AA 279 C – SPACECRAFT ADCS: LECTURE 1

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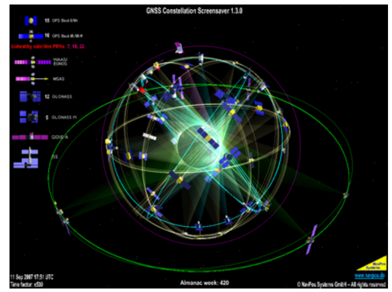
- Mission classification
- System engineering aspects
- Attitude and orbit control
- Sensors and actuators

- Reading for this week (lectures 1 and 2)
  - Wertz 1, 15, 16.1-16.2

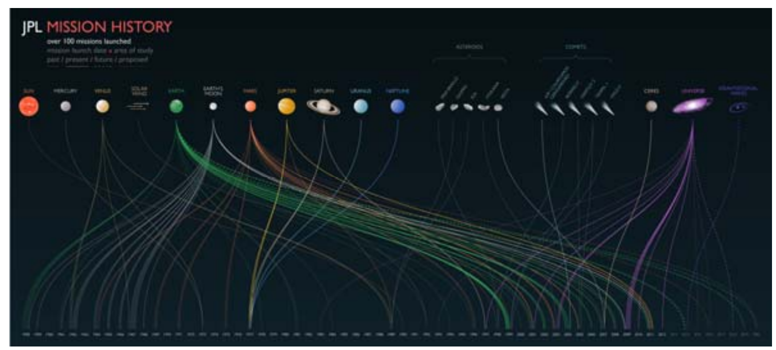
Mission Classification: Orbit and Payload

- Low Earth Orbit (LEO)
- Highly Elliptical Orbit (HEO)
- Medium Earth Orbit (MEO)
- Geostationary Orbit (GEO)
- Interplanetary Orbit



GNSS

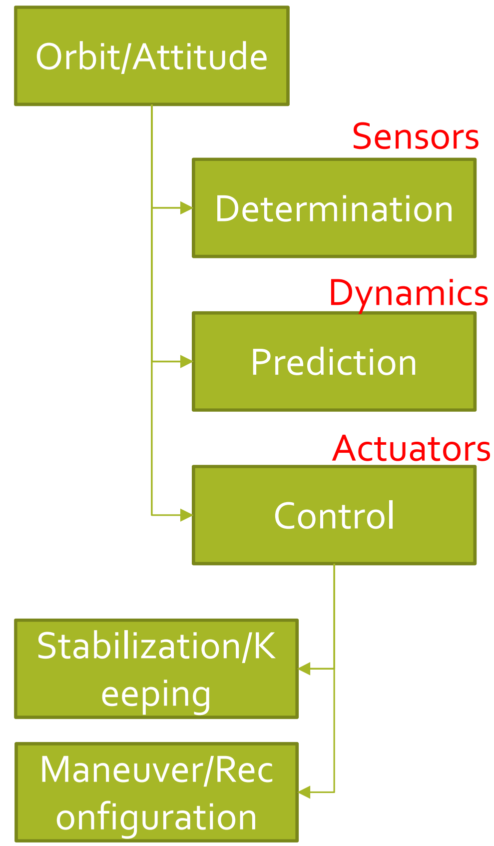
Nasa's Earth science



JPL's exploration history

Subject of Study: Spacecraft Motion

- The motion of a rigid spacecraft is specified by
  - Translation of center of mass (orbit)
  - Rotation about the center of mass (attitude)
- Orbit and attitude are interdependent, but in the majority of the cases one aspect can be studied by assuming a-priori knowledge of the other
- Historically, orbit and attitude problems have been developed differently
  - Orbit motion of celestial bodies is one of the oldest sciences
  - Attitude motion has advanced mainly since the launch of Sputnik in 1957
  - No science is without antecedents. Newton knew that the Moon was probably "gravity-gradient stabilized"



