acceleration Errors	3									3				
Angle Misalignments Between Computed and True Tangent Plane Axes		2												
Altitude Error (open-loop)		1					1	1						
External Altitude Reference Error		1	1	1		1					1	1	1	
GPS Clock Phase Error		1	1	1							1	1		
GPS Clock Frequency Error		1	1	1							1	1		
IMU Misalignment Angles		3	3	3		3	3	3	3		3	3	3	
IMU Bias Gryo Drift-Rates								3					3	
JTIDS Clock Phase Error					1	1	1	1	1	1	1	1	1	
JTIDS Clock Frequency Error					1	1	1	1	1	1	1	1	1	
Relative Position Error					2	2	2	2	2		2	2	2	
Relative Velocity Error					2		2	2	2		2		2	
Relative Azimuth Error (with respect to north)						1	1	1	1		1	1	1	
Controller Clock Phase Error											1		1	
Controller Clock Frequency Error											1		1	
Controller Related Velocity Errors												2		
GPS/JTIDS Clock Phase Error														Suggested but not yet used.
GPS/JTIDS Clock Frequency Error														
Correlated Velocity Errors						2								
Heading Error					1									
Heading Drift-Rate Error					1									
Total Number of States	6	12	12	12	8	15	15	18	14	11	21	19	22	

THIS ORIGINAL TABULAR FORMAT OFFERS EASE IN CROSS-COMPARING 13 DIFFERENT DESIGNS TO REVEAL EXPLICIT STATE UTILIZATION SIMILARITIES AND DIFFERENCES

SPECIFYING STATE VARIABLES FOR THE MODEL

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \end{bmatrix} \triangleq \begin{bmatrix} \lambda \\ \phi \\ V_N \\ V_{GE} \\ \psi_E \\ \psi_N \\ \psi_A \\ D_E \\ D_N \\ D_A \\ E_E \\ E_N \end{bmatrix} = \begin{bmatrix} \text{Latitude of aircraft} \\ \text{Longitude of aircraft} \\ \text{North velocity of aircraft} \\ \text{ground East velocity of aircraft} \\ \text{gyro psi — angle misalignment, EAST} \\ \text{gyro psi — angle misalignment, North} \\ \text{gyro psi — angle misalignment, Azimuth} \\ \text{gyro drift — rate bias, East} \\ \text{gyro drift — rate bias, North} \\ \text{gyro drift — rate bias, Azimuth} \\ \text{accelerometer bias, East} \\ \text{accelerometer bias, North} \end{bmatrix}$$

THE LASERNAV II ACCELEROMETER PARAMETERS

1-σ values:

GYRO ERROR SOURCES

- Bias Instability:
  - x- and y-, 0.004°/hr,
  - z-, 0.0088°/hr,

Specifies Initial Conditions

- Gyro angle random walk:
  - x- and y- $0.00214^{\circ}/\sqrt{hr}$,
  - z-, $0.005^{\circ}/\sqrt{hr}$,

Specifies process noise covariance intensity levels

- Gyro scale factor error:
  - x-, y-, and z-, 5 parts per million (ppm),
- Gyro orthogonality error:
  - x-, y-, and z-, 56 micro-radians,
- Gyro misalignment error:
  - x-, y-, and z-, 20 micro-radians.

Specifies Initial Conditions

ACCELEROMETER ERROR SOURCES

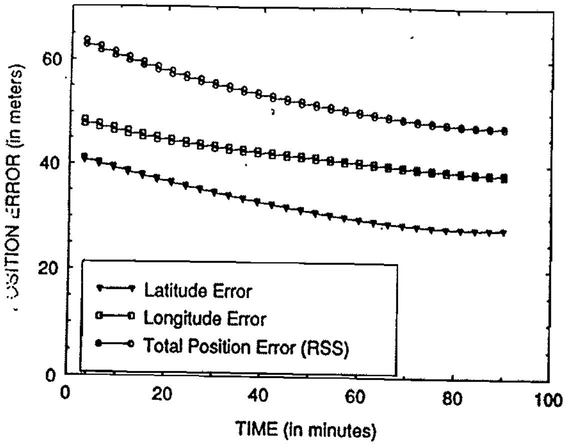
- Bias Instability:
  - x- and y-, 56 micro-g's,
  - z-, 840 micro-g's,

