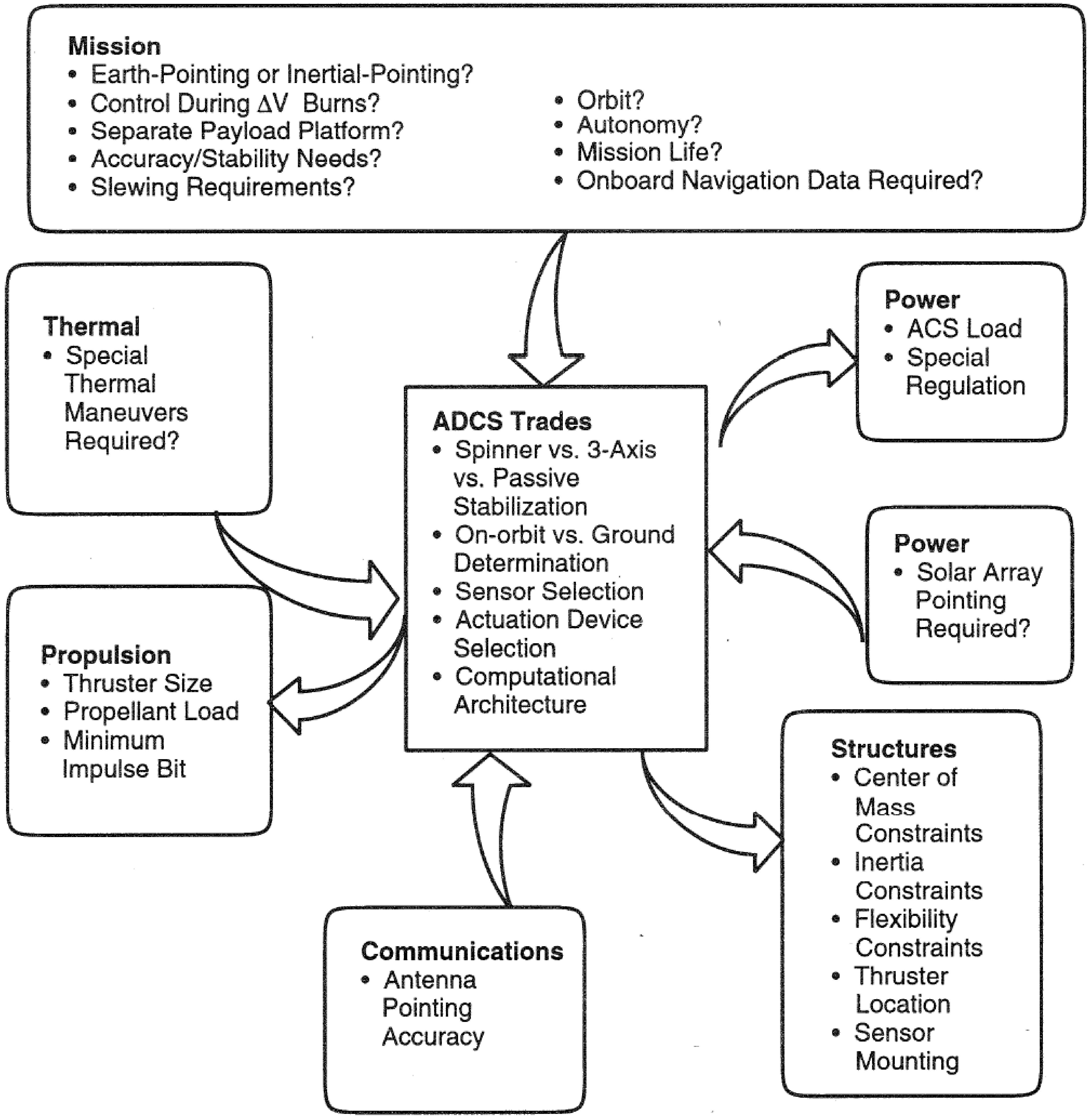
ADCS couples with many other subsystems.



Different attitude control modes

TABLE 11-2. Typical Attitude Control Modes. Performance requirements are frequently tailored to these different control operating modes.

Mode	Description
Orbit Insertion	Period during and after boost while spacecraft is brought to final orbit. Options include no spacecraft control, simple spin stabilization of solid rocket motor, and full spacecraft control using liquid propulsion system.
Acquisition	Initial determination of attitude and stabilization of vehicle. Also may be used to recover from power upsets or emergencies.
Normal, On-Station	Used for the vast majority of the mission. Requirements for this mode should drive system design.
Slew	Reorienting the vehicle when required.
Contingency or Safe	Used in emergencies if regular mode fails or is disabled. May use less power or sacrifice normal operation to meet power or thermal constraints.
Special	Requirements may be different for special targets or time periods, such as eclipses.

ADCS requirements typically include:

- **Jitter**: Amplitude and spectral characteristics of high-frequency variations
- **Drift**: Limits on low-frequency variations
- **Transient response**: Max settling time or overshoot for slew maneuvers
- **Range**: Angular motions over which other requirements must be met.

TABLE 11-4. Attitude Control Methods and Their Capabilities. As requirements become tighter, more complex control systems become necessary.

Type	Pointing Options	Attitude Maneuverability	Typical Accuracy	Lifetime Limits
Gravity-gradient	Earth local vertical only	Very limited	±5 deg (2 axes)	None
Gravity-gradient and Momentum Bias Wheel	Earth local vertical only	Very limited	±5 deg (3 axes)	Life of wheel bearings
Passive Magnetic	North/south only	Very limited	±5 deg (2 axes)	None
Pure Spin Stabilization	Inertially fixed any direction Repoint with precession maneuvers	High propellant usage to move stiff momentum vector	±0.1 deg to ±1 deg in 2 axes (proportional to spin rate)	Thruster propellant (if applies)*
Dual-Spin Stabilization	Limited only by articulation on despun platform	Momentum vector same as above Despun platform constrained by its own geometry	Same as above for spin section Despun dictated by payload reference and pointing	Thruster propellant (if applies)* Despin bearings
Bias Momentum (1 wheel)	Best suited for local vertical pointing	Momentum vector of the bias wheel prefers to stay normal to orbit plane, constraining yaw maneuver	±0.1 deg to ±1 deg	Propellant (if applies)* Life of sensor and wheel bearings
Zero Momentum (thruster only)	No constraints	No constraints High rates possible	±0.1 deg to ±5 deg	Propellant
Zero Momentum (3 wheels)	No constraints	No constraints	±0.001 deg to ±1 deg	Propellant (if applies)* Life of sensor and wheel bearings
Zero Momentum CMG	No constraints	No constraints High rates possible	±0.001 deg to ±1 deg	Propellant (if applies)* Life of sensor and wheel bearings

*Thrusters may be used for slewing and momentum dumping at all altitudes. Magnetic torquers may be used from LEO to GEO.

Attitude Sensor Technologies

(most slides stolen from Prof. Savransky)

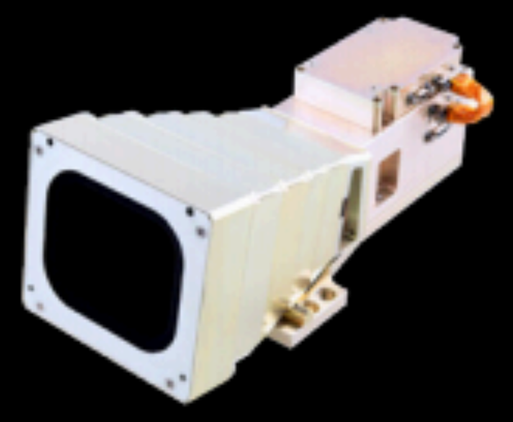
- What is attitude determination?
- What information is required to solve the attitude determination problem?

TABLE 11-8. Effect of Control Accuracy on Sensor Selection and ADCS Design. Accurate pointing requires better, higher cost, sensors, and actuators.