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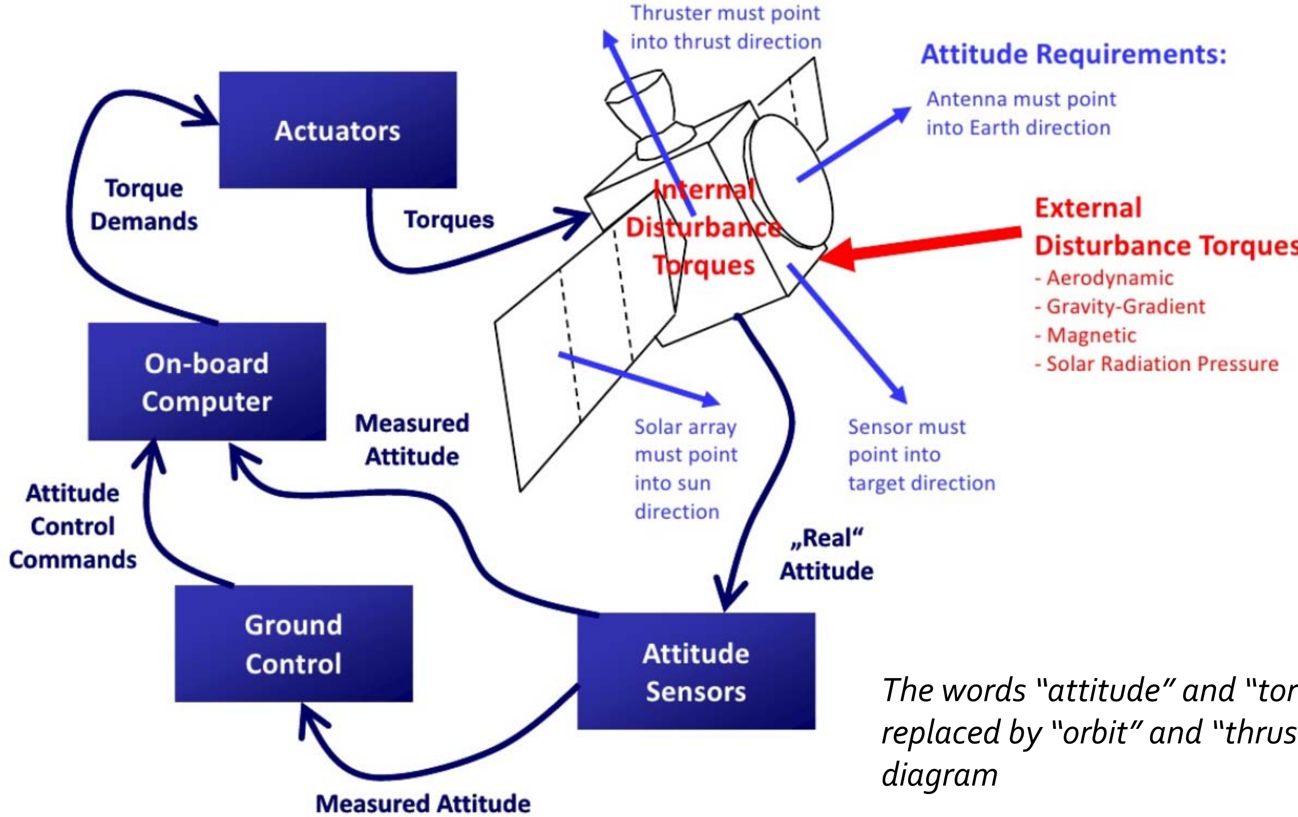
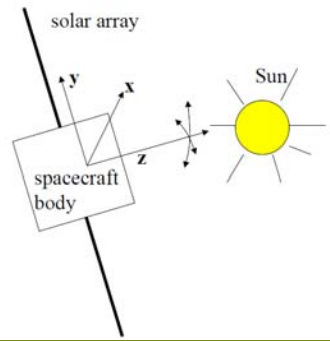
Attitude and Orbit Control Process



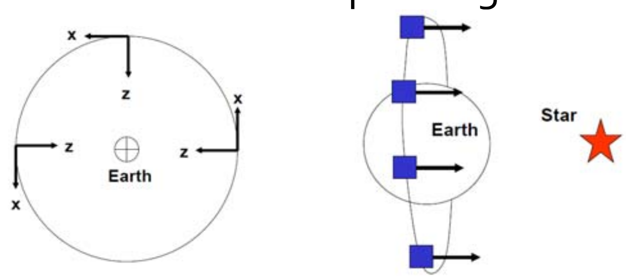
The words "attitude" and "torque" can be replaced by "orbit" and "thrust" in this diagram

Typical Attitude Control Tasks (1)

