Spacecraft Design 101

Tony Pellerin

CCP-CSA-00008-WEB Rev -

Canadian Space Agency Agence spatiale canadienne

Canada

Timeline of Canadian Satellites

Alouette I 1962
Alouette II 1965

ISIS I 1969
ISIS II 1971

Anik-A1 1971
Anik-A2 1973
Anik-A3 1975

Hermes
1976

Anik-B
1978

Anik-D1 1982
Anik-C3 1982
Anik-C2 1983
Anik-D2 1984
Anik-C2 1984

MSAT II 1995
MSAT I 1996

Anik-E1 1991
Anik-E2 1991

Radarsat
1995

Nimiq 1 1999
Nimiq 2 2002
Nimiq 4 2008
Nimiq 5 2009

Anik-F1 2000
Anik-F2 2004
Anik-F1R 2005
Anik-F3 2007

SciSat
2003

MOST
2003

Radarsat-2
2007

NEOSat
2011

CASSIOPE
2013

M3MSat
2016

Upcoming Canadian Spacecraft Missions

Space Telescope James Webb
Launch: 2021

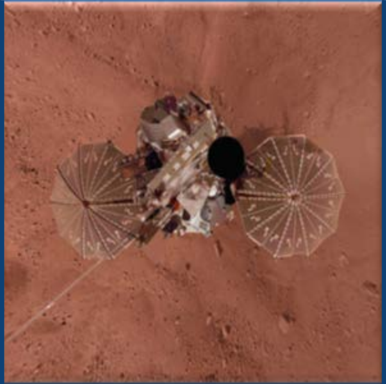
Canadian CubeSat Initiative
Launch: 2020-2021

Radarsat Constellation
Launch: 2018

Canadian Legacy in Space

Apollo Lunar Landing Gear
1969

Canadarm1
1981



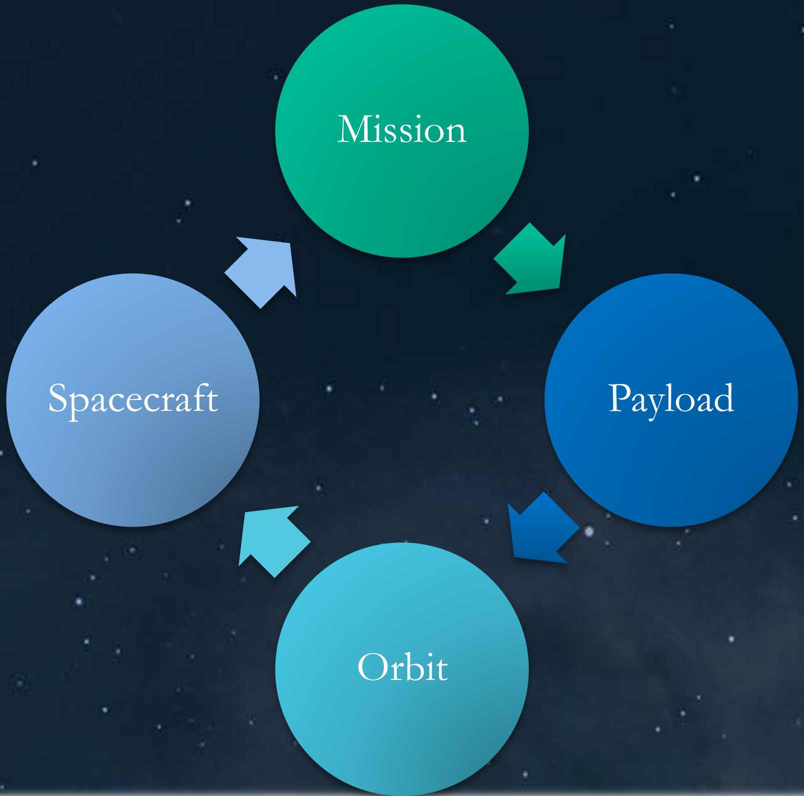
Canada's meteorological station on Mars

Phoenix
2007

Canadarm2
2001

Dextre
2008

Spacecraft Design



Iterative approach

- Start with the Mission requirements
- Design Payload and select orbit
- Design Spacecraft
- Iterate for optimum design with minimum risk

Mission Example

- What is the goal?
  - Example: EC request a spacecraft to monitor the level of fresh water on the Canadian territory.

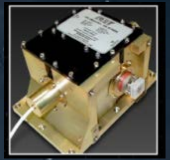
Mission

Payload Example

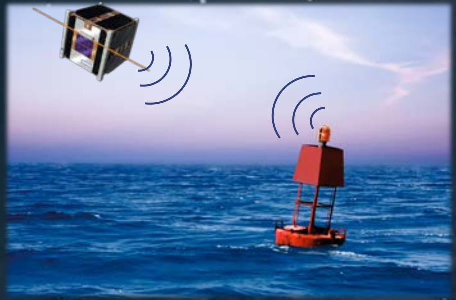
- What device is needed to achieve that goal?

Parameter	Microsat	Cubesat
Lifetime	2 years	1 year
Payload Mass	30 kg	5 kg
Payload Power	30 W (avg) 60 W (peak)	2 W (avg) 5 W (peak)
Cost	30-50 $M	1-10 $M + cost of distributed water level sensors

Payload



Radar instrument to collect precise water measurements



Orbit Example

- How much data will be transferred?
  - ↳ What is the coverage area? Memory size? Transfer rate?
    - ↳ How many ground segment is needed to achieve the mission req.
- Is it preferable to have a polar orbit or a sun-synchronous orbit?

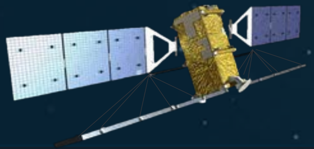
Orbit

Spacecraft Example

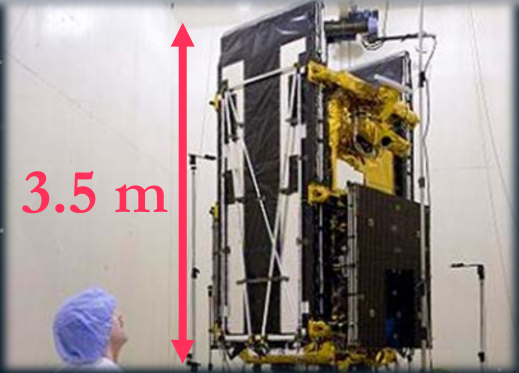
- How much power does the payload requires?
- How precise does the pointing needs to be?
- What will be the stabilization method?
- What communication frequencies will be used?
- …

Spacecraft

Spacecraft Categories

LARGE	RADARSAT-2 	2 000 kg	~15 m	~3 000 W
MEDIUM	CASSIOPE	500 – 1 000 kg	~2 m	~600 W
SMALL	SCISAT	100 – 350 kg	~1,5 m	~200 W
MICRO	M3MSat 	10 – 100 kg	~0,8 m	~50 W - 150 W
NANO including CubeSat	Ex-Alta 1 	1 – 10 kg ~1 kg per unit 1U = 10x10x10cm	~0,34 m to ~0,75 m	~7 W - 50 W

