Lunar Orbit Formation Flying and Platform Concept Design

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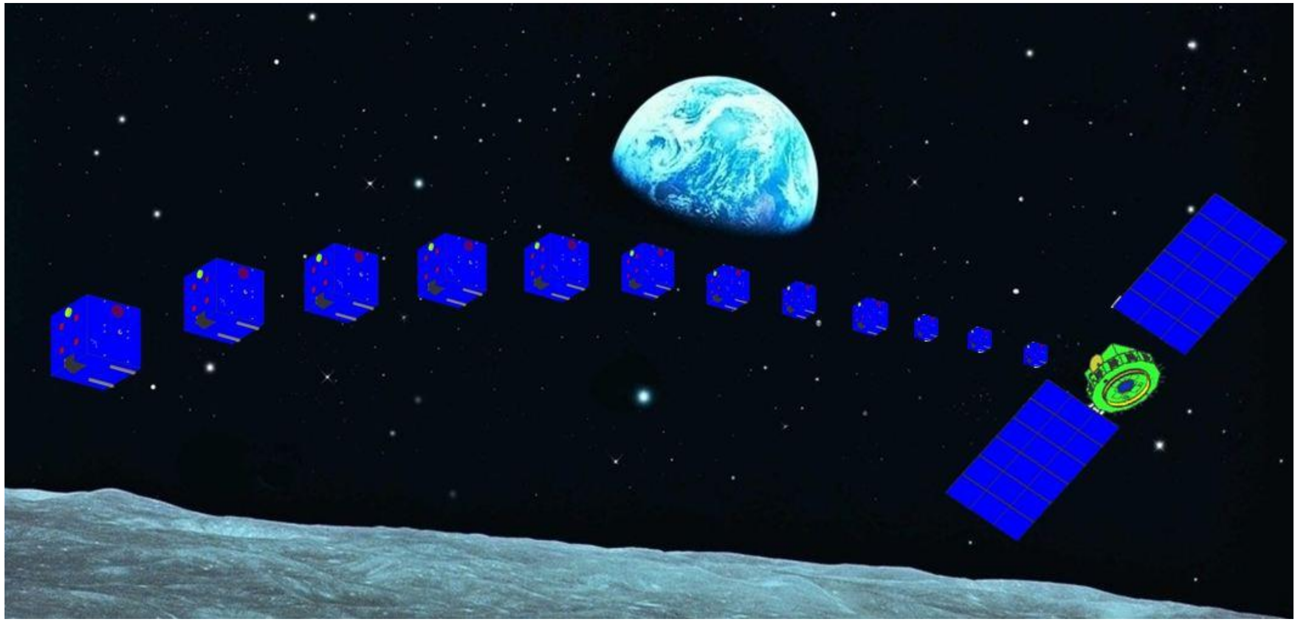
Outline

- Overview
- Orbit Design and Analysis
- Concept Design
- Key Techniques
- Heritage from previous studies/missions

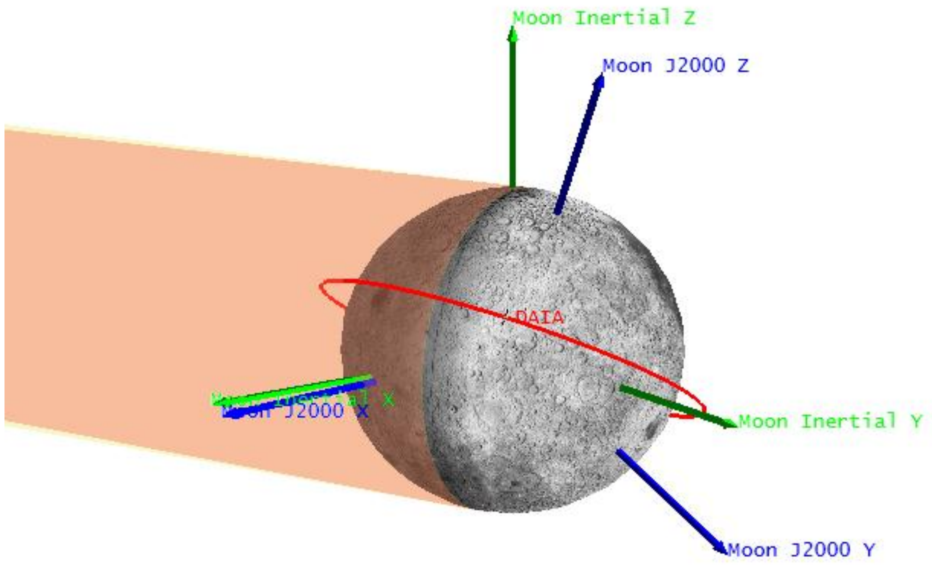
Overview

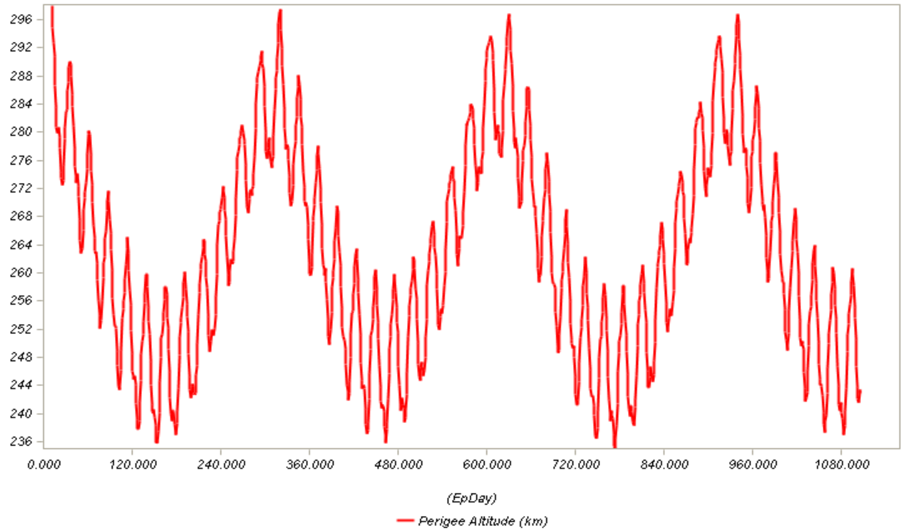
- One mothership and 12 daughters are formation flying in low lunar orbit.
- Low frequency radiometry will be mounted on each daughter satellite.
- In the far side of the moon, with Spaceborne interferometric radiometer based on 12 daughter formation flying ,it is used for
  - dark ages exploration
  - 3D mapping of the Milky Way
  - Extragalaxy census
  - a complete picture of CME at AU size scale
  - ……

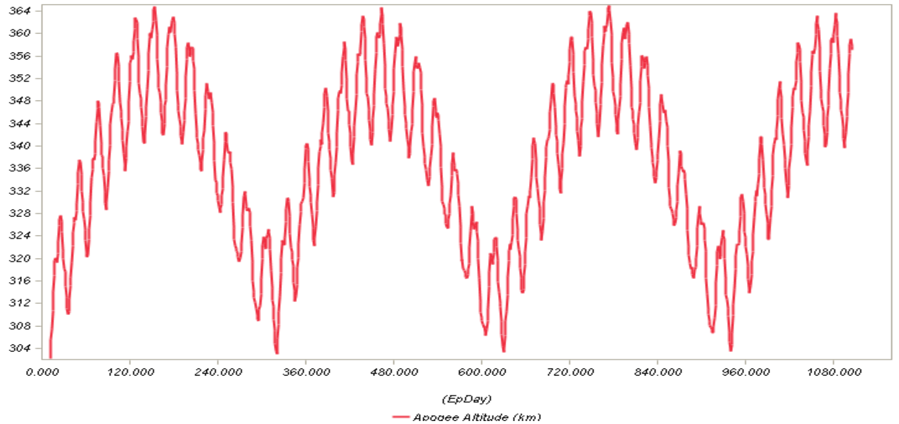


Orbit Design and Analysis

- 300km lunar orbit with inclination 30° in lunar inertial coordinate system(near ecliptic plane)
- Orbit plane precession rate is about 0.76° /day
- The nominal orbit is stable, no need for orbit keep in three years.

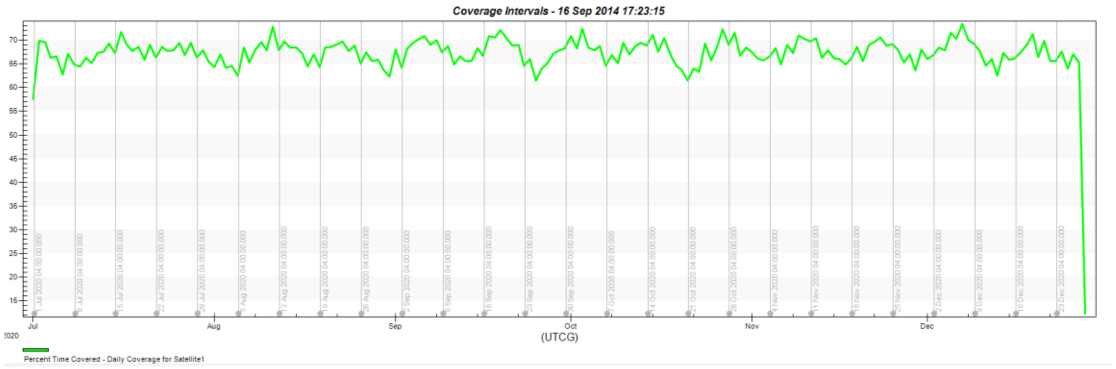






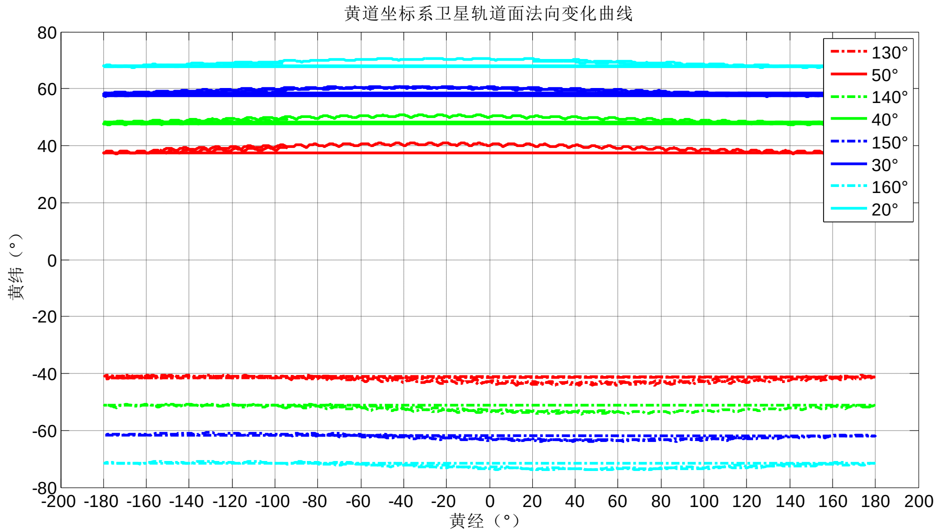
Orbit Design and Analysis

- Solar Lighting Analysis
  - the average umbra time is about 30% of lunar flight time.
  - There are one long shadow duration every half year when the moon enters the shadow of the Earth.
- Earth Occultation Analysis
  - Earth occultation time is defined as the time when Earth is not in the sight of the satellites due to the shield of Moon.
  - the Earth occultation time is about 30.88% of lunar flight time.
- Data Receiving Station Coverage
  - Miyun(Chinese), Kashi(Chinese) and Malargue(ESA)
  - It is about 67% of lunar orbit flight time
  - Suppose the downlink data rate is 20Mbps, ground stations receive 1.15Tb data per day.

