EE 565: Position, Navigation and Timing

Navigation Equations: Nav Mechanization

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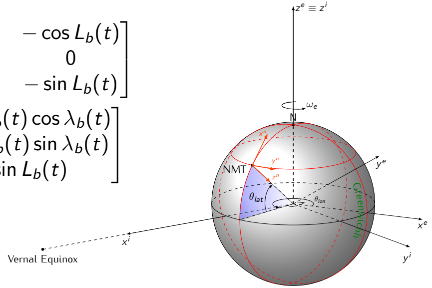
- Determine the position, velocity and attitude of the **body** frame *wrt* the **Nav** frame.
  - **Position** — Typically described in curvlinear coordinates: $[L_b, \lambda_b, h_b]^T$
  - **Velocity** — Velocity of the body frame *wrt* the earth frame resolved in the navigation frame: $\vec{v}^{\,n}_{eb}$
  - **Attitude** — Orientation of the body frame *wrt* the navigation frame: C_b^n

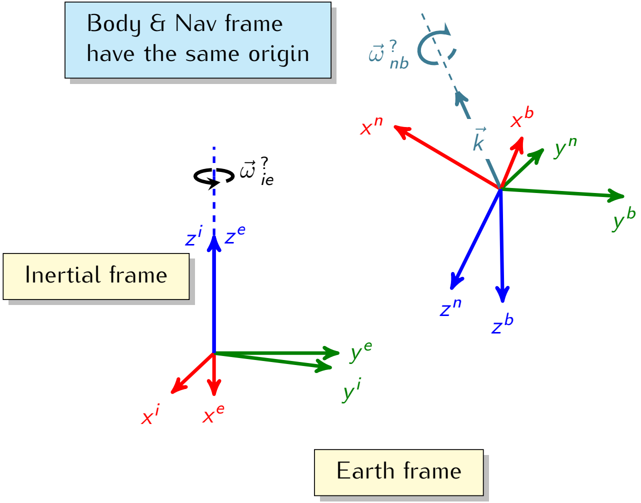
- Description of the Nav frame
  - Orientation of the *n*-frame *wrt* the *e*-frame

$$C_n^e(t) = R_{(\vec{z},\lambda_b(t))} R_{(\vec{y},-L_b(t)-90^\circ)}$$
$$= \begin{bmatrix} \cos\lambda_b(t) & -\sin\lambda_b(t) & 0 \\ \sin\lambda_b(t) & \cos\lambda_b(t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -\sin L_b(t) & 0 & -\cos L_b(t) \\ 0 & 1 & 0 \\ \cos L_b(t) & 0 & -\sin L_b(t) \end{bmatrix}$$
$$= \begin{bmatrix} -\sin L_b(t)\cos\lambda_b(t) & -\sin\lambda_b(t) & -\cos L_b(t)\cos\lambda_b(t) \\ -\sin L_b(t)\sin\lambda_b(t) & \cos\lambda_b(t) & -\cos L_b(t)\sin\lambda_b(t) \\ \cos L_b(t) & 0 & -\sin L_b(t) \end{bmatrix}$$

where geodetic Lat $= L_b$ and Geodetic Lon $= \lambda_b$



Body *wrt* Nav Frame



- Start with angular velocity

$$\vec{\omega}^{b}_{ib} =$$

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$$\vec{\omega}^{b}_{ib} = \vec{\omega}^{b}_{ie} + \vec{\omega}^{b}_{en} + \vec{\omega}^{b}_{nb} \rightarrow \vec{\omega}^{b}_{nb} = \vec{\omega}^{b}_{ib} - \vec{\omega}^{b}_{ie} - \vec{\omega}^{b}_{en}$$

