Module 3 | Lesson 2

THE INERTIAL MEASUREMENT UNIT

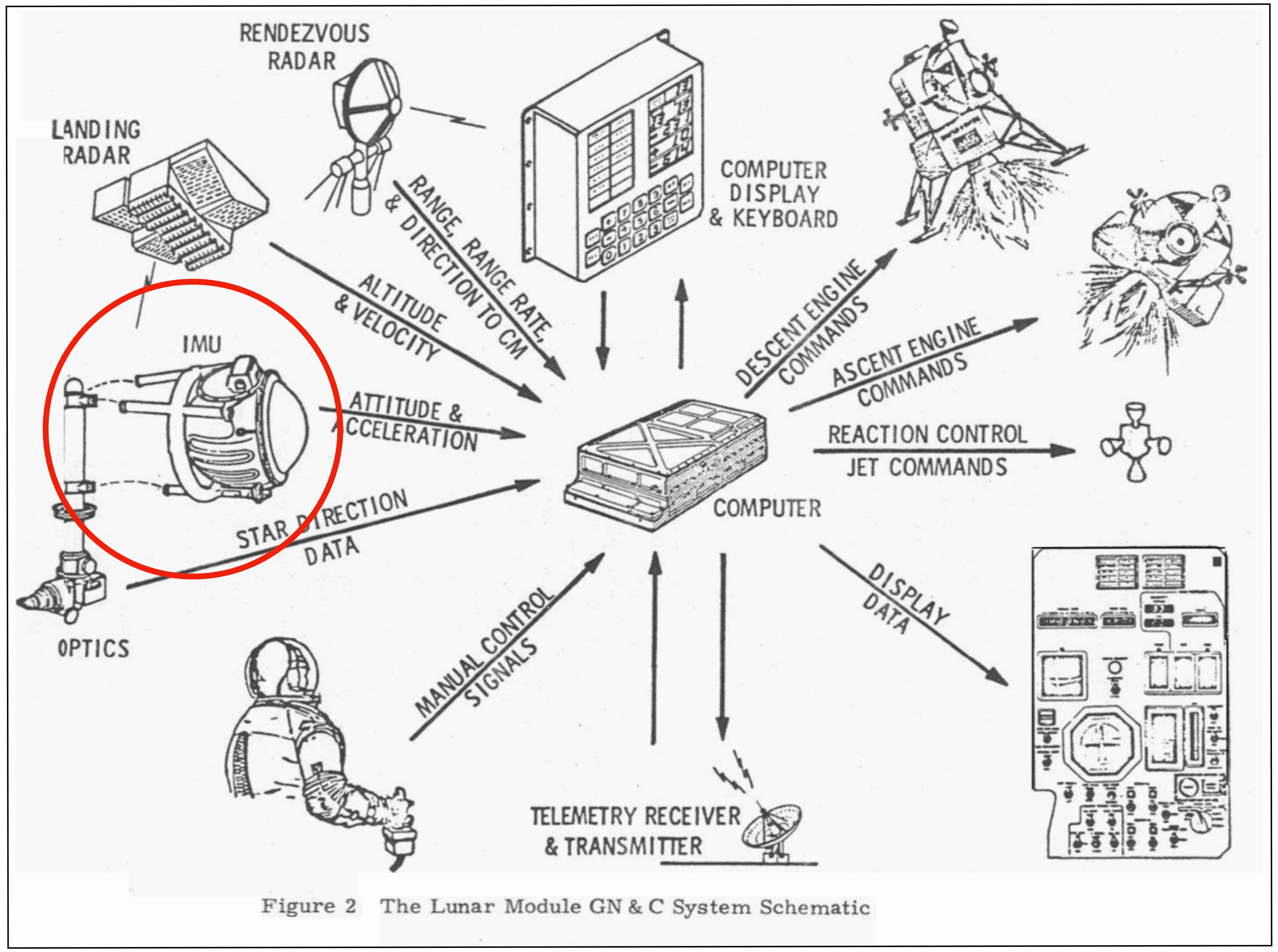
The Inertial Measurement Unit

By the end of this video, you will be able to…

- Describe the individual components (accelerometers and gyroscopes) of an inertial measurement unit and their basic operating principles.
- Define the measurement models used for accelerometers and gyroscopes.