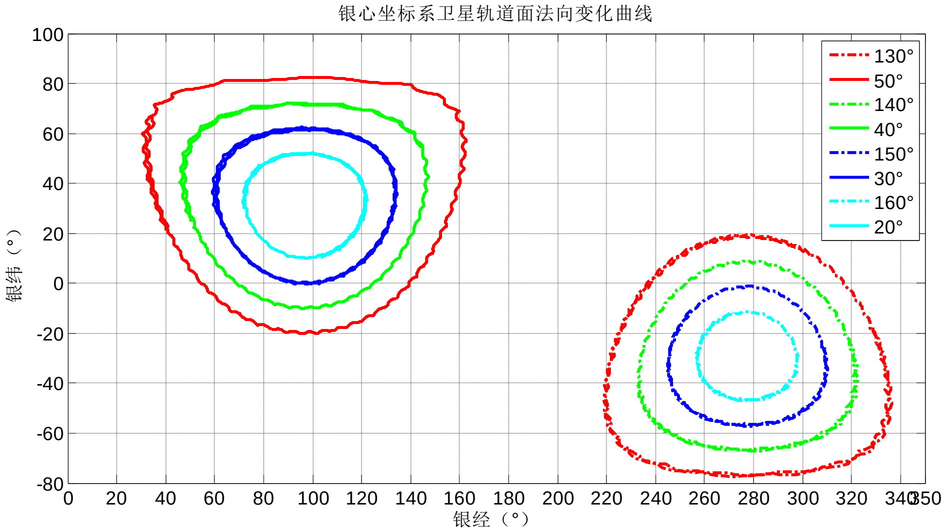


Orbit Design and Analysis

- Orbit Normal Vector Evolution Analysis



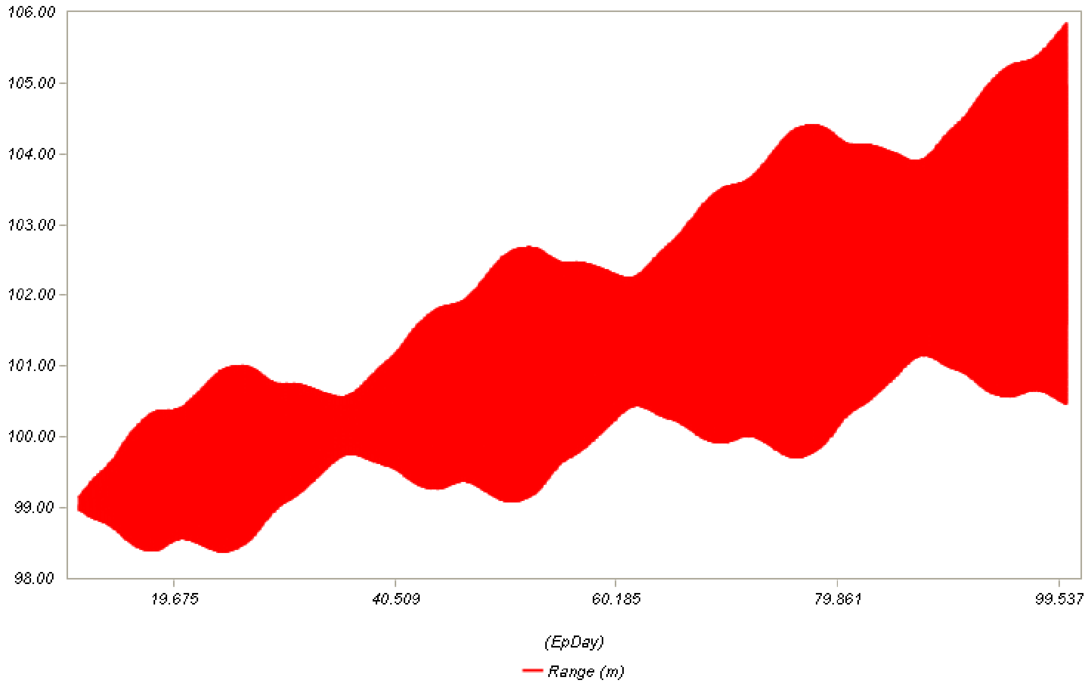
projection of orbit normal vector in ecliptic coordinate system

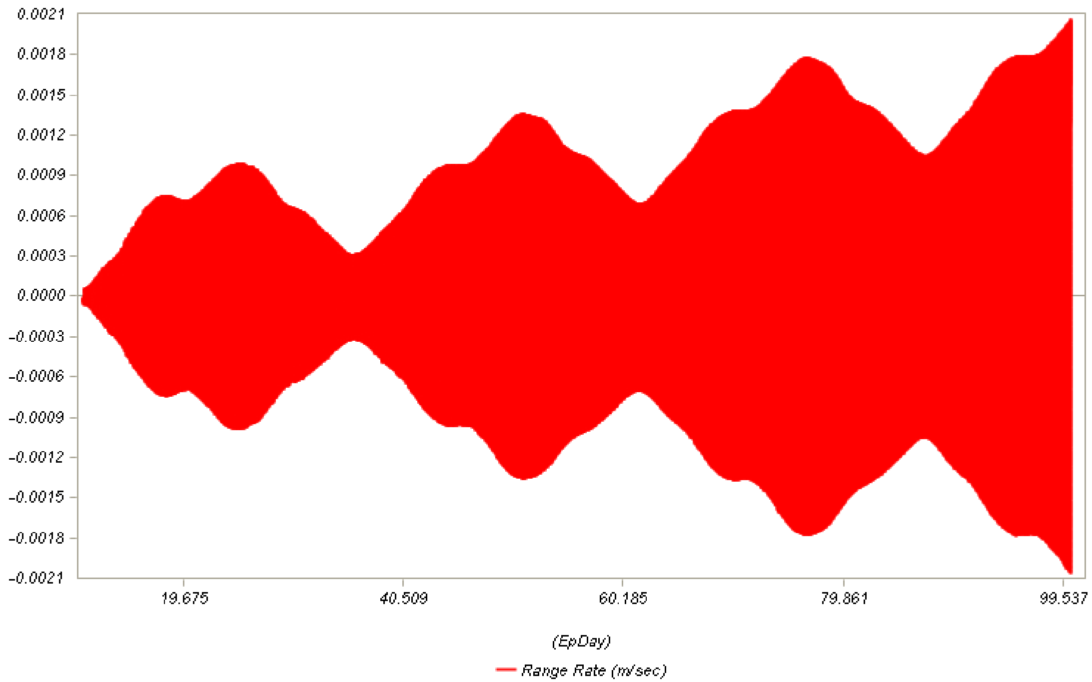


projection of orbit normal vector in galactic coordinate system

Orbit Design and Analysis

- Formation Stability Analysis
  - The relative range changes from 99 m to 106 m in 3 months





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Orbit Design and Analysis

- Formation Reconfiguration Control
  - Fuel balance strategy

Initial states: S1 S2 ....S11 S12

Shrink states: S1 S2 ......S11 S12

Expand states: S1 S2 ....S11 S12

Assume that the reconfiguration period is 180 orbit ,each satellites needs 80mm/s delta-V in every formation reconfiguration period.

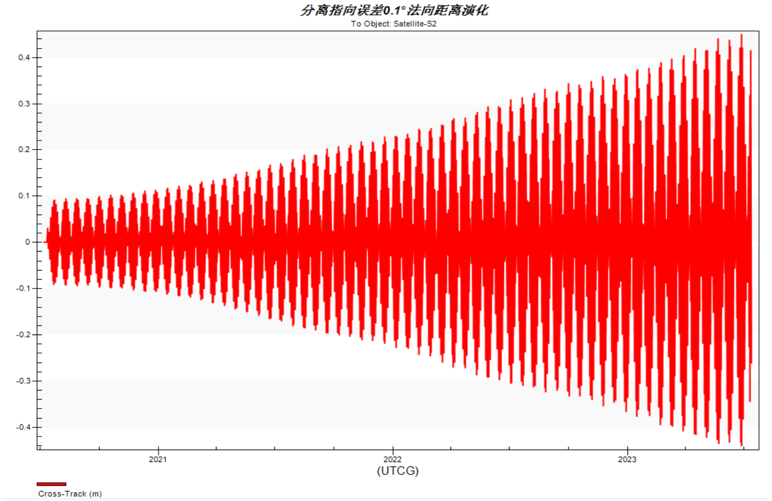
If the reconfiguration period is 20 days, we can reconfigure the formation about 50 times in 3 years.