Specifies Initial Conditions

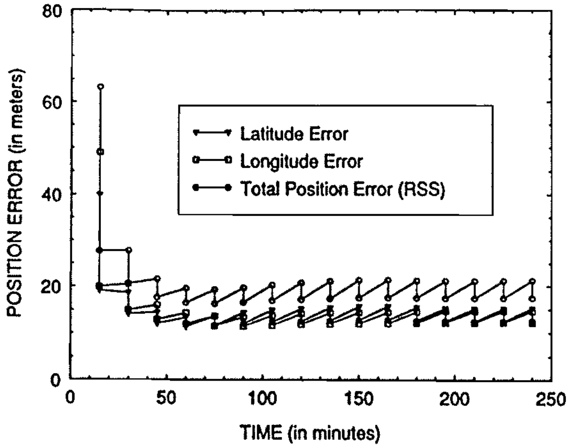
- Accelerometer nonlinearity:
  - x- and y-, 13.3 micro-g's,
  - z-, 200 micro-g's,
- Accelerometer scale factor error:
  - x- and y-, 300 parts per million (ppm),
  - z-, 1500 ppm,
- Accelerometer orthogonality error (i.e., non-orthogonalities in mounting):
  - x-, y-, 56 micro-radians,
  - z-, 840 micro-radians,
- Accelerometer bias trending during alignment:
  - x-, y-, 0.011 micro-g's/sec,
  - z-, 0.25 micro-g's/sec.

PREDICTING SYSTEM NAVIGATION ACCURACY VIA KF COVARIANCE ANALYSIS

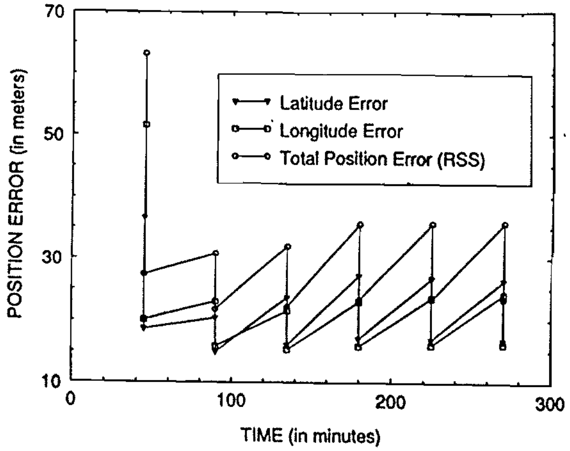
PREDICTIONS OF NAV ACCURACY



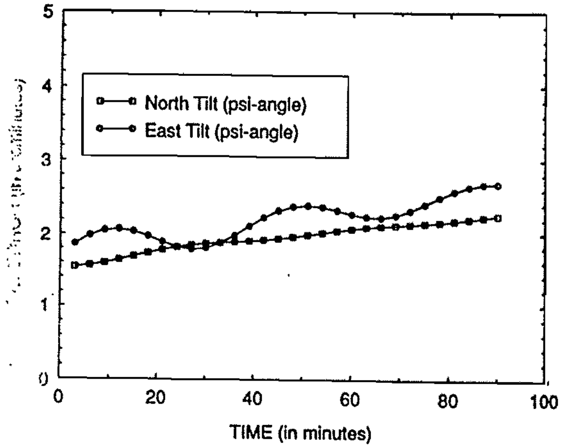
Simulated Covariance Analysis Computations: ***ENSEMBLE STD. DEV. OF N ERROR VS. TIME (3 min VOR/DME fixes)***



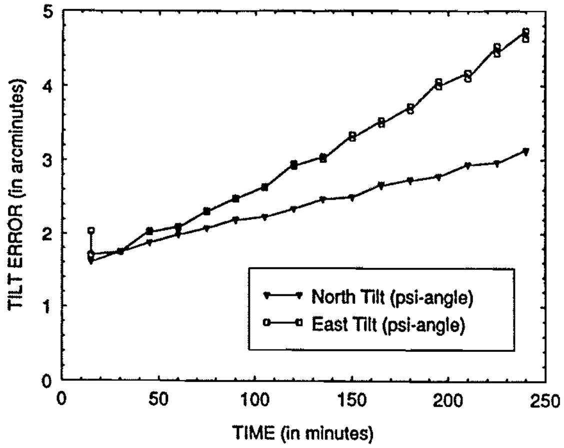
Simulated Covariance Analysis Computations: ***ENSEMBLE STD. DEV. OF POSITION ERROR VS. TIME (15 min Retro/Pos fixes)***