Required Accuracy (3σ)	Effect on Spacecraft	Effect on ADCS
> 5 deg	• Permits major cost savings • Permits gravity-gradient (GG) stabilization	***Without attitude determination*** • No sensors required for GG stabilization • Boom motor, GG damper, and a bias momentum wheel are only required actuators ***With attitude determination*** • Sun sensors & magnetometer adequate for attitude determination at ≥ 2 deg • Higher accuracies may require star trackers or horizon sensors
1 deg to 5 deg	• GG not feasible • Spin stabilization feasible if stiff, inertially fixed attitude is acceptable • Payload needs may require despun platform on spinner • 3-axis stabilization will work	• Sun sensors and horizon sensors may be adequate for sensors, especially a spinner • Accuracy for 3-axis stabilization can be met with RCS deadband control but reaction wheels will save propellant for long missions • Thrusters and damper adequate for spinner actuators • Magnetic torquers (and magnetometer) useful
0.1 deg to 1 deg	• 3-axis and momentum-bias stabilization feasible • Dual-spin stabilization also feasible	• Need for accurate attitude reference leads to star tracker or horizon sensors & possibly gyros • Reaction wheels typical with thrusters for momentum unloading and coarse control • Magnetic torquers feasible on light vehicles (magnetometer also required)
< 0.1 deg	• 3-axis stabilization is necessary • May require articulated & vibration-isolated payload platform with separate sensors	• Same as above for 0.1 deg to 1 deg but needs star sensor and better class of gyros • Control laws and computational needs are more complex • Flexible body performance very important

This lecture:

- **Star trackers**
- Sun/Earth sensors
- Horizon sensors
- Magnetometers
- Carrier phase differential GPS
- Gyroscopes
- Optical navigation (a little)



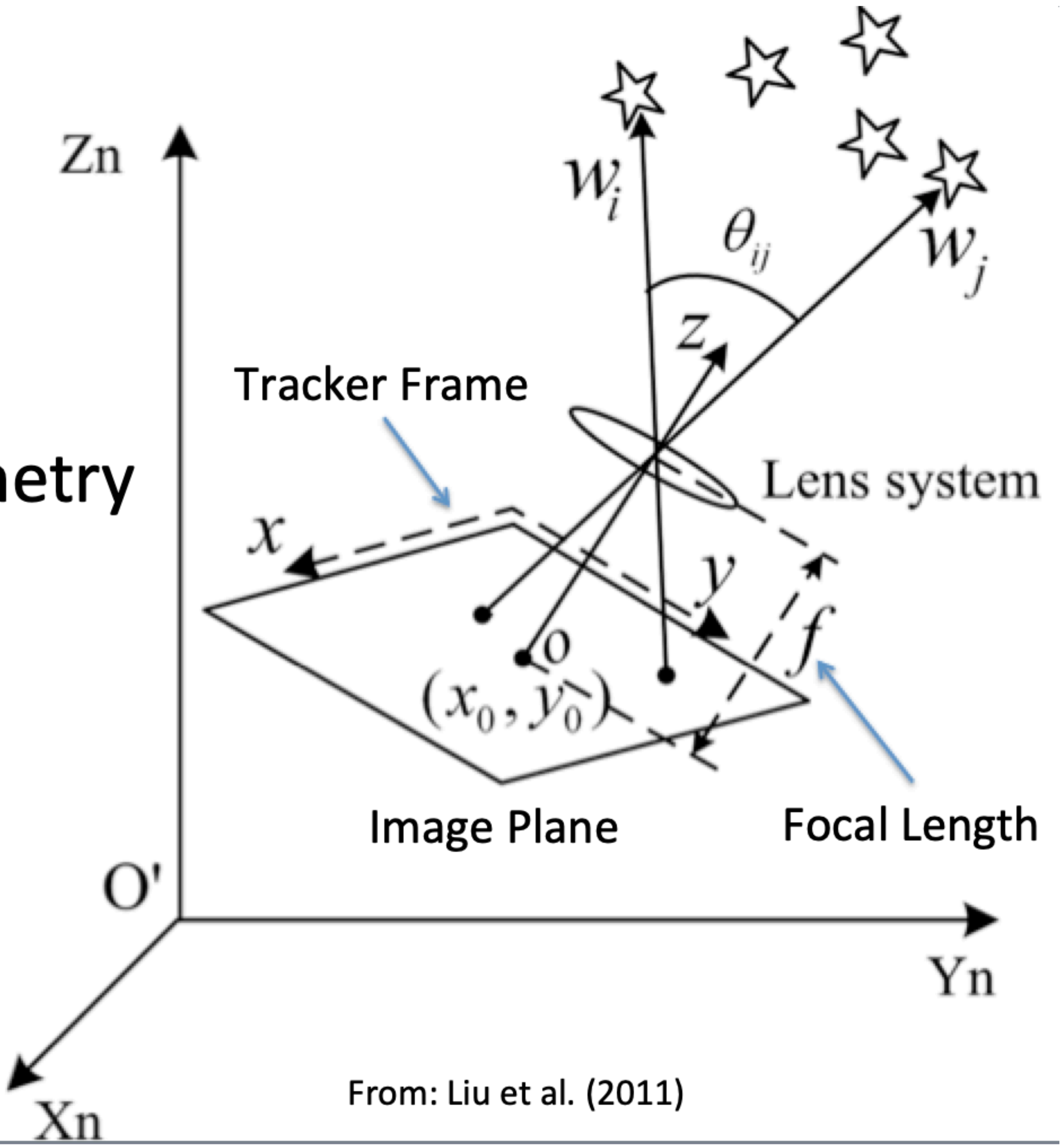
	STANDARD NST	EXTENDED NST
ATTITUDE KNOWLEDGE	6 asec (cross boresight) and 40 asec (about boresight)	6 asec (cross boresight) and 40 asec (about boresight)
SKY COVERAGE	> 99 %	> 99 %
MASS	0.35 kg w/ baffle	1.3 kg w/ baffle
VOLUME	10 x 5.5 x 5 cm	25 x 10 x 10 cm
PEAK POWER	< 1.5W	< 1.5W
FIELD OF VIEW	10 x 12 degrees	10 x 12 degrees
SUN KEEP OUT	45 degrees (half cone)	17.5 degrees (half cone)
DESIGN LIFE	> 5 Years (LEO)	

Blue Canyon Technologies star trackers

High-Accuracy Star Tracker (HAST) - Ball Aerospace
1e-5 degrees of accuracy

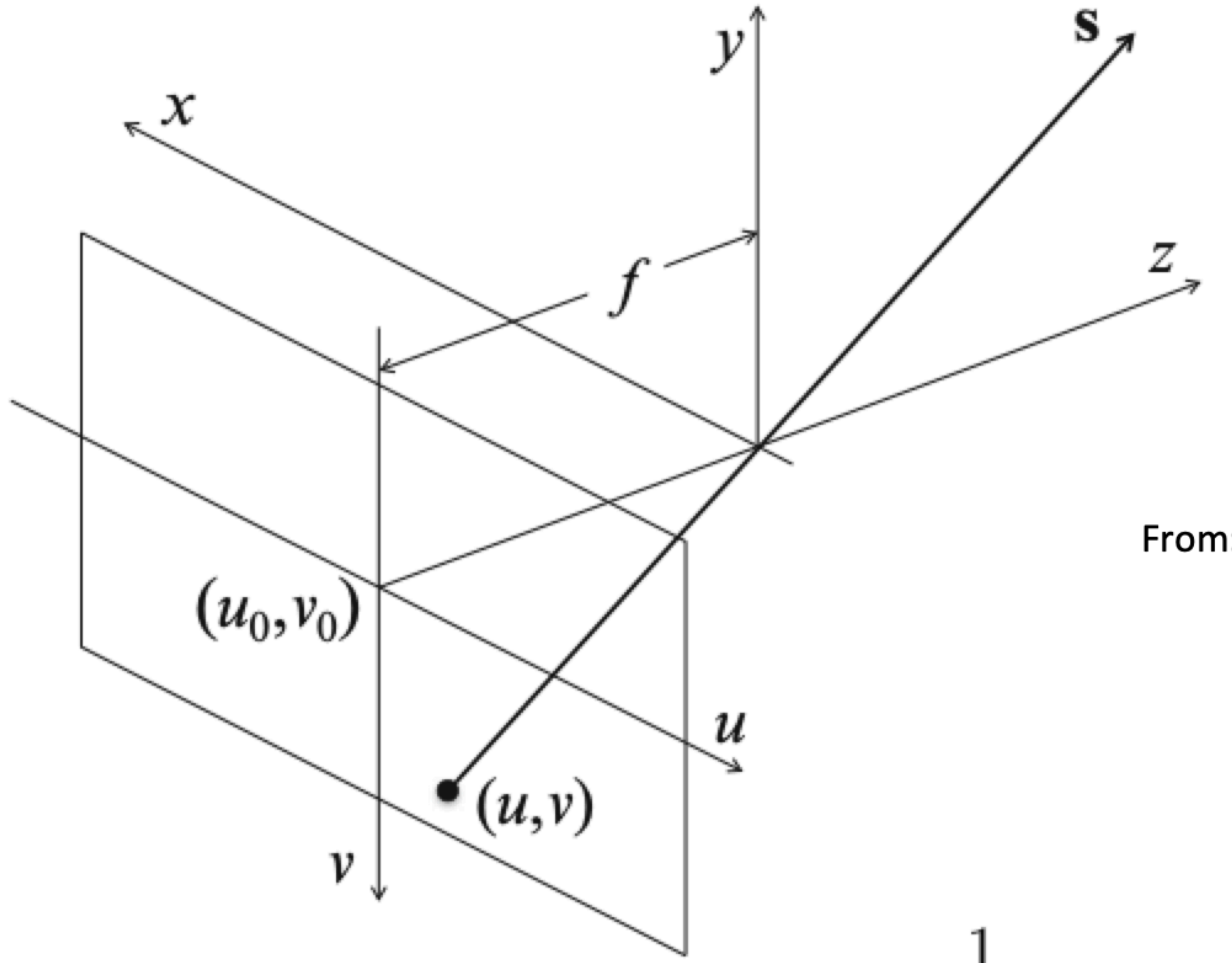
How do star trackers work?