Shrink control	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Initial position(km)	0	1	5	13	28	31	45	50	67	80	95	100
Target position(km)	0	0.1	0.5	1.3	2.8	3.1	4.5	5.0	6.7	8.0	9.5	10
Moving distanceII(km)	0	0. 9	4.5	11.7	25.2	27.9	40.5	45	60.3	72	85.5	90
Delt-V(mm/s)	**0.0**	**0.8**	**4**	**10.4**	**22.4**	**24.8**	**36**	**40**	**53.6**	**64**	**76**	**80**

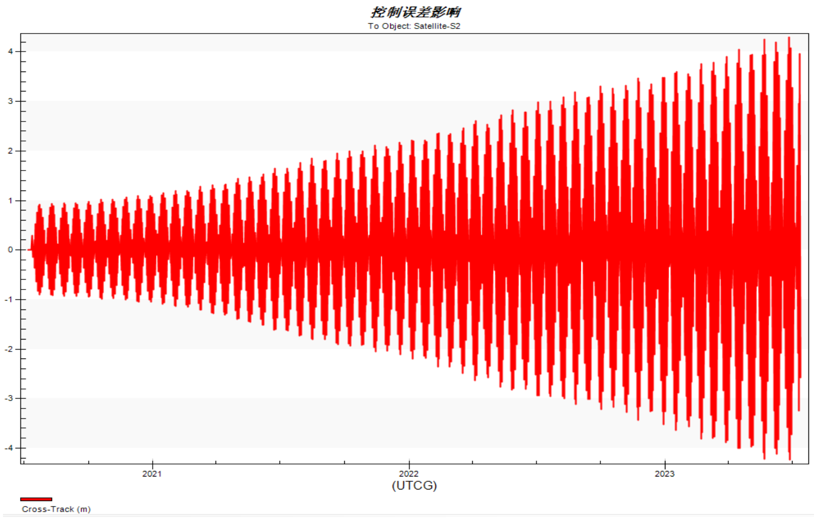
Expand control	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Initial position (km)	0	0.1	0.5	1.3	2.8	3.1	4.5	5.0	6.7	8.0	9.5	10
Target position(km)	-90	-89	-85	-77	-62	-59	-45	-40	-23	-10	5	10
Move distance	90	89.1	85.5	78.3	64.8	62.1	49.5	45	29.7	18	4.5	0
Delt-V (mm/s)	**80**	**79.2**	**76**	**69.6**	**57.6**	**55.2**	**44**	**40**	**26.4**	**16**	**4**	**0**

Orbit Design and Analysis

- Out-of-Plane orbit motion analysis
  - Separation direction error caused by attitude pointing error(0.1°) of mothership. Suppose the separation velocity is 0.04m/s, the out-of-plane motion is less than 0.5m in 3 years.
  - Orbit control direction error mainly caused by attitude pointing error(1°) of daughter satellite. The motion of attitude pointing is 2s periodic motion. The thrust level of propulsion system is about 4mN. So the out-of-plane motion caused by control error is less than 5m in 3 years.



out-of-plane motion with separation error

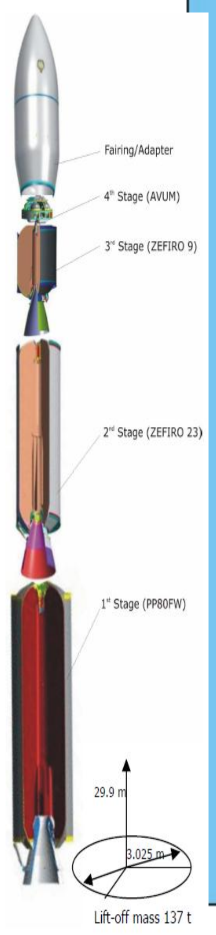


out-of-plane motion evolution with control error

Orbit Design and Analysis

- Transfer Orbit Selection
  - Directly being launched into the lunar orbit, it needs capturing delt-V of 0.77km/s.
  - For the limitation of mass, low energy transfer trajectory using invariant manifolds and electrical propulsion is proposed for the transfer of DSL.
- Both Vega and CZ-2C/D can meet launching requirements.

	Vega [with bi-liquid propulsion module]	Soyuz	LM-2C [LM-2C/CTS]	LM-2D [LM-2D/TY-2]
Sun Earth L1/L2 (C_3 = 0 km^2/s^2)	[~ 420 kg]	2160 kg	[820kg with LM-2C/CTS]	[380kg with LM-2D/TY-2]



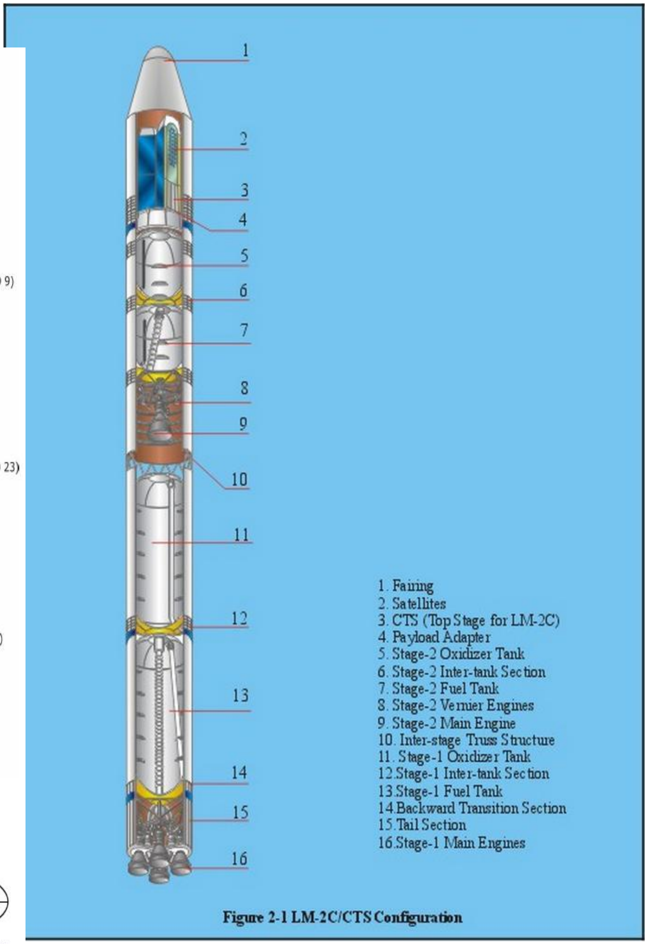
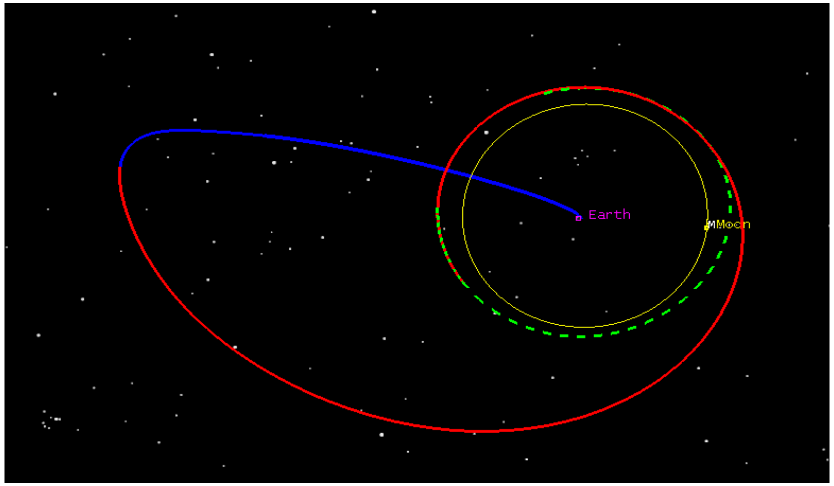


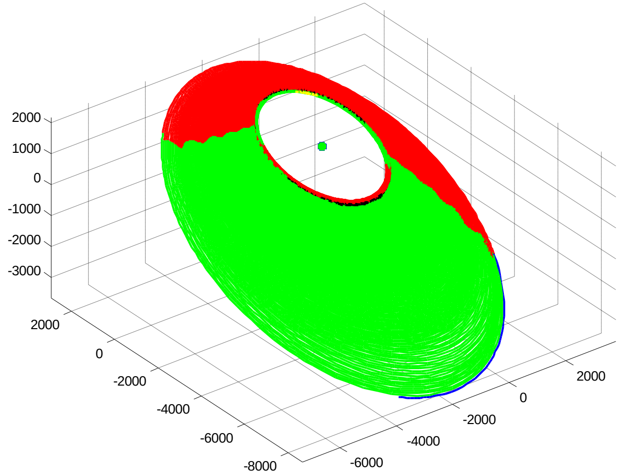
Figure 2-1 LM-2C/CTS Configuration

Orbit Design and Analysis

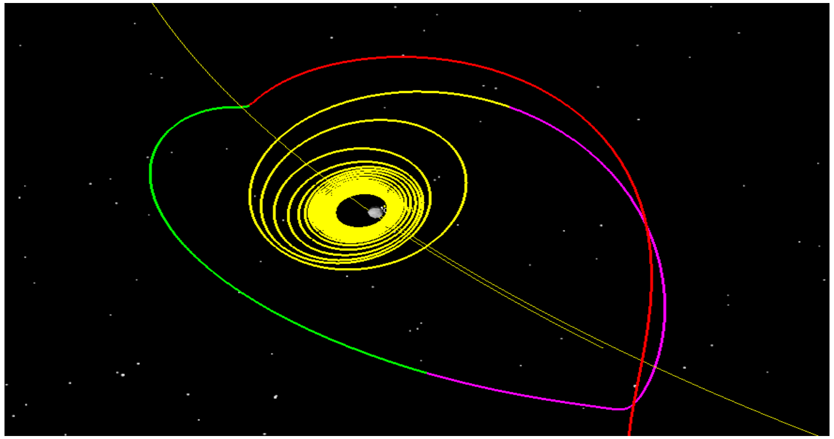
- Transfer and capture Orbit Design
  - Transfer from Earth to Sun-Earth L1 via stable manifolds.
  - Leave Sun-Earth L1 via unstable manifolds.
  - Transfer to Earth-Moon L2 via stable manifolds.
  - EML2-Moon capture phase via electrical propulsion.



from Earth to Earth-Moon L2 Halo orbit in Earth Inertial frame



On-off thrust stage of Moon capture trajectory in Moon inertial frame


Continuous thrust stage of Moon capture trajectory in Moon inertial frame

Orbit Design and Analysis

- Delt-V and Fuel Budget

Time	Events	Performance
22 Sep 2021	Earth escaping	3.195 km/s escaping maneuver velocity from 200 km Earth parking orbit, with inclination of 19.5°
7 Nov 2021	Deep space maneuver	3 m/s
27 Jan 2022	Earth-Moon Halo orbit injection	0.5 m/s
2 Feb 2022	Halo departure	0.4 m/s
15 Feb 2022	Continuous thrust stage begin	32 days
19 Mar 2022	On-off thrust stage begin	77.87 days
4 Jun 2022	Final capture	25.03 kg fuel
	Total flight time	255 days
	Total fuel	25.1kg

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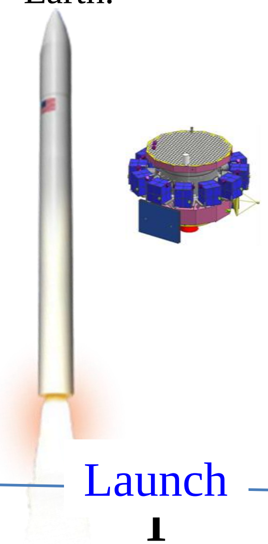
Mission Flying Phases

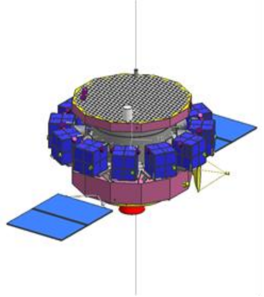
The mother satellite with daughter satellites are launched in Sep 22, 2021.

