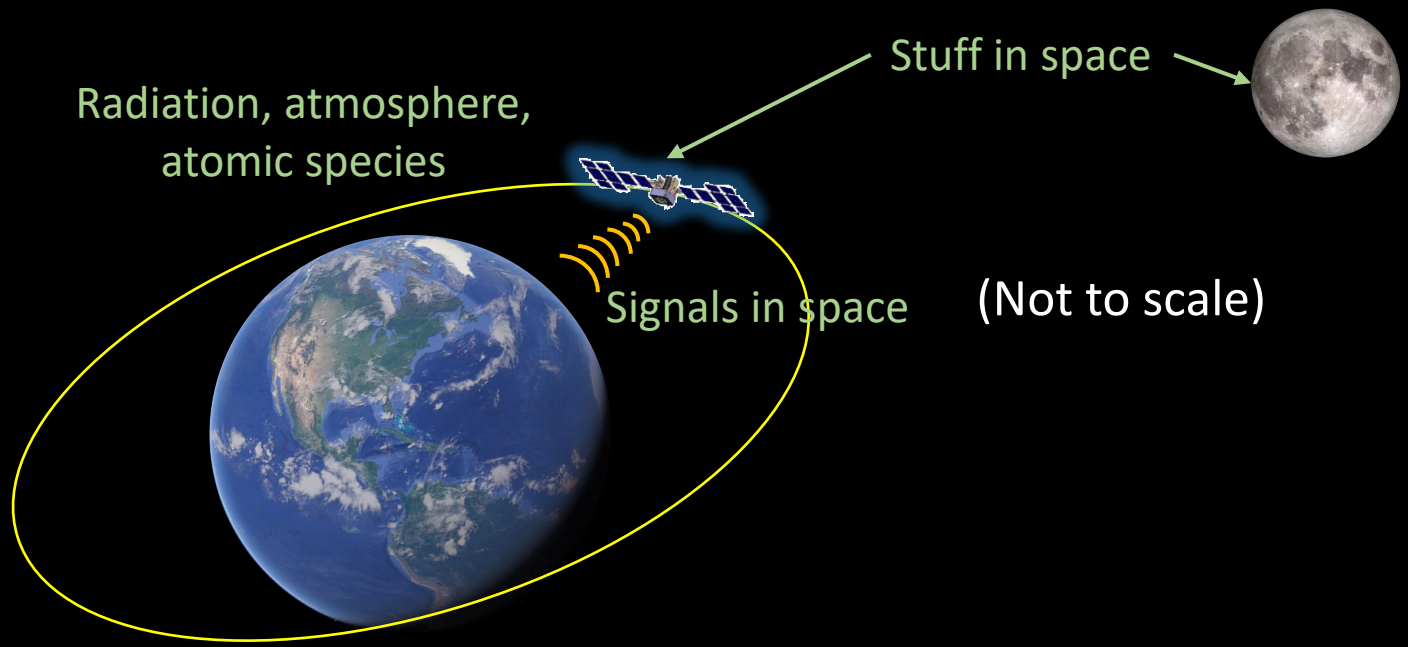
An Introduction to the Space Domain

New Mexico Tech
2024 Space Cyber Resiliency Lecture Series

Brian Engberg – Air Force Research Laboratory

What is the Space Domain?

The ***space domain*** is the region beyond the ***air domain*** that includes natural & man-made objects, the total radiation and chemical environment, and all operations conducted therein.



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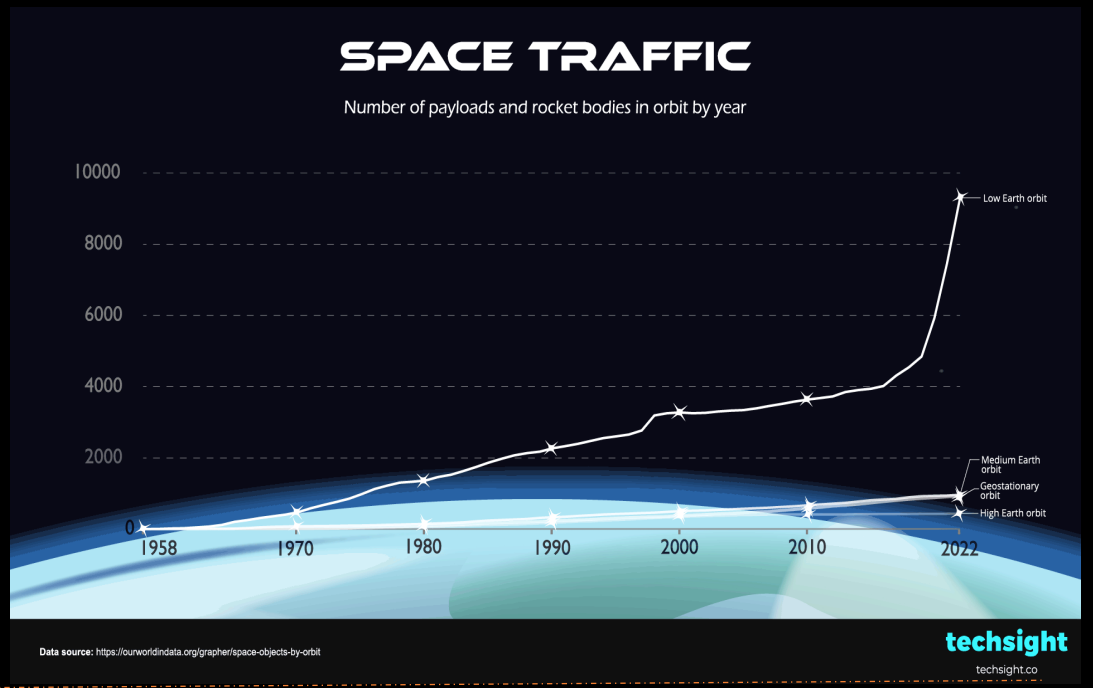
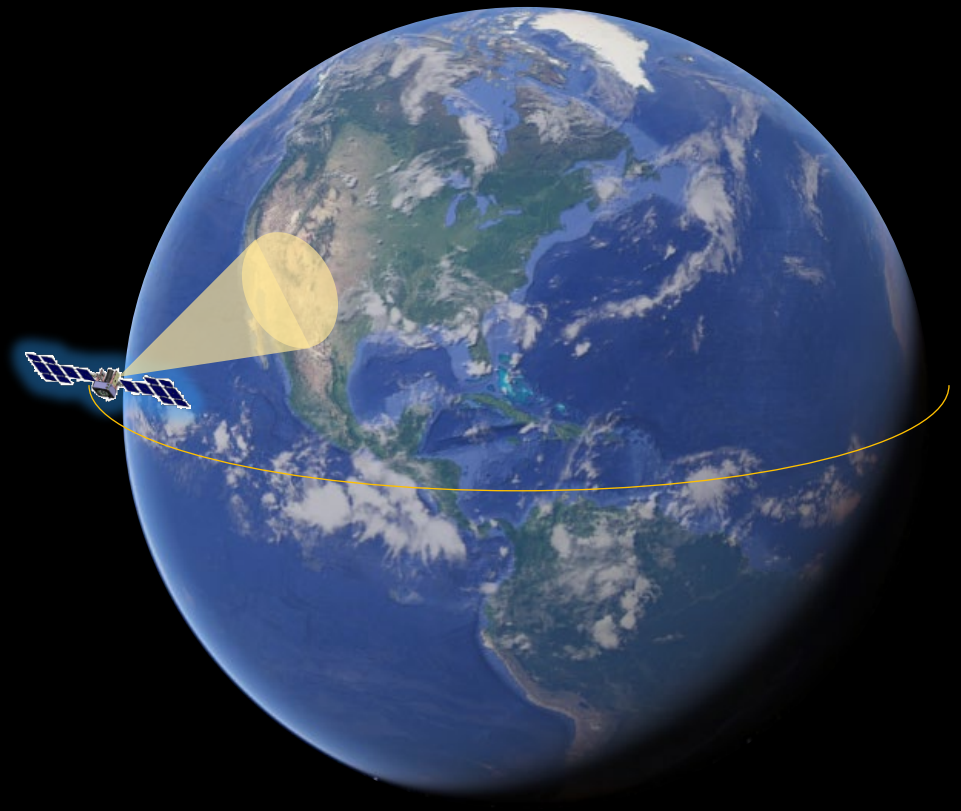