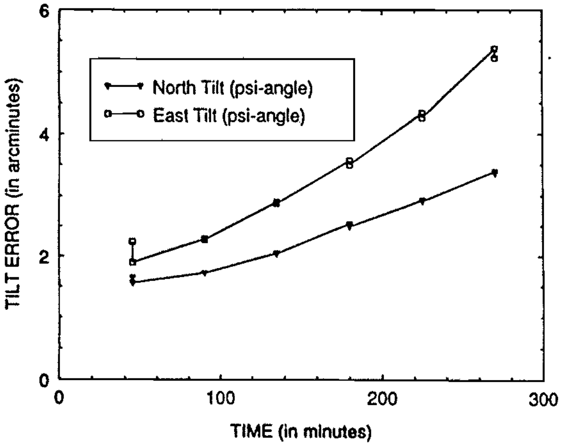
Simulated Covariance Analysis Computations: ***ENSEMBLE STD. DEV. O POSITION ERROR VS. TIME (45 min combined VOR/DME and Retro/Pos fixes)***



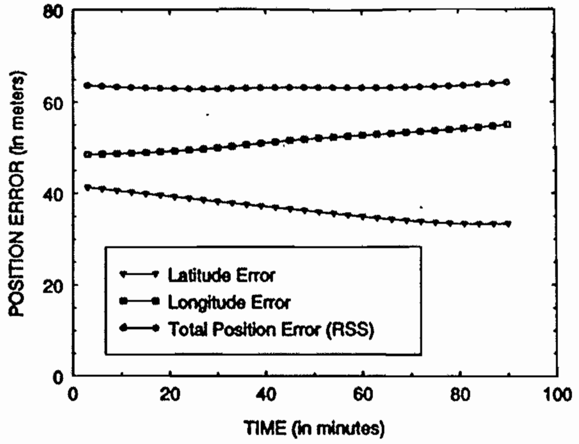
Simulated Covariance Analysis Computations: ***ENSEMBLE STD. DEV. OF RROR VS. TIME (3 min VOR/DME fixes)***



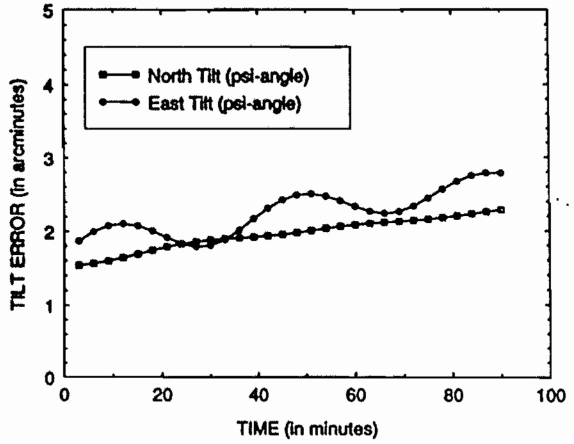
Simulated Covariance Analysis Computations: ***ENSEMBLE STD. DEV. OF TILT ERROR VS. TIME (15 min Retro/Pos fixes)***



Simulated Covariance Analysis Computations: ***ENSEMBLE STD. DEV. TILT ERROR VS. TIME (45 min combined VOR/DME and Retro/Pos fixes)***



Simulated Covariance Analysis Computations: ***ENSEMBLE STD. DEV. OF POSITION ERROR VS. TIME (NO navaid fixes used at all following initial Cal/Align)***



Simulated Covariance Analysis Computations: ***ENSEMBLE STD. DEV. OF TILT ERROR VS. TIME (NO navaid fixes used at all following initial Cal/Align)***

SPECIFYING TYPE AND FREQUENCY OF EXTERNAL NAVAID FIXES

SUMMARIZING RESULTS OF 19 TEST CASES

Maximum Steady-State 1-sigma Position Error for Airborne LASERNAV II

LASERNAV II INS with the following external navaids:	Every 14 seconds	Every 35 seconds	Every 3 minutes	Every 15 minutes	Every 30 minutes	Every 45 minutes
Periodic fixes from VOR/DME	26 meters	36 meters	54 meters	88 meters (increasing)	93 meters (increasing)	106 meters (increasing)
Periodic fixes from Surveyed Retroreflector	2.5	3.2	6	12	17	22
Simultaneous Periodic fixes from both VOR/DME and Surveyed Retroreflector	2.5	3.2	6	12	17	22

---

[1] Results displayed here under common assumption that initial steady-state calibration/alignment of INS was performed prior to take-off.

[2] Accuracy Disclaimer: above numerical evaluations are only good ± 20 % (but always in the same direction to enable relative comparisons) by avoiding greater computational burden of using joint truth model and filter model. VOR/DME fixes may be correlated over short time intervals (e.g., 14 and 35 sec.) and therefore violate assumption of independent measurements for accurate evaluation via Kalman covariance methodology.

[3] Airborne Differential GPS already demonstrated to provide 1 to 2 meter accuracy in real-time.