Solar panel s are deployed after escaping from the Earth.



Launch

1



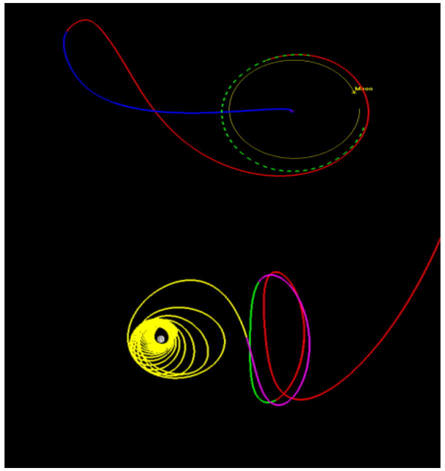
46th days, transfer into Sun-Earth L1.Deep space orbit correction is 3m/s.

126.6th days, injected into Earth-Moon L2 orbit with Delt-V about 0.5m/s.

133th days, DSL leaves Earth-Moon L2 Halo orbit with Delt-V about 0.4 m/s.

Transfer orbit

2

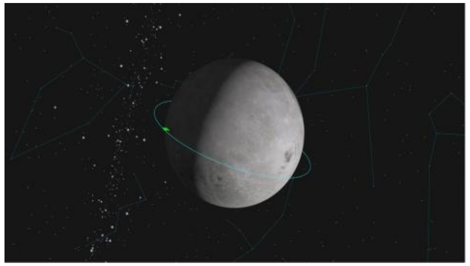


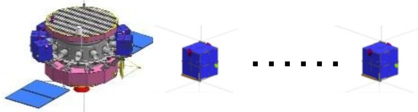
146th days, electrical propulsion system begins to work in continuous operation mode.

178th days, DSL is captured into an elliptic lunar orbit. Electrical propulsion system begins to work in on-off operation mode.

Electrical propulsion and moon capturing

3





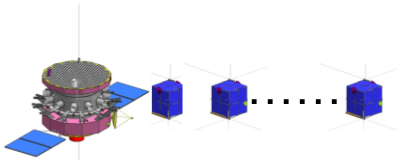
255th days, DSL is captured into 300 km altitude operational lunar orbit.

The mothership releases daughter satellites one by one with the same direction.

270th days, the separation is completed and configuration is formed.

Release and initial formation flying

4



285th days, completed on-board test of platform and payload, enter into mission operation phase.

In operational phase, payload work in the far side of the moon, data downlink in the close side of the moon.

The formation shrink and expand orbit control is done every 20 days

Test and operation

5

Concept Design

Items		Mothership	Daughter
System Parameters	Mass（kg）	≤180kg	12 daughters, each ≤10kg
	orbit	300km lunar orbit formation flying with inclination of 30°	
	baseline	100m-100km	
	Lifetime	3 years	
	Launcher	Vega or CZ-2C/2D	
Payload	Mass（kg）	4	2
	Power（W）	25	1.5
	Data Rate（Mbps)		27
	antenna	Two stick, each 2.5m	two triple antennas, each stick 2.5m
Structure and mechanism	Size(mm)	Φ1630×540	230*230*230
	Primary frequency	lateral>15Hz , longitudinal>30Hz	>100Hz
GNC	Control mode	3-axis stabilized to the moon	
	Attitude knowledge error	0.01 °	
	Pointing error	0.1 °	1 °
	Attitude stability	0.02 °/s	0.1 °/s
Propulsion	Electric propulsion	specific impulse: 1500 s, power: 500~1100W thruster: 68 mN , propellant: 30kg Xenon	none
	Chemical propulsion	Monopropellant propulsion system, N2H4 specific impulse: 200 s ,8 thrusters, each <1N Delt-V: 40m/s	Butane propulsion with total impulse 80mN Specific impulse: 90-110s, Thruster: 0.01-1mN
Power	Power(W)	1200	10
	Solar panel	Triple-junction GaAs	Triple-junction GaAs, 0.16m^2
	Battery cells	Lithium-Ion	Lithium-Ion

Concept Design

Items		Mothership	Daughter
Data handling and processing	TM data rate	10bps-20Mbps	27Mbps
	TC data rate	125bps	1024bps
	Mass Memory	Input rate ≤400Mbps,Output rate ≥ 30Mbps Capacity: 512Gbits~ 2Tbits	2Gbits
TT&C	Frequency	X band	none
	Uplink Modulation	BPSK/PM	
	Ranging	Regenerated Tausworth PN	
	RF Power	10W	
	Downlink Modulation	GMSK+PN	
	Baseband rate	200kbps/20Mbps	
Inter-satellite Link	Frequency	C/X band	C/X band
	modulation	GMSK+PN	GMSK+PN
	Data rate(Mbps)	Receiving: 27*12	Sending:27
	Ranging & Synchronization approach	Dual One Way Ranging with Accuracy 2cm(RMS) Baseline direction Knowledge: 0.01° Synchronization jitter 1ns(RMS)	
	RF Power	1W	1W
Thermal control	Thermal control mode	Passive and active thermal control	

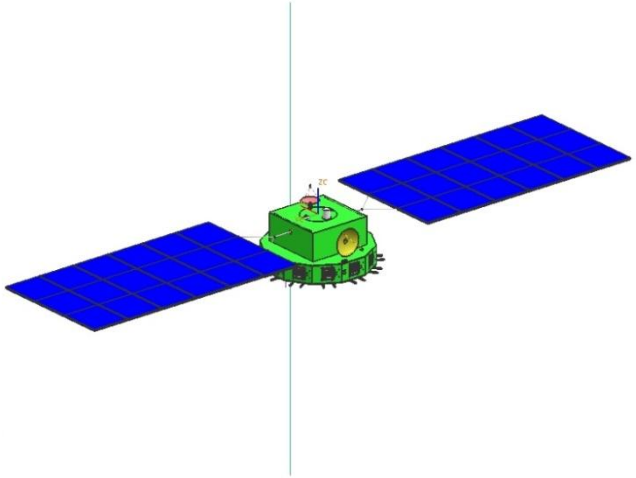
Concept Design

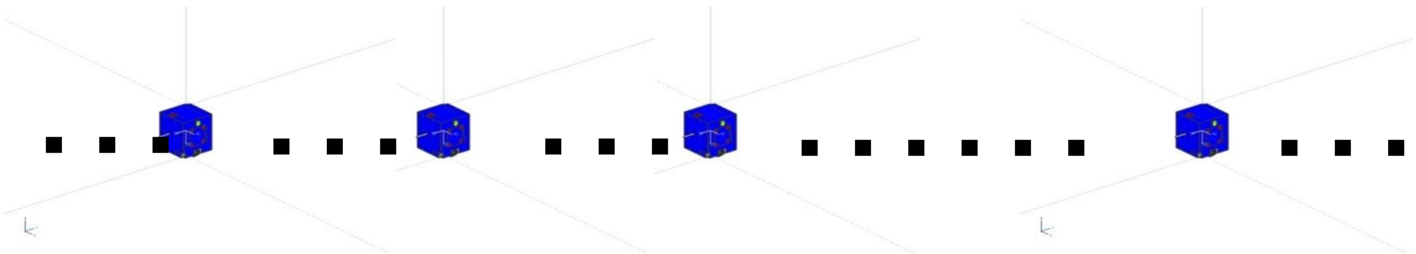
- Mass and Power Budget

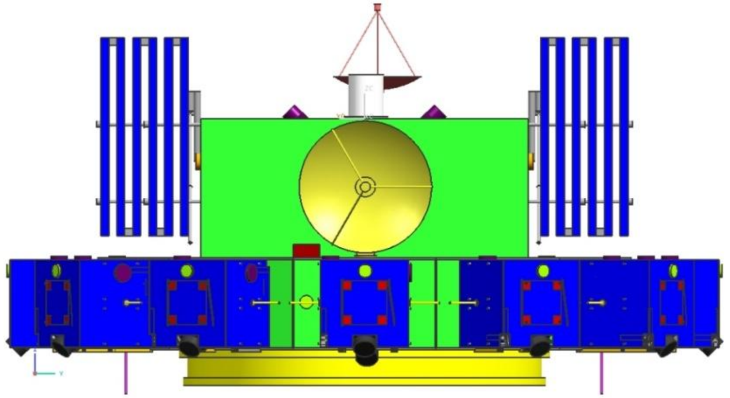
Mothership	Mass(kg)	Power(W)
ADCS	3.87	14.6
Propulsion	65.00	1100.0
Structure and Power	90.00	0.0
Thermal	6.00	8.0
Communications	7.86	97.0
Payload	4.00	25.0
Data Handling and Processing	1.40	9.0
Total	**178.13**	**1253.6**

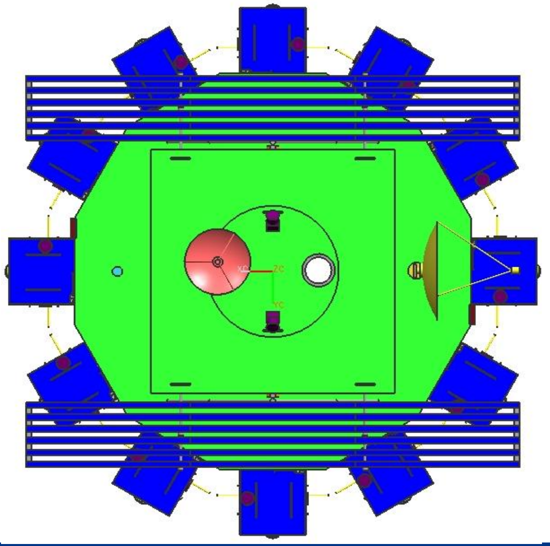
Daughter	Mass(kg)	Power(W)
ADCS	1.08	2.3
Propulsion	0.60	2.0
Structure and Power	3.55	0.0
Thermal	1.00	1.0
Communications	0.50	6.0
Payload	2.00	1.5
Data Handling and processing	0.60	3.0
Total	**9.33**	**15.8**