The Inertial Measurement Unit

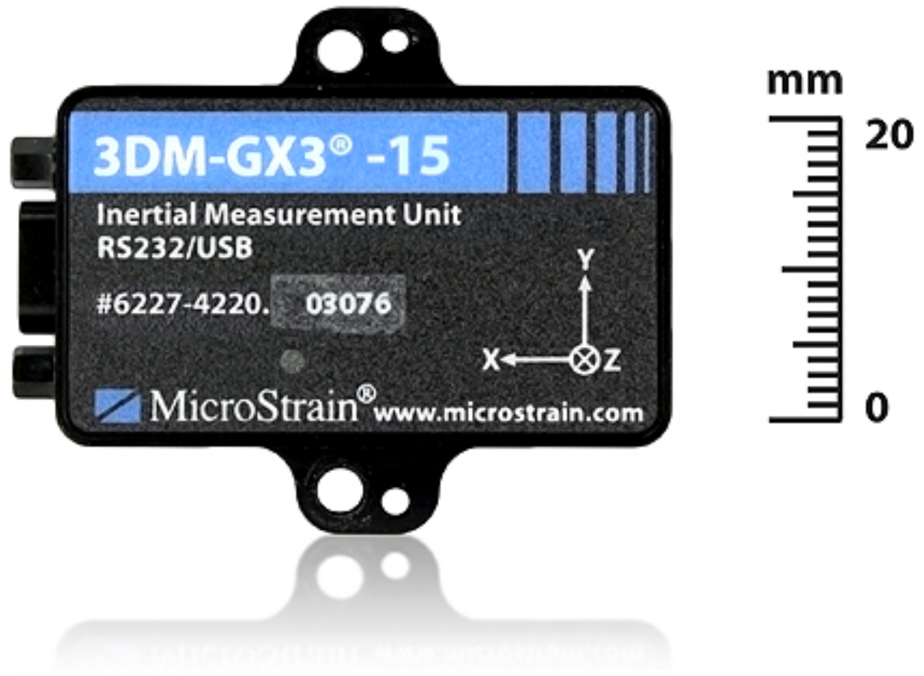
iPhone X IMU

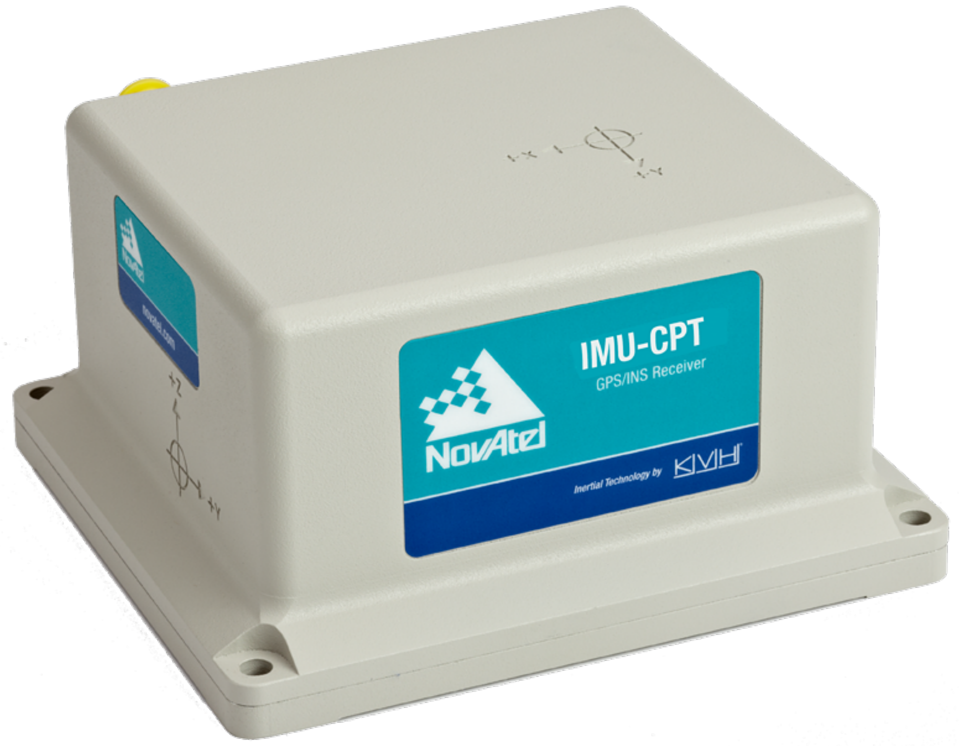


Apollo Lunar Module Guidance Navigation & Control

The Inertial Measurement Unit

- An IMU is typically composed of
  - gyroscopes (measure angular rotation rates about three separate axes)
  - accelerometers (measure accelerations along three orthogonal axes)
- IMUs come in many form factors; cost varies from ~$10 to ~$100K+