Camera Geometry



From: Liu et al. (2011)

More Geometry



From: Markley and Crassidis

$$\hat{\mathbf{r}}_{\text{star/spacecraft}} \equiv \mathbf{s} = \frac{1}{\sqrt{f^2 + (u - u_0) + (v - v0)^2}} \begin{bmatrix} u - u_0 \\ v - v_0 \\ f \end{bmatrix}$$

Why are they so accurate?

We have many measurements for determination of a small number of parameters.
What concept from linear algebra does that remind you of?

Advantages and limitations:

- What happens if you point a star tracker at Sun, Earth, or Moon?
- Do you need to know your location in order to use a star tracker?

This lecture:

- Star trackers
- **Sun/Earth sensors**
- Horizon sensors
- Magnetometers
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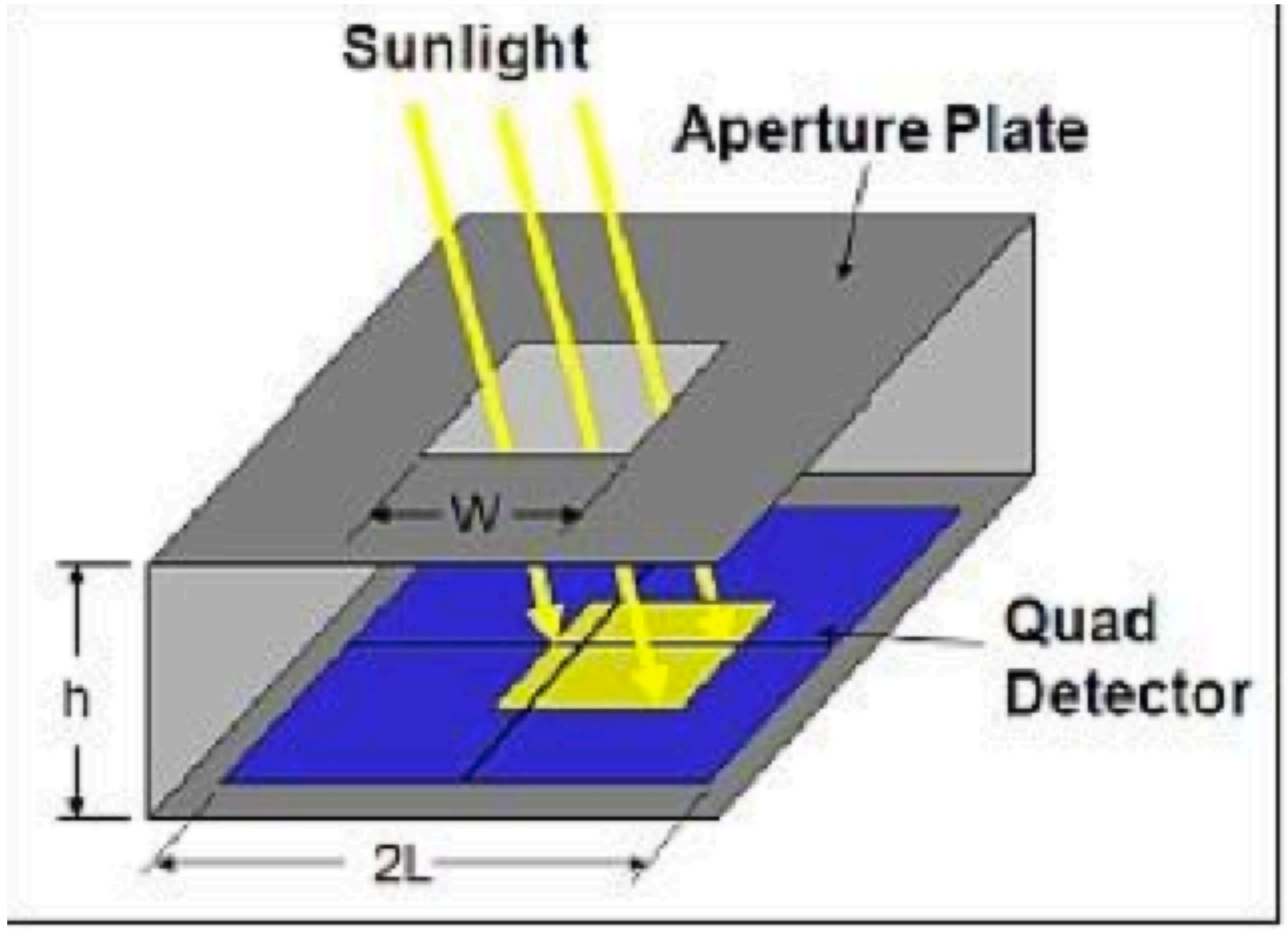
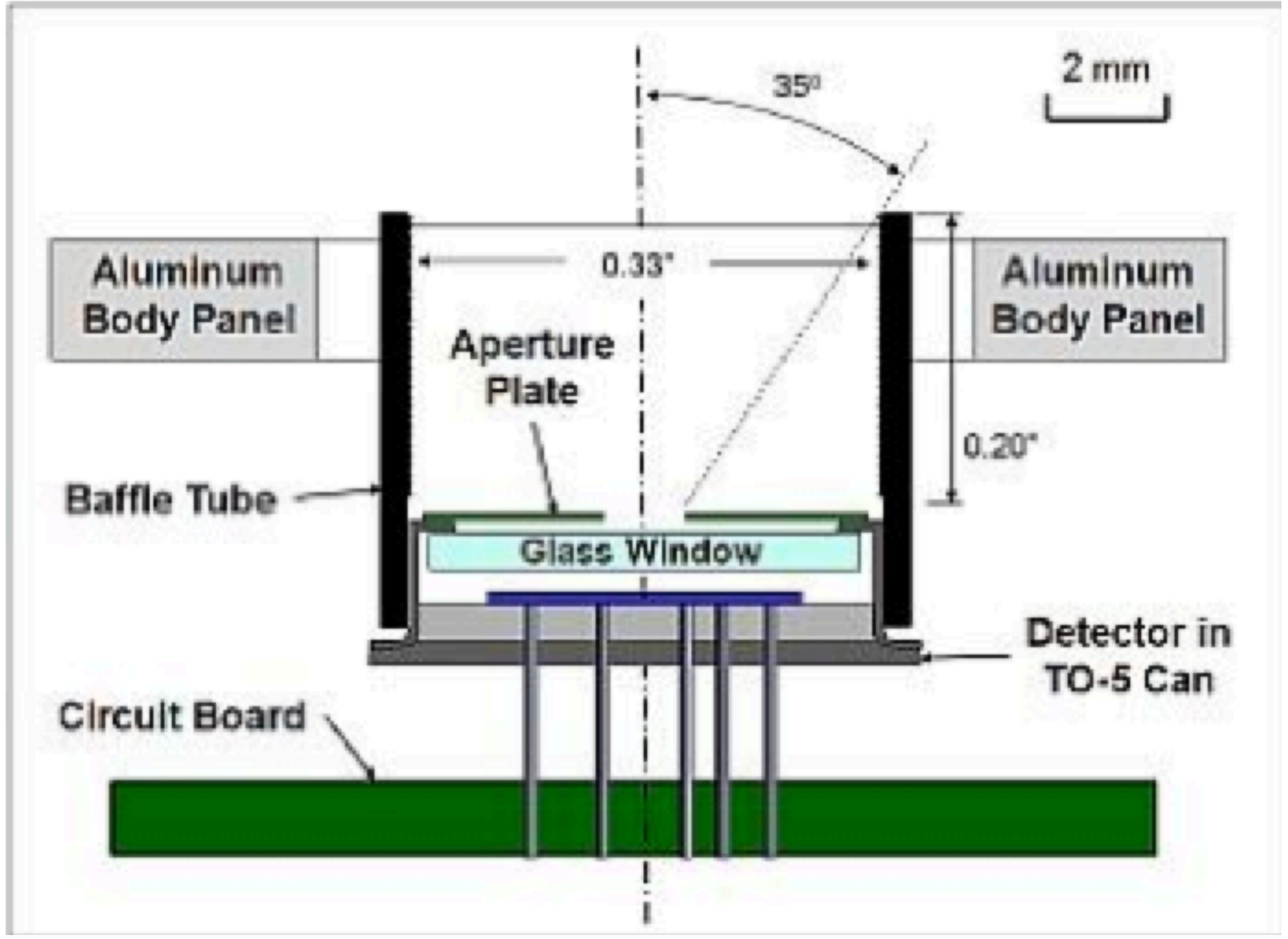
- Gyroscopes
- Optical navigation (a little)