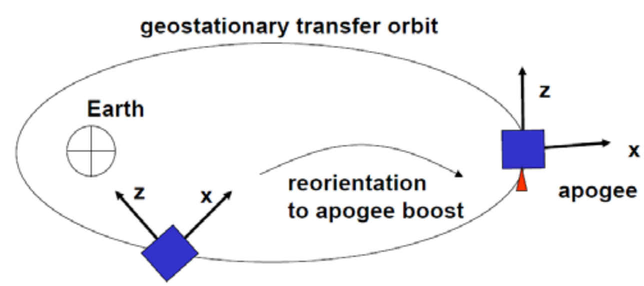
- Rate only
- Two-axis

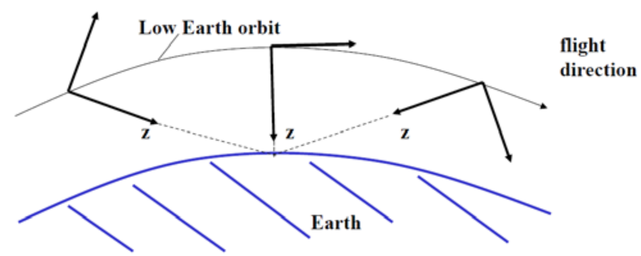


- Three-axis
  - Earth or inertial pointing



- Three-axis
  - Rotating reference



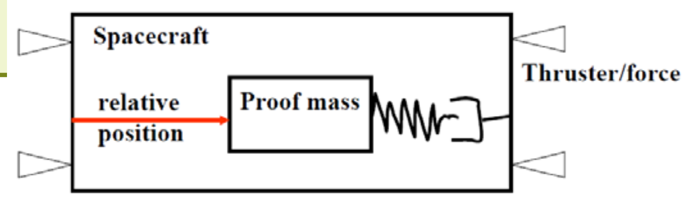


Typical Attitude Control Tasks (2)

Tumbling S/C after separation	*High angular rate* *Arbitrary orientation*
Slow-down angular speed	*Low angular rate* *Arbitrary orientation*
Attain safe attitude (power, thermal)	*Low angular rate* *Sun-pointing* *Low accuracy*
Attain operational attitude (payload operations)	*Low angular rate* *Operational orientation* *High accuracy*
Slew to support orbit operations	*Low angular rate* *Oriented to support orbit maneuver* *Large disturbances*

Typical Orbit Control Tasks

Orbit injection	*No control authority*
Acquire or establish reference orbit	*Large delta-v* *Injection errors*
Maintain or keep reference orbit	*Small routine delta-v* *Perturbations*
Reconfigure	*Large delta-v* *New reference orbit*
Advanced applications: - reference orbit is a satellite - continuous vs impulsive control - coupled orbit/attitude control	*Formation flying* *Rendezvous and docking* *Drag-free satellite*



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AOCS System Design: Process

Step#, Description		Inputs	Outputs
1	Define / derive functional and performance requirements	Spacecraft system specification	Functional and performance requirement for GNC system
2	Quantify disturbance environment	Spacecraft geometry, mass properties, orbit and mission profile, solar and magnetic models	Values and profiles for external forces and torque, and internal disturbances (e.g. fuel sloshing, magnetic disturbances, etc.)
3	System Design: Select type and define architecture of GNC system	Spacecraft system specification (interfaces with other subsystems), payload needs, mission requirements, disturbance environment	Navigation system type (attitude and orbit), control system type (attitude and orbit), degree of autonomy
4	System Design: Select and size hardware	Spacecraft system specification (geometry), mission requirements, GNC functional and performance requirements	Sensor and actuator equipment, on-board computer, requirement for other computers on board and on ground
5	Define GNC algorithms, implement and test	All of above	Algorithms, design and analysis results, [software]
6	Iterate and document	All of above	GNC system description [and software]

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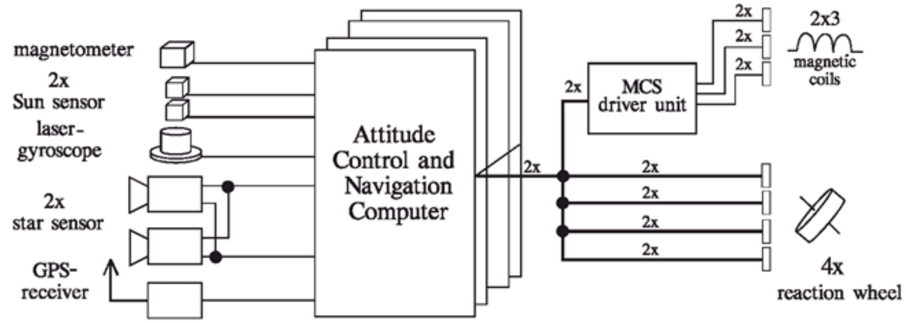
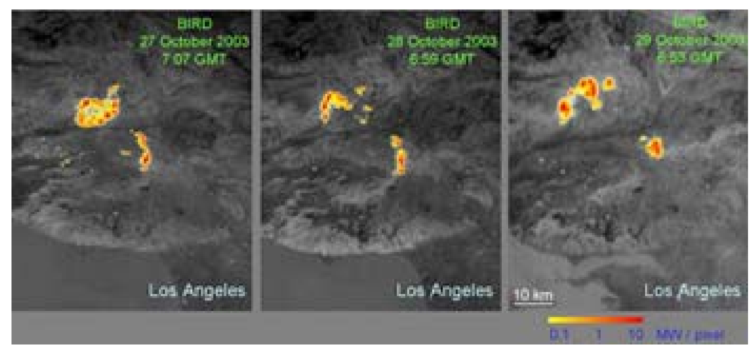
AOCS System Design: Requirements