[4] Airborne Differential GPS already demonstrated to provide 5 to 12 centimeter accuracy in post-processing mode.

[5] Airborne GPS provides ~ 30 meter accuracy (SEP=16 meters) in real-time (using military P-code, otherwise 100 meters with commercial C/A-code).

Maximum 1-sigma Tilt Error for Airborne LASERNAV II, After 4 Hours

LASERNAV II INS with the following external navaids:	Every 14 seconds	Every 35 seconds	Every 3 minutes	Every 15 minutes	Every 30 minutes	Every 45 minutes
Periodic fixes from VOR/DME	5.0 $\overset{\frown}{\text{min}}$ (1.45 milliradian)	5.3 $\overset{\frown}{\text{min}}$ (1.54)	5.3 $\overset{\frown}{\text{min}}$ (1.54)	5.3 $\overset{\frown}{\text{min}}$ (1.54)	5.1 $\overset{\frown}{\text{min}}$ (1.48)	6 $\overset{\frown}{\text{min}}$ (1.75)
Periodic fixes from Surveyed Retroreflector	1.46 (0.42)	1.5 (0.43)	1.94 (0.56)	3.6 (1.05)	4.2 (1.22)	4.8 (1.4)
Simultaneous Periodic fixes from both VOR/DME and Surveyed Retroreflector	1.46 (0.42)	1.5 (0.43)	1.94 (0.56)	3.6 (1.05)	4.2 (1.22)	4.8 (1.4)

---

[10] Results displayed here under common assumption that initial steady-state calibration/alignment of INS was performed prior to take-off.

[11] Accuracy Disclaimer: above numerical evaluations are only good ± 20 % by avoiding greater computational burden of using joint truth model and filter model. VOR/DME fixes may be correlated over short time intervals (e.g., 14 and 35 sec.) and therefore violate assumption of independent measurements for accurate evaluation via Kalman covariance methodology.

[12] Compare results here to situation of no fixes being taken yielding maximum tilt error of 2.8 arcminutes.

[13] GPS phase-differences received over a 1 meter baseline have been used for attitude determination to 1-3 milliradians.

INTERMEDIATE CONCLUSIONS

- **BETWEEN THE CONVENTIONAL NAVAIDS AVAILABLE TO LASERNAV II, BEING VOR/DME AND PRE-SURVEYED RETROREFLECTORS:**
  - Use of retroreflectors alone provides as much position fix accuracy as simultaneous VOR/DME and retroreflector fix together;
  - Position accuracy availed from fixes every 3 minutes is TWICE as good as that every 15 min and THREE times better than offered every 30 or 45 min.

- **ATTITUDE OR TILT INFO FROM LASERNAV II IS CONTINUALLY WORSENING (to 1.57 milliradians) AND IS EVIDENTLY AGGRAVATED BY THE NECESSARY USE OF POSITION FIXES UNLESS HIGH RATE 3 min FIXES ARE USED (*but represent a high workload for NAV operator in manual insertion*).**

- **HIGH RATE FOR VOR/DME (< 3 min) LIKELY VIOLATES "INDEPENDENCE OF MEASUREMENTS" REQUIREMENT FOR STANDARD KALMAN FILTERING.**

- **HIGH RATE FOR RETROREFLECTOR FIXES LOOK GOOD BUT PRESENT OTHER DIFFICULTIES OF PRACTICALITY (*addressed in the next section*).**

RECOMMENDED SOLUTION

DATA COLLECTION OVER 10 km × 10 km PATCH

PATCHES TO BE:

- In varied TERRAIN
- In various GEOGRAPHICAL AREAS and CLUTTER
- Under various ENVIRONMENTAL CONDITIONS
  - Seasonal
  - Diurnal/Temporal
  - Snow
  - Sunny
- With various TARGETS present at KNOWN LOCATIONS

LASERNAV II WAYPOINTS

(Entered During Mission Flight Planning Using Conventional Map of Anticipated Patch Area)

Serve as Navigation Guideposts to provide visible (flashing instrument lights) or audible alarm indicators for crew that signal:

- Point-of-Closest-Approach (CPA) to current WAYPOINT
- ARRIVAL within specified distance of current WAYPOINT
- DEVIATION from proper course to follow (in accounting for wind-induced deviations) that exceed specified tolerance in progressing toward NEXT designated WAYPOINT

CONSTRAINTS ON USE: 255 WAYPOINT capability/capacity in LASERNAV II

- Can be distributed over up to 20 Flight Plans (MAX)
- Each Flight Plan consists of from 2 WAYPOINTS (MIN) to 20 WAYPOINTS (MAX)
- Flight Plans can be strung together sequentially
- MAX of 255 WAYPOINTS in LASERNAV II can be augmented by additional WAYPOINT capacity of any supplementary NAVAID introduced