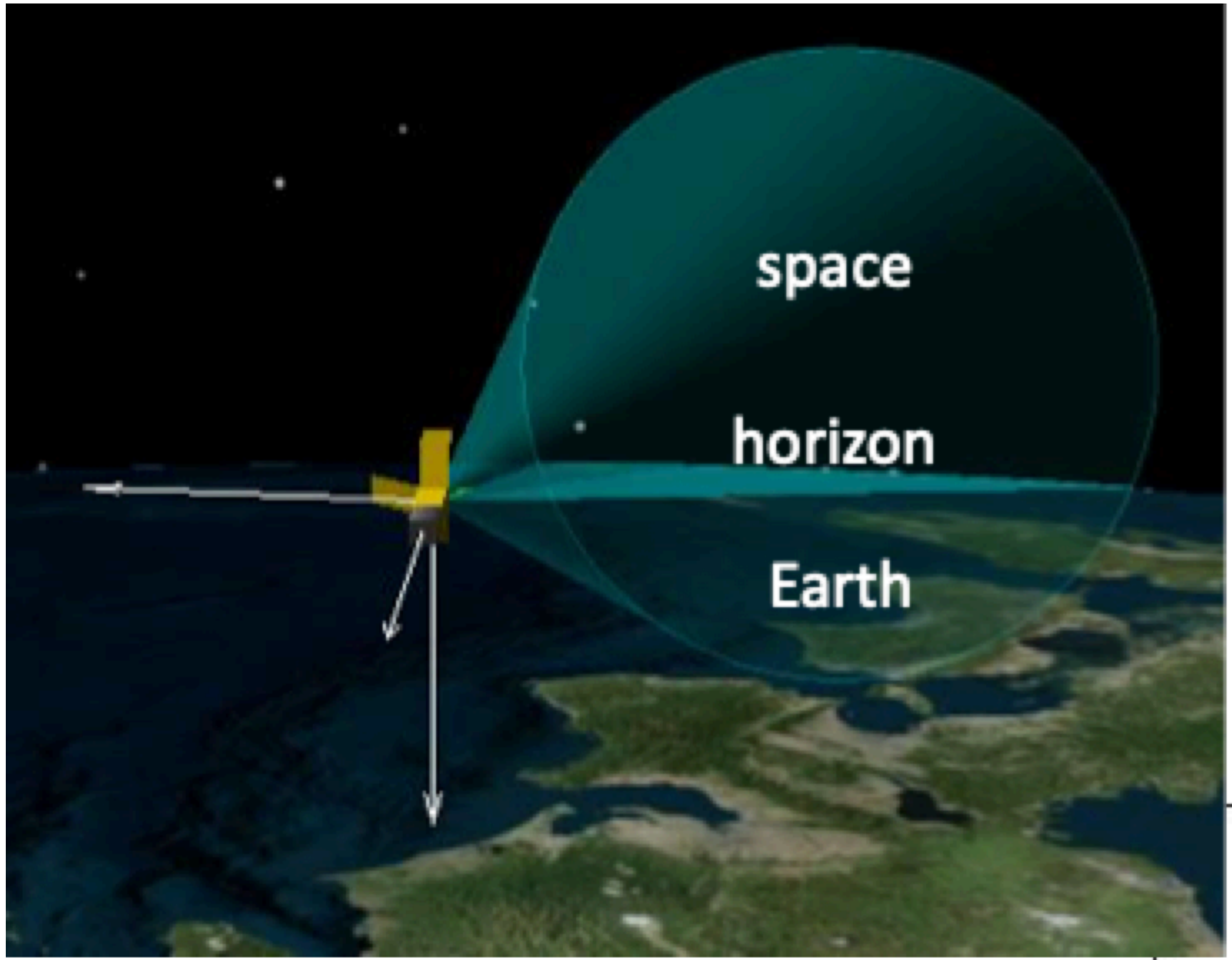
Credit: The Aerospace Corporation



Can you think of any other tricks for determining the Sun vector, using infrastructure already on your spacecraft?

This lecture:

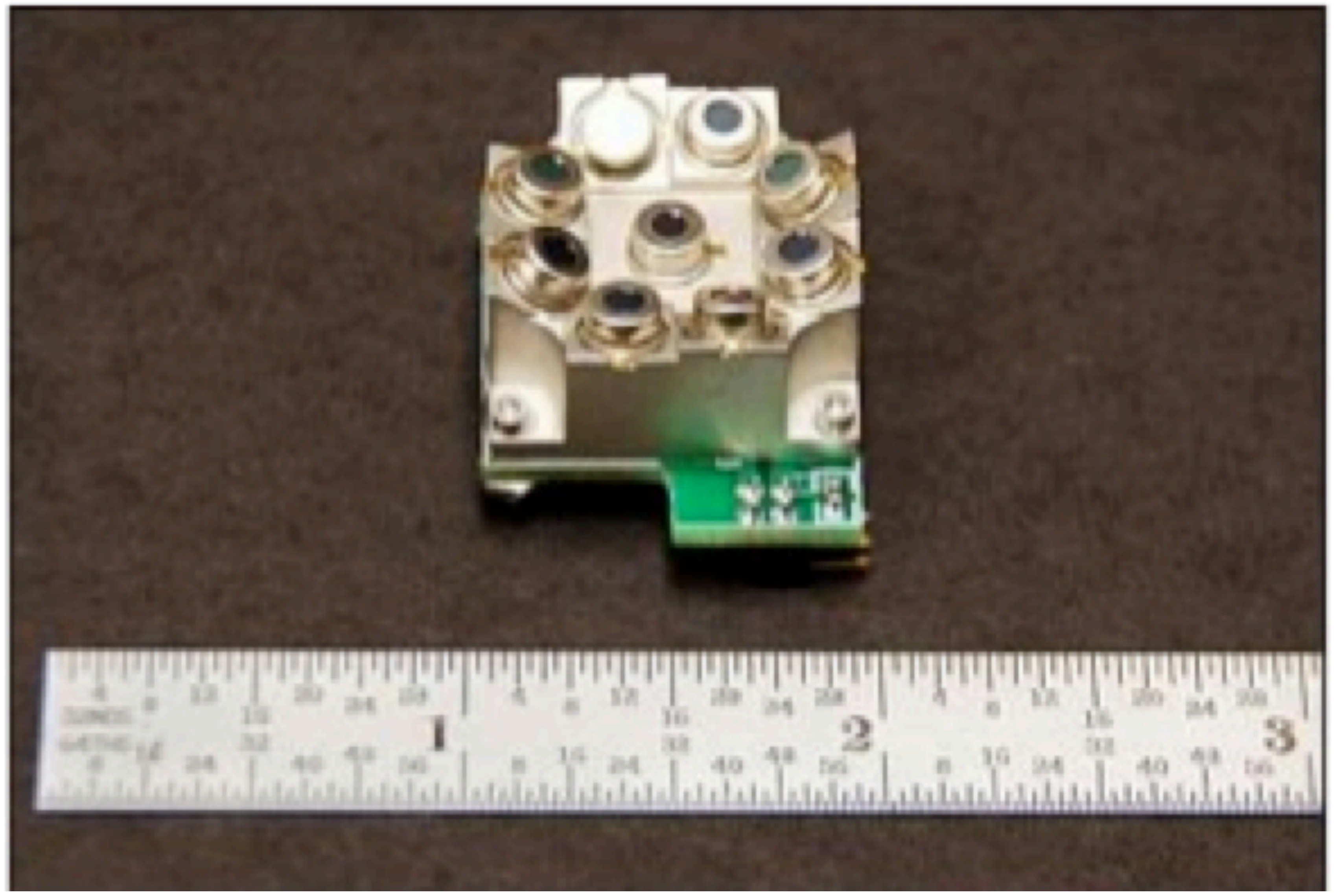
- Star trackers
- Sun/Earth sensors
- **Horizon sensors**
- Magnetometers
- Carrier phase differential GPS
- Gyroscopes
- Optical navigation (a little)