Concept Design---Structure



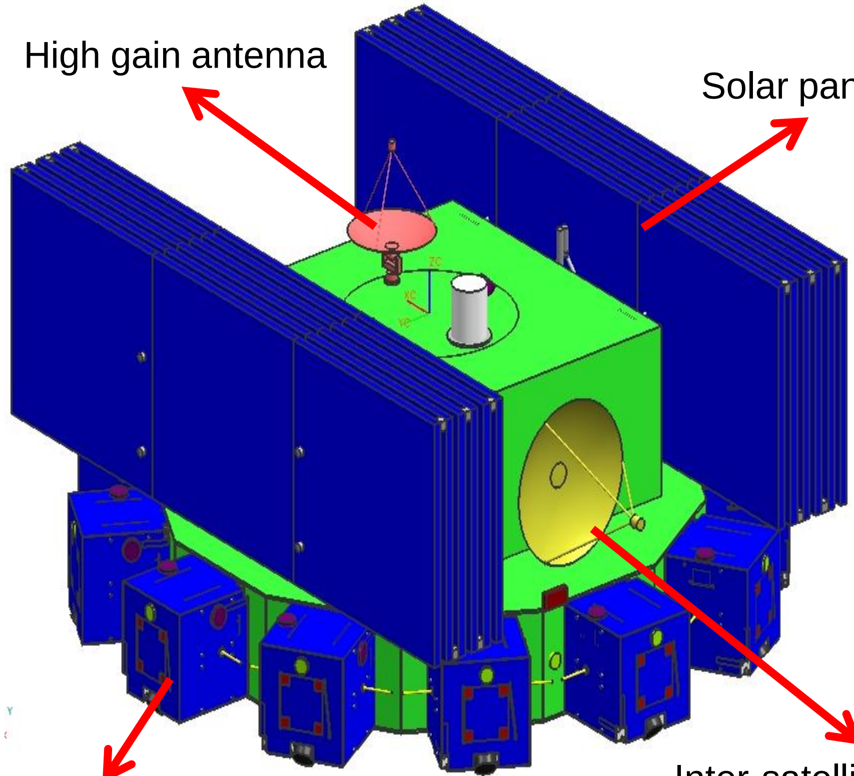


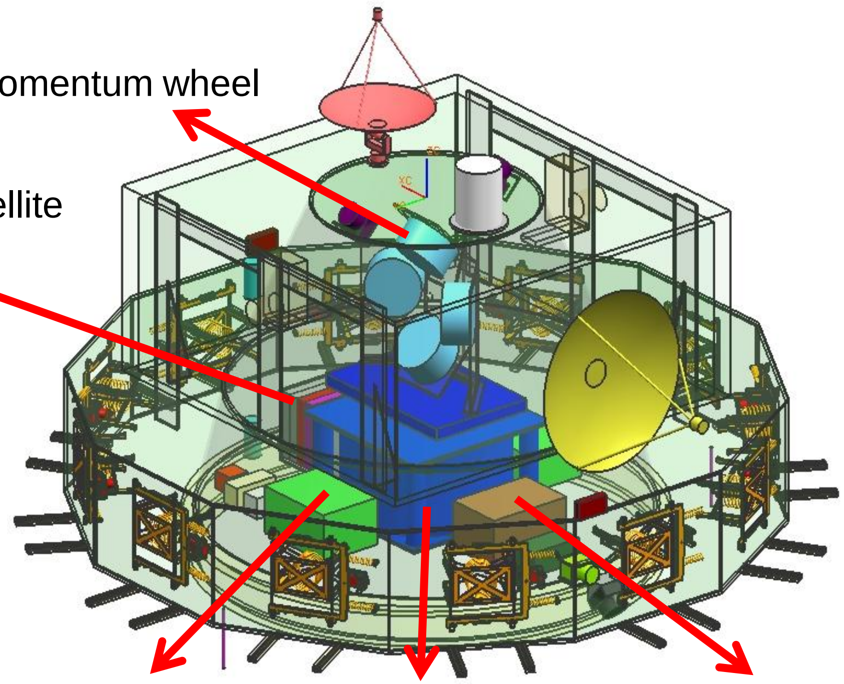




Concept Design

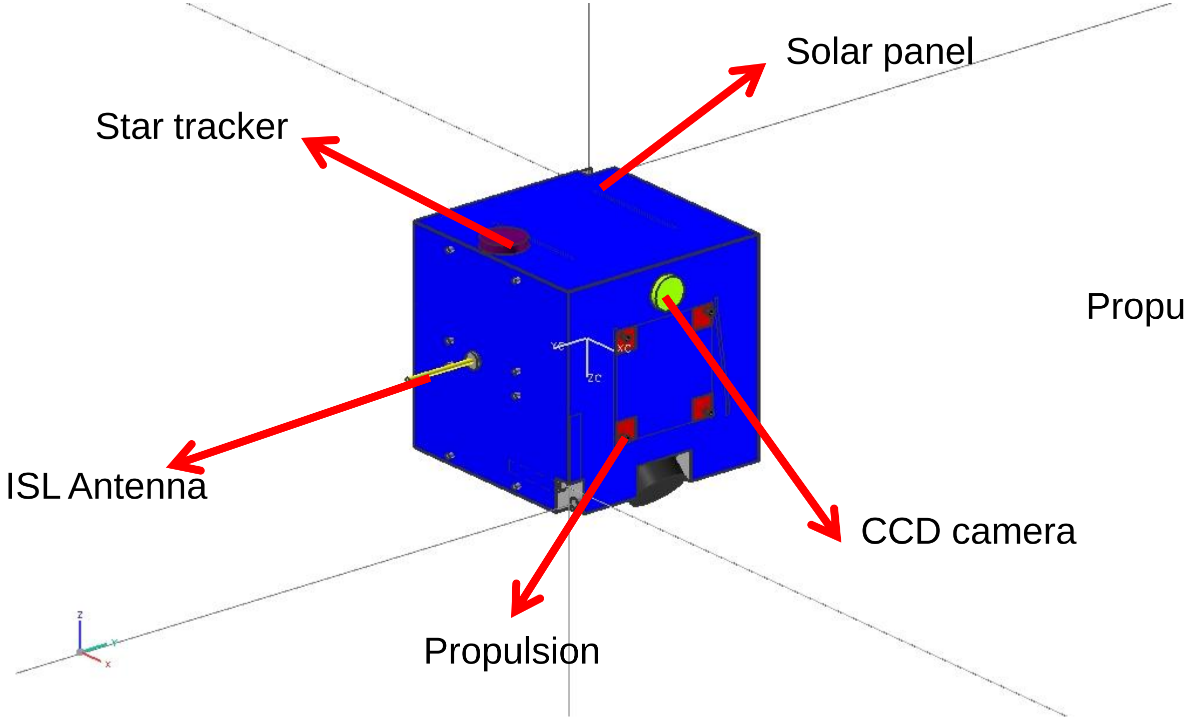
- Mothership

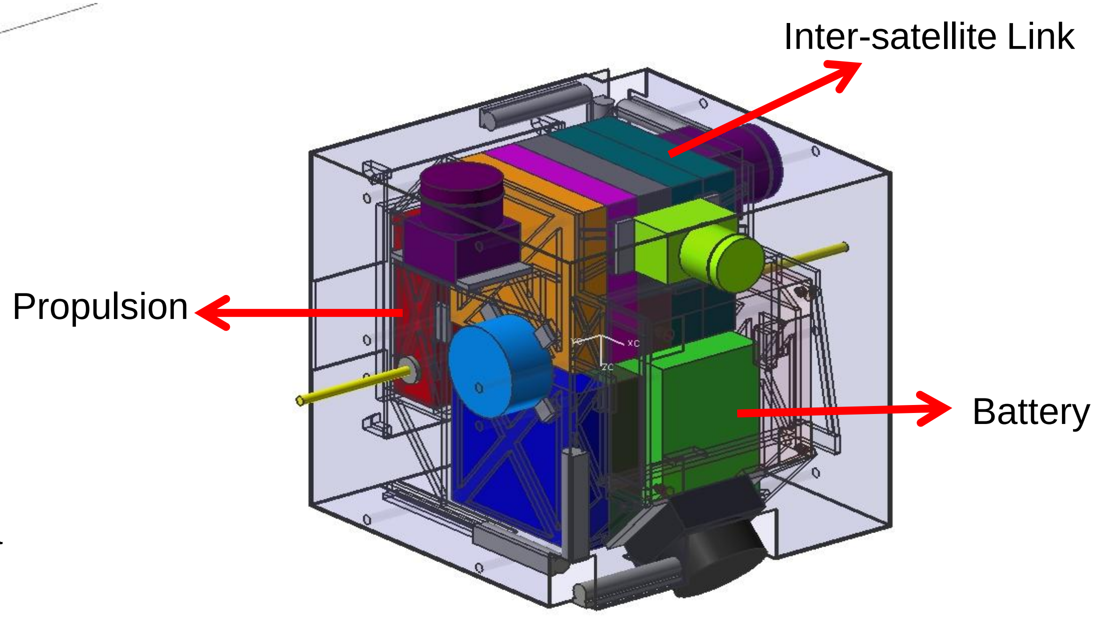




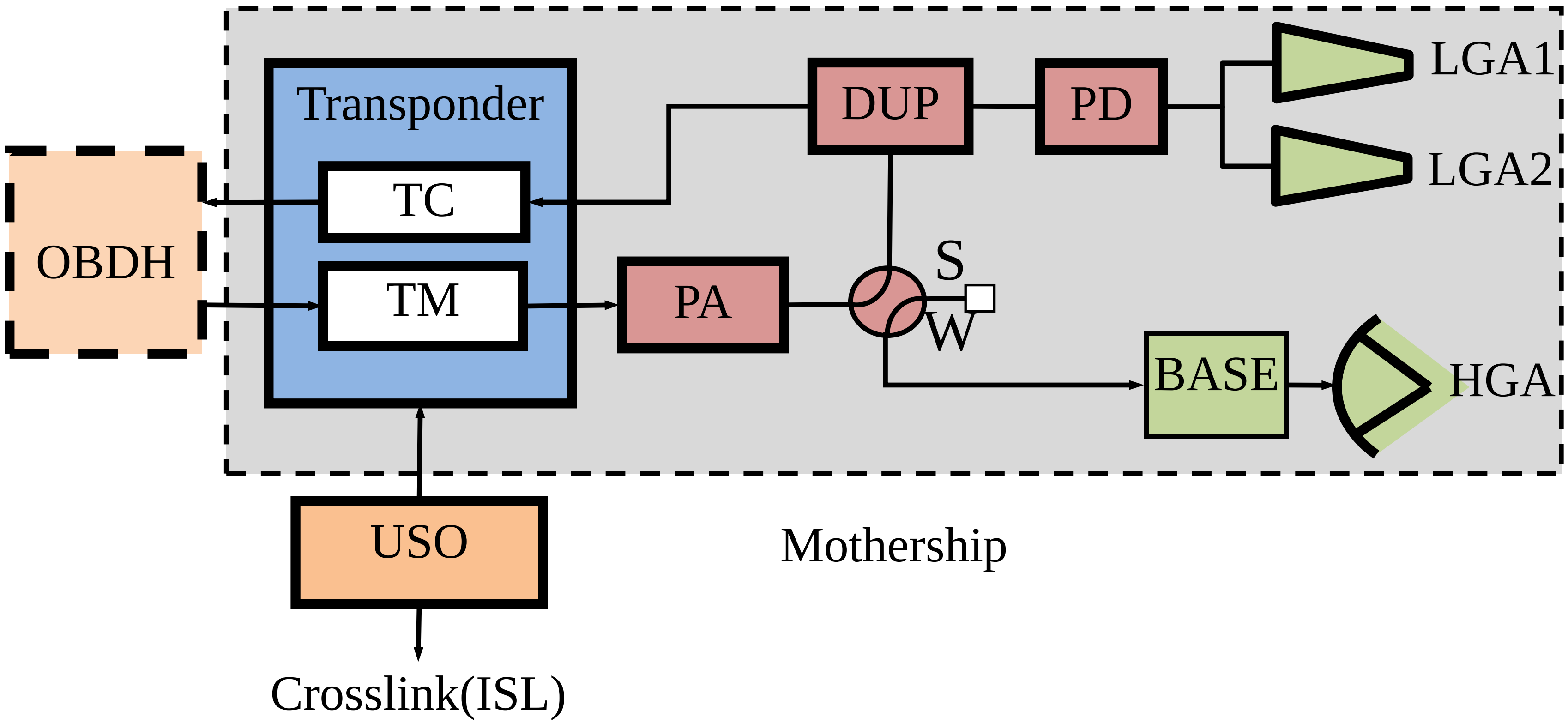
Concept Design---Structure

- Daughter Satellite





Concept Design---TT&C

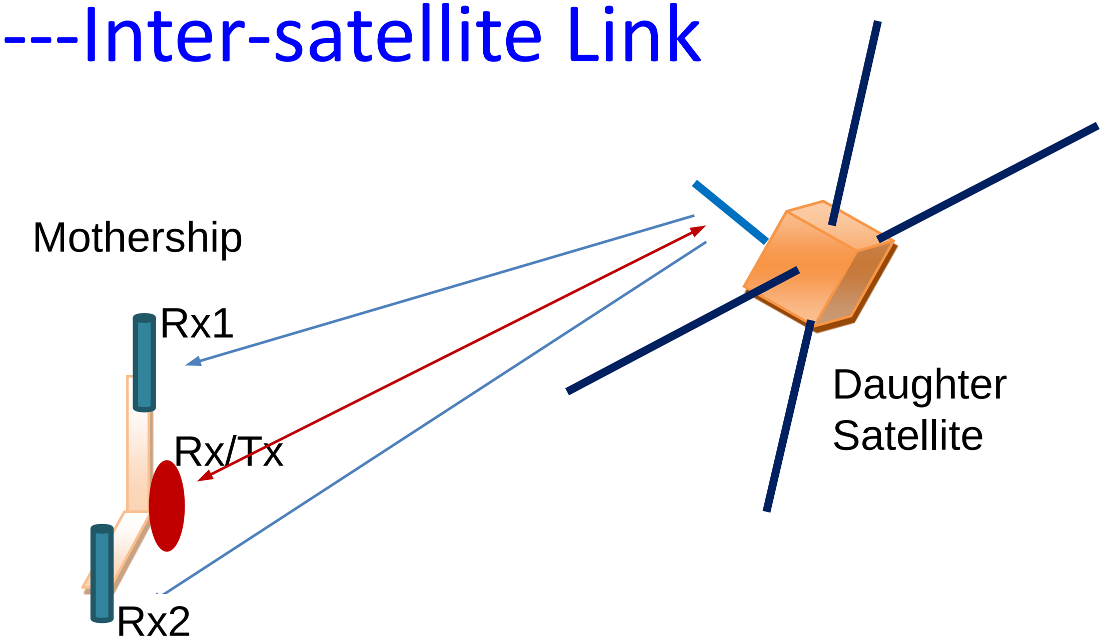


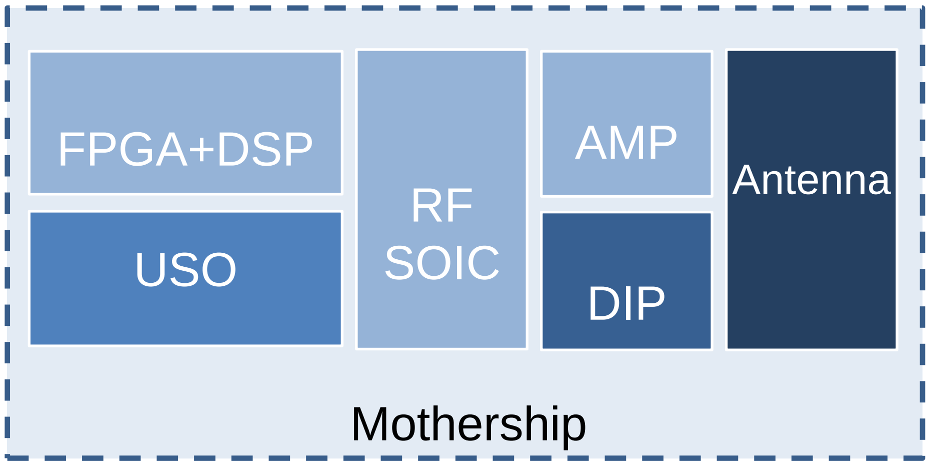
Concept Design---TT&C

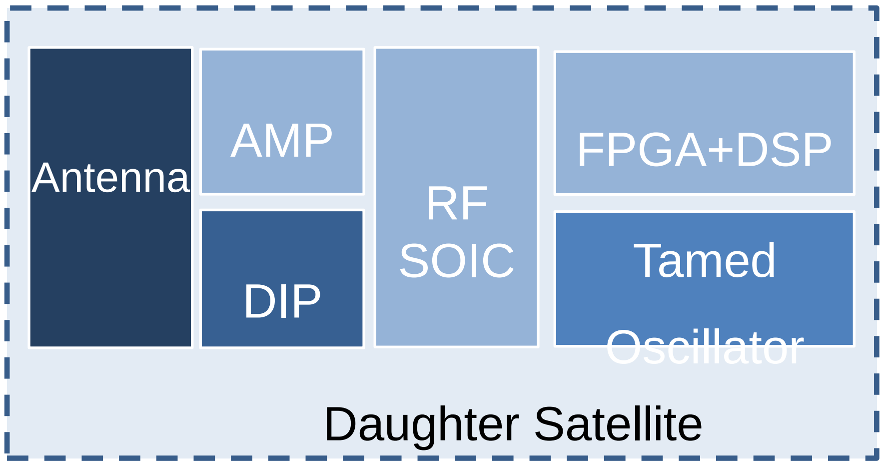
- TT&C
  - Providing telecommand uplink and data downlink between mothership and deep space stations
  - Providing orbit measurement information by VLBI.
  - The data downlink and VLBI measurement will function in time division mode.
- Uplink
  - Frequency: 7.2GHz
  - Modulation type: PM
  - Command Modulation: BPSK
  - Data rate: 125bps
  - Ranging modulation: BPSK with Tausworth PN
- Downlink
  - Frequency: 8.2GHz(downlink)
  - RF Output Power: 10W
  - Modulation Type: GMSK+PN@Downlink & Ranging, PM@ΔDOR
  - Data rate: 20Mbps
  - ΔDOR tone: 20MHz(1st), 2MHz(2nd)

Concept Design---Inter-satellite Link

- Inter-Satellite Link
  - One main and two sub antennas are mounted in mothership composing a right angled triangle. The angle of arrival (AOA) is measured by ranging difference of the antennas.