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- Now

$$\begin{aligned}\dot{C}^n_b &= C^n_b \Omega^b_{nb} = C^n_b \left(\Omega^b_{ib} - \Omega^b_{ie} - \Omega^b_{en}\right) \\ &= C^n_b \Omega^b_{ib} - C^n_b \Omega^b_{ie} - C^n_b \Omega^b_{en} \\ &= C^n_b \Omega^b_{ib} - \left(\Omega^n_{ie} + \Omega^n_{en}\right) C^n_b\end{aligned}$$

- Start with angular velocity

$$\vec{\omega}^{\,b}_{ib} = \vec{\omega}^{\,b}_{ie} + \vec{\omega}^{\,b}_{en} + \vec{\omega}^{\,b}_{nb} \rightarrow \vec{\omega}^{\,b}_{nb} = \vec{\omega}^{\,b}_{ib} - \vec{\omega}^{\,b}_{ie} - \vec{\omega}^{\,b}_{en}$$

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Recall that:
$[(C\vec{\omega})\times] = C[\vec{\omega}\times]C^T$
$C[\vec{\omega}\times] = [(C\vec{\omega})\times]C$

- Start with angular velocity

$$\vec{\omega}^{\,b}_{ib} = \vec{\omega}^{\,b}_{ie} + \vec{\omega}^{\,b}_{en} + \vec{\omega}^{\,b}_{nb} \rightarrow \vec{\omega}^{\,b}_{nb} = \vec{\omega}^{\,b}_{ib} - \vec{\omega}^{\,b}_{ie} - \vec{\omega}^{\,b}_{en}$$

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Recall that:
$[(C\vec{\omega})\times] = C[\vec{\omega}\times]C^T$
$C[\vec{\omega}\times] = [(C\vec{\omega})\times]C$

$$\omega^n_{ie} = C^n_e \omega^e_{ie} = \omega_{ie} \begin{bmatrix} \cos L_b \\ 0 \\ -\sin L_b \end{bmatrix}$$

- $\Omega^n_{en} = [\vec{\omega}^{\,n}_{en} \times]$
- Courtesy of Prof. Bruder and Mathematica

$$\dot{C}^e_n = C^e_n \Omega^n_{en} \rightarrow \Omega^n_{en} = \left(C^e_n\right)^T \dot{C}^e_n = \begin{bmatrix} 0 & \dot{\lambda}_b \sin L_b & -\dot{L}_b \\ -\dot{\lambda}_b \sin L_b & 0 & -\dot{\lambda}_b \cos L_b \\ \dot{L}_b & \dot{\lambda}_b \cos L_b & 0 \end{bmatrix}$$

- $\Omega_{en}^{n} = [\vec{\omega}\,_{en}^{n} \times]$
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$$\dot{C}_n^e = C_n^e \Omega_{en}^n \to \Omega_{en}^n = \left(C_n^e\right)^T \dot{C}_n^e = \begin{bmatrix} 0 & \dot{\lambda}_b \sin L_b & -\dot{L}_b \\ -\dot{\lambda}_b \sin L_b & 0 & -\dot{\lambda}_b \cos L_b \\ \dot{L}_b & \dot{\lambda}_b \cos L_b & 0 \end{bmatrix}$$

- therefore,

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- therefore,

$$\omega^n_{en} = \begin{bmatrix} \dot{\lambda}_b \cos L_b \\ -\dot{L}_b \\ -\dot{\lambda}_b \sin L_b \end{bmatrix}$$

- Finally since,

$$\begin{bmatrix} \dot{L}_b \\ \dot{\lambda}_b \\ \dot{h}_b \end{bmatrix} = \begin{bmatrix} \frac{\vec{v}^{\,n}_{eb,N}}{R_N + h_b} \\ \frac{\vec{v}^{\,n}_{eb,E}}{\cos(L_b)(R_E + h_b)} \\ -\vec{v}^{\,n}_{eb,D} \end{bmatrix}$$