(Approximately to scale)

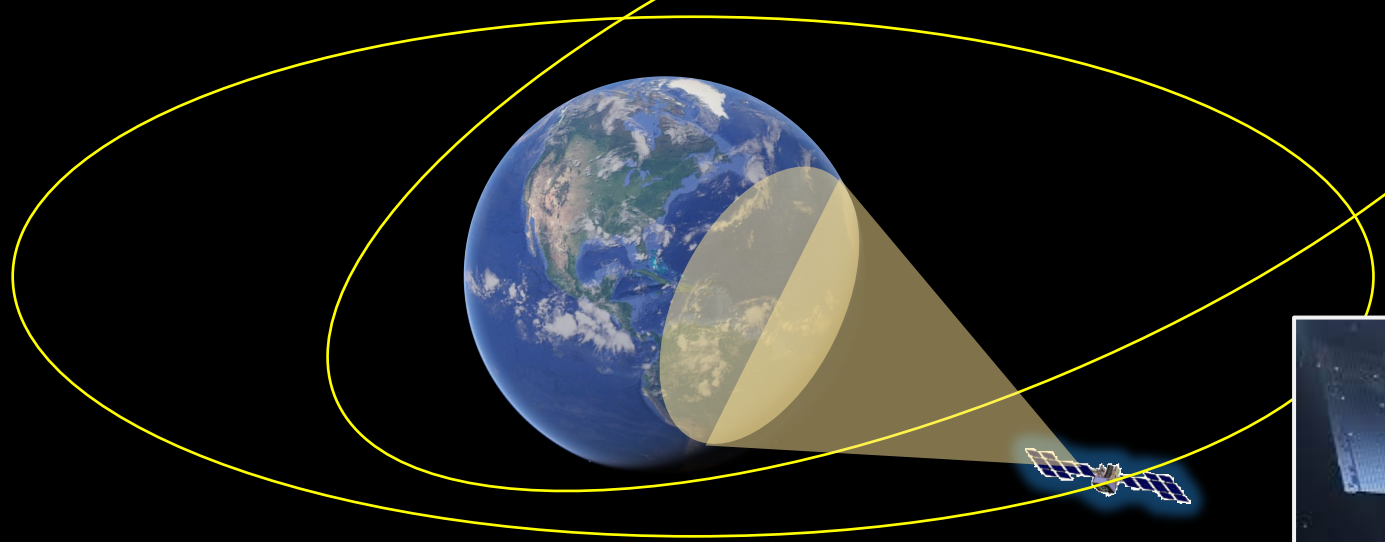
Different Types of Orbits – Low Earth Orbit (LEO)



Altitude range: 300-1000 km
Orbit periods: 90-105 min
Ground path/coverage area: 1-7% coverage
Typical missions: Earth sensing, Manned Flight, Experiments
Missions here tend to be one-off satellites or very large constellations

Different Types of Orbits – Mid-Earth Orbit (MEO)/Highly Elliptical Orbit (HEO)

Altitude range: 2500 – 15000 km
Orbit Periods: 2-12 hours
Ground path/coverage area: 14-40%
Typical missions: Navigation, communications
Good ground coverage leads to smaller constellation sizes



Also
GLONASS
Galileo
BiDou

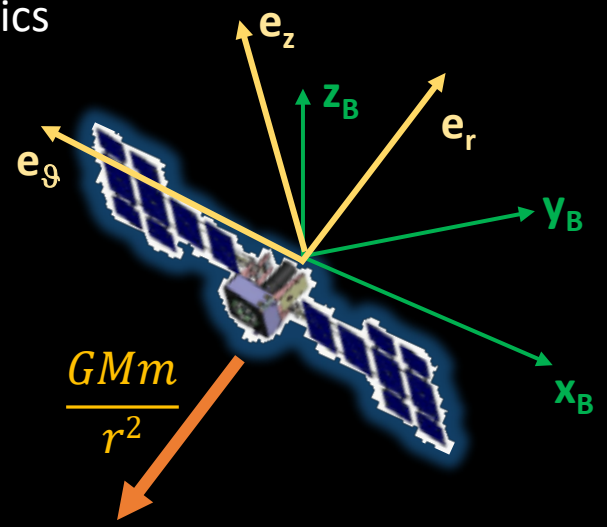
Different Types of Orbits – Geosynchronous Orbit (GEO)

Altitude : 36000 km
Orbit Periods: 24 hours
Ground path/coverage area: ~42%
Typical missions: Communications, weather, Earth sensing
THE MOST valuable orbits in the space domain

Long mission lifetimes (15-30 years) means these satellites tend to be quite large