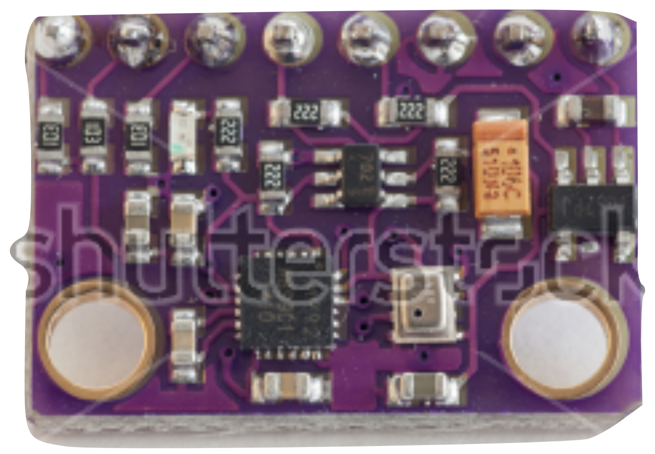


The Gyroscope

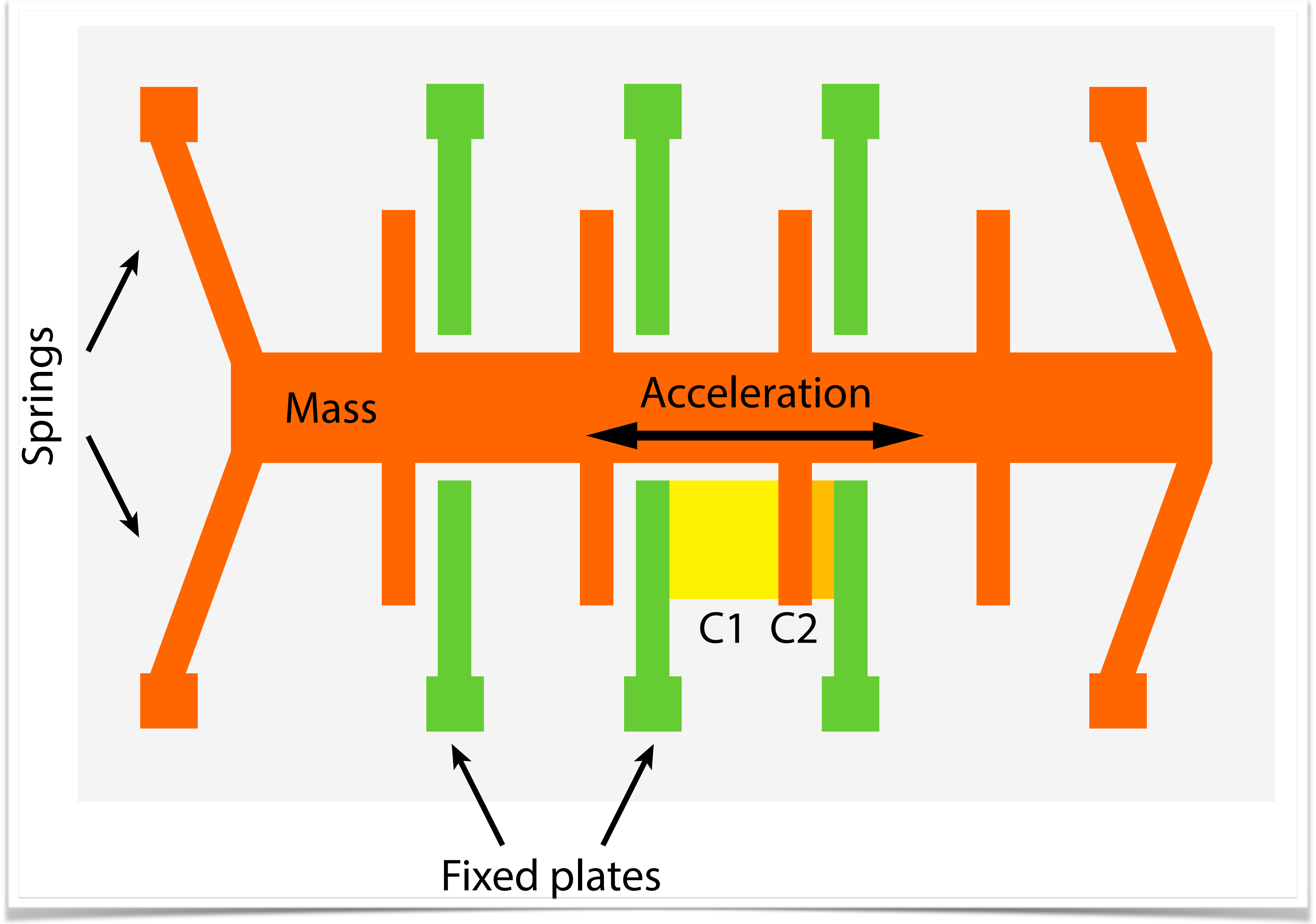
- Gyroscope: γῦρος gûros, "circle" + σκοπέω skopéō, "to look"
  - Historically: a spinning disc that maintains a specific orientation relative to *inertial space,* providing an orientation reference
  - Modern spinning-disk gyroscopes spin at up to 24,000 RPM!