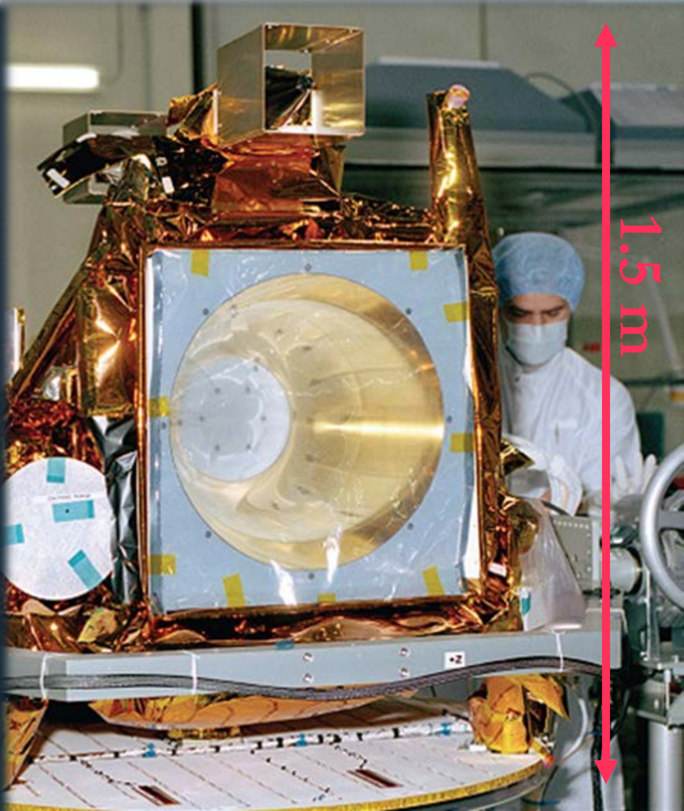
Satellites Size



RADARSAT-1 ▲

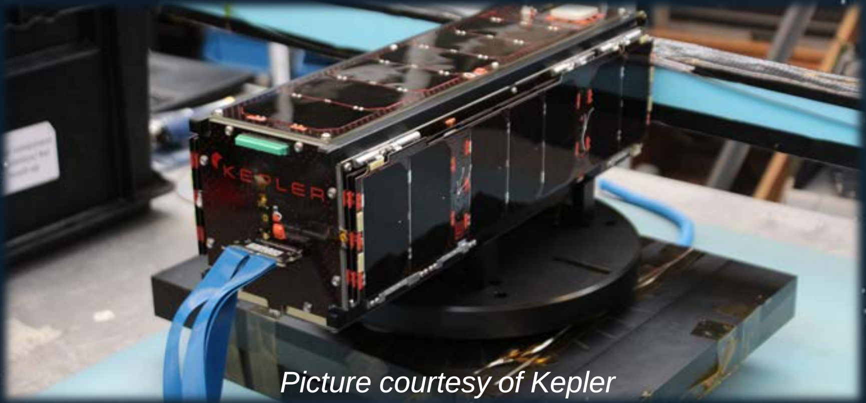
ENVISAT (ESA) ◀

SCISAT ▶



Nano satellite and smaller

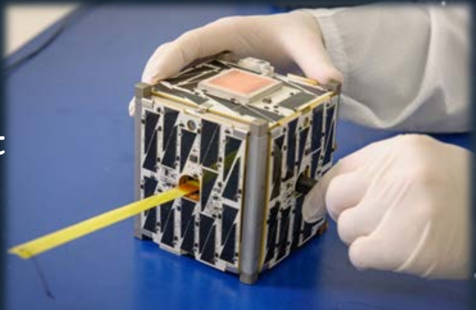
▼ Kepler's 3U CubeSat

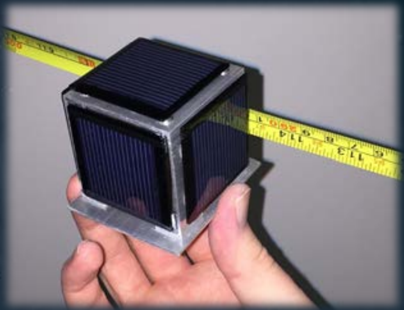


Picture courtesy of Kepler

Nanorack
CubeSat deployment from ISS
▼

1U CubeSat
▶





Pico satellite
◀

Designing for Space

Major challenge

Once it's launched, you can't go up and fix it

Solutions:

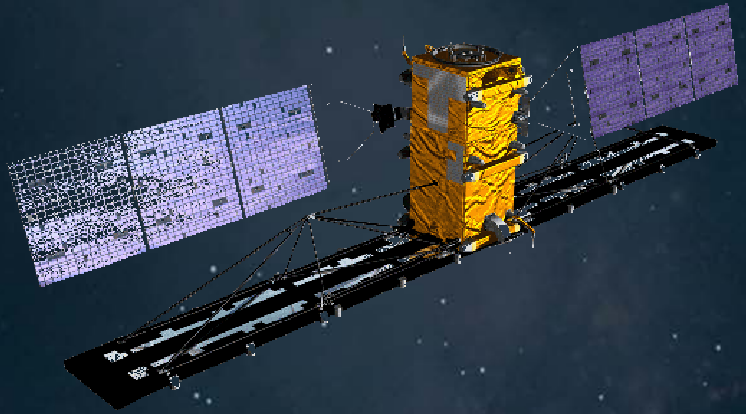
- Rigorous design process;
- Redundancy and mitigation techniques;
- Include margin of safety;
- Tests procedures…and test again;

Considerations:

- Cost;
- Weight;
- Size;
- Power consumption;
- Operations;

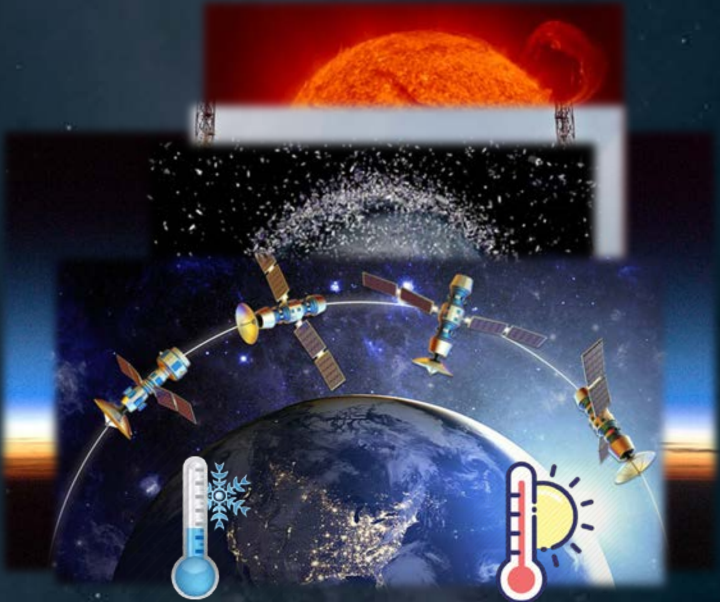
Topics Cover Today

1. Environment
2. Orbits
3. Spacecraft Payload
4. **Spacecraft Bus**
   - Structure, Mechanism
   - Thermal
   - Power and Electronics
   - Attitude Control Sub-system (ACS)
   - Communication
   - Command and Data Handling (C&DH)