The Space Environment

Physics

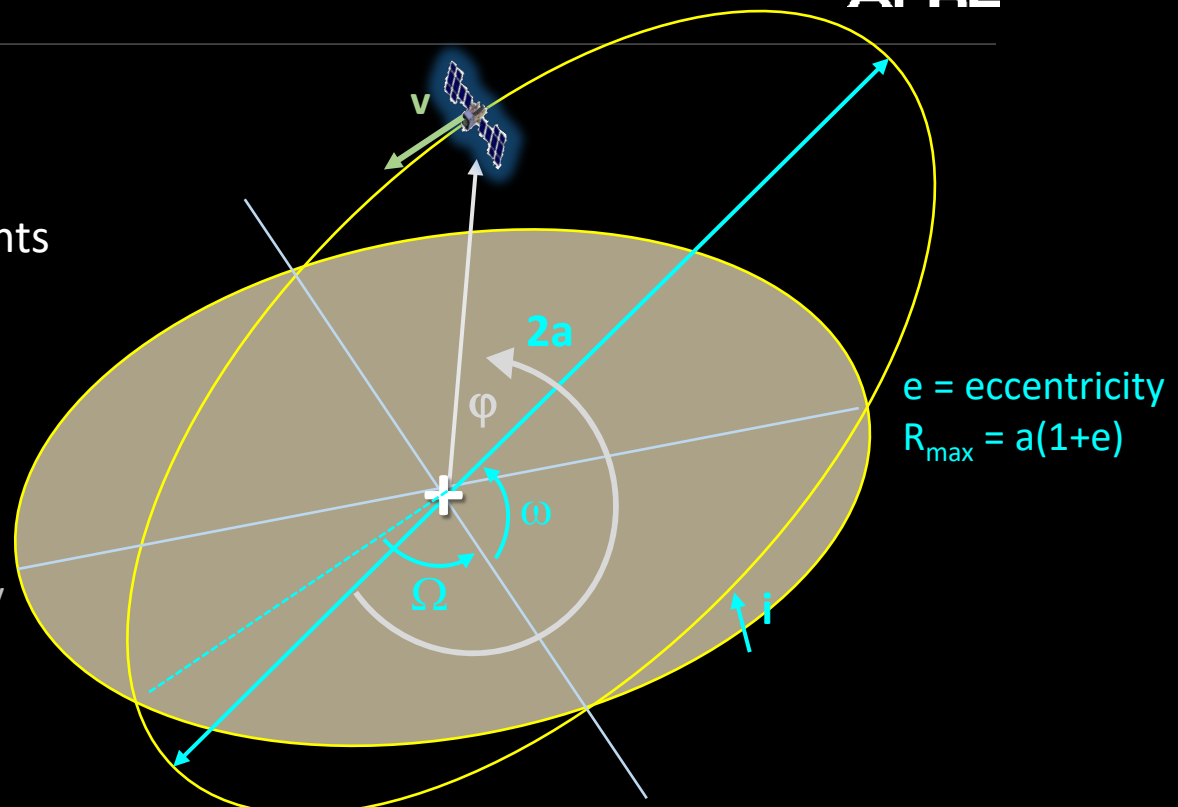


Orbits & Orbit Elements

$\{a, e, i, \varphi, \omega, \Omega\}$

Translates to $\bar{r}$ & $\bar{v}$

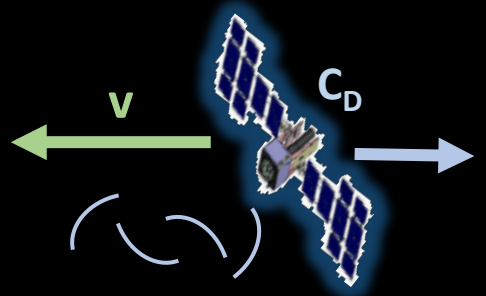
Conservation of energy & angular momentum



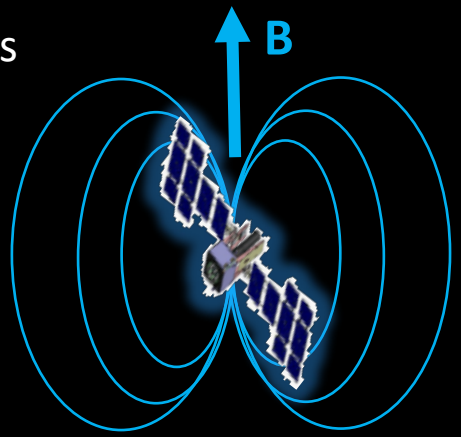
e = eccentricity

$R_{max} = a(1+e)$

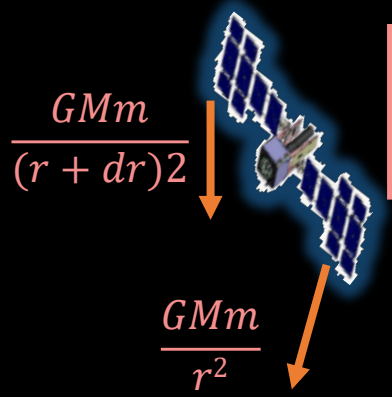
Perturbation Forces & Torques



Aerodynamic drag & torque



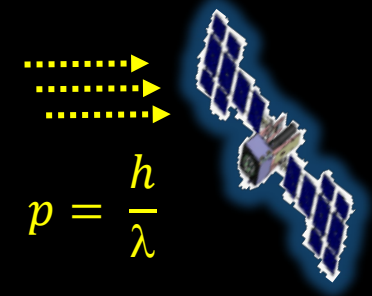
Electromagnetic torque



$$\begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{yz} & I_{zz} \end{bmatrix}$$

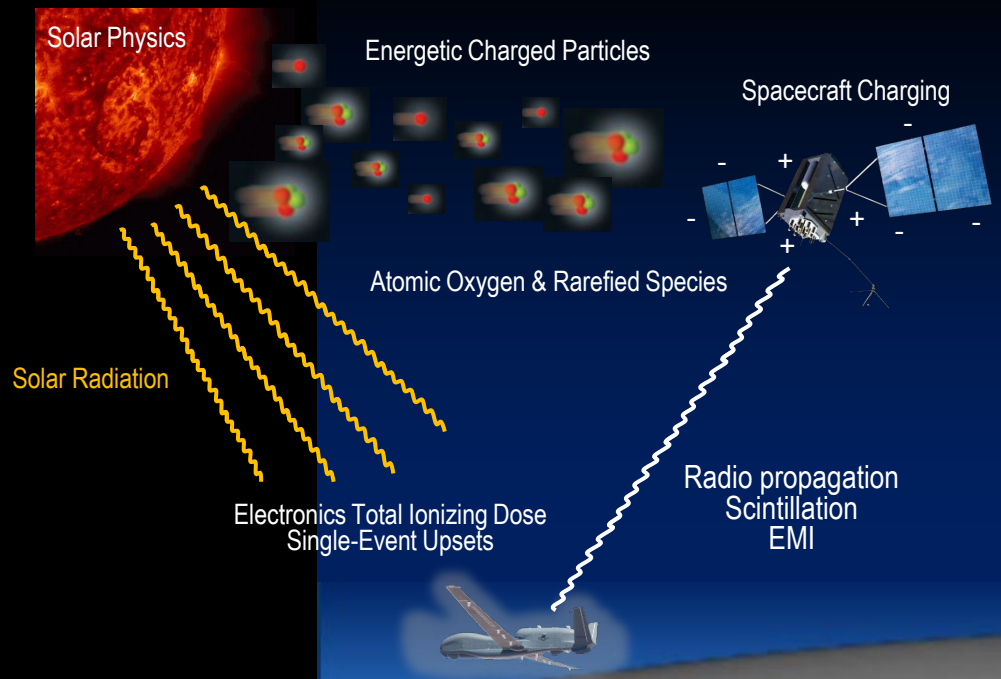
Gravity gradient torque

Solar radiation pressure



$$p = \frac{h}{\lambda}$$

The Space Environment



GEO

Micrometeorites
Solar Radiation & charged particles

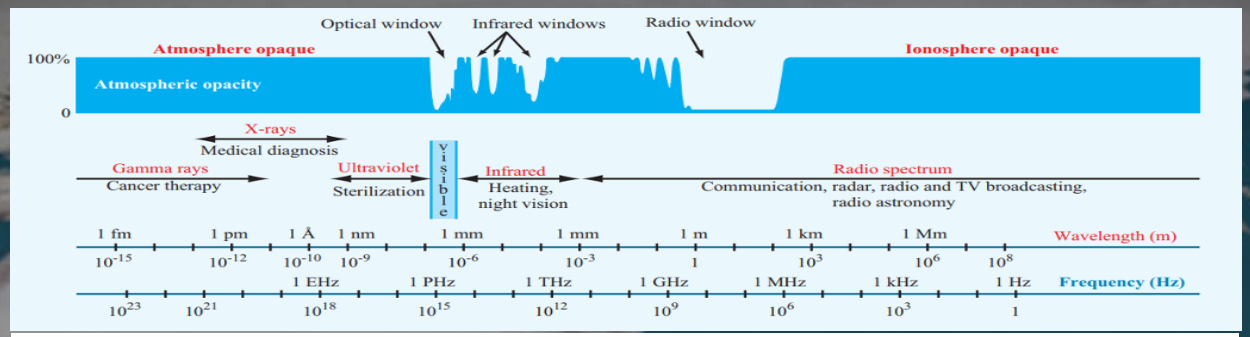
MEO

Van Allen Radiation Belts

LEO

(Man-made) Emissions & Transmissions
Atomic Oxygen & Rarefied Species
Temperature: -70C – 220C