- then

$$\omega^n_{en} = \begin{bmatrix} \frac{\vec{v}^{\,n}_{eb,E}}{R_E + h_b} \\ -\frac{\vec{v}^{\,n}_{eb,N}}{R_N + h_b} \\ -\frac{\tan(L_b)\vec{v}^{\,n}_{eb,E}}{R_E + h_b} \end{bmatrix} \qquad (1)$$

Attitude — Method A

$$C_b^n(+) - C_b^n(-) \approx \Delta t \dot{C}_b^n$$

$$\begin{aligned} C_b^n(+) &\approx C_b^n(-) + \Delta t \left[C_b^n \Omega_{ib}^b - \left(\Omega_{ie}^n + \Omega_{en}^n \right) C_b^n(-) \right] \\ &= C_b^n(-) \left(\mathcal{I} + \Omega_{ib}^b \Delta t \right) - \left(\Omega_{ie}^n + \Omega_{en}^n \right) C_b^n(-) \Delta t \end{aligned}$$

- Body orientation frame at time "k" *wrt* time "$k-1$"
  - $\Delta t = t_k - t_{k-1}$
- Start with the angular velocity

$$\omega^b_{nb} = \omega^b_{ib} - \omega^b_{ie} - \omega^b_{en}$$

$$\begin{aligned}\Omega^b_{nb} &= \Omega^b_{ib} - \Omega^b_{ie} - \Omega^b_{en} \\ &= \Omega^b_{ib} - C^b_n \Omega^n_{ie} C^n_b - C^b_n \Omega^n_{en} C^n_b\end{aligned}$$

$$C^n_b(+) = C^n_b(-) e^{\Omega^b_{nb}\Delta t}$$

$$C^n_b(+) = C^n_b(-)\left[\mathcal{I} + \sin(\Delta\theta)\mathfrak{K} + [1-\cos(\Delta\theta)]\,\mathfrak{K}^2\right]$$

$$e^{\Omega^b_{nb}\Delta t} = e^{\mathfrak{K}\Delta\theta}$$

- Body orientation frame at time "k" *wrt* time "$k-1$"
  - $\Delta t = t_k - t_{k-1}$

$$\bar{q}\,^n_b(+) = \bar{q}\,^n_b(-) \otimes \Delta\bar{q}\,^{b(k-1)}_{b(k)}$$

$$\vec{\omega}\,^b_{nb}\Delta t = \vec{k}\Delta\theta$$

$$\Delta\bar{q}\,^{b(k-1)}_{b(k)} = \begin{bmatrix} \cos(\frac{\Delta\theta}{2}) \\ \vec{k}\sin(\frac{\Delta\theta}{2}) \end{bmatrix}$$

Need to periodically renormalize $\bar{q}$

Attitude Update— Summary

$\vec{\omega}^{\,b}_{nb}\Delta t = \vec{k}\Delta\theta$

$\mathfrak{K} = [\vec{k}\times]$

- High fidelity

$$C^n_b(+) = C^n_b(-)\left[\mathcal{I} + \sin(\Delta\theta)\mathfrak{K} + [1 - \cos(\Delta\theta)]\,\mathfrak{K}^2\right] \quad (2)$$

or

$$\bar{q}^{\,n}_{\,b}(+) = \bar{q}^{\,n}_{\,b}(-) \otimes \Delta\bar{q}^{\,b(k-1)}_{\,b(k)}$$

$$\Delta\bar{q}^{\,b(k-1)}_{\,b(k)} = \begin{bmatrix} \cos(\frac{\Delta\theta}{2}) \\ \vec{k}\sin(\frac{\Delta\theta}{2}) \end{bmatrix} \quad (3)$$

- Low fidelity

$$C^n_b(+) \approx C^n_b(-)\left(\mathcal{I} + \Omega^b_{ib}\Delta t\right) - \left(\Omega^n_{ie} + \Omega^n_{en}\right) C^n_b(-)\Delta t \quad (4)$$