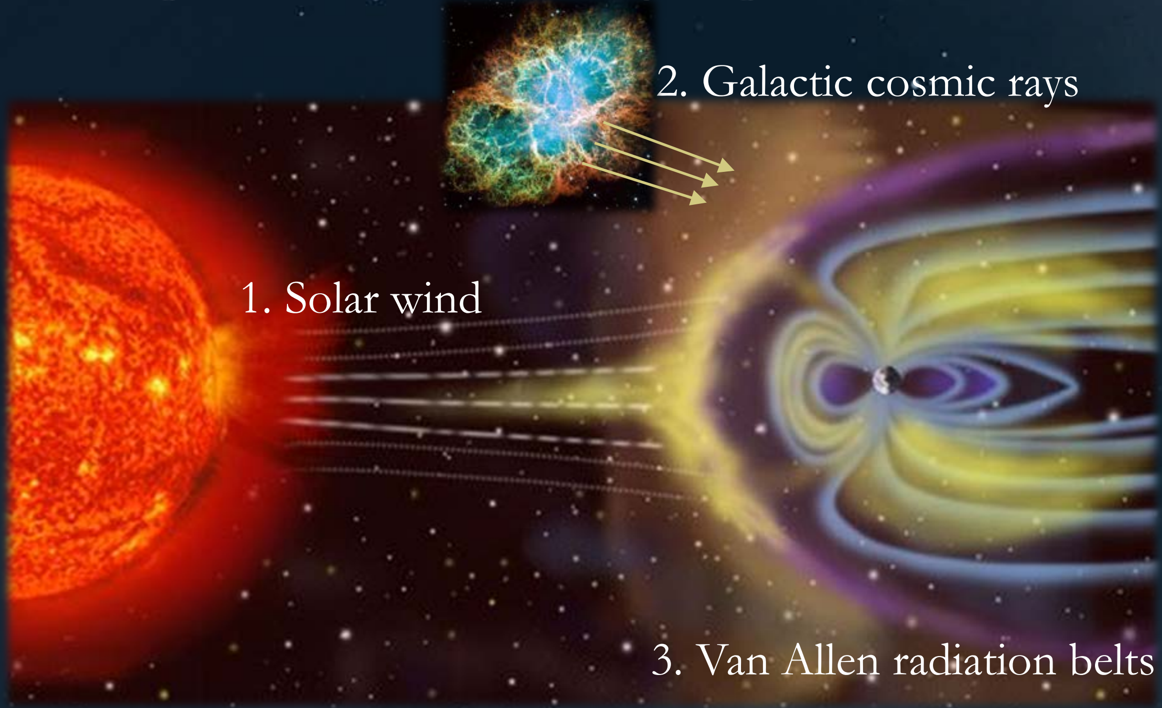
1. Environment
Overview

- Radiation and Charged Particles
- Earth Atmosphere
- Launch
- Space Debris
- Temperature (Frost and Heat)



1. Environment
Radiation and Charged Particles

Principal sources of charged particles:

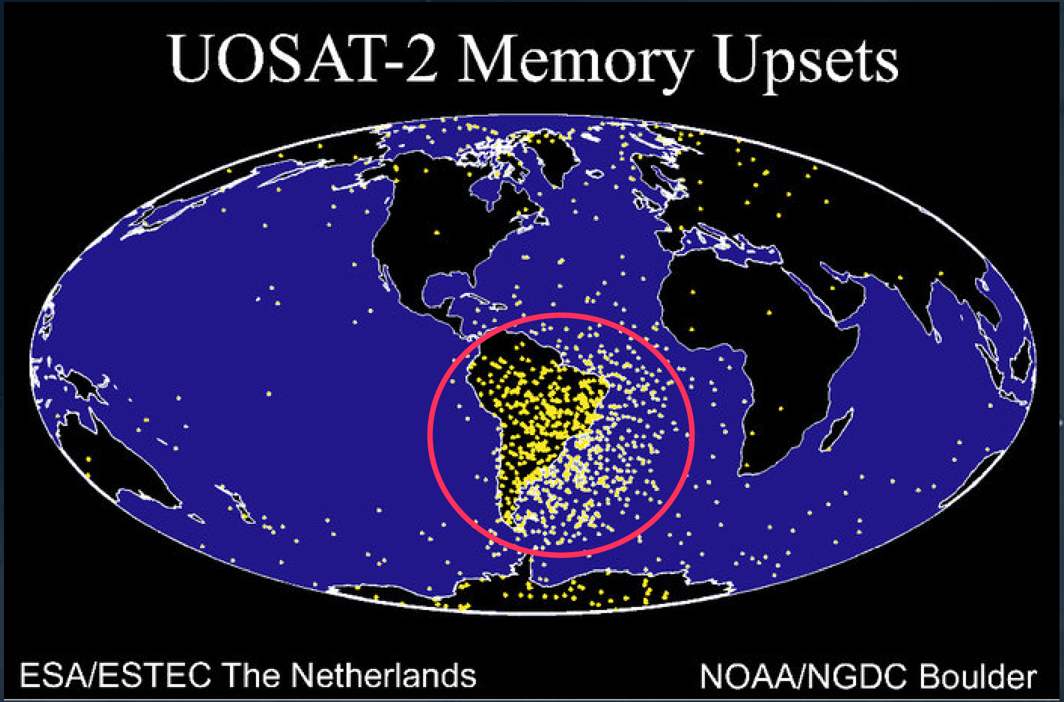


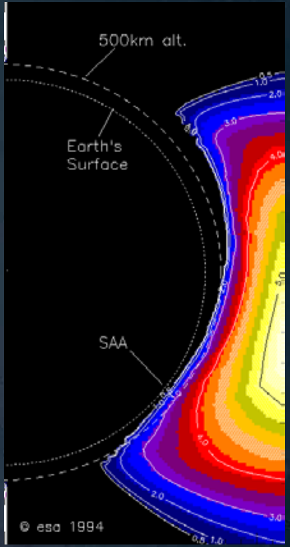
Impacts:

- Charging
- Single Event Effect
- Latch-up

Overall damage to semi-conductors in spacecraft's electronics.

1. Environment
Radiation and Charged Particles



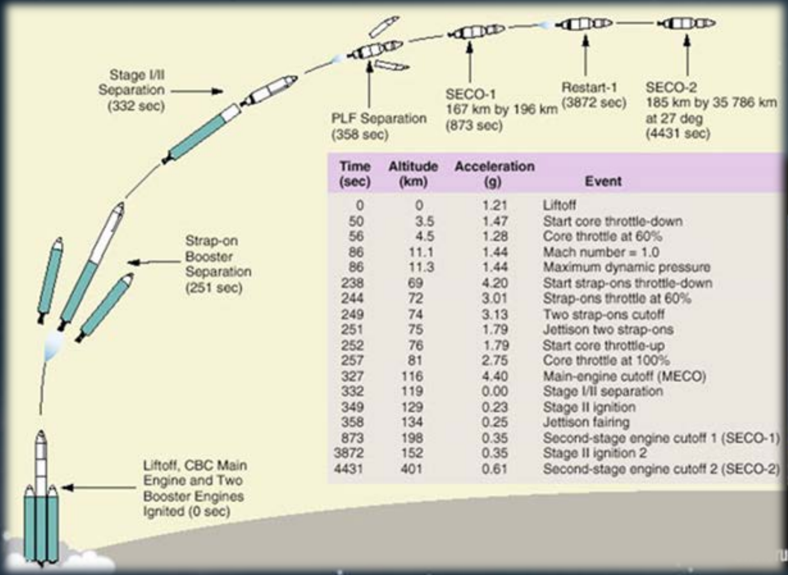


1. Environment
Earth Atmosphere

Spacecraft in **LEO** are affected by:

- **Atmospheric drag**
  - Low air density but air resistance high enough
  - Slowing down satellite => Gradual orbit decay
- **Atomic oxygen**
  - Material Decay (thermal blanket weakens)

1. Environment
Launch



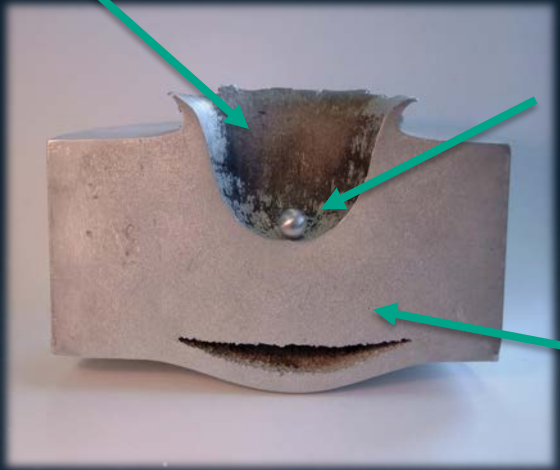
Time (sec)	Altitude (km)	Acceleration (g)	Event
0	0	1.21	Liftoff
50	3.5	1.47	Start core throttle-down
56	4.5	1.28	Core throttle at 60%
86	11.1	1.44	Mach number = 1.0
86	11.3	1.44	Maximum dynamic pressure
238	69	4.20	Start strap-ons throttle-down
244	72	3.01	Strap-ons throttle at 60%
249	74	3.13	Two strap-ons cutoff
251	75	1.79	Jettison two strap-ons
252	76	1.79	Start core throttle-up
257	81	2.75	Core throttle at 100%
327	116	4.40	Main-engine cutoff (MECO)
332	119	0.00	Stage I/II separation
349	129	0.23	Stage II ignition
358	134	0.25	Jettison fairing
873	198	0.35	Second-stage engine cutoff 1 (SECO-1)
3872	152	0.35	Stage II ignition 2
4431	401	0.61	Second-stage engine cutoff 2 (SECO-2)

Launch vehicles use staging to get to orbit

=> Spacecraft could be destroyed due to vibrations if not designed properly

1. Environment
Space Debris

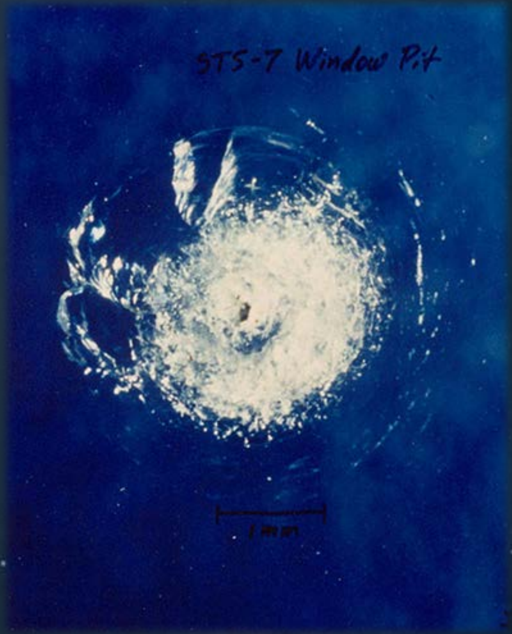
Impact Crater:
18cm



Aluminum sphere:
1.2 cm diameter

Aluminum
block

Velocity of sphere: 6.8 km/s



Damage from paint
flake on STS-7

1. Environment
Temperature

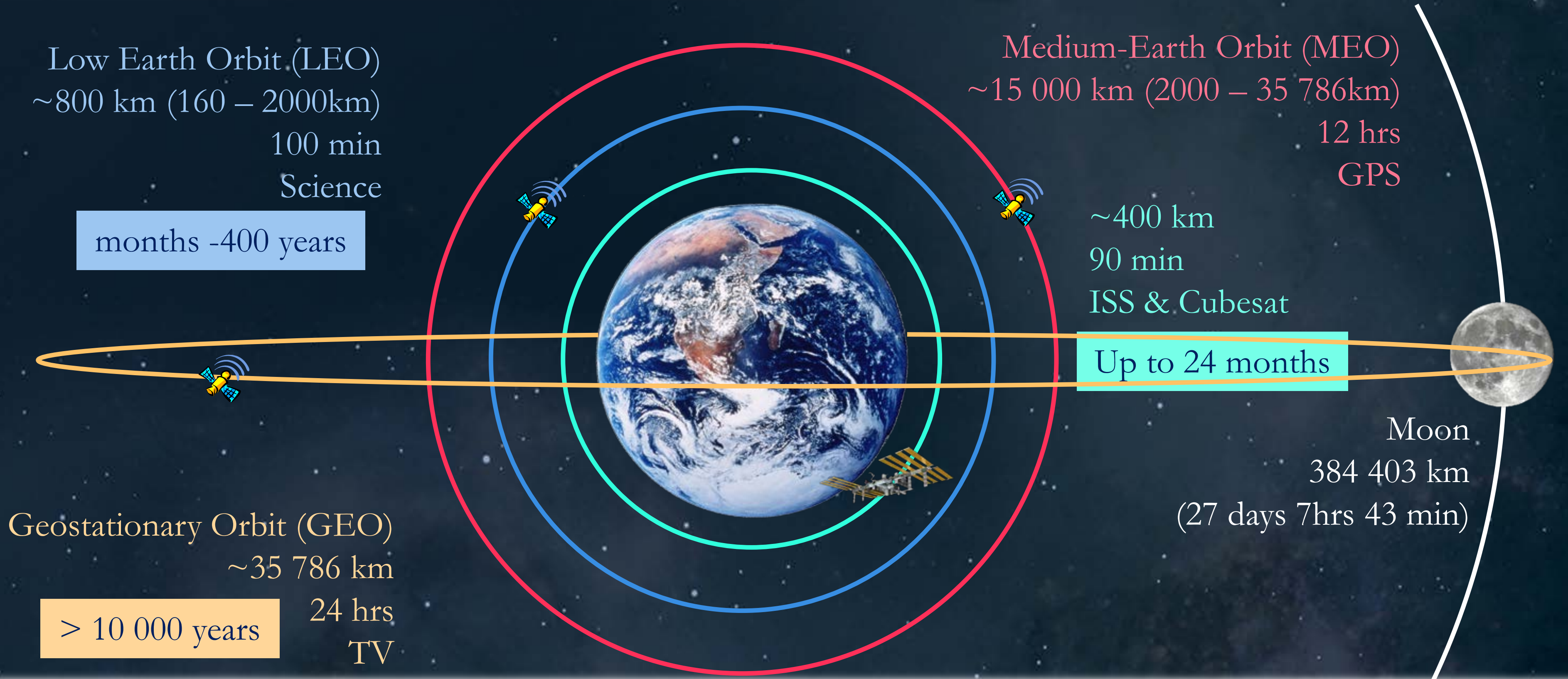
Temperature of a spacecraft in orbit:

- -150 °C to +125 °C

Sources of heat:

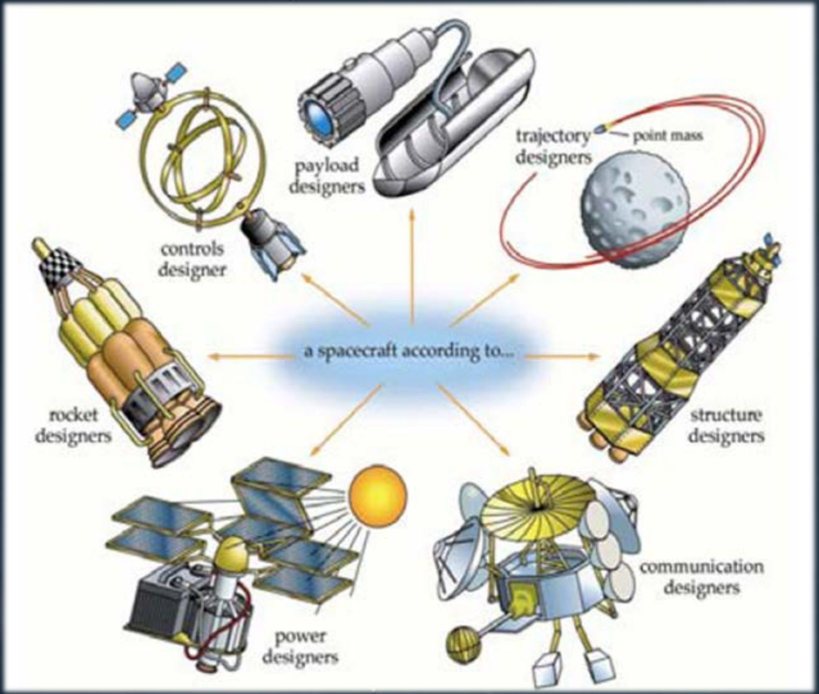
- Direct sunlight
- Sunlight reflecting off Earth (Albedo)
- Internal sources:
  - Electronics
  - Batteries

2. Orbits



Low Earth Orbit (LEO)
~800 km (160 – 2000km)
100 min
Science
months -400 years
Medium-Earth Orbit (MEO)
~15 000 km (2000 – 35 786km)
12 hrs
GPS
~400 km
90 min
ISS & Cubesat
Up to 24 months
Moon
384 403 km
(27 days 7hrs 43 min)
Geostationary Orbit (GEO)
~35 786 km
24 hrs
TV
> 10 000 years

4. Spacecraft Bus



J. Sellers "Understanding Space: An Introduction to Astronautics"
Fig. 11-25

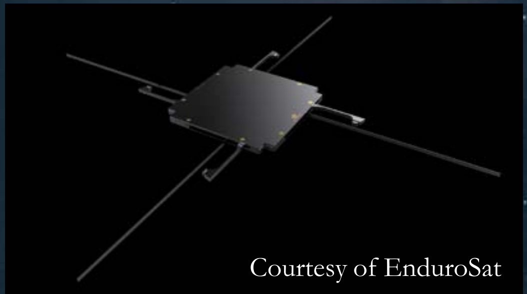
Building a spacecraft is making compromise!

4. Spacecraft Bus

- Precise alignment
- Integration of all subsystem
- Launch environment
- Deployment mechanisms

Severe vibrations during launch

- May cause spacecraft to resonate



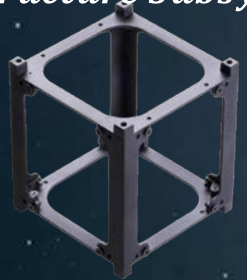
Courtesy of EnduroSat

4. Spacecraft Bus

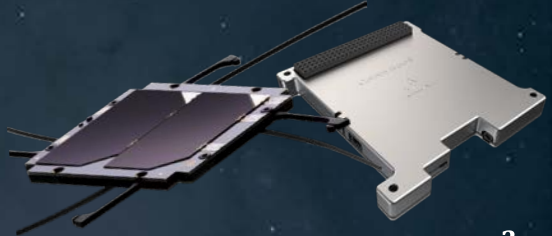
Mass Budget example for 1U

Component	Weight (kg)		
	Unit Mass (kg)	Margin	Mass + Margin
Structure Subsystem			
1U Cubesat Structure	0.10	10.00%	0.110
TMTC Subsystem			
VHF and UHF Antenna	0.10	18.00%	0.118
Transceiver/Modem/Signal Processing	0.09	18.00%	0.1062
Power Subsystem			
Battery (cell, support plate and holding bracket)	0.40	25.00%	0.500
Battery Charge Regulator (BCR)	0.20	18.00%	0.236
Solar Array Module	0.23	18.00%	0.640
Harness	0.40	25.00%	0.500
Attitude Sensor and Control Subsystem			
Magnetorquer Rod	0.03	10.00%	0.033
Reaction Wheel (x1)	0.20	10.00%	0.220
Sun Sensor	0.03	10.00%	0.033
Command and Data Handling Subsystem			
Onboard Computer	0.09	18.00%	0.1062
Thermal Control Subsystem			
Thermal Blanket	0.05	18.00%	0.0590
Spacecraft Payload			
Variable for each team (Camera)	0.25	18.00%	0.295
Total	**2.17 kg**		**2.956 kg**

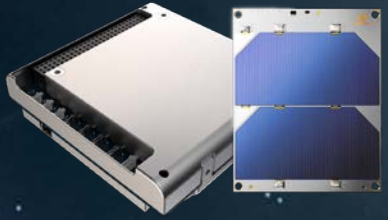
Structure Subsystem[1]



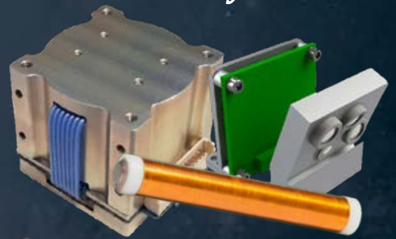
TMTC Subsystem[1]



Power Subsystem[1]



Attitude Sensor and Control Subsystem[2]



Command and Data Handling Subsystem[3]