- Microelectromechanical systems (MEMS) are much smaller and cheaper
  - Measure rotational *rates* instead of orientation directly
  - Measurements are **noisy** and **drift** over time

integrated to determine



The Accelerometer



- Accelerometers measure acceleration relative to *free-fall* - this is also called the *proper acceleration* or *specific force*:

$$\mathbf{a}_{\text{meas}} = \mathbf{f} = \frac{\mathbf{F}_{\text{non-gravity}}}{m}$$

Sitting still at your desk, your *proper* acceleration is g upwards! (think of the 'normal' force holding you up)

In localization, we typically require the acceleration relative to a fixed reference frame

- 'coordinate' acceleration
- computed using fundamental equation for accelerometers in a gravity field:

$$\mathbf{f} + \mathbf{g} = \ddot{\mathbf{r}}_i$$

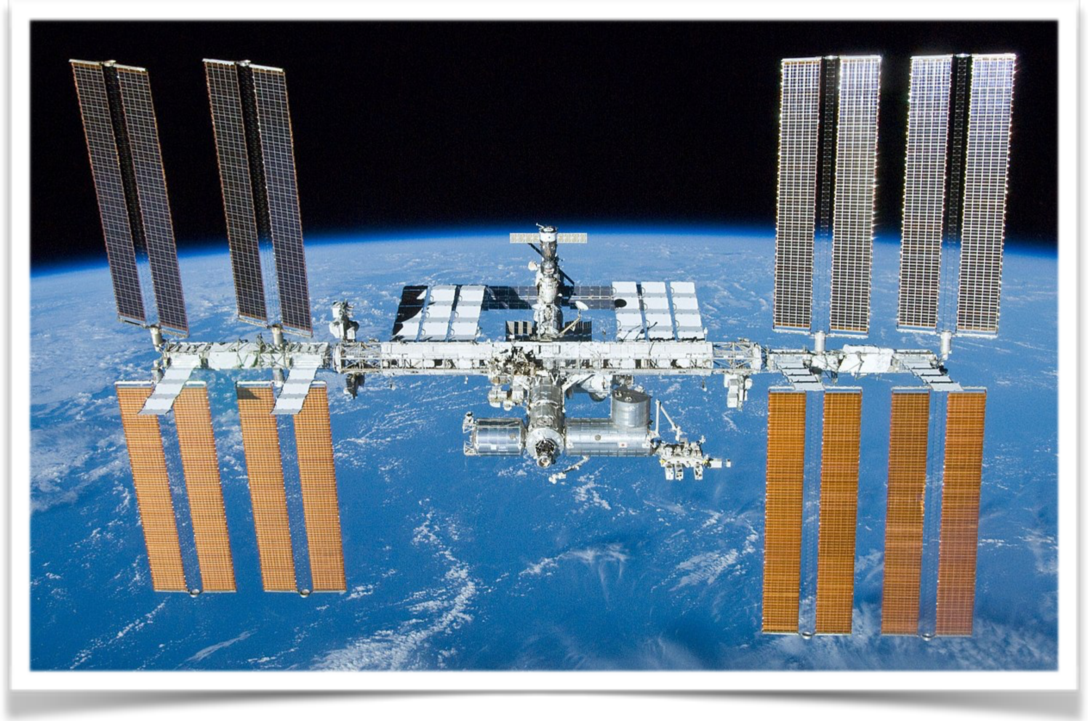
The Accelerometer | Examples

- An accelerometer in a stationary car measures:

$$\mathbf{f} = \ddot{\mathbf{r}}_i - \mathbf{g} \approx \mathbf{0} - \mathbf{g} \approx -\mathbf{g} \qquad g \text{ 'up'}$$