2. Specific force transformation
   - Simply coordinatize the specific force

$$\vec{f}^{\,n}_{ib} = C^n_b(+)\vec{f}^{\,b}_{ib} \tag{5}$$

Steps 2–4

3. Velocity update
   - Note that: $\vec{v}^{\,n}_{eb} = C^n_e \vec{v}^{\,e}_{eb}$

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$$\dot{\vec{v}}\,^e_{eb} = \vec{a}\,^e_{eb} = \vec{f}\,^e_{ib} + \vec{g}\,^e_b - 2\Omega^e_{ie}\vec{v}\,^e_{eb}$$

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$$\dot{\vec{v}}^{\,n}_{eb} = \dot{C}^n_e \vec{v}^{\,e}_{eb} + C^n_e \dot{\vec{v}}^{\,e}_{eb}$$

$$= \Omega^n_{ne} C^n_e \vec{v}^{\,e}_{eb} + C^n_e \left(\vec{f}^{\,e}_{ib} + \vec{g}^{\,e}_{b} - 2\Omega^e_{ie}\vec{v}^{\,e}_{eb}\right)$$

Steps 2–4

$$\dot{\vec{v}}^{\,e}_{eb} = \vec{a}^{\,e}_{eb} = \vec{f}^{\,e}_{ib} + \vec{g}^{\,e}_{b} - 2\Omega^e_{ie}\vec{v}^{\,e}_{eb}$$

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$$\begin{aligned}
\dot{\vec{v}}^{\,n}_{eb} &= \dot{C}^n_e \vec{v}^{\,e}_{eb} + C^n_e \dot{\vec{v}}^{\,e}_{eb} \\
&= \Omega^n_{ne} C^n_e \vec{v}^{\,e}_{eb} + C^n_e \left(\vec{f}^{\,e}_{ib} + \vec{g}^{\,e}_{b} - 2\Omega^e_{ie}\vec{v}^{\,e}_{eb}\right) \\
&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \Omega^n_{en}\vec{v}^{\,n}_{eb} - 2C^n_e\Omega^e_{ie}\vec{v}^{\,e}_{eb}
\end{aligned}$$

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&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \Omega^n_{en}\vec{v}^{\,n}_{eb} - 2C^n_e\Omega^e_{ie}\vec{v}^{\,e}_{eb} \\
&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \Omega^n_{en}\vec{v}^{\,n}_{eb} - 2\Omega^n_{ie}C^n_e\vec{v}^{\,e}_{eb}
\end{aligned}$$

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$$\begin{aligned}
\dot{\vec{v}}^{\,n}_{eb} &= \dot{C}^n_e \vec{v}^{\,e}_{eb} + C^n_e \dot{\vec{v}}^{\,e}_{eb} \\
&= \Omega^n_{ne} C^n_e \vec{v}^{\,e}_{eb} + C^n_e \left(\vec{f}^{\,e}_{ib} + \vec{g}^{\,e}_{b} - 2\Omega^e_{ie}\vec{v}^{\,e}_{eb}\right) \\
&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \Omega^n_{en}\vec{v}^{\,n}_{eb} - 2C^n_e\Omega^e_{ie}\vec{v}^{\,e}_{eb} \\
&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \Omega^n_{en}\vec{v}^{\,n}_{eb} - 2\Omega^n_{ie}C^n_e\vec{v}^{\,e}_{eb} \\
&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \left(\Omega^n_{en} + 2\Omega^n_{ie}\right)\vec{v}^{\,n}_{eb}
\end{aligned}$$

$$\dot{\vec{v}}^{\,e}_{eb} = \vec{a}^{\,e}_{eb} = \vec{f}^{\,e}_{ib} + \vec{g}^{\,e}_{b} - 2\Omega^e_{ie}\vec{v}^{\,e}_{eb}$$