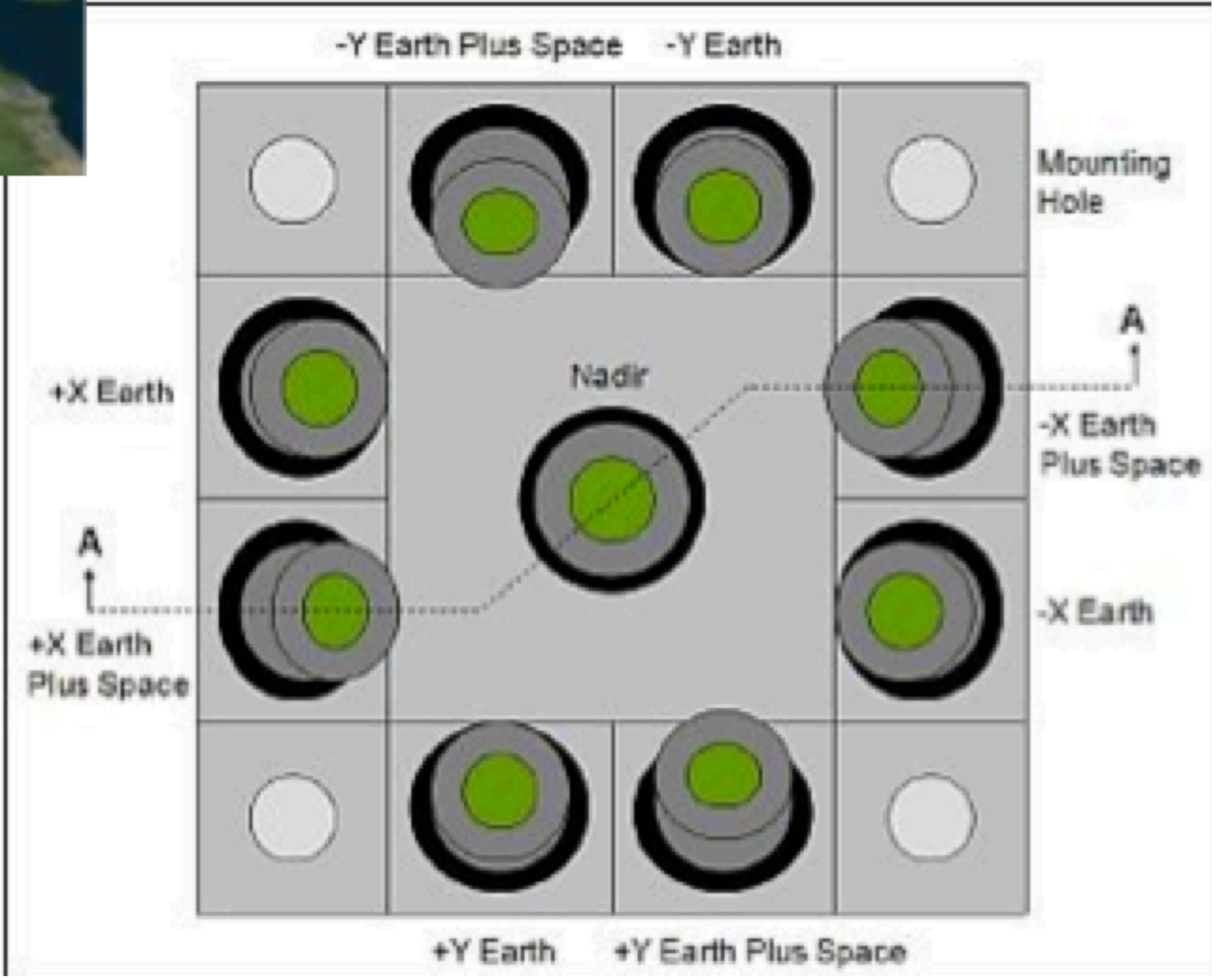


Credit: T. Nguyen

Horizon Sensors

Credit: The Aerospace Corporation

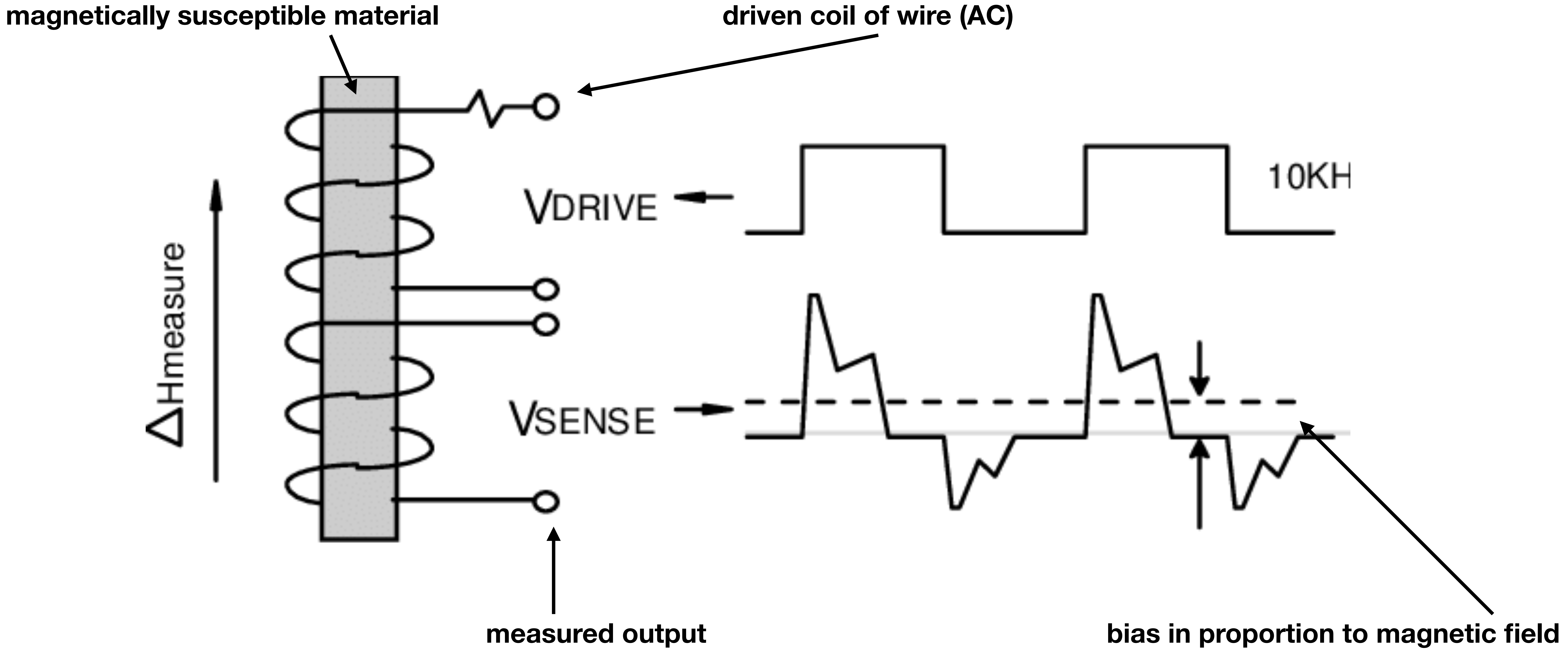




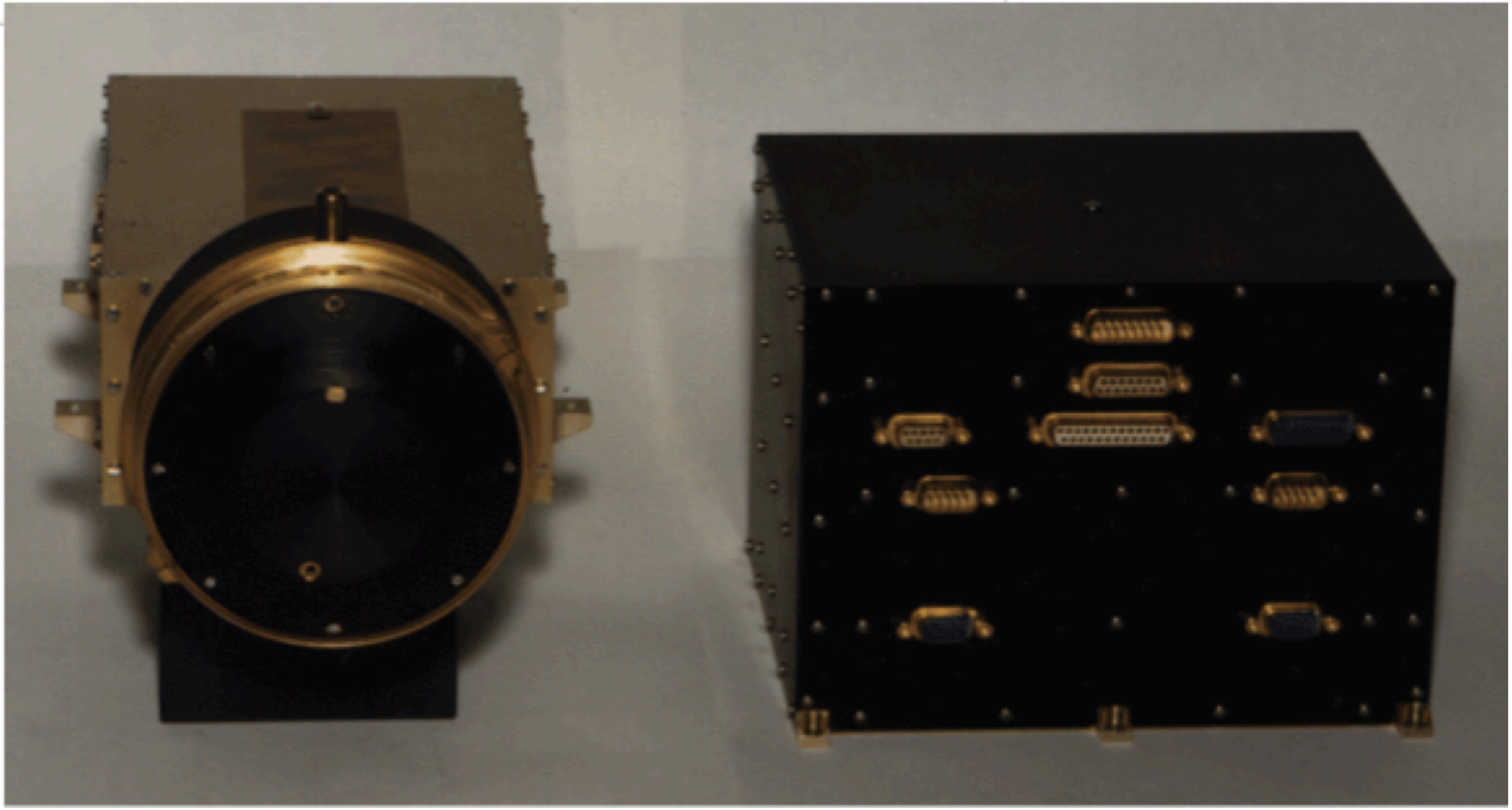
This lecture:

- Star trackers
- Sun/Earth sensors