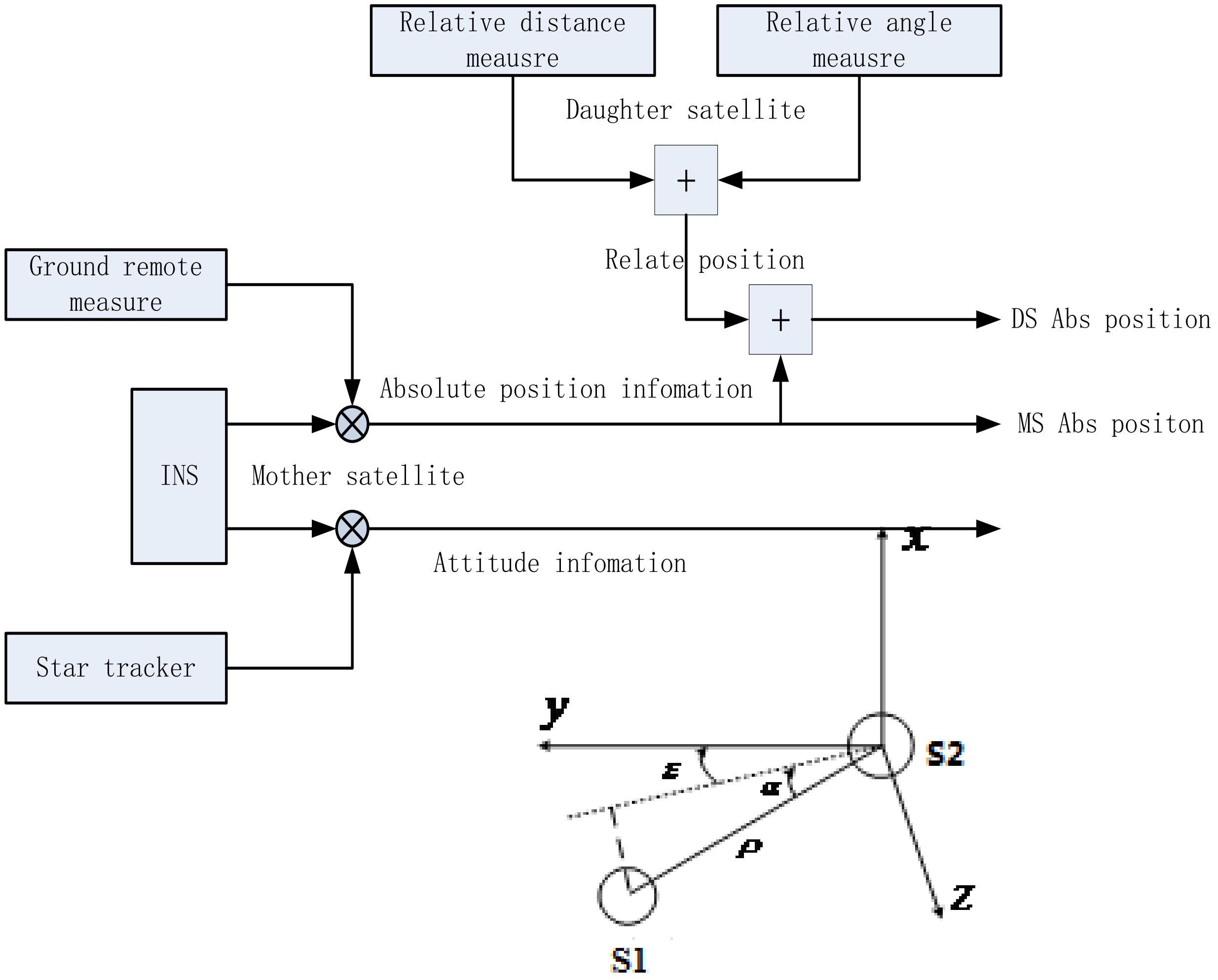






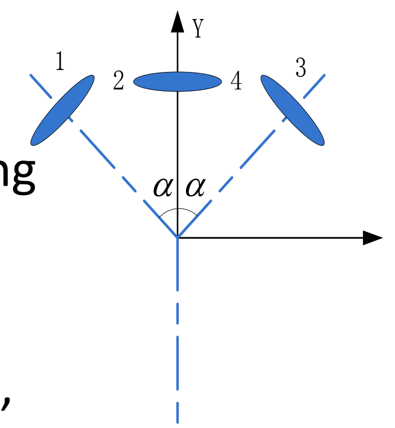
Concept Design---GN&C

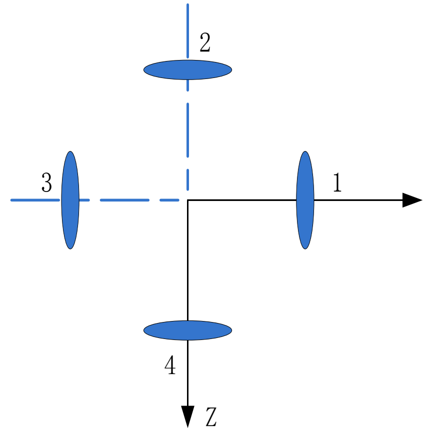
- Navigation
  - For mothership, the orbit is determinated by ground orbit measurement of range information and VLBI.
  - For daughter satellite, there is only relative radio ranging and angle measurement.
  - Daughter orbit is determined by mothership orbit information, relative orbit,etc.

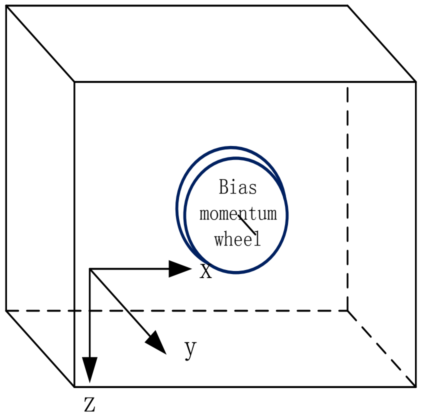


Concept Design---GN&C

- Attitude Determination&Control
  - 3 axis stabilized to the moon. The main function of the mother satellite is attitude acquire and releasing the daughter satellites.
  - Attitude measurement
    - Mothership: two sun sensors, two star trackers, one lunar sensor
    - Daughter: each with two star trackers and one lunar sensor
  - Attitude control Actuator
    - Mothership: four zero momentum wheels, eight attitude nozzles for wheel unloading
    - Daughter: each with one bias momentum wheel and eight nozzles