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$$\begin{aligned}
\dot{\vec{v}}^{\,n}_{eb} &= \dot{C}^n_e \vec{v}^{\,e}_{eb} + C^n_e \dot{\vec{v}}^{\,e}_{eb} \\
&= \Omega^n_{ne} C^n_e \vec{v}^{\,e}_{eb} + C^n_e \left(\vec{f}^{\,e}_{ib} + \vec{g}^{\,e}_{b} - 2\Omega^e_{ie}\vec{v}^{\,e}_{eb} \right) \\
&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \Omega^n_{en}\vec{v}^{\,n}_{eb} - 2C^n_e\Omega^e_{ie}\vec{v}^{\,e}_{eb} \\
&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \Omega^n_{en}\vec{v}^{\,n}_{eb} - 2\Omega^n_{ie}C^n_e\vec{v}^{\,e}_{eb} \\
&= \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \left(\Omega^n_{en} + 2\Omega^n_{ie}\right)\vec{v}^{\,n}_{eb}
\end{aligned}$$

   - Finally,

$$\vec{v}^{\,n}_{eb}(+) = \vec{v}^{\,n}_{eb}(-) + \Delta t \left[\vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - \left(\Omega^n_{en} + 2\Omega^n_{ie}\right)\vec{v}^{\,n}_{eb}(-) \right]$$

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4. Position update
   - Recalling that

$$\begin{bmatrix} \dot{L}_b \\ \dot{\lambda}_b \\ \dot{h}_b \end{bmatrix} = \begin{bmatrix} \frac{\vec{v}^{\,n}_{eb,N}}{R_N+h_b} \\ \frac{\vec{v}^{\,n}_{eb,E}}{\cos(L_b)(R_E+h_b)} \\ -\vec{v}^{\,n}_{eb,D} \end{bmatrix}$$

5. then

$$h_b(+) = h_b(-) - \Delta t \left[\vec{v}^{\,n}_{eb,D}\right]$$

$$L_b(+) = L_b(-) + \Delta t \left[\frac{\vec{v}^{\,n}_{eb,N}}{R_N + h_b}\right]$$

$$\lambda_b(+) = \lambda_b(-) + \Delta t \left[\frac{\vec{v}^{\,n}_{eb,E}}{\cos(L_b)(R_E + h_b)}\right]$$

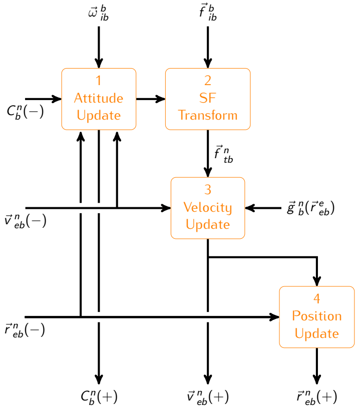
$$C_b^n(+) = C_b^n(-)\left[\mathcal{I} + \sin(\Delta\theta)\mathfrak{K} + [1-\cos(\Delta\theta)]\,\mathfrak{K}^2\right] \qquad (6)$$

or

$$\bar{q}\,{}_b^n(+) = \bar{q}\,{}_b^n(-) \otimes \Delta\bar{q}\,{}_{b(k)}^{b(k-1)}, \quad \Delta\bar{q}\,{}_{b(k)}^{b(k-1)} = \begin{bmatrix} \cos(\frac{\Delta\theta}{2}) \\ \vec{k}\sin(\frac{\Delta\theta}{2}) \end{bmatrix} \qquad (7)$$

or

$$C_b^n(+) \approx C_b^n(-)\left(\mathcal{I} + \Omega_{ib}^b\Delta t\right) - \left(\Omega_{ie}^n + \Omega_{en}^n\right)C_b^n(-)\Delta t \qquad (8)$$



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$$\vec{f}^{\,n}_{ib} = C^n_b(+)\vec{f}^{\,b}_{ib} \tag{9}$$