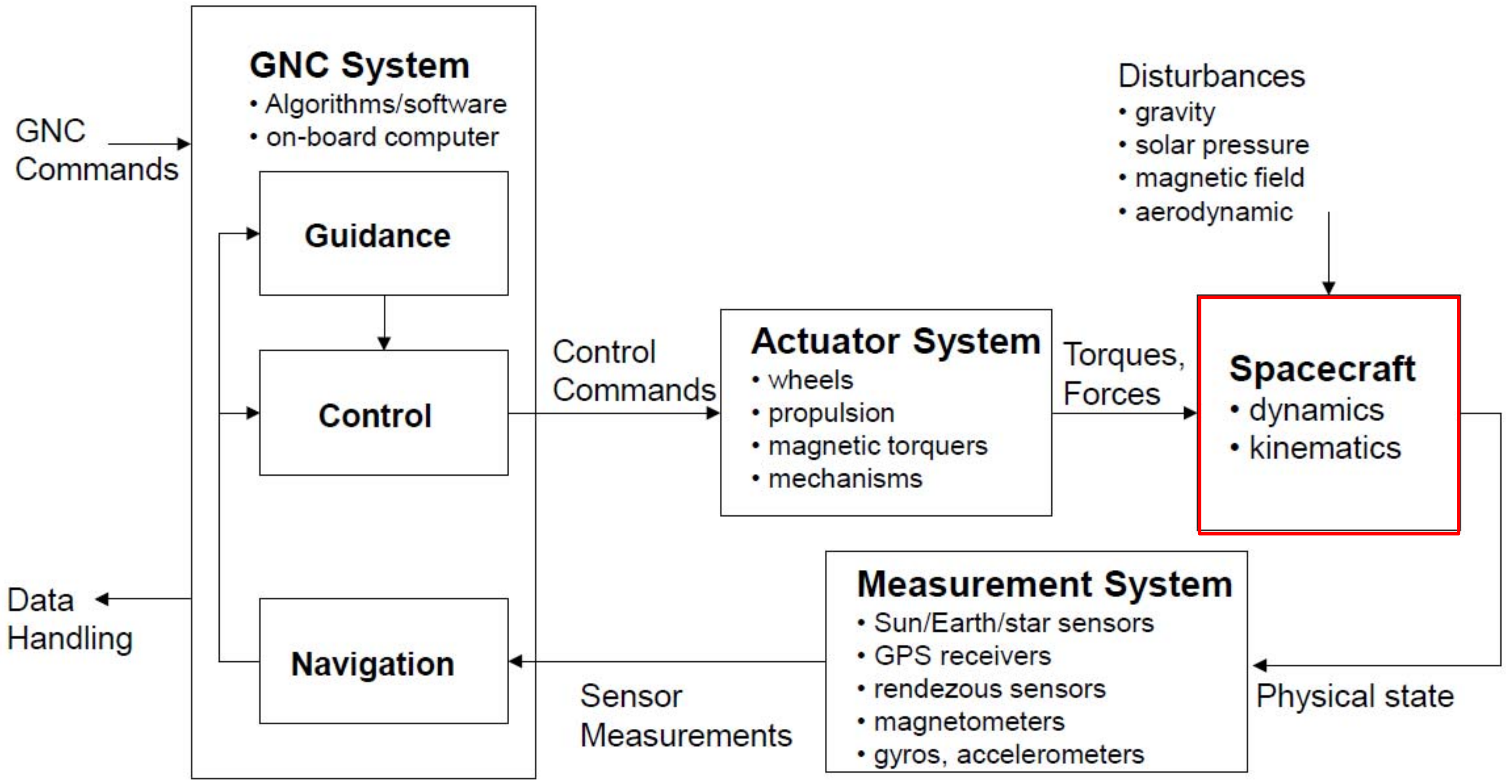
- Functional requirements
  - Well defined modes
    - Acquisition
    - Nominal
    - Safe
    - Orbit
    - Special
- Performance requirements
  - Determination vs control
    - Accuracy and Range
  - Steady state vs transient
  - Constraints