- An accelerometer on the International Space Station measures:

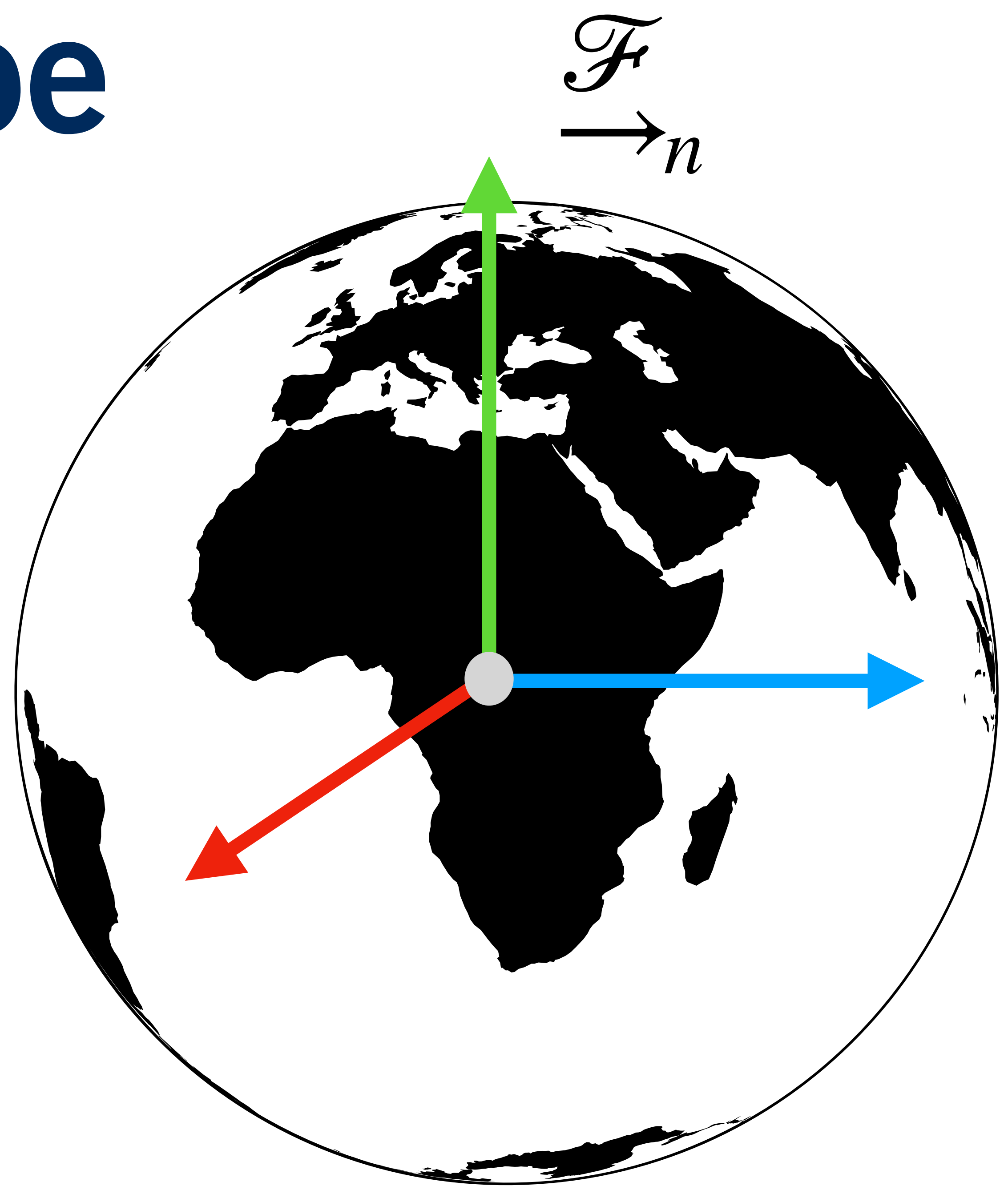
$$\mathbf{f} = \ddot{\mathbf{r}}_i - \mathbf{g} \approx \mathbf{g} - \mathbf{g} \approx \mathbf{0} \quad \text{(zero-g!)}$$

