# Lecture

## Navigation Mathematics: Kinematics (Earth Surface & Gravity Models)

### EE 565: Position, Navigation and Timing

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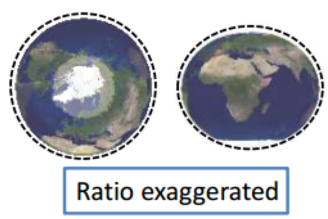
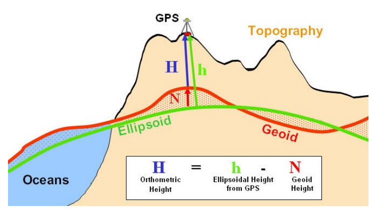
### Earth Modeling

- The earth can be modeled as an oblate spheroid
  - A circular cross section when viewed from the polar axis (top view)
  - An elliptical cross-section when viewed perpendicular to the polar axis (side view)




- This ellipsoid (i.e., oblate spheroid) is an approximation of the "geoid"
- The geoid is a gravitational equipotential surface which "best" fits (in the least square sense) the mean sea level

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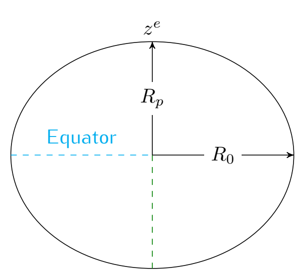
### Earth Modeling

- WGS 84 provides as model of the earth's geoid
  - More recently replace by EGM 2008
- The equatorial radius radius $R_0 = 6,378,137.0\text{m}$
- The polar radius radius $R_p = 6,356,752.3142\text{m}$
- Eccentricity of the ellipsoid

$$e = \sqrt{1 - \frac{R_p^2}{R_0^2}} \approx 0.0818$$

- Flattening of the ellipsoid

$$f = \frac{R_0 - R_p}{R_0} \approx \frac{1}{298}$$

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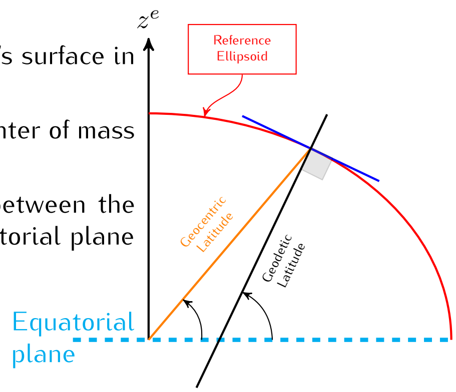
## Earth Modeling

- We can define a position “near” the earth’s surface in terms of latitude, longitude, and height
  - Geocentric latitude intersects the center of mass of the earth
  - Geodetic latitude ($L$) is the angle between the normal to the ellipsoid and the equatorial plane

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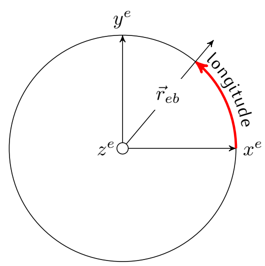
## Earth Modeling

- The longitude ($\lambda$) is the angle from the $x$-axis of the ECEF frame to the projection of $\vec{r}_{eb}$ onto the equatorial plane

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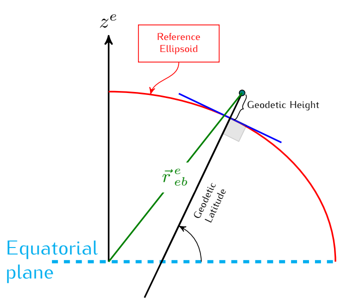
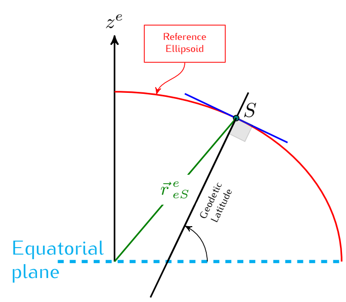
## Earth Modeling

- The geocentric radius is the distance from center of the Earth to the point $S$
- The geodetic (or ellipsoidal) height ($h$) is the distance along the normal from the ellipsoid to the body

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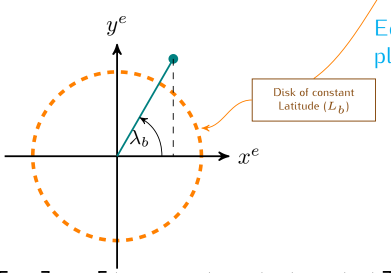
## Earth Modeling