AOCS of BIRD (Bi-spectral and Infrared Remote Detection) Satellite



Block Diagram of AOCS/GNC System



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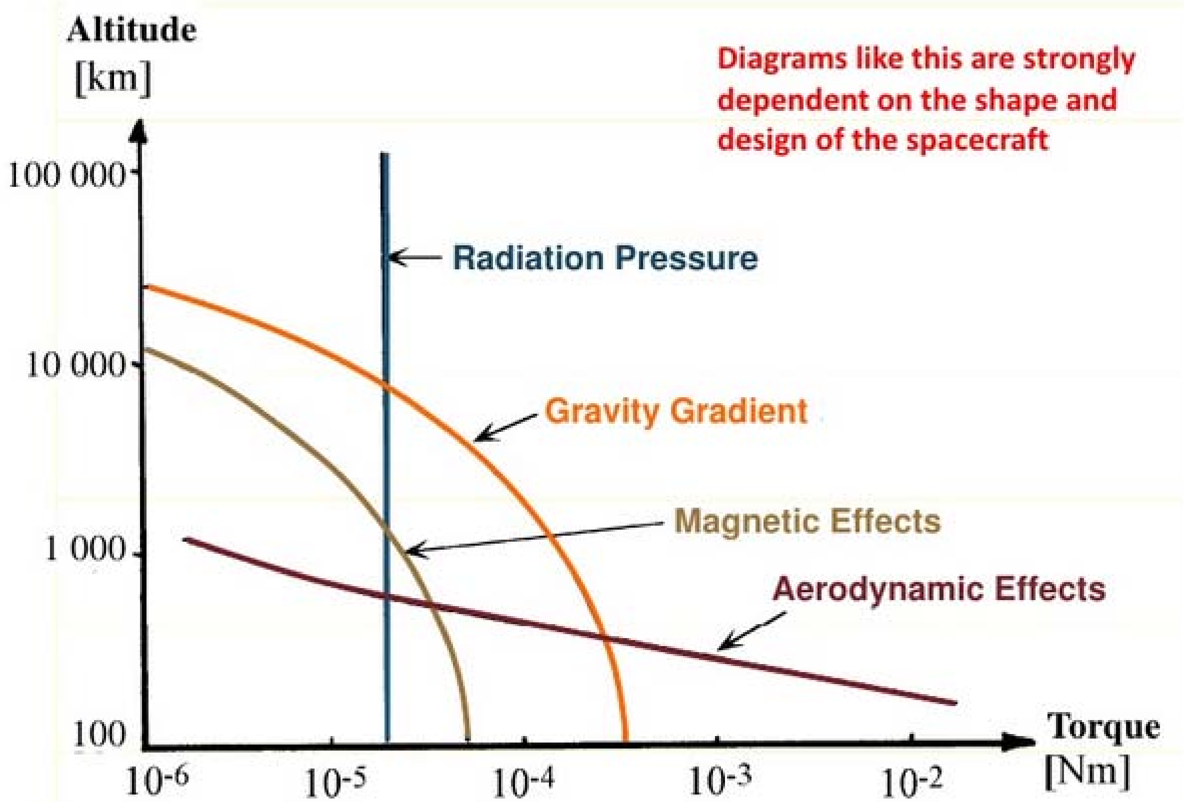
Disturbance: Forces and Torques

- **Aerodynamics**
  - From planetary atmospheres ($e^{-\alpha R}$), Earth: altitude <500 km
- **Gravity gradient**
  - From planetary gravity fields ($1/R^3$), Earth: altitude 500-35000 km
- **Magnetic**
  - From planetary magnetic fields ($1/R^3$), Earth: altitude 500-35000 km
- **Solar radiation**
  - In the inner solar system ($1/r^2$), Earth: altitude >600 km
- **Micrometeorites and debris**
  - At all altitudes, higher concentration in some regions, often negligible
- **Spacecraft generated**
  - Mass movements at all latitudes, important with flexible spacecraft

R: distance from central body
r: distance from Sun

Disturbance: Magnitude of Torques



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Disturbance: Typical Effect of Forces