Ionosphere

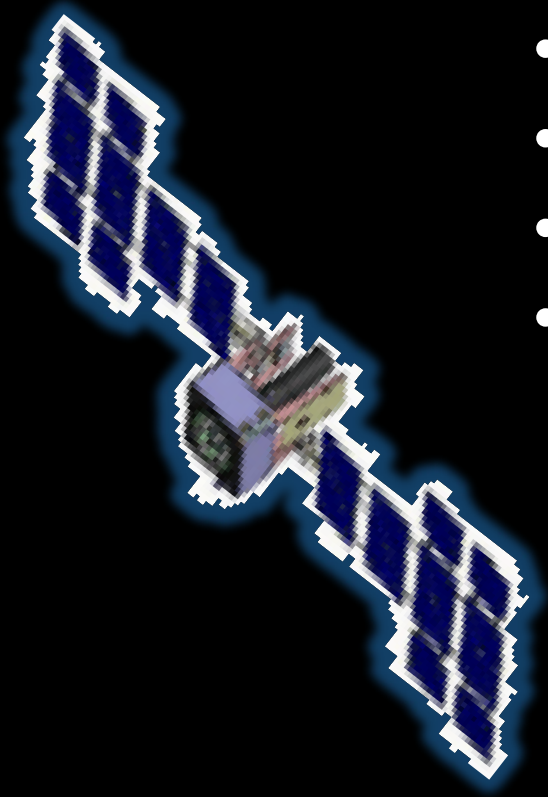


Atmospheric opacity of the electromagnetic wave spectrum with the infrared and radio windows used by spacecraft for communication.
Credit: Microwave Radar and Radiometric Remote Sensing by Ulaby and Long

Terrestrial Environment:
Pressure: 1 atm
Temperature: -50C – 50C
Atmosphere: O_2 & N_2

Satellite Design - Subsystems

- Structures
- Power
- C&DH
- Communications
- Propulsion
- GNC
- ADCS
- Thermal
- Software
- Payload



Systems Engineering

- Requirements
- Verification & Validation
- Size, Weight & Power (SWaP)
- Design Budgets
- Integration & Test

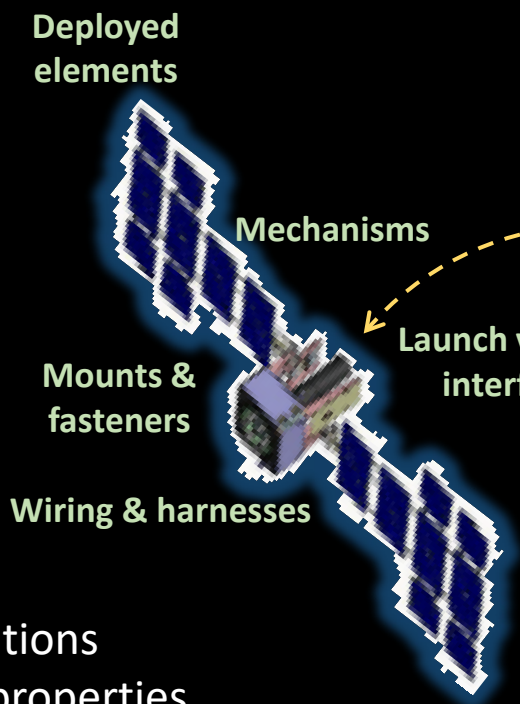
This brief addresses the technical aspects of the space domain & space missions, not the program management aspects

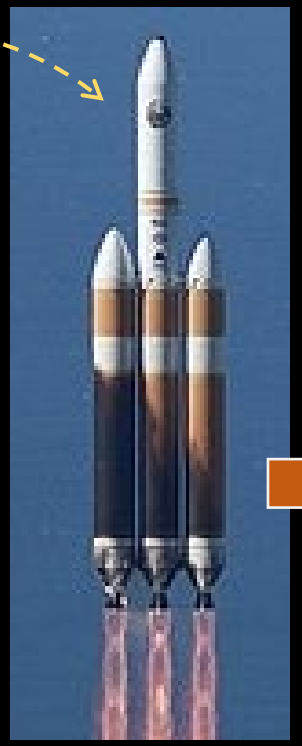
Satellite Design - Structures

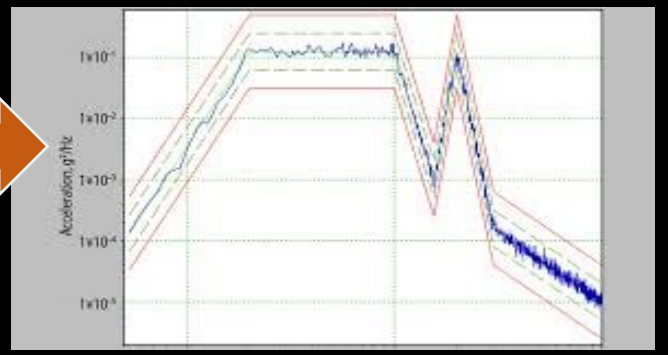
The physical structure of a satellite that connects all hardware elements

Related requirements:
- Launch safety
- Rigidity
- Material life & aging
- Size envelope/dimensions
- Manufacturing tolerances

Design concepts:
- Center of mass
- Center of pressure
- Inertia Tensor
- Deployed & stowed configurations
- Material strength & thermal properties
- *Manufacturability*
- *Transportability*
- End of life considerations







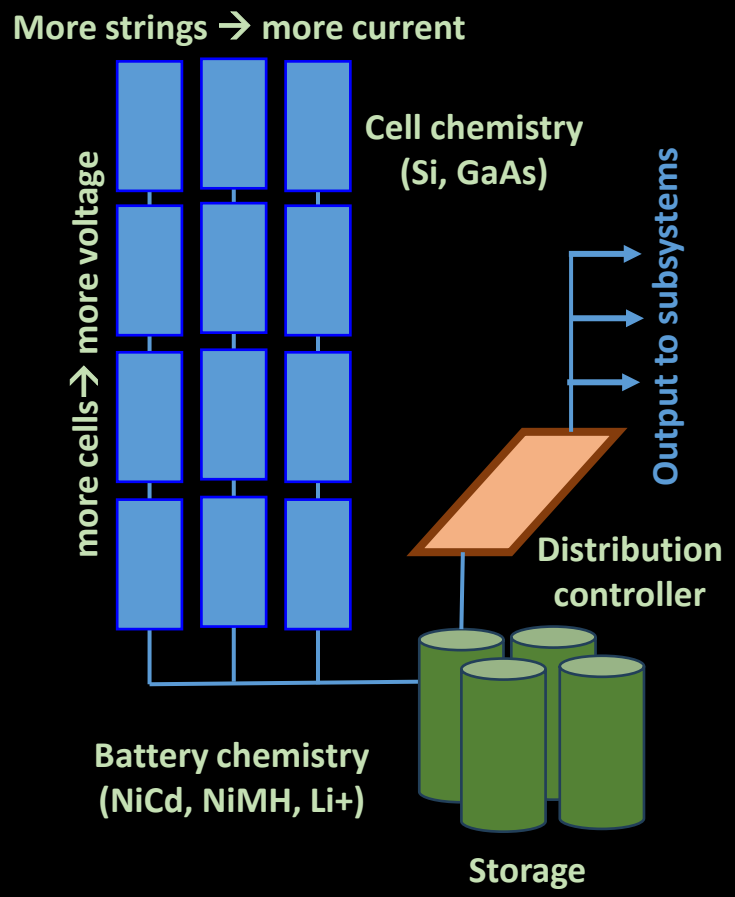
Systems Engineering concepts:
- Mass budget
- Volume Budget
- Test & Evaluation
  - Vibration frequency response
  - Thermal-vacuum testing
  - CoM & inertia characterization