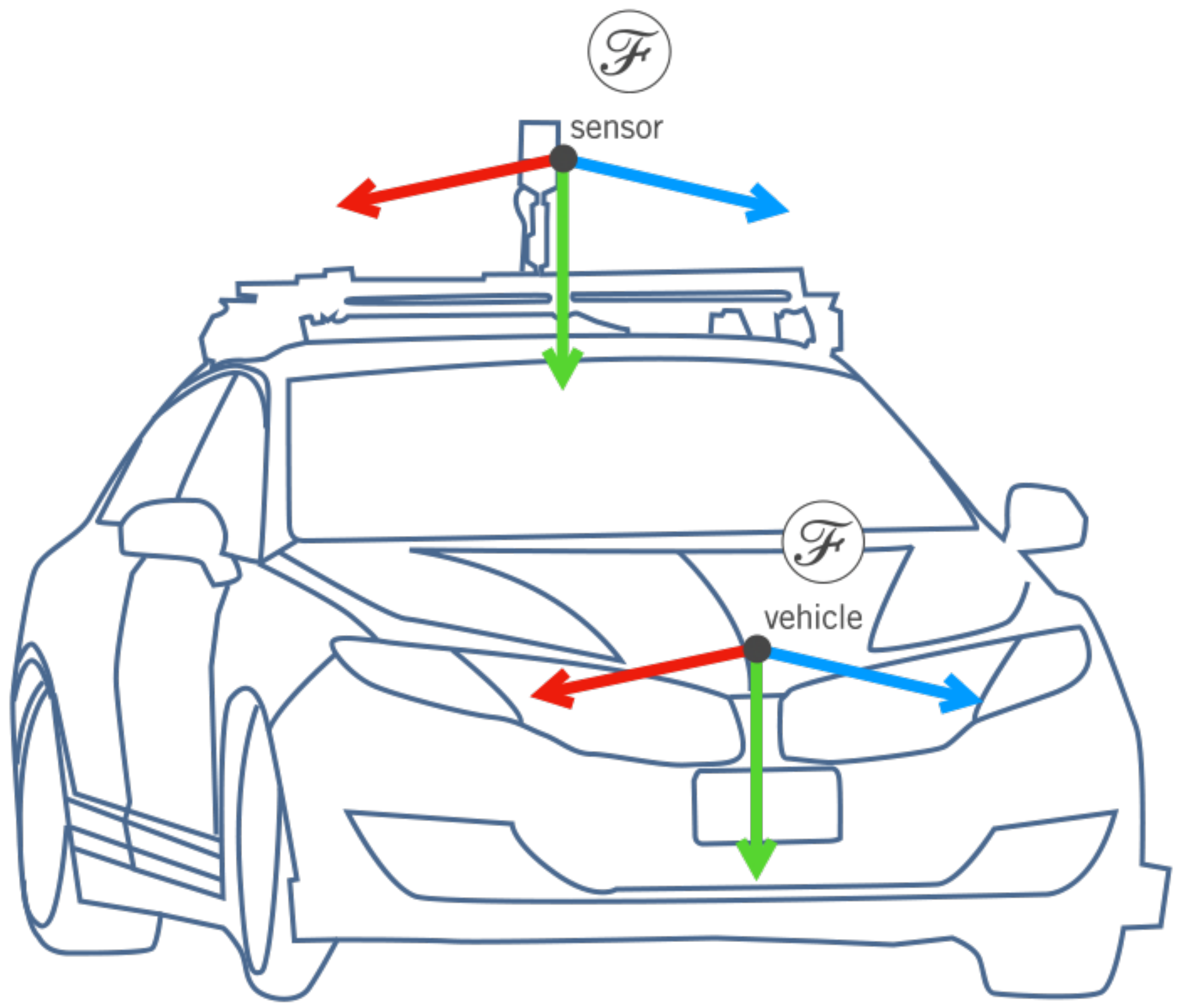


Measurement Model: **Gyroscope**

$$\boldsymbol{\omega}(t) = \boldsymbol{\omega}_s(t) + \mathbf{b}_{\text{gyro}}(t) + \mathbf{n}_{\text{gyro}}(t)$$

$\boldsymbol{\omega}_s(t)$	angular velocity of the sensor expressed in the sensor frame.
$\mathbf{b}_{\text{gyro}}(t)$	slowly evolving bias
$\mathbf{n}_{\text{gyro}}(t)$	noise term