Contribution	LEO (1 rev)	LEO (1 day)	GEO (1 day)
Earth gravity; terms $>J_{2,0}$	600 m	5000 m	670 m
Earth gravity; terms $>J_{2,2}$	220 m	3000 m	2 m
Earth gravity; terms $>J_{4,4}$	150 m	1900 m	0 m
Earth gravity; terms $>J_{10,10}$	23 m	460 m	0 m
Third body solar gravity	3 m	34 m	3100 m
Third body lunar gravity	6 m	66 m	5100 m
Solar radiation pressure	1 m	14 m	415 m
Atmospheric drag	1 m	100 m	0 m

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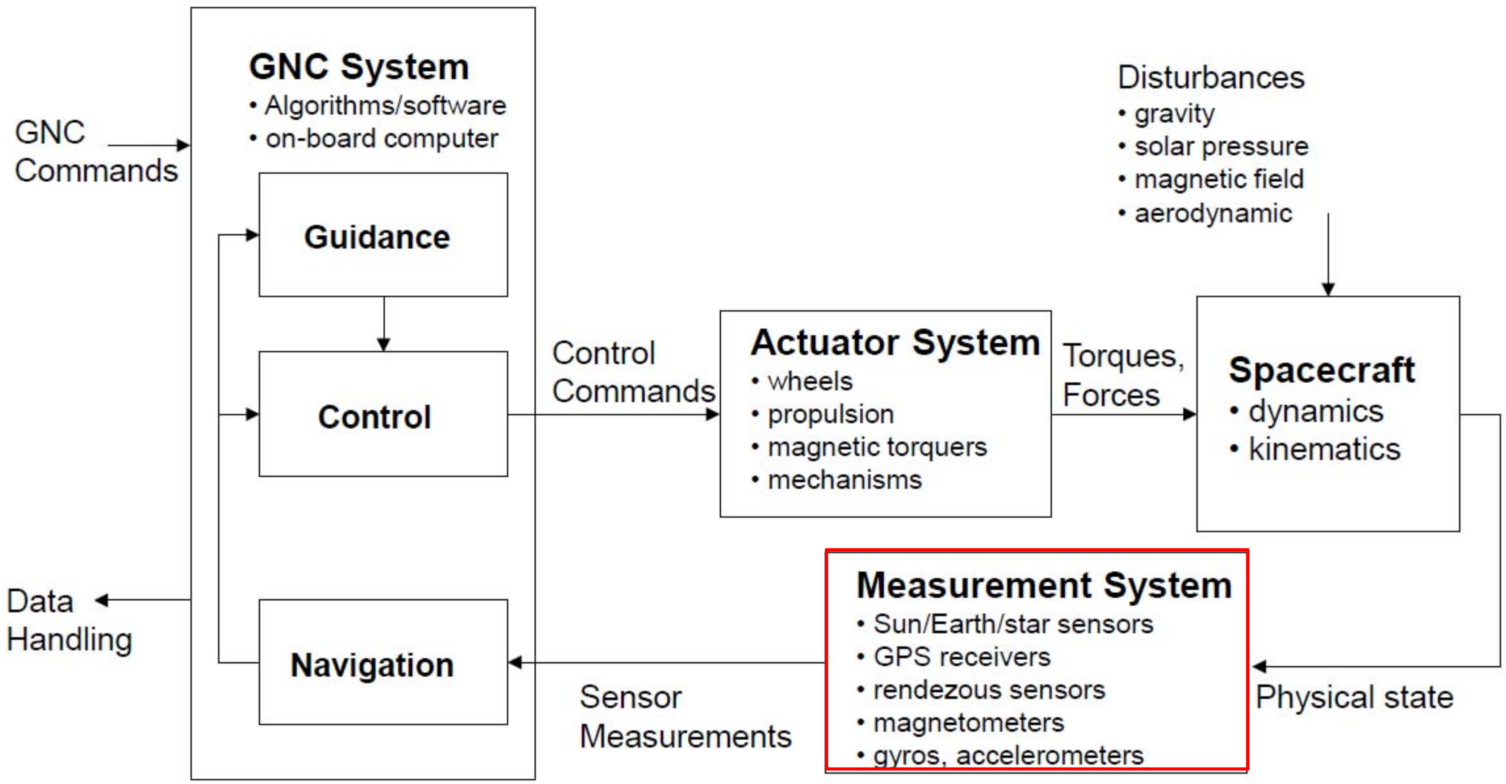