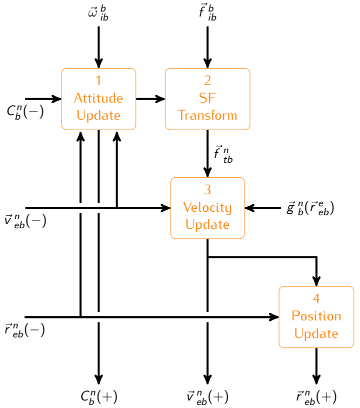
$$\vec{a}^{\,n}_{eb} = \vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - (\Omega^n_{en} + 2\Omega^n_{ie})\vec{v}^{\,n}_{eb} \tag{10}$$

$$\vec{v}^{\,n}_{eb}(+) = \vec{v}^{\,n}_{eb}(-) + \Delta t\left[\vec{f}^{\,n}_{ib} + \vec{g}^{\,n}_{b} - (\Omega^n_{en} + 2\Omega^n_{ie})\,\vec{v}^{\,n}_{eb}(-)\right] \tag{11}$$

$$L_b(+) = L_b(-) + \Delta t\left[\frac{\vec{v}^{\,n}_{eb,N}}{R_N + h_b}\right] \tag{12}$$

$$\lambda_b(+) = \lambda_b(-) + \Delta t\left[\frac{\vec{v}^{\,n}_{eb,E}}{\cos(L_b)(R_E + h_b)}\right] \tag{13}$$

$$h_b(+) = h_b(-) - \Delta t\left[\vec{v}^{\,n}_{eb,D}\right] \tag{14}$$



- In continuous time notation
  - Attitude: $\dot{C}_b^n = C_b^n \Omega_{ib}^b - (\Omega_{ie}^n + \Omega_{en}^n) C_b^n$
  - Velocity: $\dot{\vec{v}}{}_{eb}^{\,n} = \vec{f}{}_{ib}^{\,n} + \vec{g}{}_{b}^{\,n} - (\Omega_{en}^n + 2\Omega_{ie}^n)\vec{v}{}_{eb}^{\,n}$
  - Position:

$$\begin{bmatrix} \dot{L}_b \\ \dot{\lambda}_b \\ \dot{h}_b \end{bmatrix} = \begin{bmatrix} \frac{\vec{v}{}_{eb,N}^{\,n}}{R_N + h_b} \\ \frac{\vec{v}{}_{eb,E}^{\,n}}{\cos(L_b)(R_E + h_b)} \\ -\vec{v}{}_{eb,D}^{\,n} \end{bmatrix}$$

- In State-space notation

$$\begin{bmatrix} \dot{L}_b \\ \dot{\lambda}_b \\ \dot{h}_b \\ \dot{\vec{v}}\,^n_{eb} \\ \dot{C}^n_b \end{bmatrix} = \begin{bmatrix} \frac{\vec{v}\,^n_{eb,N}}{R_N + h_b} \\ \frac{\vec{v}\,^n_{eb,E}}{\cos(L_b)(R_E + h_b)} \\ -\vec{v}\,^n_{eb,D} \\ \vec{f}\,^n_{ib} + \vec{g}\,^n_b - (\Omega^n_{en} + 2\Omega^n_{ie})\vec{v}\,^n_{eb} \\ C^n_b \Omega^b_{ib} - (\Omega^n_{ie} + \Omega^n_{en}) C^n_b \end{bmatrix} \tag{15}$$

$$[\bar{q}\otimes] = \begin{bmatrix} q_s & -q_x & -q_y & -q_z \\ q_x & q_s & -q_z & q_y \\ q_y & q_z & q_s & -q_x \\ q_z & -q_y & q_x & q_s \end{bmatrix}$$

$$[\bar{q}\circledast] = \begin{bmatrix} q_s & -q_x & -q_y & -q_z \\ q_x & q_s & q_z & -q_y \\ q_y & -q_z & q_s & q_x \\ q_z & q_y & -q_x & q_s \end{bmatrix}$$