[1]: EnduroSat
[2]: CubeSatShop
[3]: ISIS

4. Spacecraft Bus
Thermal

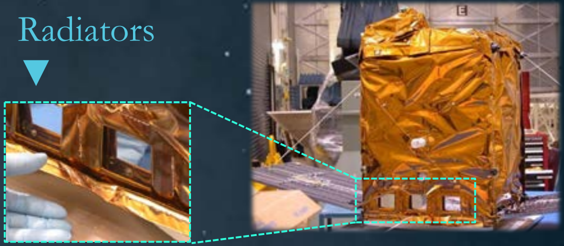
Thermal Control

- Absence of thermal convection


▲ Thermistor

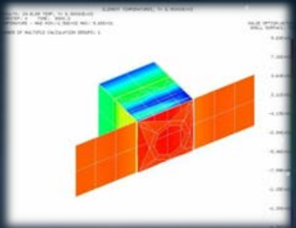

▲ Heater

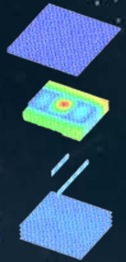
Radiators
▼

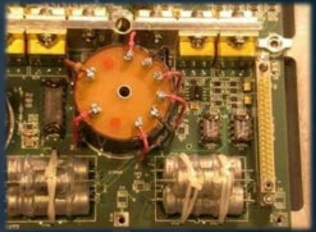


Thermal Design

- Need to ensure that electronics don't overheat



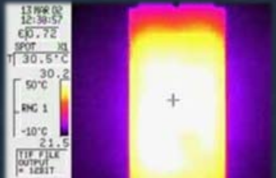




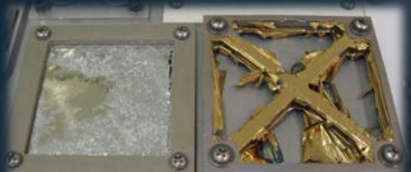
Thermal Deformation

- Consequence of temperature variation (thermal cycling) within the satellite

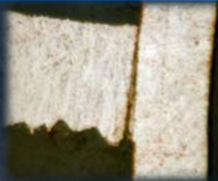
Battery overheat ▶



Catastrophic coating failure ▶

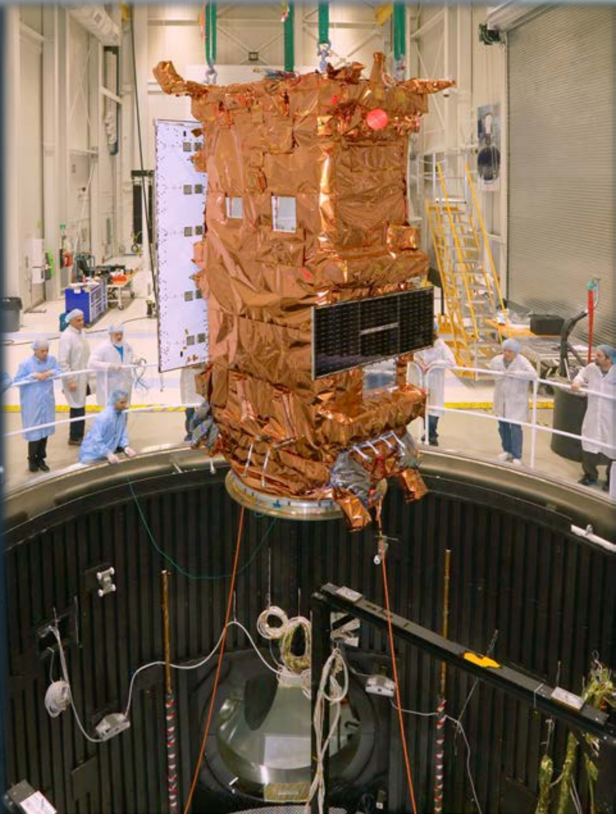


Broken PCB trace ▶



4. Spacecraft Bus
Thermal

- Thermal Testing
  - Simulation of the space environment:
    - – Vacuum
    - – Hot temperatures (>100°C)
    - – Cold temperatures (<-150°C)

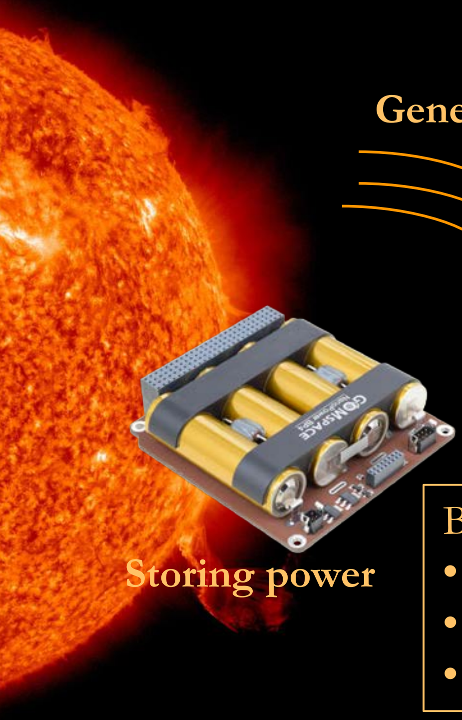


First RCM satellite
Thermal vacuum testing (TVAC)
David Florida Laboratory
January 2017 ▶

4. Spacecraft Bus

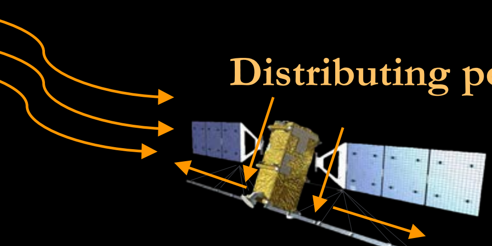
Power and electronics

Power: $3.83 * 10^{26}$ W



Received solar flux around Earth: $1358 W/m^2$

Generating power



Distributing power

Solar cell efficiency: 30%

Storing power

Intense use of batteries during eclipse period

Battery's **lifetime** depends on:

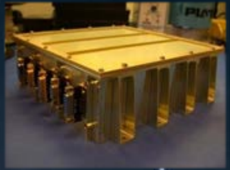
- Depth-of-discharge
- Number of charge/discharge cycles
- Temperature

4. Spacecraft Bus
Power and electronics

<u>Important points:</u>

- Components selection
- Dissipate heat through conduction
- Designed rugged to withstand vibration and radiation



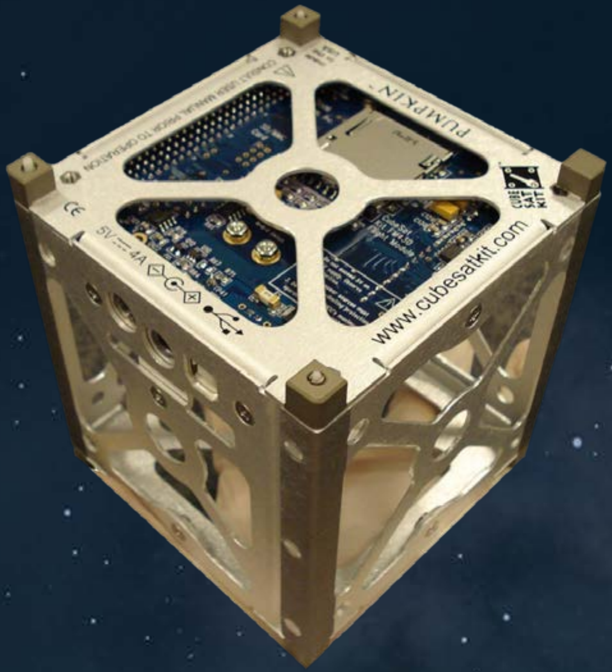



Deep charge destruction on solar array.