- Horizon sensors
- **Magnetometers**
- Carrier phase differential GPS
- Gyroscopes
- Optical navigation (a little)

Fluxgate magnetometers

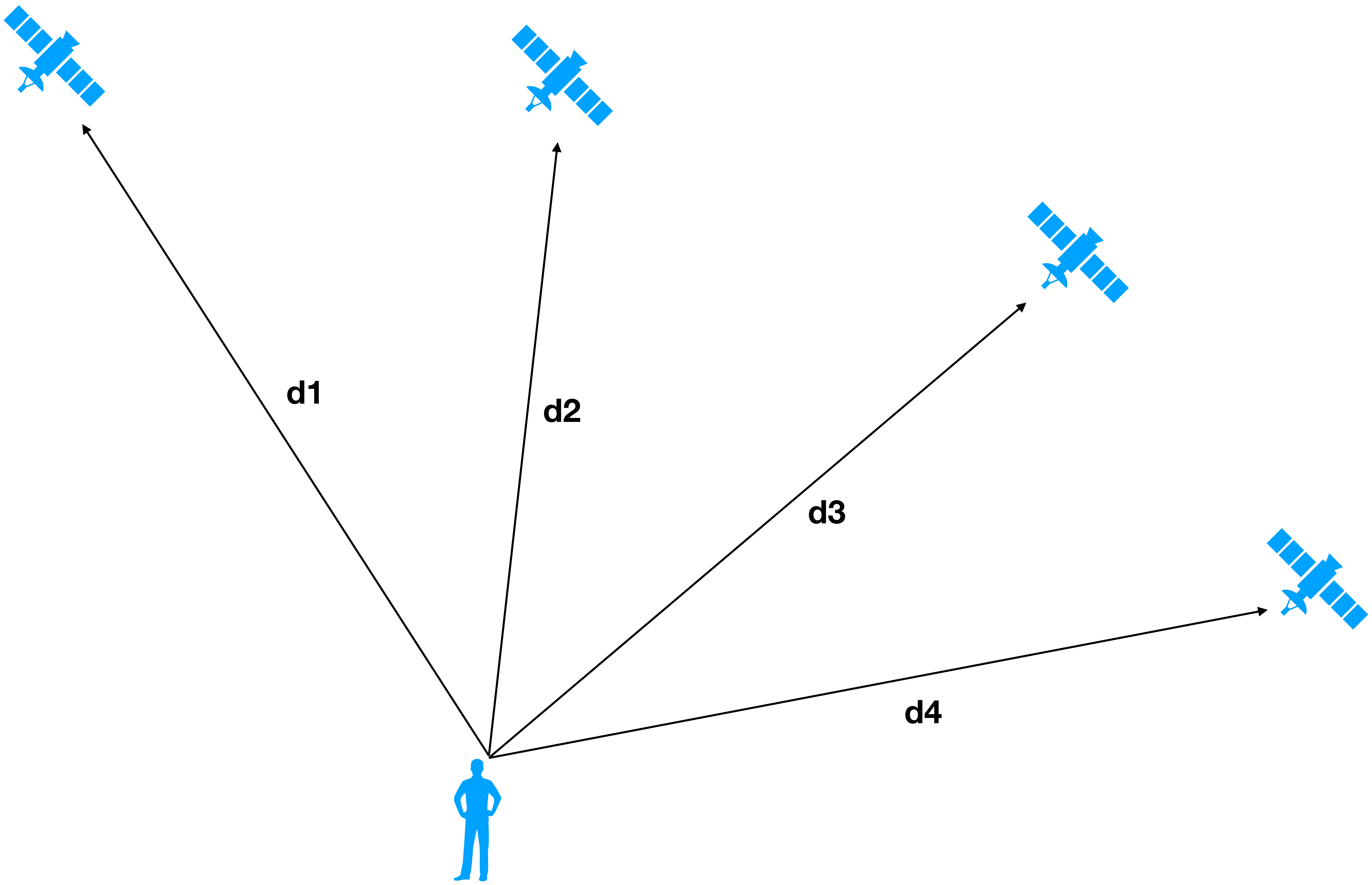


Fluxgate magnetometers



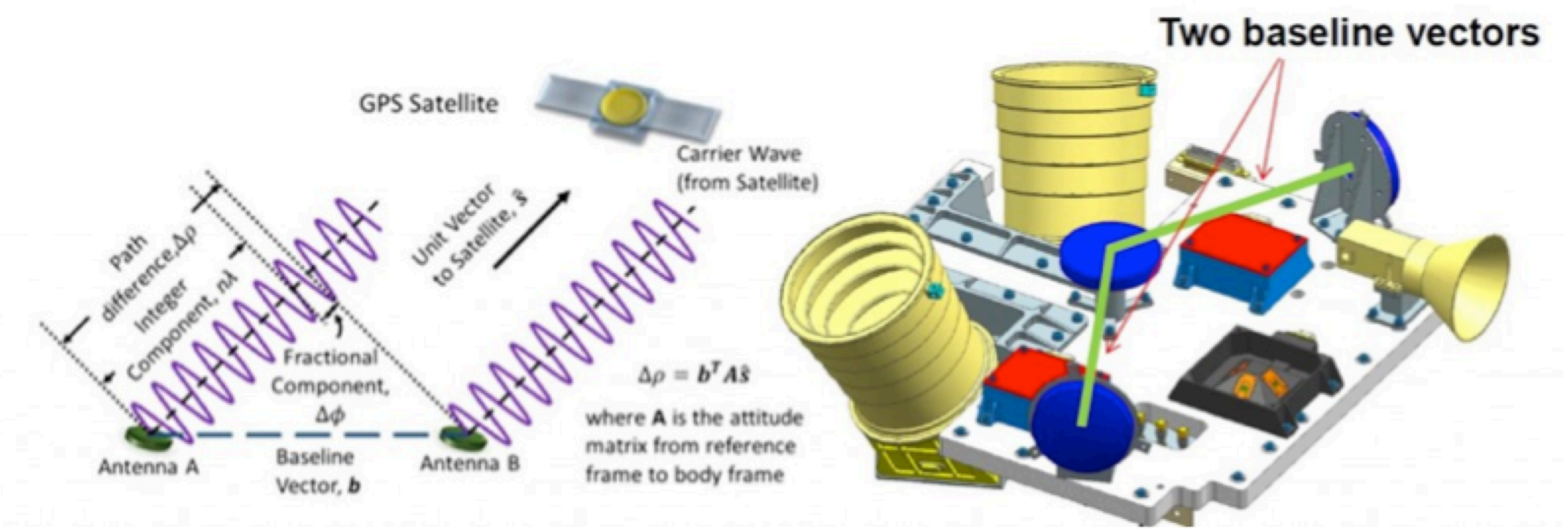
This lecture:

- Star trackers
- Sun/Earth sensors
- Horizon sensors
- Magnetometers
- **Carrier phase differential GPS**
- Gyroscopes
- Optical navigation (a little)



Reminder about GPS

Carrier phase differential GPS

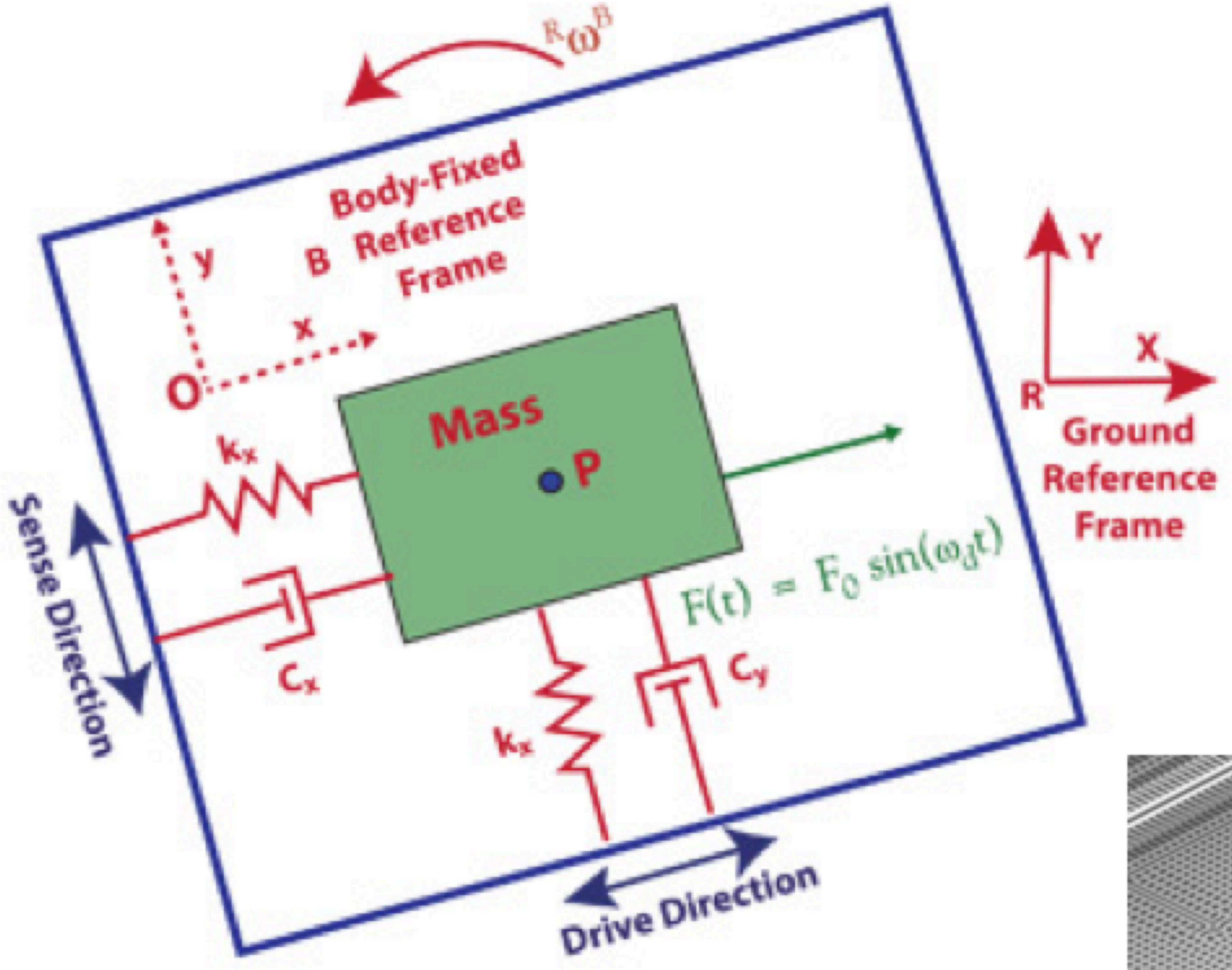


Credit: Nanyang Technological University

This lecture:

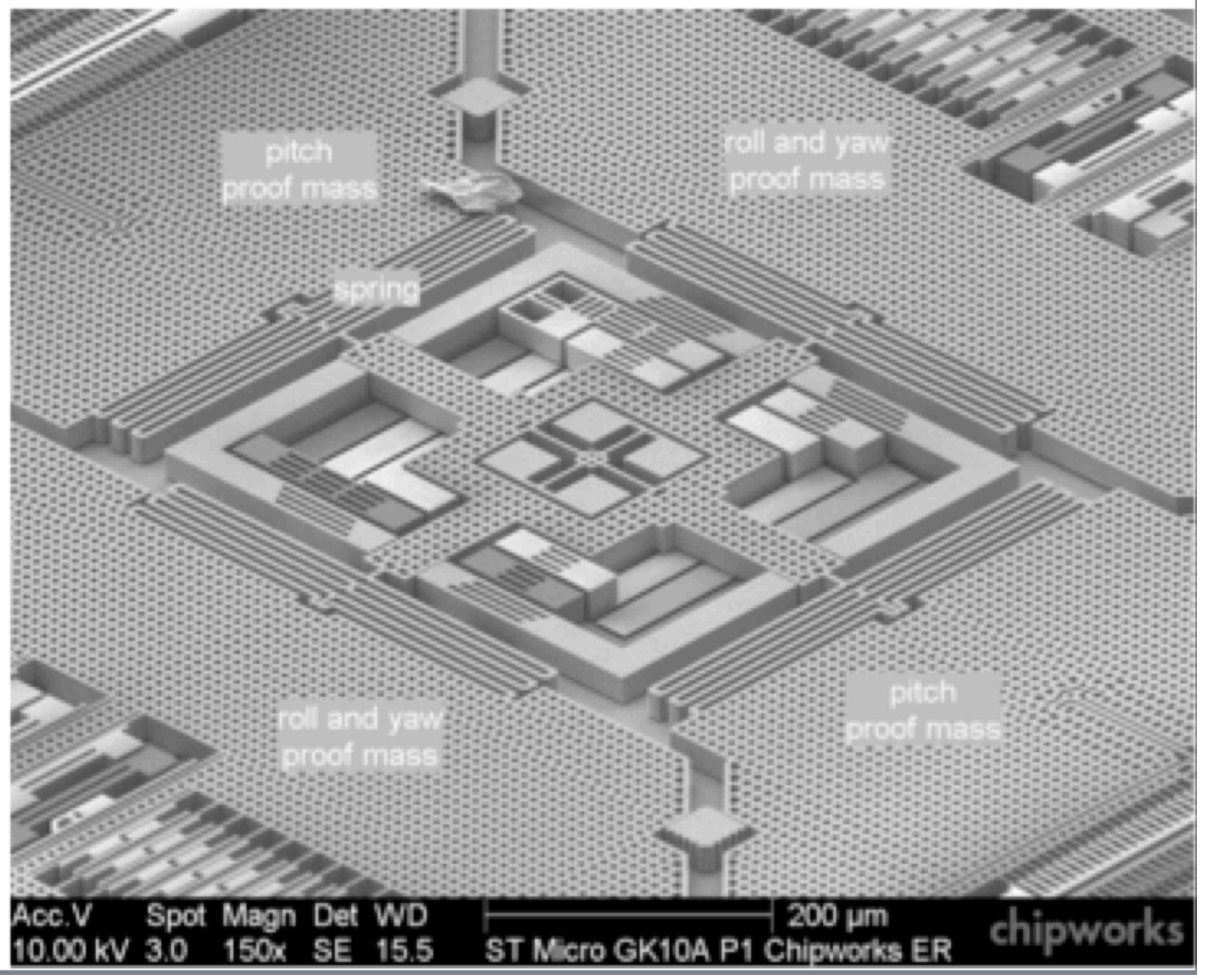
- Star trackers
- Sun/Earth sensors
- Horizon sensors
- Magnetometers
- Carrier phase differential GPS
- **Gyroscopes**
- Optical navigation (a little)