HARD CONSTRAINTS BEING SATISFIED ARE:

- Abiding by allowable total mission time (*related to available fuel and other human factors*);
- Satisfying requisite airborne navigation accuracy to be maintained aloft by availing sufficient quality and frequency of navaid fixes;
- Avoid exceeding 255 as the total number of waypoints available within LASERNAV II that can be used to point the plane in the right direction along the planned row swaths (*despite presence of wind gusts*);
- Providing sufficient fiduciary markers (*every 1 km on the upper and lower borders*) inserted within the images to aid in satisfactorily lining up adjacent rows back at the Laboratory without ambiguity within the computer, and compatible with how the aligning aspect is currently done.

SOFTER CONSTRAINTS BEING SATISFIED ARE:

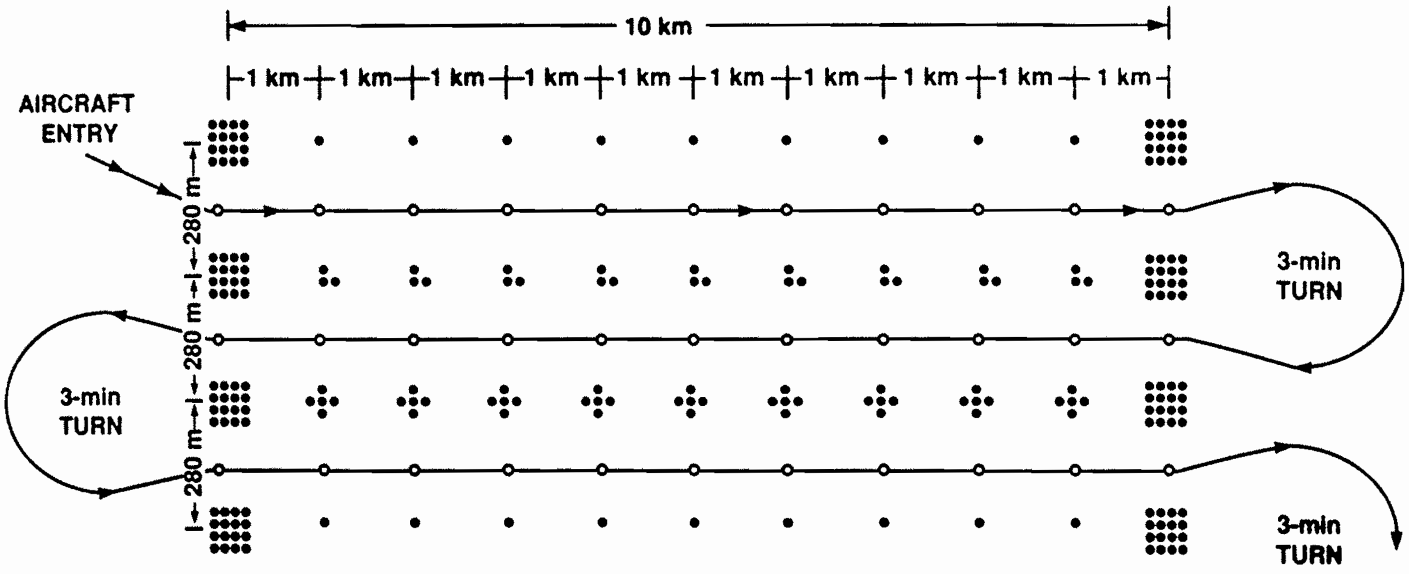
- Providing necessary visual cues to signal the pilot in real-time to initiate end-of-row turns and to aid in knowing where to return to start the next row as a back-sweep (*e.g., by alternating the color of the attached visible balloons and by providing end-of-row markers*);

- Avoid exceeding practically achievable fix rates (*of databus, of human operator*) in seeking fast NAVAID measurements to maintain assured nav accuracy, consistent with tenents of Kalman filtering (*needing independent measurements*) so can't be so fast that independence is lost;

- Introducing a retroreflector survey policy that is not exorbitantly expensive or intractable or that depends on technology not yet available.