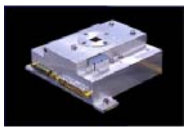
Attitude Sensors: Overview

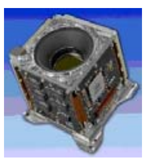
Reference vectors

Centrifugal

Type	Application	Accur.	Price
Sun Sensors			
Solar cell	Sun acquisition	5°	$
V-slit	Sun maintenance	0.1°	$$$
Digital	Sun maintenance	0.05°	$$$
Earth Sensors			
Static	Earth acquisition	5°	$
Horizon crossing	Earth maintenance	0.1°	$$$
Star Sensors	Precise pointing	0.01°	$$$($)
Magnetometers	Coarse attitude control, damping	3°	$
GNSS	Experimental	1°	$$
Gyros			
Spinning	Eclipse transits, rate damping, slews	0.01°	$$$
Ring laser	Eclipse transits, rate damping, slews	0.005°	$$$

Attitude Sensors: Pros and Cons





Type	Advantages	Disadvantages
Sun Sensor	▪ Low cost ▪ Low mass and power	▪ Does not work on night side ▪ Limited accuracy (0.5°) due to apparent diameter of Sun
Earth Sensor	▪ Robust ▪ Available for all orbits	▪ Limited resolution (0.1°) ▪ Sensitive to blinding ▪ Scan motion to sense horizon
Star Sensor	▪ High accuracy ▪ Orbit independent	▪ Sensitive to blinding / stray light ▪ Limited attitude change rate ▪ Potentially high mass & power ▪ Often requires initial attitude
Magnetometer	▪ Modest cost ▪ Low mass and power ▪ Robust	▪ Low accuracy (0.5°) ▪ Works only at low altitude ▪ Magnetic cleanliness needs
Gyroscope	▪ Orbit independent ▪ High accuracy achievable	▪ Senses only attitude changes ▪ Sensor drift ▪ Moving parts (except fiber optical)

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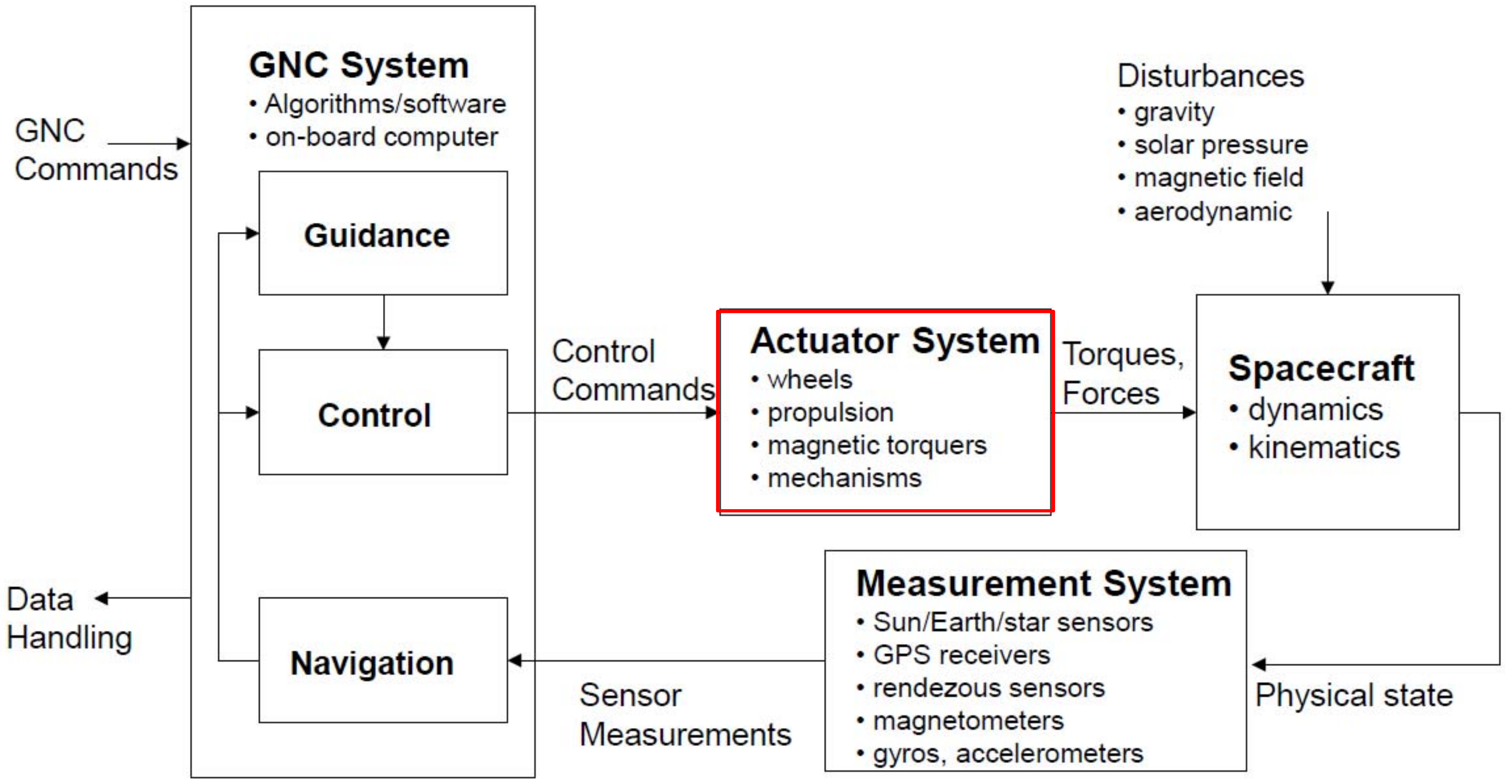
Block Diagram of AOCS/GNC System