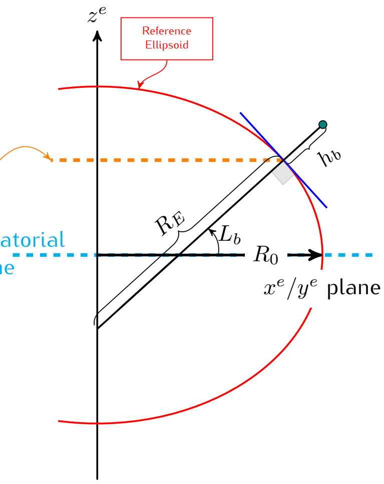
- Transverse radius of curvature

$$R_E(L) = \frac{R_0}{\sqrt{1 - e^2 \sin^2(L)}} \qquad (1)$$

- Meridian radius of curvature

$$R_N(L) = \frac{(1 - e^2)R_0}{\left(1 - e^2 \sin^2(L)\right)^{3/2}} \qquad (2)$$



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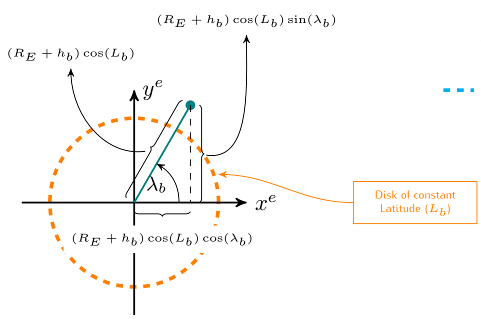
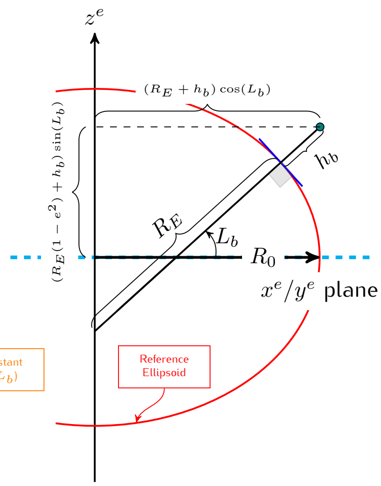
## Earth Modeling

$$\vec{r}^{\,e}_{eb} = \begin{bmatrix} x^e_{eb} \\ y^e_{eb} \\ z^e_{eb} \end{bmatrix} = \begin{bmatrix} (R_E + h_b)\cos(L_b)\cos(\lambda_b) \\ (R_E + h_b)\cos(L_b)\sin(\lambda_b) \\ (R_E(1 - e^2) + h_b)\sin(L_b) \end{bmatrix}$$



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## Gravity Models

- Specific force ($\vec{f}_{ib}$)
  - Non-gravitational force per unit mass (unit of acceleration)
    - Accelerometers measure specific force
- Specific force sensed when stationary (*wrt* earth) is referred to as the acceleration due to gravity ($\vec{g}_b$)
  - Actually, the reaction to this force
- Gravitational force ($\gamma_{ib}$) is result of mass attraction
  - The gravitational mass attraction force is different from the acceleration due to gravity

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## Gravity Models

- Relationship between specific force, inertial acceleration, and gravitational attraction

  **Specific force**

$$\vec{f}_{ib} = \vec{a}_{ib} - \vec{\gamma}_{ib} \qquad (3)$$

- When stationary on the surface of the earth
  - A fixed point in a rotating frame

$$\ddot{\vec{r}}^{\,0}_{02}(t) = \overset{\color{red}\dot{\omega}=0}{\cancel{\dot{\vec{\omega}}^{\,0}_{01} \times \vec{r}^{\,0}_{12}(t)}} \qquad + \vec{\omega}^{\,0}_{01} \times \left(\vec{\omega}^{\,0}_{01} \times \vec{r}^{\,0}_{12}(t)\right)$$

    * Consider frame {0} to be the {i} frame, {1}={e}, and {2}={b} gives

$$\ddot{\vec{r}}^{\,i}_{ib}(t) = \vec{\omega}^{\,i}_{ie} \times \left(\vec{\omega}^{\,i}_{ie} \times \vec{r}^{\,i}_{eb}(t)\right)$$

    * coordinatizing in the $e$-frame

$$\ddot{\vec{r}}^{\,e}_{ib}(t) = \vec{\omega}^{\,e}_{ie} \times (\vec{\omega}^{\,e}_{ie} \times \vec{r}^{\,e}_{eb}(t))$$

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## Gravity Models

- Thus, when stationary on the surface of the earth the acceleration is due to centrifugal force

$$\vec{a}^{\,e}_{ib} = \Omega^e_{ie}\Omega^e_{ie}\vec{r}^{\,e}_{eb}$$

- Therefore, the acceleration due to gravity is

$$\vec{g}^{\,e}_{b} = -\left.\vec{f}_{ib}\right|_{\vec{v}^{\,e}_{eb}=0} = -\Omega^e_{ie}\Omega^e_{ie}\vec{r}^{\,e}_{eb} + \vec{\gamma}^{\,e}_{ib} \tag{4}$$