RECOMMENDED DESIGN OF DATA PATCH PREPARATION AND FLIGHT PLANNING

Row-Bracketing Retroreflectors Used as Guideposts while Pre-inserted INS Waypoints Serve as the Path to Follow



- • RETROREFLECTORS
- ○ INS WAYPOINTS
- ▦ END OF ROW MARKERS (Also Have Colored Balloons Attached That Alternate in Color From Row to Row)

RECOMMENDED DATA COLLECTION DESIGN FOR MISSION/PATCH PREPARATION

APPROXIMATE DOVETAILING, 10 km × 10 km PATCH, exclusive GPS fixes every 1 sec:

- 280 meter EFFECTIVE row width for Line Scanner at 500 ft (*with 24 meter total anticipated/planned top and bottom row overlap of* ± 12 *meters*);
- 36 ($\approx$ 10 km/280m) rows (of length 10 km) for aircraft traversing (@ 70 m/s) = 1.43 hrs;
- 35 aircraft turns (@ 3 min/turn) = 1.75 hrs;
- 1 hr to leave and return (i.e., 140 nmi) to local airport from being "on station" yields TOTAL TIME = 1.43+1.75+1.00 = 4.18 (*close to 4 hr total mission time*);
- WAYPOINTS at beginning of row, every 1 km and at end (every 14 sec @ 140 kts) = 36 × 11 = 396 TOTAL (*MORE THAN the 255 available from LASERNAV II*) using 13 ($\approx$ 255/20) MISSION PLANS (*each consisting of 20 waypoints*) but augmented by effective MISSION PLANS available from GPS (*need additional 141 WAYPOINTS*);
- DISADVANTAGES: Exceeds 255 WAYPOINT capacity of LASERNAV II alone but can augment with WAYPOINT capacity of GPS receiver to obtain required total of 396. Can automatically enter GPS fixes into LASERNAV II this fast (*every 1 sec*) but must ALTER LASERNAV II to do so as a standard upgrade (*returning to prior automatic fix/reset configuration from factory but replacing VOR/DME option by GPS as NAVAID fix source*).

ALTERNATIVE DATA COLLECTION DESIGNS FOR MISSION/PATCH PREPARATION

By Direction, Also Investigated these Design Perturbations

- Triangulation on the retroreflectors (*from a MOVING PLATFORM*) DOESN'T show promise as a useful approach to be performed in either real-time or in post-processing mode (*since fundamental uncertainties exist in INS tilts as well as in surveyed retroreflector locations, upon which calculations would be based*). Also would need to maintain EXACT IDENTITY of all retroreflectors and their LOCATIONS (*nominally hard to distinguish unless patterns are used, but distinguishing between large numbers becomes taxing*).

- Use of SUPER-PIXELS (*aggregates of pixels recorded or blurred together into a larger one*) apparently offers NO benefits (except fewer pixels to be recorded for the same scene as a type of data reduction) but reduces resolution capability (*i.e., looses information*) and defeats use of the patterns of retroreflectors to be used as fiduciary markings that can later serve as anchors in lining up adjacent row strips. Once sensor data is collected, resolution can always be reduced in the laboratory environment, but it CAN'T be increased once THROWN AWAY.

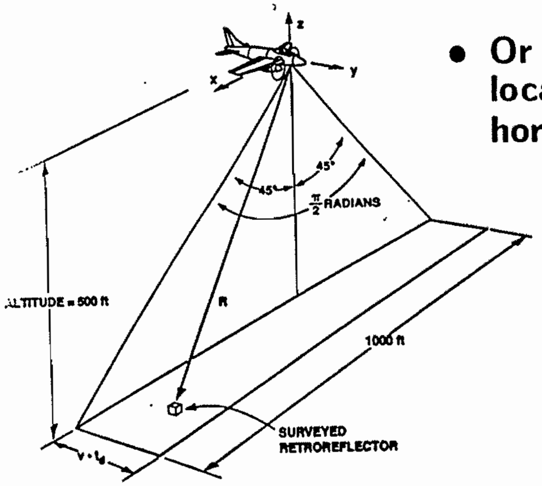
REAL-TIME COMPENSATION OF TERRAIN HEIGHT DISCREPANCIES

Which Otherwise Corrupt Computed Range, R, Since Range Uncertainty Depends on Altitude Uncertainty

$$(\sigma_R^2 = 2\,\sigma_h^2 \text{ and } \sigma_h = 13 \text{ FT})$$

<u>CAVEAT:</u> TO PIN DOWN EXPLICIT GROUND-TO-AIRCRAFT ALTITUDE IN VARIABLE TERRAIN CAN UTILIZE EITHER

- A *working* Radar Altimeter (*of sufficient accuracy*).