Picture courtesy of ESA

4. Spacecraft Bus

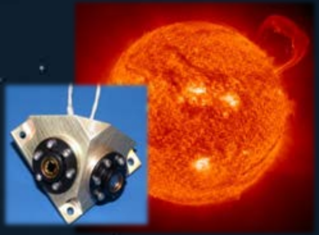
Power Budget example for 1U



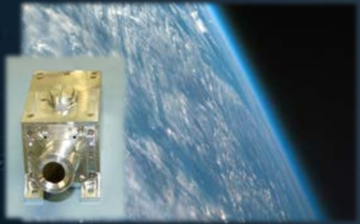
Power Budget	Spacecraft Mode								
	Safe Hold			Nominal			Peak		
Component	Duty Cycle %	Power (W)	Total	Duty Cycle %	Power (W)	Total	Duty Cycle %	Power (W)	Total
TMTC Subsystem									
Receiver	100 %	0.115	0.115	100 %	0.115	0.115	100 %	0.115	0.115
Transmitter	0	5.000	0	10 %	5.000	0.500	100 %	5.00	5.00
Modem interface	10 %	0.100	0.01	100 %	0.100	0.100	100 %	0.10	0.10
Power Subsystem									
Power conditioner	50 %	0.150	0.075	100 %	0.150	0.150	100 %	0.15	0.15
Battery heaters	0	1.000	0	5 %	1.000	0.050	100 %	1.00	1.00
Attitude Sensor and Control Subsystem									
Magnetorquer Rod	0	0.200	0	20 %	0.200	0.040	100 %	0.200	0.200
Reaction Wheel (x1)	0	0.850	0	100 %	0.850	0.850	100 %	2.500	2.500
IR Earth Sensor	0	0.130	0	50 %	0.130	0.065	100 %	0.130	0.130
Control Electronics	0	0.250	0	100 %	0.250	0.250	100 %	0.250	0.250
Command and Data Handling Subsystem									
Onboard Computer	100 %	0.130	0.130	100 %	0.310	0.310	100 %	0.435	0.435
Spacecraft Payload									
Variable for each team	0	0.500	0	40 %	0.500	0.200	100 %	0.750	0.750
Total Power									
	0.330 W			2.63 W			10.41 W		

4. Spacecraft Bus
Attitude Control Sub-system (ACS)

1. Determine spacecraft attitude (sensors)

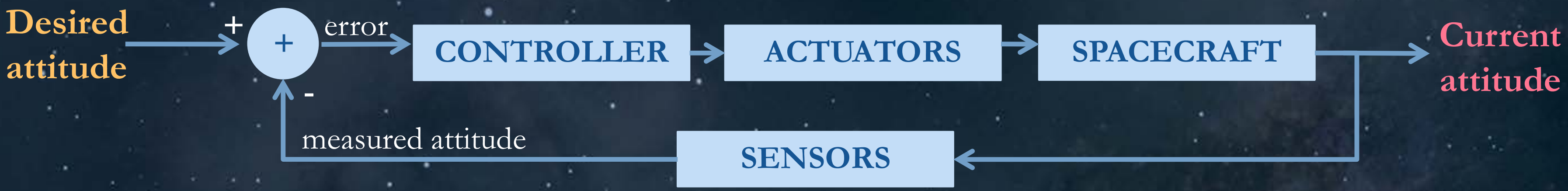

Sun Sensor


Star Tracker


Earth Sensor


Magnetometer

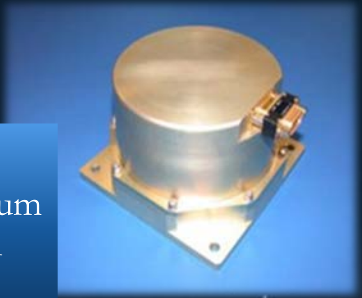
2. Adjust spacecraft attitude



4. Spacecraft Bus
Attitude Control Sub-system (ACS)

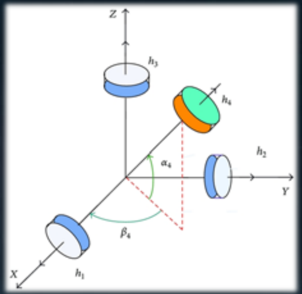
Actuators:

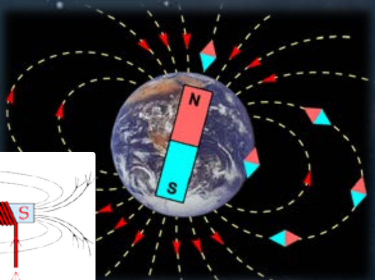
Momentum Wheel

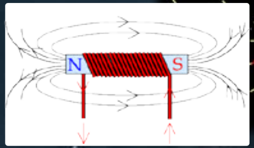


Reaction Wheels

Magnetic Torquer







4. Spacecraft Bus
Communication

The higher the frequency, the smaller the antenna

Transformation of a high frequency electric signal into an electromagnetic wave.

- Antennas

- Transceiver

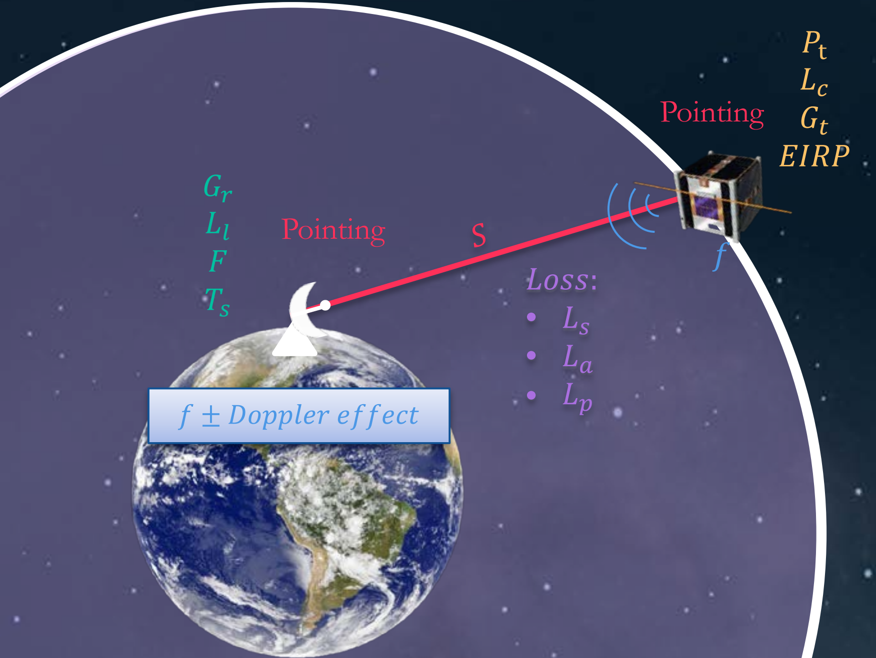
- Modem

◀ Gaussteam Ground station

4. Spacecraft Bus

Communication

Link Budget: Downlink example



Tx Cubesat Power			Satellite
Transmitter power output	P_t	dBm	30.0
Total transmission line losses	L_c	dB	1.0
Tx Antenna Gain	G_t	dBic	2.2
EIRP	–	dBW	31.2
Propagation Losses			
Slant range (worst case)	S	km	1 804.50
Free space path loss	L_s	dB	150.34
Atm. Gaz Attenuation	–	dB	~0
Rain and Clouds Attenuation	–	dB	~0
Scintillation	–	dB	~0
Polarisation Losses	L_p	dB	3
Pointing Losses	L_a	dB	0.5
Total Losses	L_{total}	dB	153.84
Rx Parameters			**Ground station**
Rx Antenna gain	G_r	dBic	18.9
Total line losses	L_l	dB	0.5
Rx Noise Figure	F	dB	1.12
Rx Station Effective Noise Temperature	T_s	K	509.87
Downlink link budget			
Signal received power	P_r	dBm	-104.24
Receiver Noise Power	N	dBm	-131.53
Carrier-to-Noise Power Ratio	C/N	dB	27.3
System Required C/N	–	dB	16
Margin	–	**dB**	**11.3**