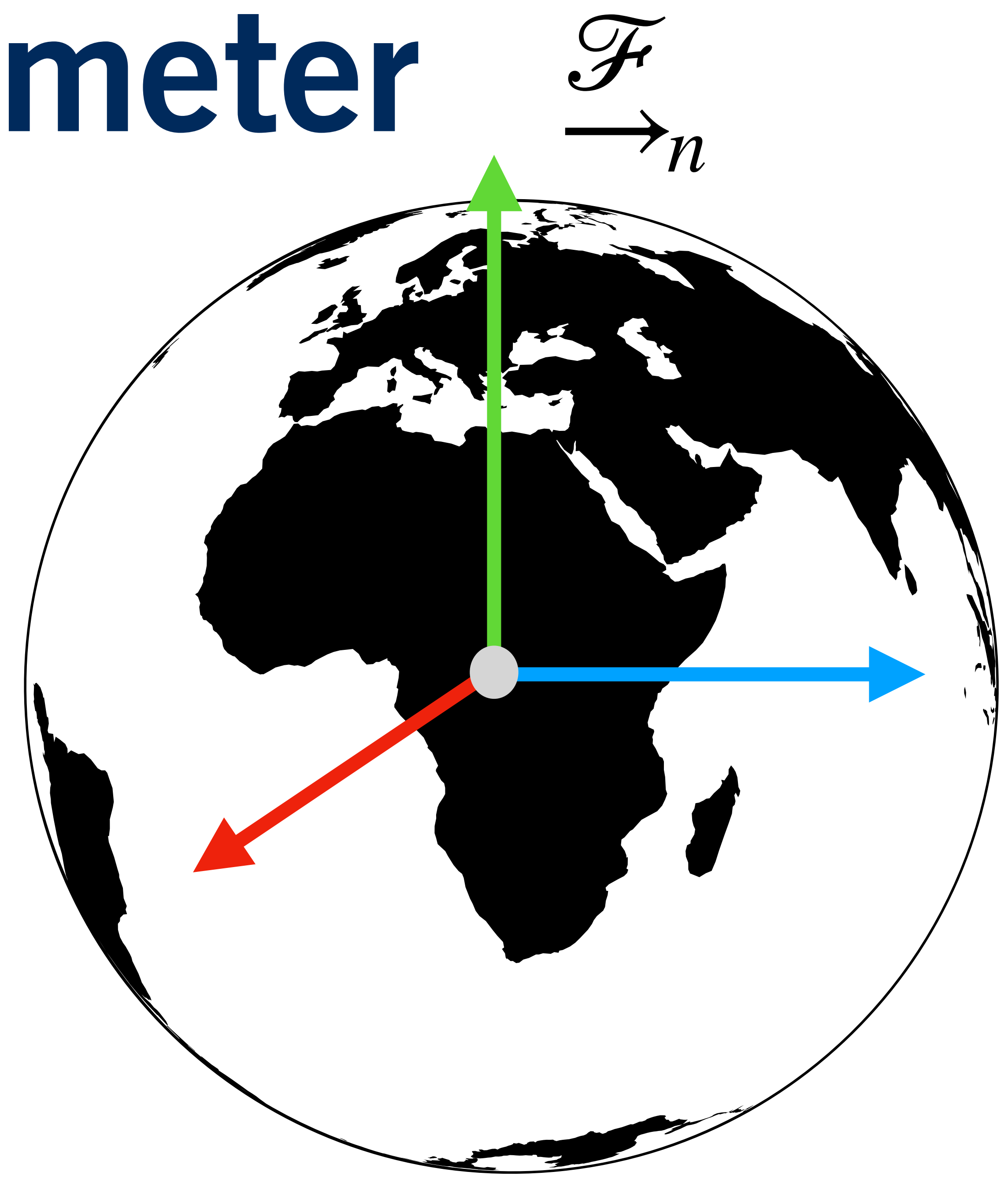


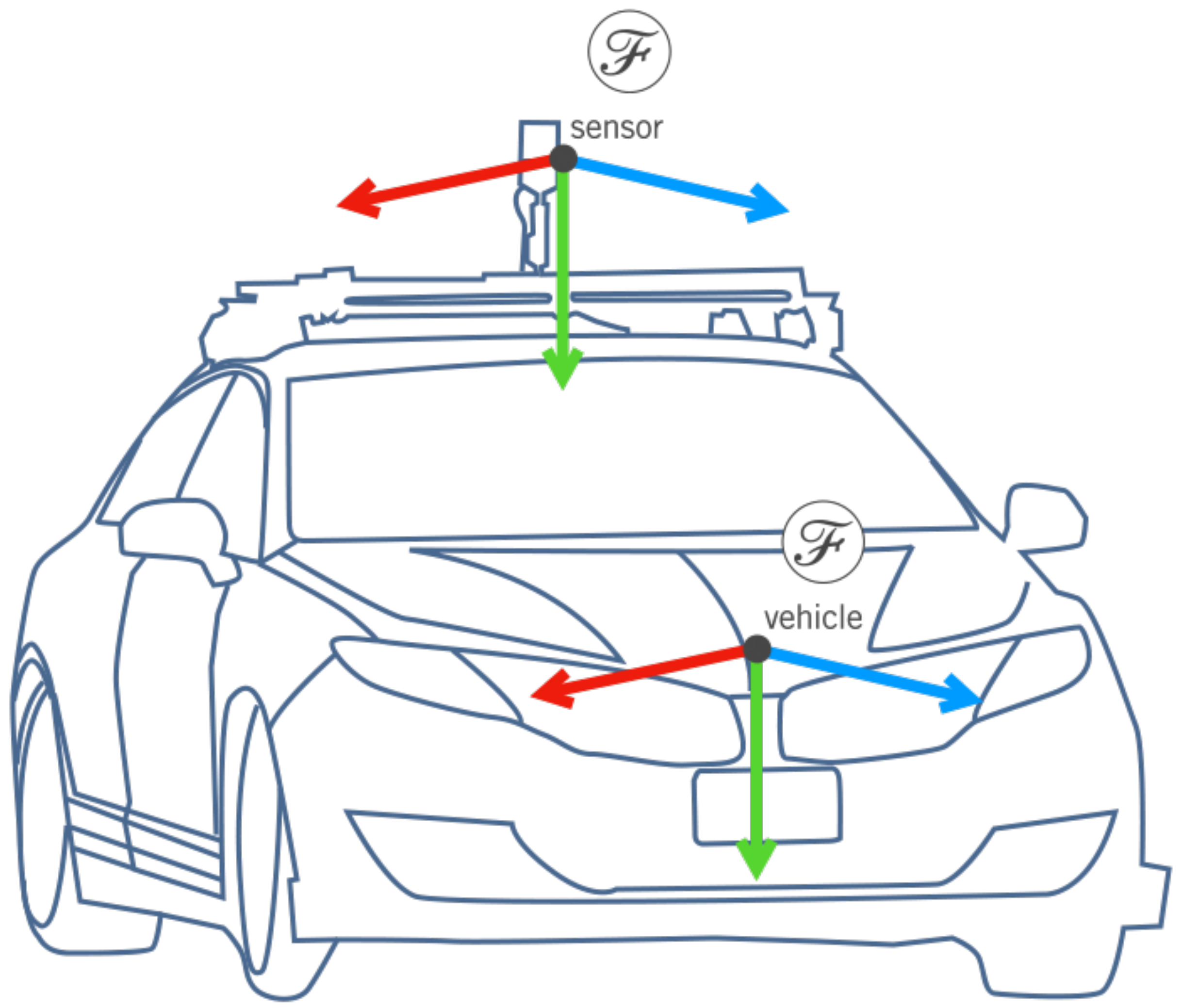


Measurement Model: **Accelerometer**

$$\mathbf{a}(t) = \mathbf{C}_{sn}(t)(\ddot{\mathbf{r}}_n^{sn}(t) - \mathbf{g}_n) + \mathbf{b}_{\text{accel}}(t) + \mathbf{n}_{\text{accel}}(t)$$

$\mathbf{C}_{sn}(t)$	orientation of the sensor (computed by integrating the rotational rates from the gyroscope)
$\mathbf{b}_{\text{accel}}(t)$	bias term
$\mathbf{n}_{\text{accel}}(t)$	noise term
$\mathbf{g}_n$	gravity in the navigation frame





Inertial Navigation: Important Notes

- When using an IMU for localization, keep in mind:

1. If we inaccurately keep track of $\mathbf{C}_{sn}(t)$, we incorporate components of $\mathbf{g}_n$ into $\ddot{\mathbf{r}}_n^{sn}(t)$ This will ultimately lead to terrible estimates of position ($\mathbf{r}_n^{sn}(t)$).

2. Both measurement models ignore the effect of **Earth's rotation**.

3. We only consider **strapdown IMUs** - where the individual sensors are rigidly attached to the vehicle and are not gimballed.

Summary | The Inertial Measurement Unit

- A 6-DOF IMU is composed of three gyroscopes and three accelerometers, mounted orthogonally.

- A strapdown gyroscope measures a rotational rate in the sensor frame.

- A strapdown accelerometer measures a specific force (or acceleration relative to free-fall) in the sensor frame.