- Or a real-time read out from an onboard CD ROM MAP of detailed local TERRAIN HEIGHT (*if such exists*) indexed on adequate horizontal position (*but only GPS horizontal position accuracy suffices*).
  - Associated retroreflectors for NAV fixes would need more expensive survey (*exacting HORIZONTAL POSITION and ALTITUDE*) than in use as mere fiduciary markers (*coarse HORIZONTAL POSITION only*);
  - Need to sequence all retroreflector position info in computer in correct order for high-rate real-time fix insertion during data collection (*mechanism for doing so doesn't yet exist*). Can't tolerate aircraft deviations (caused by confusion or wind gusts) from preplanned sequence;

RECOMMEND

- NIX retroreflector fixes entirely and instead use LASERNAV II (*revamped to accept standard GPS fixes automatically without operator intervention*).

<u>OTHERWISE:</u> RETROREFLECTOR FIXES NOT ACCURATE ENOUGH TO PREVENT LASERNAV II WAYPOINTS FROM DRIFTING

ALTERNATIVE DATA COLLECTION DESIGNS FOR MISSION/PATCH PREPARATION

By Direction, Also Investigated these Design Perturbations

- EXACT DOVETAILING, 10 km × 10 km PATCH, exclusive RETROREFLECTOR fixes every 1 km (14 sec @ 140 kts):
  - 304.8 meter (1000 ft) row width for Line Scanner at 500 ft (*with NO anticipated/planned row overlap*);
  - 33 (≈ 10 km/280m) rows (of length 10 km) for aircraft traversing (@ 70 m/s) = 1.31 hrs;
  - 33 aircraft turns (@ 3 min/turn) = 1.65 hrs;
  - 1 hr to leave and return (i.e., 140 nmi) to local airport from being "on station" yields TOTAL TIME = 1.31+1.65+1.00 = 3.96 (*within 4 hr total mission time*);
  - WAYPOINTS at beginning of row, 2.5, 5, 7.5 km and at end (every 35 sec @ 140 kts) = 33 × 5 = 165 TOTAL (*out of 255 available*) using 9 (≈ 165/20) MISSION PLANS (*each consisting of 20 waypoints*);
  - DISADVANTAGES: Wind gusts WILL cause aircraft DRIFT and LASERNAV II fix source (*of merely retroreflectors*) not accurate enough to prevent substantial WAYPOINT DRIFT. Human can't manually enter retroreflector fixes into LASERNAV II this fast (*every 14 sec*).

- APPROXIMATE DOVETAILING, 6.5 km × 10 km PATCH, exclusive RETROREFLECTOR fixes every 1 km (14 sec @ 140 kts):
  - 280 meter EFFECTIVE row width for Line Scanner at 500 ft (*with 24 meter total anticipated/planned top and bottom row overlap of* ± 12 *meters*);
  - 23 (≈ 6.5 km/280m) rows (of length 10 km) for aircraft traversing (@ 70 m/s) = 0.90 hrs;
  - 22 aircraft turns (@ 3 min/turn) = 1.10 hrs;
  - 2 hrs to leave and return (i.e., 280 nmi) to local airport from being "on station" yields TOTAL TIME = 0.90+1.10+2.00 = 4.00 (*within 4 hr total mission time*);
  - WAYPOINTS at beginning of row, every 1 km and at end (every 14 sec @ 140 kts) = 23 × 11 = 253 TOTAL (*out of 255 available*) using 13 (≈ 253/20) MISSION PLANS (*each consisting of 20 waypoints*);
  - DISADVANTAGES: Wind gusts WILL cause aircraft DRIFT and LASERNAV II fix source (*of merely retroreflectors*) not accurate enough to prevent substantial WAYPOINT DRIFT. Human can't manually enter retroreflector fixes into LASERNAV II this fast (*every 14 sec*).

Potential for Use of Standard GPS (30 ft Std. Dev.) for LASERNAV II Automatic Fix/Resets:

COMMEND

- Would suffice to simply provide measurements (every second) instead of *needing* any other navaid fixes (every 14 or 34 seconds).
- Would also provide additional needed waypoint insertion capability that augments the 255 already offered by LASERNAV II.
- Would avoid need for additional equipment or technical innovations like an on-line CD ROM map for real-time compensation of altitude discrepancies.