Satellite Design - Power

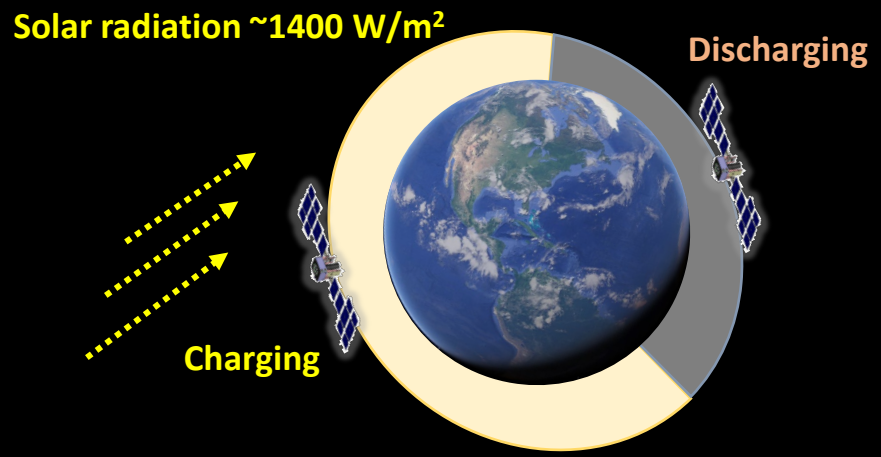
The generation, storage, and distribution of energy on a satellite

Related requirements:
- Launch safety
- SWaP
- Bus voltages

Design concepts:
- Battery sizing (energy & energy rate)
- Solar panel design (energy rate)
- Solar cell/battery chemistry
- Capacity & max power
- Depth of discharge
- Mission life



Systems Engineering concepts:
- Power budget
- Flight modes
- Operations Analysis (day-in-the-life)
- Test & Evaluation
  - Solar panel output
  - Battery characterization



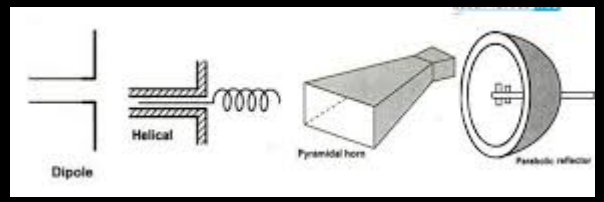
Satellite Design - Communications

The system that encodes & decodes EM waves to receive and transmit data

Related requirements:
- Link margin
- Data rate
- ***Frequency allocation***
  - **Licensing is a National / International process!**

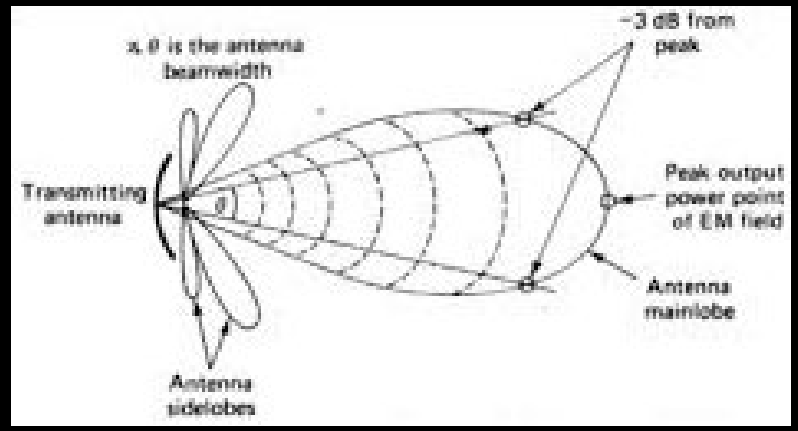
Design concepts:
- Modulation scheme
- Antenna Gain
- Single vs dual band
- Radio band (L, S, C, X, Ku, Ka, V)
- Signal-to-noise ratio
- Error rate per bit
- Polarization
- Impedance matching (radio-line-antenna)
- Ground system design

Antenna types



Dipole Helical Horn Parabolic
Patch Phased array

Antenna radiation patterns

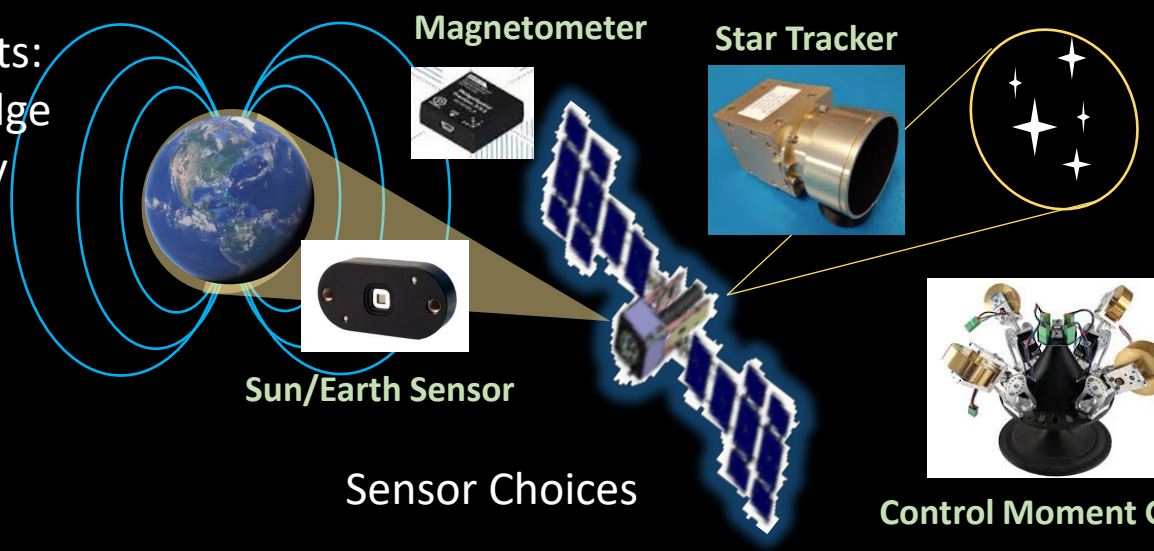


Systems Engineering concepts:
- Link budget
  - Radiated power
  - Antenna gain
  - Receiver gain
  - Loss terms
  - Data rate
  - Error rate per bit
  - Signal-to-noise ratio
- Test & Evaluation
  - Antenna characterization
  - Losses & efficiencies

Satellite Design – Attitude Determination and Control

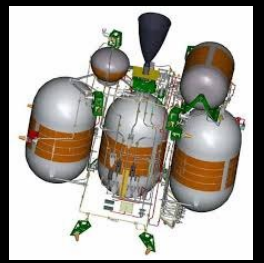
Sensing and orienting the satellite in a local reference frame

Related requirements:
- Pointing knowledge
- Pointing accuracy
- Slew rate



Sensor Choices

Momentum Wheels



Propulsion

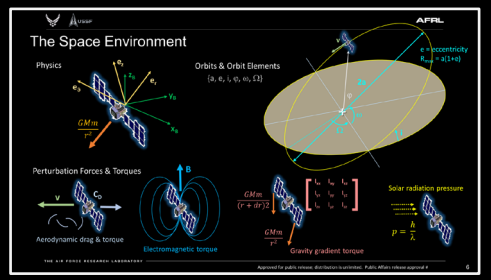
Control Moment Gyros

Actuator Choices

Magnetorquer

Design concepts:
- Sensor type
- Actuation type
- Control law
- Inertia tensor
- Jitter
- Disturbance torques