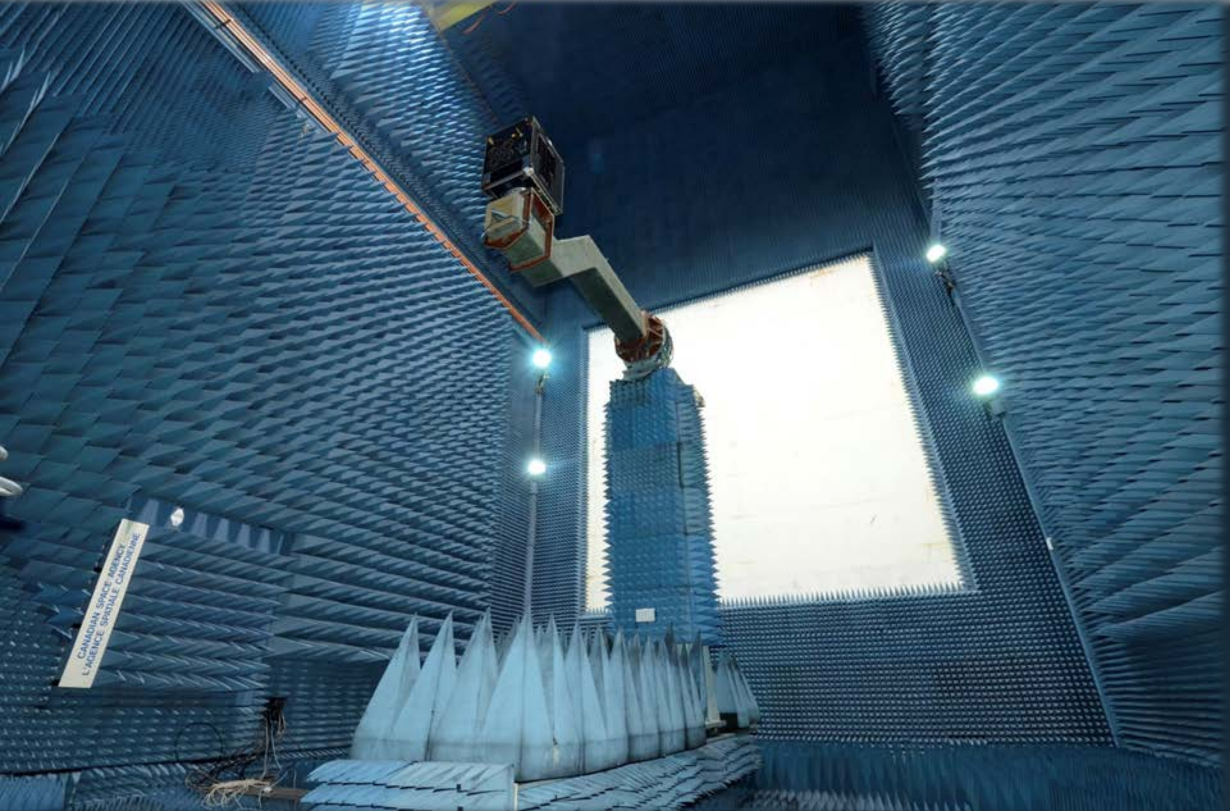
4. Spacecraft Bus

Communication

Antennas

Quicksat
Tests in DFL
2005
▶

4. Spacecraft Bus
Communication



Anechoic chamber:

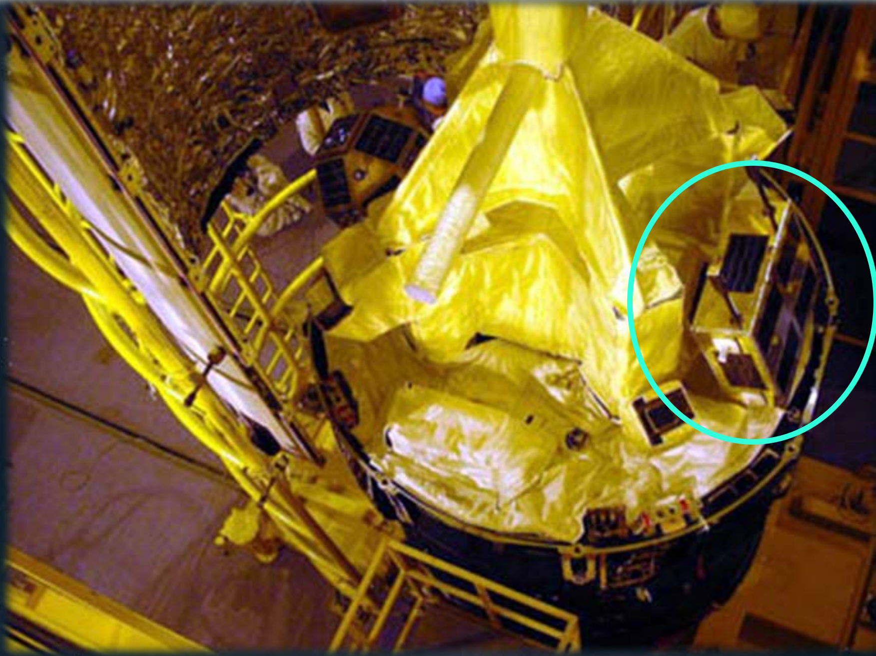
- Test room where all the electromagnetics waves are absorbed

M3MSat
David Florida Laboratory
2016

Canadian satellite tests

MOST
Functionality tests in DFL
◀

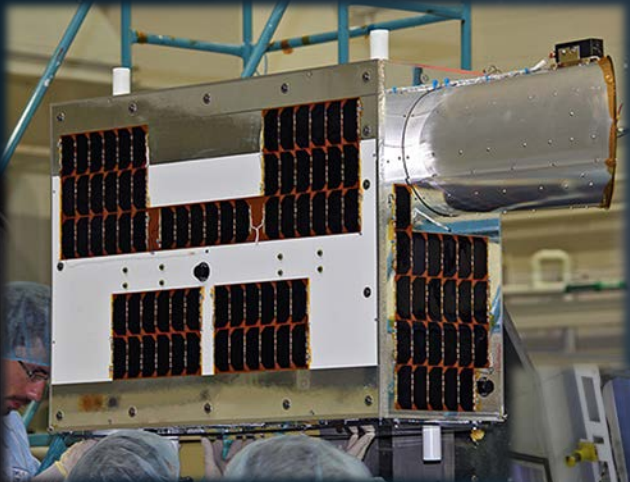
MOST
▶



▲ MOST satellite installed in launcher

Canadian satellite tests

NEOSat in TVAC
▼



NEOSat
◀

NEOSat
satellite installed in
launcher next to Saphire
▶

Canadian satellite tests

▲ M3MSAT
EMC tests in anechoic chamber

▲ M3MSAT
Mass property test

Question Period