Potential for Use of Differential GPS

- **Real-time mode of Differential GPS operation (5 m std. dev.) for LASERNAV II fix/resets (*available less frequently than every 14 seconds*) incurs additional complications in implementation since then need to process the double- and triple-differences on-line.**

ECOMMEND

- **Non-real-time NAV mode of Differential GPS data recorded on Imaging Sensor data tapes allows PC-based post-processing determination of position (*5-12 cm std. dev.*) that allows compensation back at the Laboratory for altitude and position biases and INS-derived attitude excursions during data recording.**

RECOMMEND

- **Existing PC-based software for Non-real-time Differential GPS position determination available from *Trimble Navigation* for $5,500.**

ECOMMEND

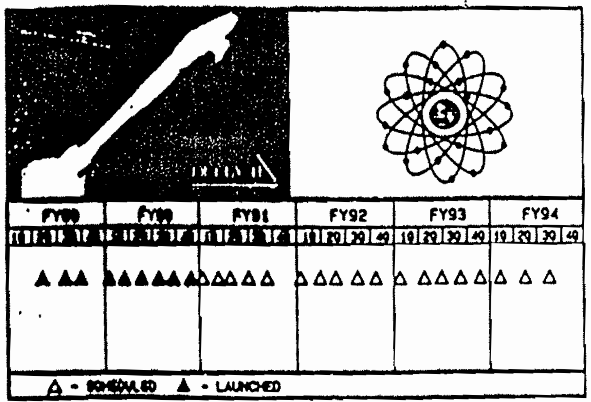
- **SOLUTION EXISTS OF PROCURRING FROM RANGE APPLICATION PROGRAM (for free) A POD-MOUNTED DIFFERENTIAL GPS SET AND INS (not ring-laser) AND REMOVE ITS 65 lb BALLAST TO YIELD NET 40 lb ADDITION TO G-1**

- **ACCURACY:**
  - GPS military users will be availed with 30 meter position accuracy, 0.1 m/sec velocity accuracy, output sampling rate of 1 Hz.
  - Differential GPS offers 1-2 cm accuracy (double/triple-differencing) airborne application (NASA/Wallops Island).
- **SCHEDULE:**
  - 6 Block I and 9 Block II GPS satellites already up (Oct 1990) now providing 24 hour global 2-D positioning capability. Users with other position info provided by altimeter or INS avoid restriction of just availing 2-D GPS position.

GPS Launch Dates (Block II Satellites)

PRN#	SV#	Plane	Carrier	Launch Date	
14	14	E1	MLV	Feb 14,	89
02	13	B2	MLV	June 10,	89
16	16	D2	MLV	Aug 18,	89
19	19	A4	MLV	Oct 21,	89
17	17	F2	MLV	Dec 11,	89
[illegible]	18	F3	MLV	Jan 24,	90
[illegible]	20	B3	MLV	Mar 26,	90
[illegible]	21		MLV	Aug 2,	90
[illegible]	15		MLV	Nov - Dec	90
[illegible]	22	.	MLV	Jan - Dec	91
[illegible]	23	.	MLV	Oct	90
	24	.	MLV	Jan - Dec	91
	25	.	MLV	Jan - Dec	91
	26	.	MLV	January	91
	27	.	MLV	March	91
	28	.	MLV	April	91
	29	.	MLV	June	91
	30	.	MLV	August	92
	31	.	MLV	October	92
	32	.	MLV	January	92
	33	.	MLV	April	92
	34	.	MLV	July	92
	35	.	MLV	October	92
	36	.	MLV	January	93
	37	.	MLV	April	93
	38	.	MLV	July	93
	39	.	MLV	January	94
	40	.	MLV	July	94

GPS BLOCK II LAUNCH SCHEDULE



PLANNED AS OF: 15 SEP 89

CONSTELLATION SIZE/ACCURACY/COVERAGE

- 12 SPACECRAFT EVENLY SPACED IN 6 PLANES
  - 10 m WORLDWIDE CEP
  - LARGE AREAS OF REDUCED 2D ACCURACY
- 18 SPACECRAFT EVENLY SPACED IN 6 PLANES
  - FULL 3D COVERAGE WITH NO AREAS OF REDUCED ACCURACY
  - 16 m WORLDWIDE SEP
  - LARGE AREAS OF REDUCED 3D ACCURACY
- 21 SPACECRAFT OPTIMALLY PLACED IN 6 PLANES
  - 16 m WORLDWIDE SEP WITH SMALL AREAS OF REDUCED ACCURACY
- 24 SPACECRAFT EVENLY OR OPTIMALLY PLACED IN 6 PLANES
  - FULL 3D COVERAGE WITH NO AREAS OF REDUCED ACCURACY

CONSTELLATION BUILDUP DESIGNED TO OPTIMIZE WORLDWIDE COVERAGE

THE GPS FIRST LAUNCH CHALLENGE

- NEW SATELLITE (BLOCK II)
- NEW BOOSTER (DELTA II)
- NEW FACILITY (CSOC/MCC-1)
- NEW LAUNCH ORGANIZATION (1SCS)
- NEW COMMAND AND CONTROL SYSTEM (DSM)