Remember these? →

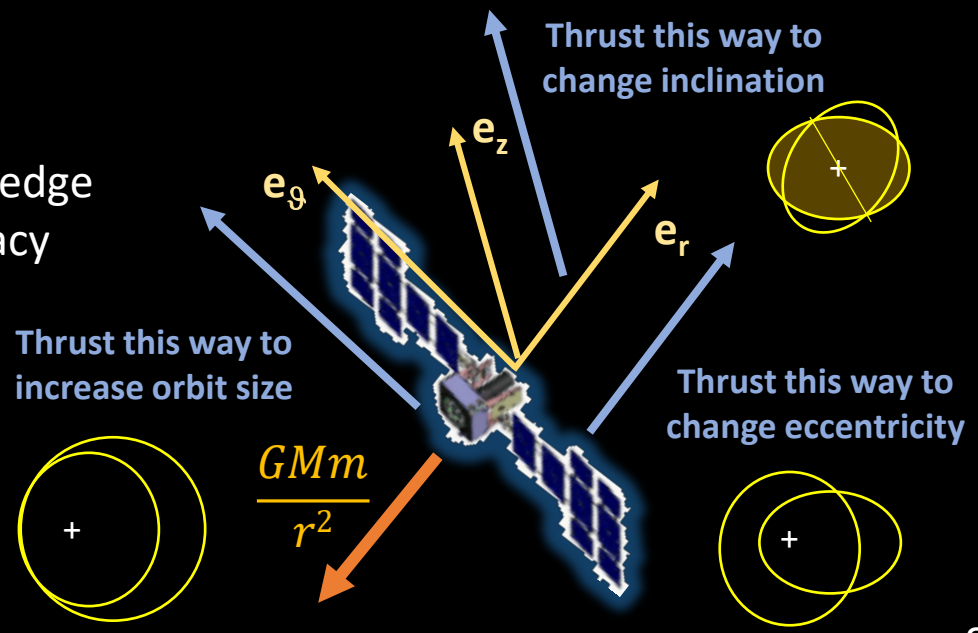


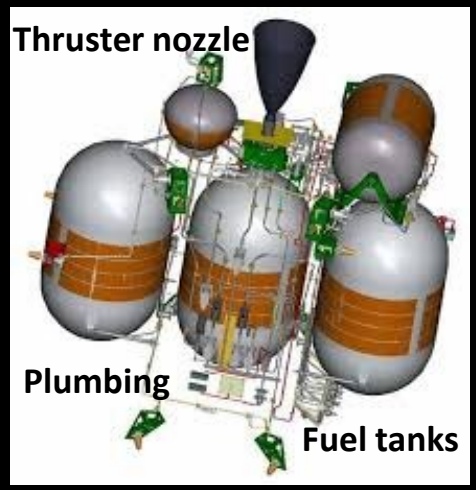
Systems Engineering concepts:
- Derived requirements from
  - Payload – point at operational target
  - Communications – point @ ground system
  - Power – point at sun
- Test & Evaluation

Satellite Design – Guidance & Navigation Control

Accurately sensing position & velocity and navigating between trajectories

Related requirements:
- Flight safety
- Position & velocity knowledge
- Position & velocity accuracy
- Mission life / total fuel
- Maneuverability





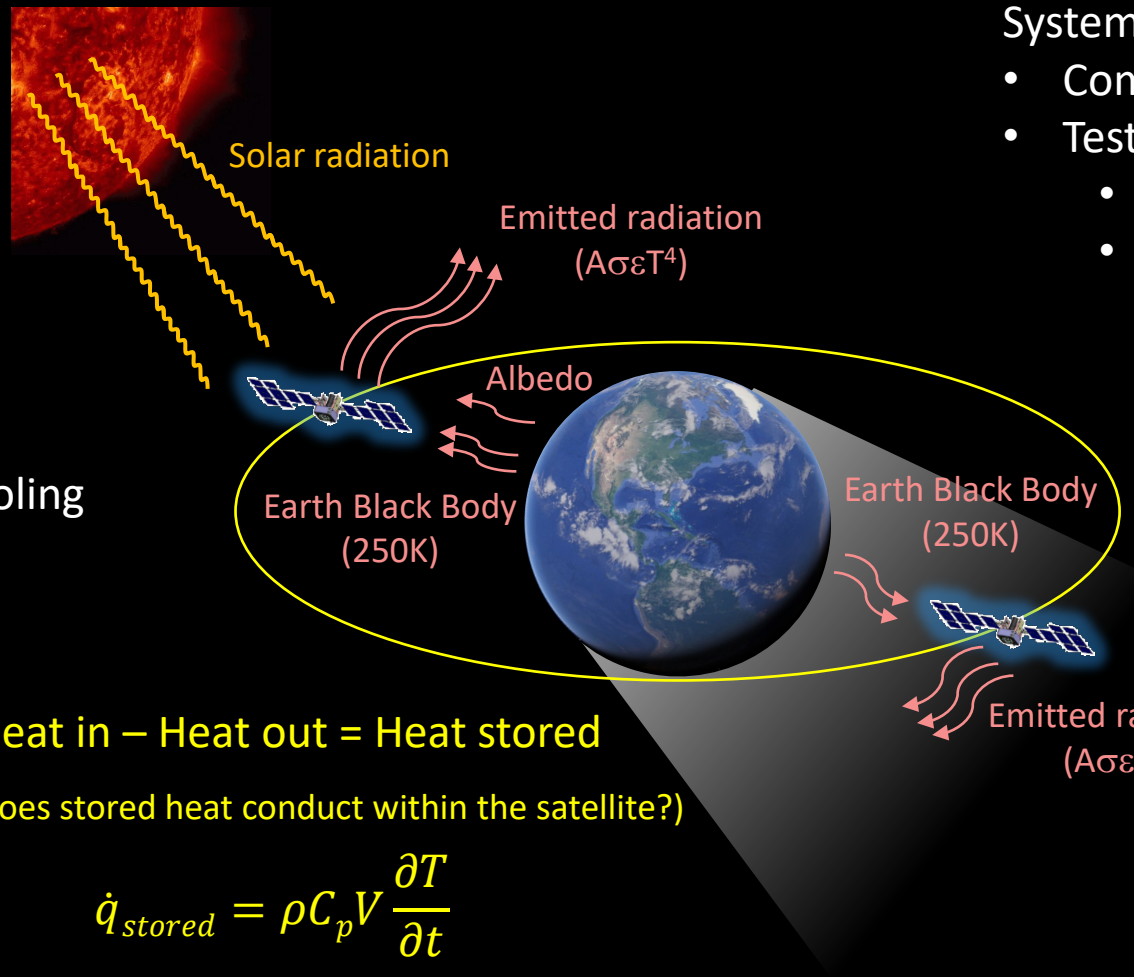
Design concepts:
- Sensor type
- Propulsion type
- Control law
- Minimum impulse bit
- Disturbance forces
- Thruster alignment

Systems Engineering concepts:
- Fuel budget
- SWaP
- Test & Evaluation
  - Thruster characterization
  - Vacuum testing

Satellite Design - Thermal

Ensure all hardware can operate within allowable thermal limits

Related requirements:
- Flight safety
- Mission operations
- Orbit & attitude



Systems Engineering concepts:
- Component operational ranges
- Test & Evaluation
  - Validation of thermal models
  - Thermal-Vacuum testing