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Methods of Passive Attitude Control

Type	Advantages	Disadvantages
Spin  Huygens Titan Probe (2005)	▪ Simple and effective ▪ Applicable anywhere ▪ Maintain inertial orientation	▪ Structural stability and rigidity ▪ Constrains sensor pointing ▪ Nutation and drift if not balanced
Gravity-gradient  DODGE (1967)	▪ Maintain orientation relative to central body ▪ Not subject to decay or drift	▪ Limited orientations ▪ Low altitude, boom required ▪ Low accuracy (1°)
Solar radiation  Nanosail (2011)	▪ Convenient for power generation	▪ High altitude ▪ Limited orientations ▪ Large surfaces required
Aerodynamic or Magnetic	▪ Special purpose methods, highly dependent on mission and structure	

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Methods of Active Attitude Control

Type	Advantages	Disadvantages
Gas thrusters 	▪ Flexible and fast ▪ High accuracy ▪ Any environment	▪ Uses limited fuel (consumable) ▪ Plumbing subject to failure
Magnetic 	▪ Low power ▪ No consumables through solar power	▪ Slow and near earth only ▪ Applicability limited by external magnetic field direction ▪ Low accuracy (degrees)
Reaction/Momentum wheels 	▪ Flexible and fast ▪ High accuracy ▪ Any environment	▪ Requires rapidly moving parts ▪ Second control system required to control angular momentum due to cumulative perturbations
Ion or electric thrusters, other active methods	▪ Special purpose methods, highly dependent on mission, low technology readiness level	

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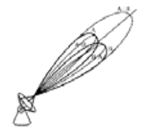
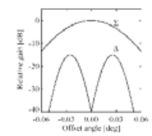
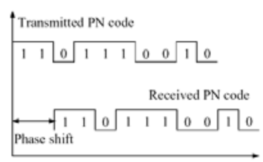
Backup

Orbit Sensors: Overview

Type	Principle	Accuracy	Notes
Angle Measurements Monopulse radar Interferometry	▪ Measure line-of-sight direction ▪ Difference of two offset horns  	10-300''	No uplink
Doppler Tracking One-way Two-way Three-/Four-way	▪ Received freq given by range-rate ▪ Sensitive to clock errors ▪ Requires transponder ▪ Require multiple receive stations $\frac{\Delta f}{f} = -\frac{1}{c}\frac{d\rho}{dt}$	<1mm/s	Uplink
Distance Measurements Tone-/PRN-code ranging Satellite laser ranging GNSS	▪ Measure turn-around travel time ▪ Phase shift causes ambiguity 	 10m-5cm <5cm 10m-5cm	Uplink Autonomous

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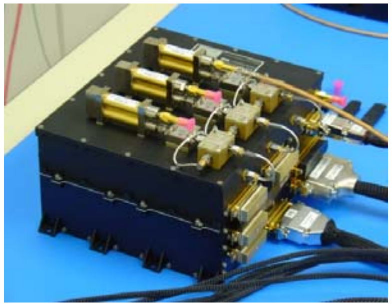
Orbit Sensors: Spaceborne GPS Receivers



	MosaicGNSS (Astrium)	Phoenix (DLR)	IGOR (Broadreach/JPL)
Type	8 channels L1	12 channels L1	16 x 3 channels L1/L2
Raw data accuracy	C/A 5 m L1 3 mm	C/A 0.4 m L1 1 mm	C/A, P(Y) 0.2 m L1, L2 1 mm
Power	10 W	1 W	15 W
Radiation tolerance	35 krad	14 krad	12 krad
Cost (ROM)	150 k€	10 k€	500 k€

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