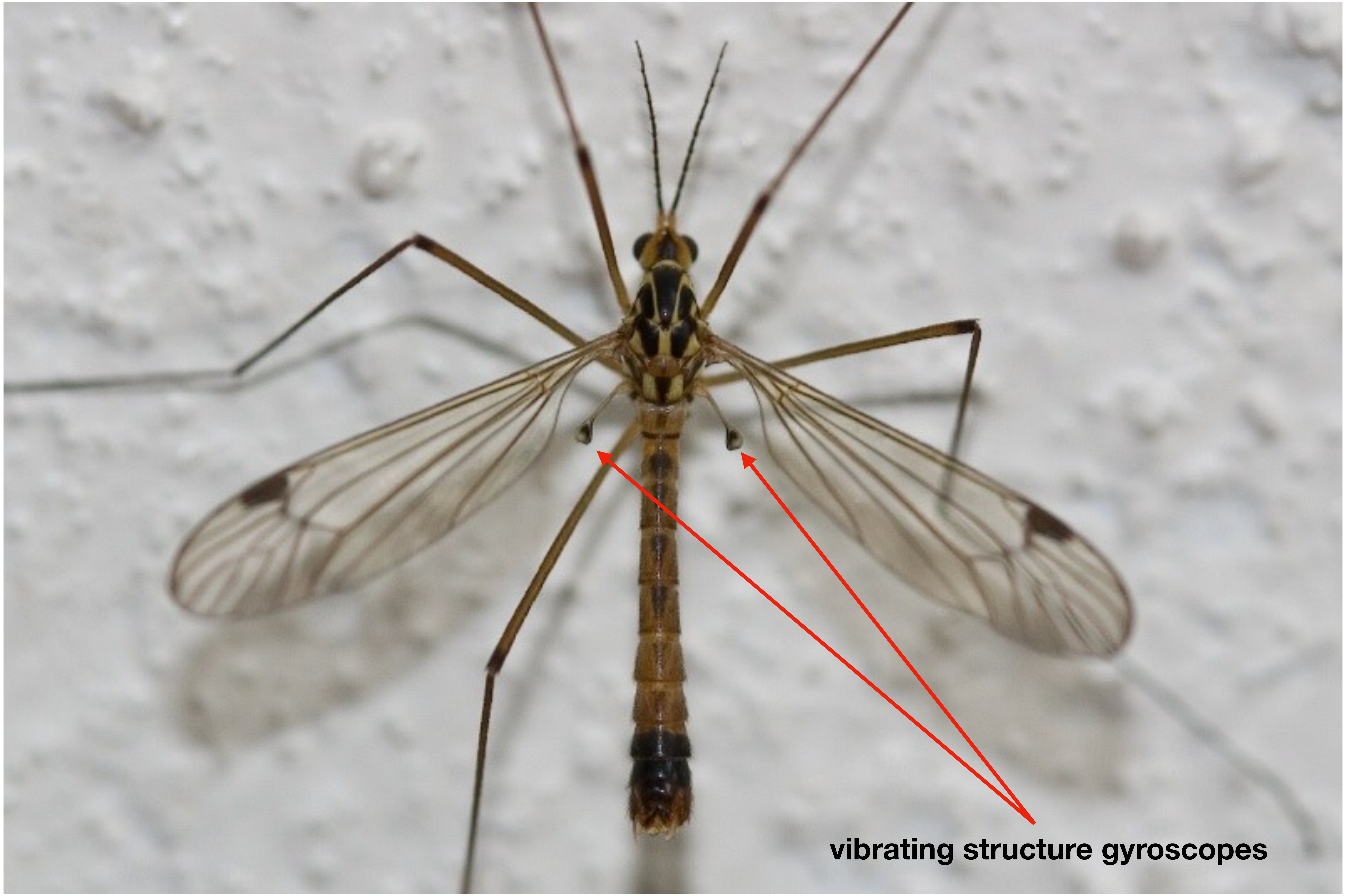
MEMS gyros



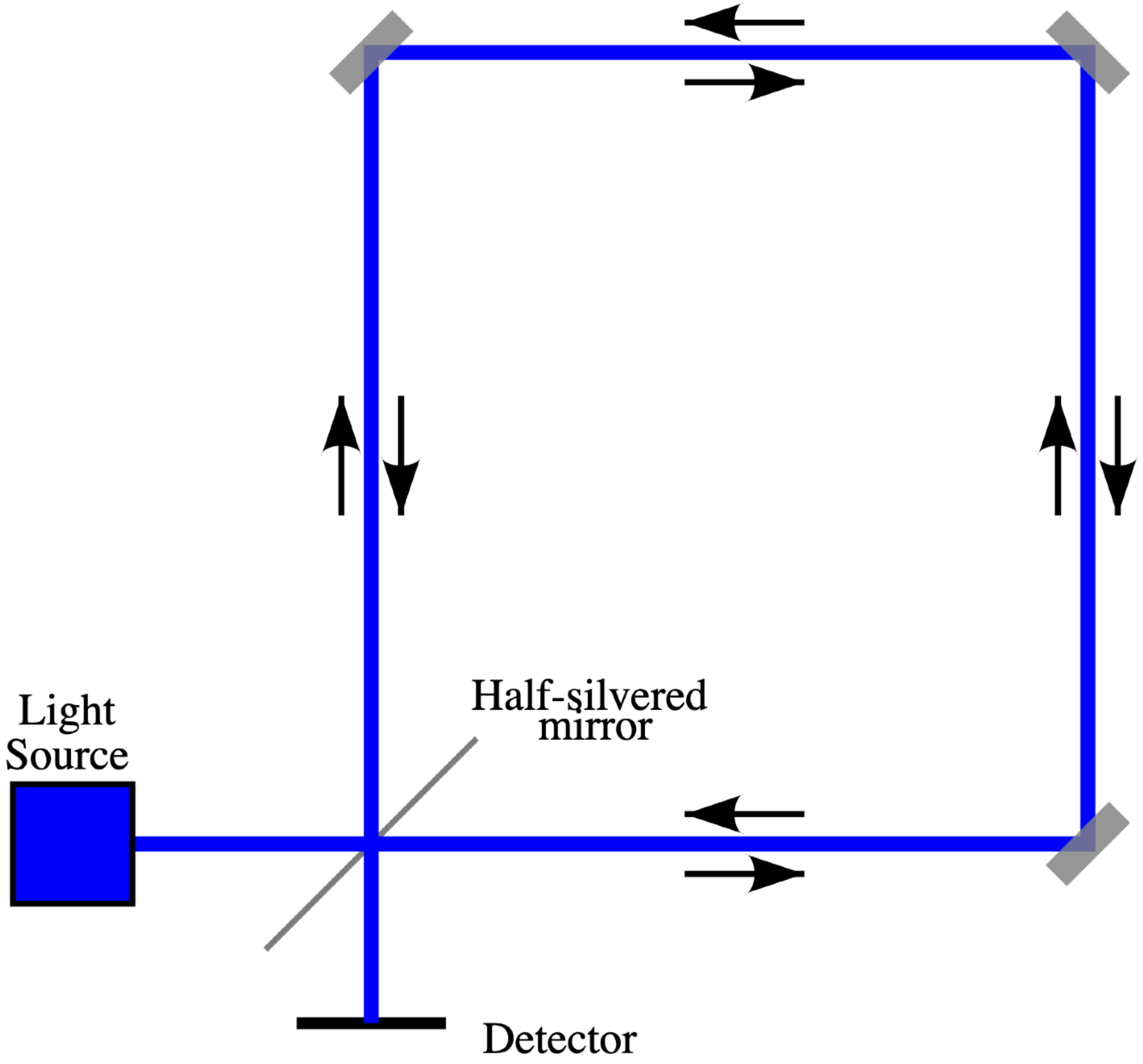
From: http://www.edn.com/electronics-blogs/mechatronics-in-design/4400475/Modeling-the-MEMS-gyroscope

Credit: Chipworks




vibrating structure gyroscopes

Fiber-optic gyroscopes



Sagnac effect

LN200 - Northrop Grumman

This lecture:

- Star trackers
- Sun/Earth sensors
- Horizon sensors
- Magnetometers
- Carrier phase differential GPS
- Gyroscopes
- **Optical navigation (a little)**

Sextant from Apollo

a) Raw image | b) Thresholded image, $\tau = 90$ | c) Closed image with best MSAC ellipse | d) Raw image with best MSAC ellipse

Figure 4.22: Planet finding algorithm applied to example image containing Earth taken by MESSENGER spacecraft's Narrow Angle Camera on 2 August 2005. Raw image is Product ID EW0031513371D from [93].

a) Raw image | b) Thresholded image, $\tau = 50$ | c) Closed image with best MSAC ellipse | d) Raw image with best MSAC ellipse

Figure 4.23: Planet finding algorithm applied to example image containing Phobos taken on 22 August 2004 by the Mars Orbiter Camera (MOC) on ESA's Mars Express spacecraft. Raw image is Product ID H0756_0000_P12 from [148].

Christian, John Allen. *Optical navigation for a spacecraft in a planetary system*. Diss. 2010.