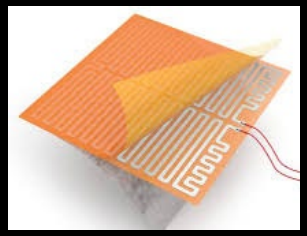
Design concepts:
- Passive vs. active heating & cooling
- Material properties
- Thermal models
- Conductivity paths
- Heat capacity
- Coatings & insulation

Heat in – Heat out = Heat stored

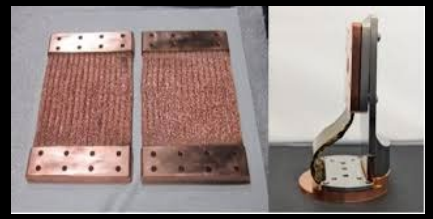
(How does stored heat conduct within the satellite?)

$$\dot{q}_{stored} = \rho C_p V \frac{\partial T}{\partial t}$$

Passive thermal blanket



Active heating element



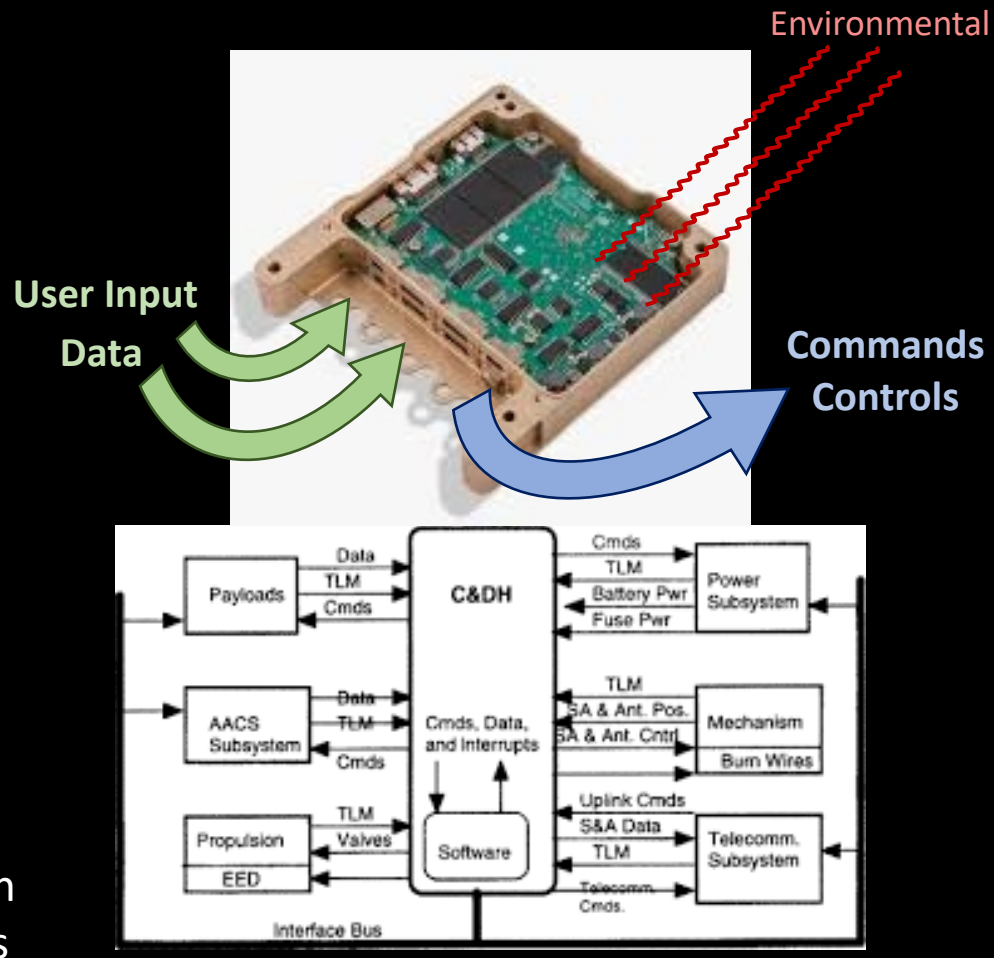
Passive heat sink/radiator

Satellite Design – Command & Data Handling

Hardware architecture that processes commands and stored data

Related requirements:
- Flight safety
- Mission life
- Mission processing
- Mission data storage

Design concepts:
- Processor architecture
- Boot process & operating modes
- Memory type
- Data bus
- Fail safes/cyber security
- Clock synchronization
- Radiation hardness / tolerance
- Wiring harness / connectors
- Years of development lag between on-orbit and terrestrial processors



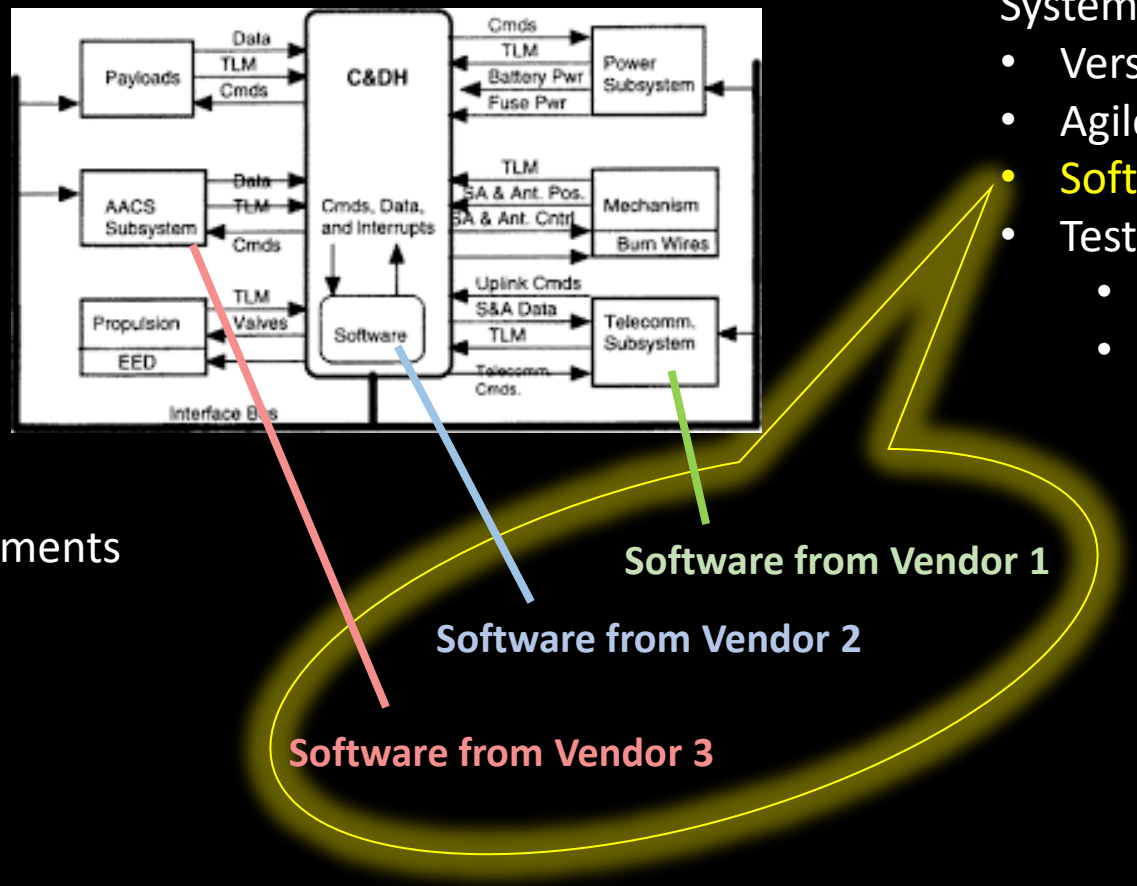
Systems Engineering concepts:
- Interface control
- Memory budget
- Processing budget
- Power budget
- Thermal design
- Test & Evaluation
  - Day-in-the-life simulation
  - Load testing
  - Component rad tests