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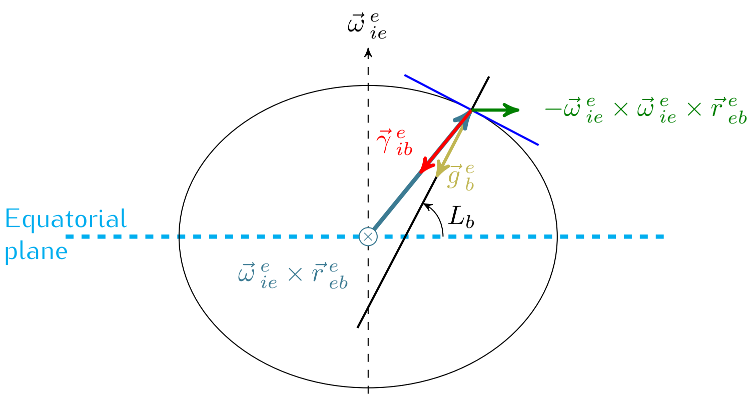
## Gravity Models




$$\underbrace{\vec{g}^{\,e}_{b}}_{1\mathrm{g}} = \underbrace{-\Omega^e_{ie}\Omega^e_{ie}\vec{r}^{\,e}_{eb}}_{\approx 3\mathrm{mg}} + \underbrace{\vec{\gamma}^{\,e}_{ib}}_{\approx 1\mathrm{g}}$$

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## Gravity Models

- Now, $\vec{\omega}^{\,e}_{ie} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \omega_{ie}$ and hence, $\Omega^e_{ie} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \omega_{ie}$, and thus

$$\vec{g}^{\,e}_{b} = \vec{\gamma}^{\,e}_{ib} + \omega^2_{ie} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \vec{r}^{\,e}_{eb}$$

- The WGS 84 model of acceleration due to gravity (on the ellipsoid) can be approximated by (Somigliana model)

$$g_0(L_b) = 9.7803253359 \frac{\left(1 + 0.001931853 \sin^2(L)\right)}{\sqrt{1 - e^2 \sin^2(L)}} \tag{5}$$

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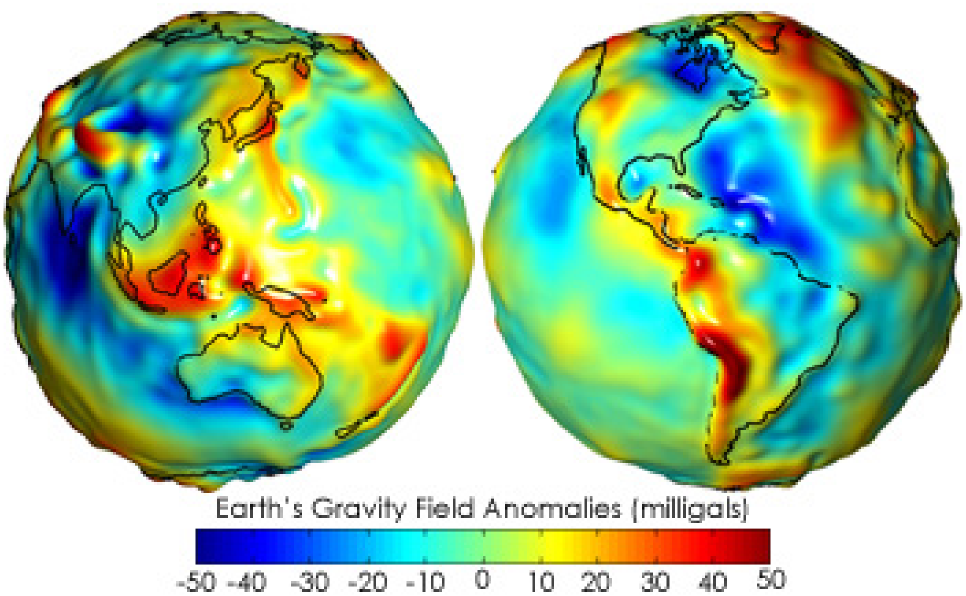
### Gravity as a Function of $L_b$, $\lambda_b$ and $h_b$

$$g^n_{b,D} = g_0(L_b, h_b)\left\{1 - \frac{2}{R_0}\left[1 + f(1 - 2\sin^2 L_b) + \frac{\omega_{ie}^2 R_0^2 R_p}{\mu}\right] h_b + \frac{3}{R_0^2} h_b^2\right\} \qquad (6)$$

where $\mu = 3.986004418 \times 10^{14}$ m$^3$/s$^2$ is the WGS 84 Earth's gravitational constant. .14

### Gravity Models

- On March 17, 2002 NASA launched the Gravity Recovery and Climate Experiment (GRACE) which led to the development of some of the most precise Earth gravity models.

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