Satellite Design - Software

All satellite code that enables the full scope of command and control for the mission

Related requirements:
- Flight safety
- Mission life
- Mission processing
- Mission data storage

Design concepts:
- COTS vs. custom code
- Software architecture that compliments hardware architecture
- Fail safes & operational modes
- Documentation & commenting
- Upgradability



Systems Engineering concepts:
- Version Control
- Agile vs. waterfall method
- Software integration
- Test & Evaluation
  - Cyber vulnerability analysis
  - Feature & functional testing

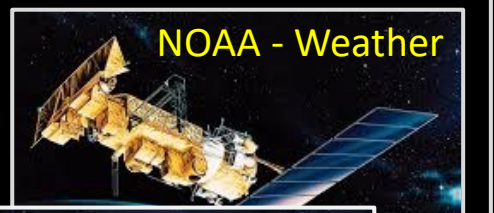
Satellite Design - Payload

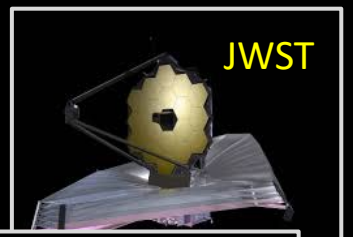
Hardware & software that provides the mission function or service

Related requirements:
- Mission requirements
- Concept of operations (CONOPs)
- Orbit requirements
- User needs

Design concepts:
- Sensor type
- Payload software

Systems Engineering concepts:
- Interface control
- SWaP
- Integration testing

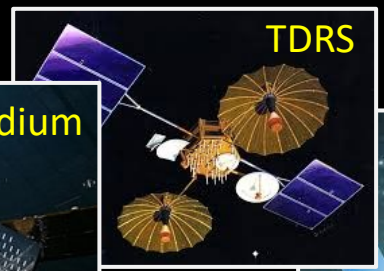




Space-based Sensing

Navigation Services

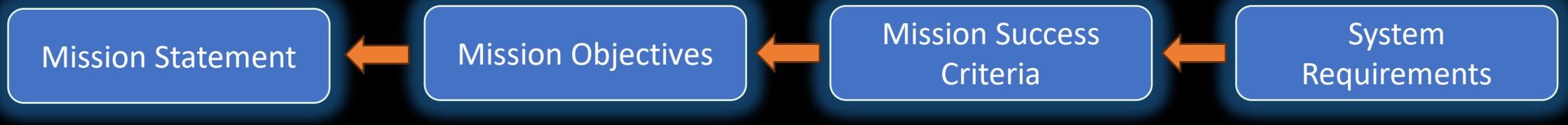
Communication Services



Mission Design

Mission definition – process where a *stakeholder* needs & objectives are identified

- This will likely be an iterative process with the stakeholder
- Key questions to answer:
  - Why is a space-based solution necessary or the most cost-effective?
  - Is it technically feasible?
  - Given cost & schedule constraints, is it executable?
  - What is the operational concept or baseline mission plan?
- Capture stakeholder needs & objectives in a mission statement
  - Document mission objectives & success criteria that support the mission statement
  - Identify broad system requirements that accomplish mission success criteria
  - Decompose system requirements for each subsystem

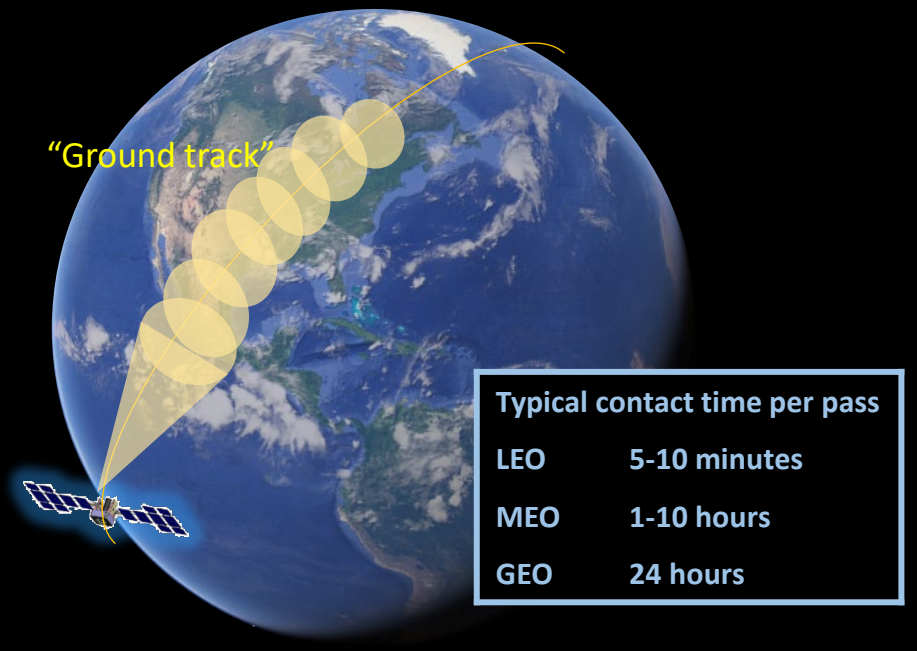


Satellite Operations

Once in orbit, ***we can never touch the satellite again***; the only interaction we have with it is through transmissions between the ground station and the communications system

Ground Station
(This must be built & designed too)

Mission Operations Team



Typical contact time per pass	
LEO	5-10 minutes
MEO	1-10 hours
GEO	24 hours

Contact windows depend on the orbit altitude and antenna lobe geometry. This affects signal-to-noise and the length of the contact

Command & Control Interface

Since satellite communications occur at specific uplink & downlink frequencies, it is not unusual for a single ground station to be designed to talk to a single satellite (or set of similar satellites). In the future, satellites and ground systems will need to be networked to achieve operational flexibility

Miscellaneous Topics

Standards of behavior
- The Outer Space Treaty of 1967
- Transparency and safety of flight
- Concepts of space sovereignty

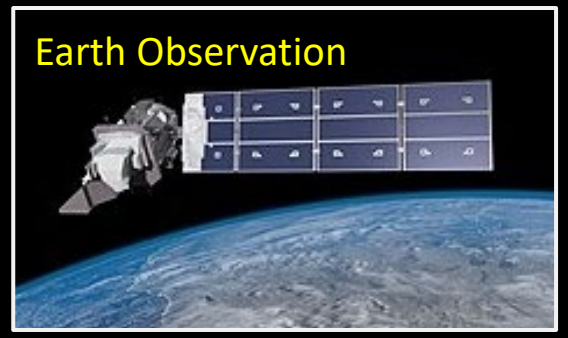
What about space above "my land" and "my water"?

If two objects in space collide, who is at fault?

Space economy
- Primarily services
  - Navigation & Timing
  - Earth sensing
  - Communication bandwidth
- But can also be goods
  - Zero-G manufacturing

~$1.4T economic impact since 1980
(NIST-funded study 2019)

- Precision agriculture
- Construction & surveying
- Fleet vehicle management
- Timing services



~$3.8T economic impact (2023-2030)
(Deloitte/World Economic Forum report 2024)

- Agriculture & agronomy
- Energy production
- Public & emergency services
- Insurance & financial services
- Supply chain & transport
- Weather forecasts

Questions?

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Next Time: Introduction to Space Cyber Resilience