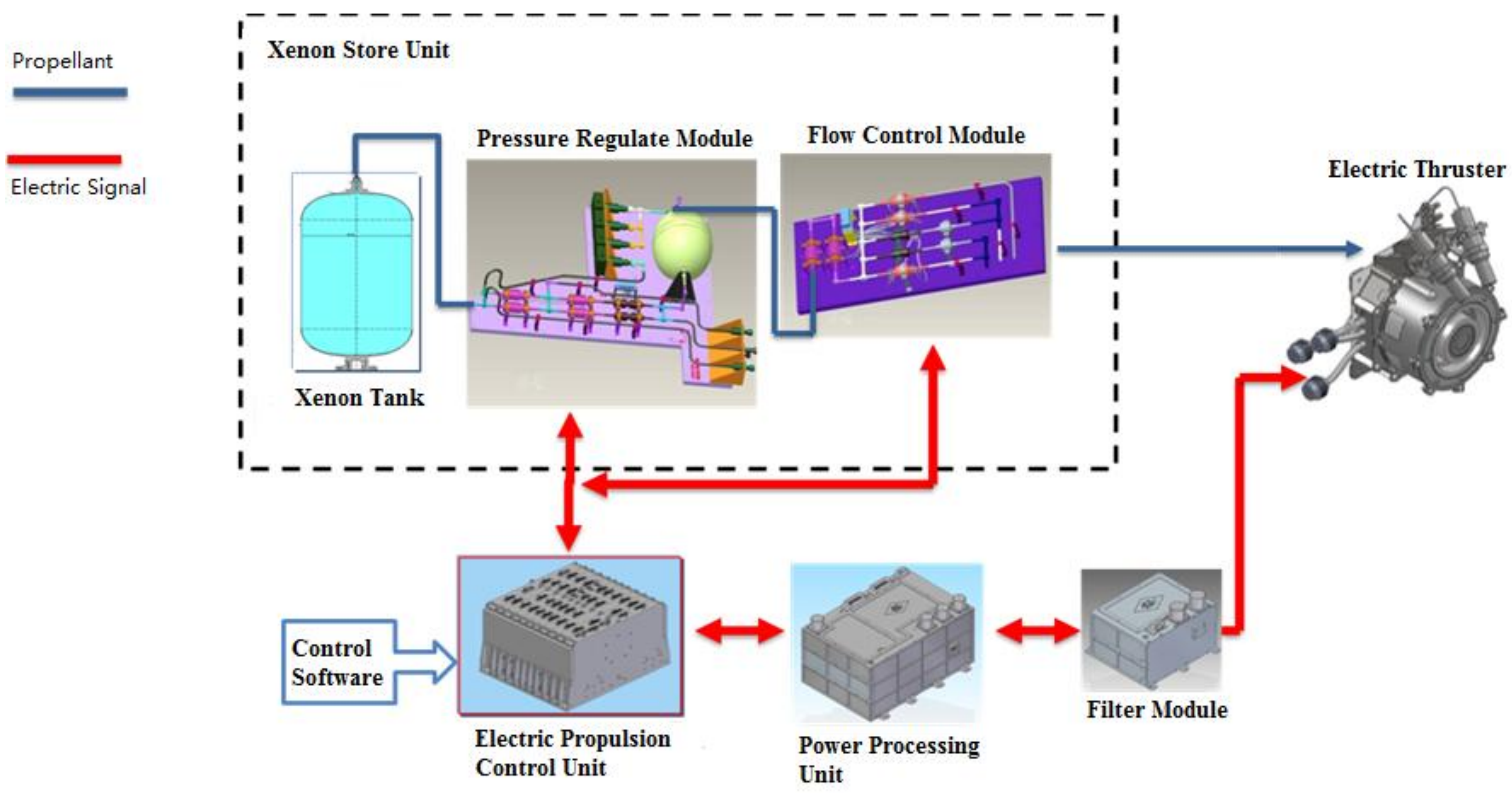






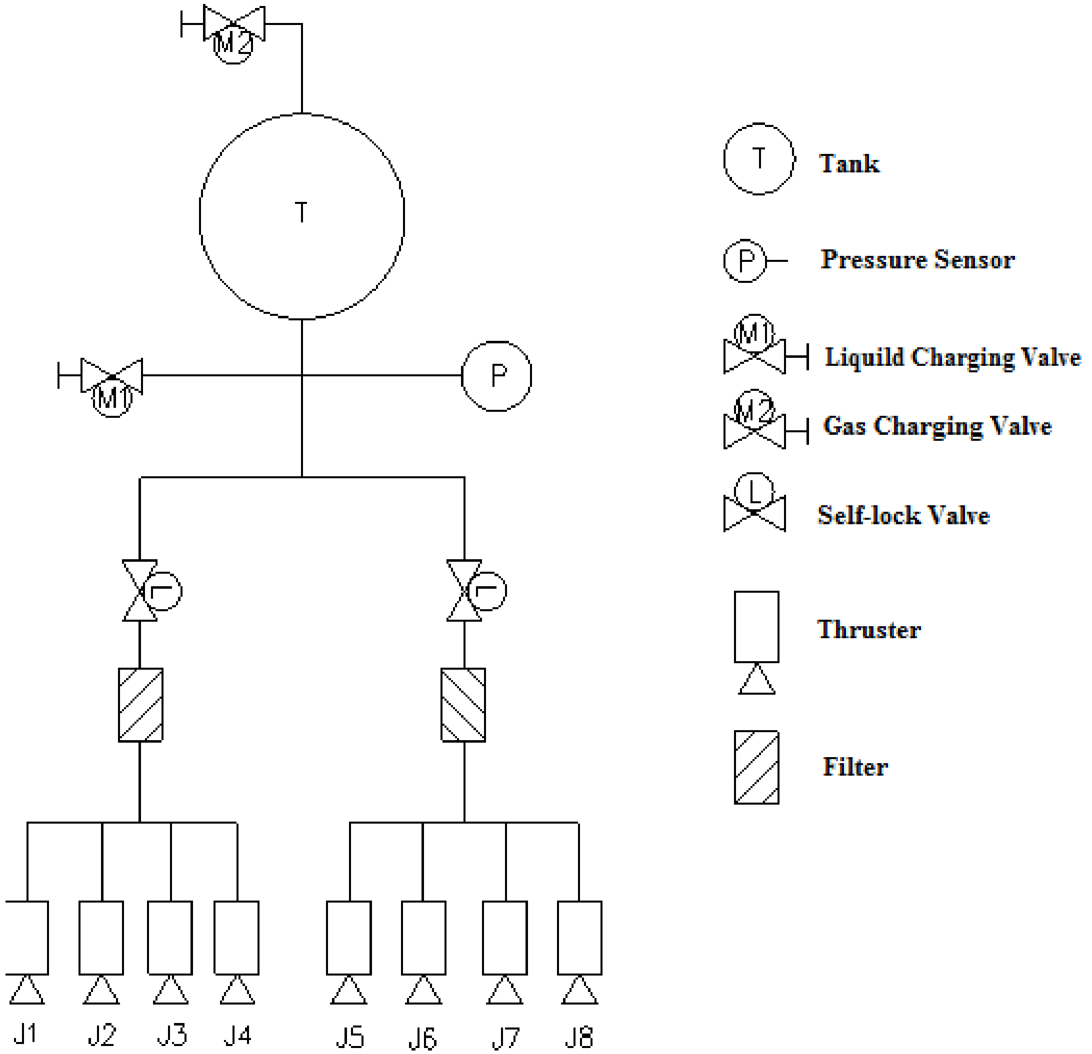
Concept Design---Propulsion

- Electric propulsion system for mothership
  - Dry mass: 23.5kg
  - Xenon:30kg



Concept Design---Propulsion

- Monopropellant propulsion system for mothership
  - Dry mass:5.5kg
  - N2H4 : 6kg



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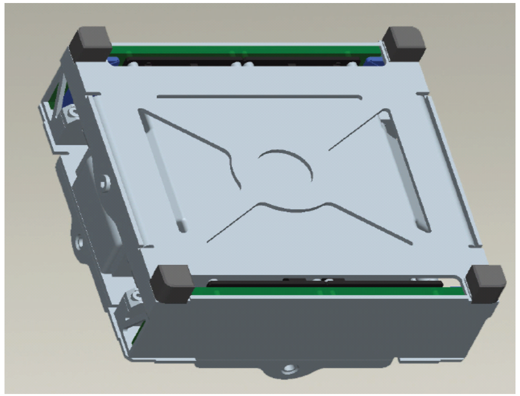
Concept Design---Propulsion

- Micro propulsion for daughter satellite
  - total delta-v is about 8 m/s, total impulse is about 80 N.s
  - Two cubesat modules from Nanospace of Sweden Space Center can provide 80 N.s impulses.

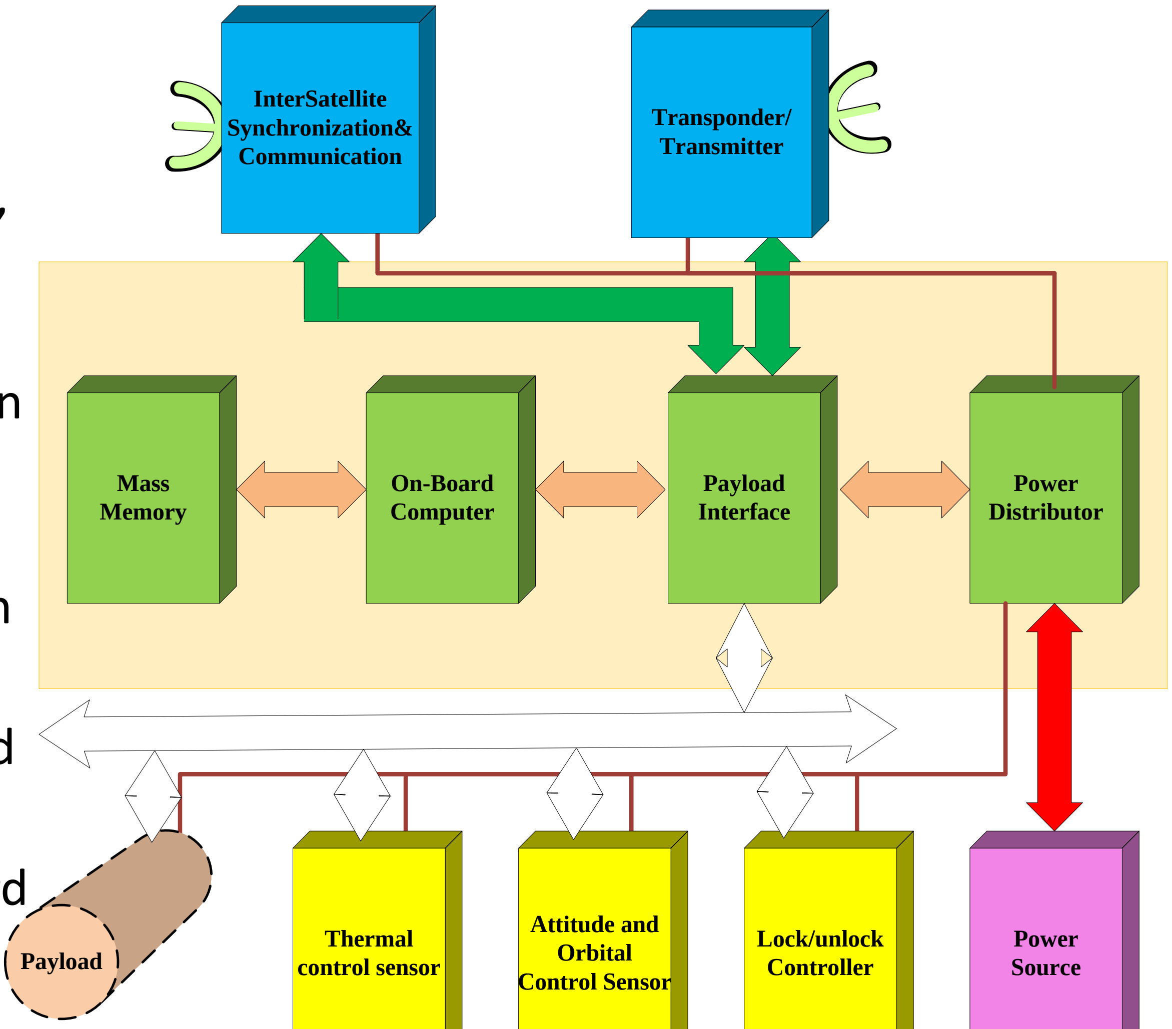
Design Specification	
Operating media	Butane
Thrust range (each thruster)	0.01–1 mN
Specific impulse	90-110 sec
Total impulse	40 Ns
Step resolution	< 10 µN
Operating pressure	2 bar
MEOP	5 bar
Proof	7.5 bar
Burst	10 bar
Temperatures operating/non-operating	10 to 50°C / -10 to 60°C
Leakage, external	10^{-6} scc/sec
Leakage, internal	10^{-4} scc/sec
Size	100 x 100 x 30 mm
Power consumption, operating average	< 2W
Mass	250 gram
Interface	
Structural mounting	CubeSat payload I/F
Electrical interface	Flying leads
Status	
Under development	TRL 5



cubesat module @ nanospace

Concept Design---Data Handling and Processing

- It is a distributed system based on communication networks .
- Management: mission plan, on-Board time, communication network ,orbital configuration monitoring, thermal control.
- Payload operation control and configuration management .
- Science and housekeeping data of experiment management, and transmission to TX.
- Implementation of AOCS, power supply and distribution.
- Tele-command and Telemetry format accord with CCSDS standard.

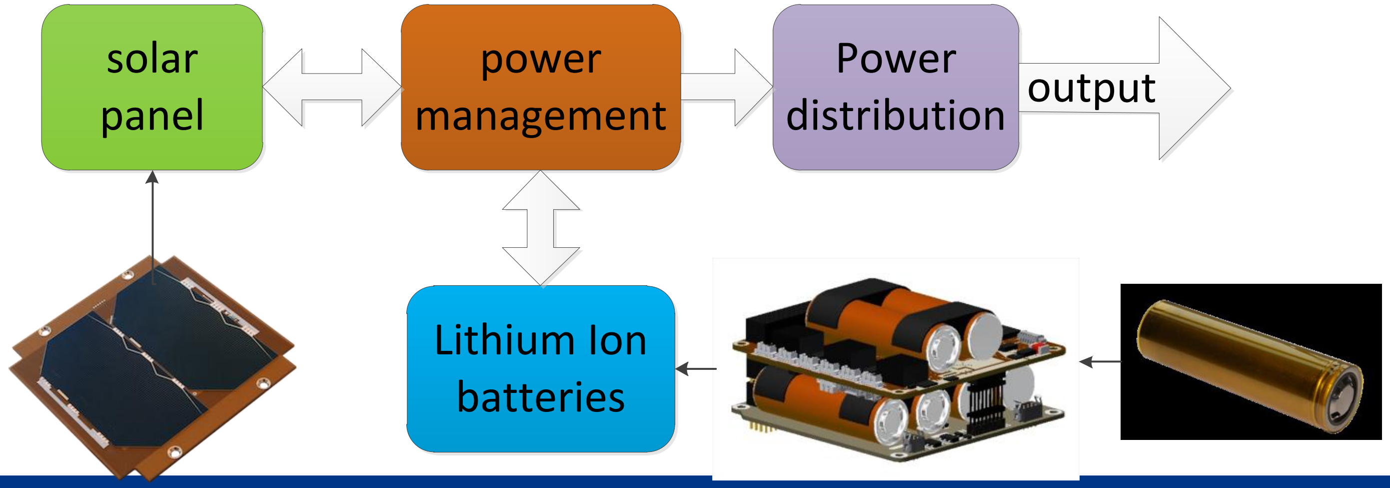


Concept Design---Data Handling and Processing

- CPU CORE Clock:100MHz , Performance up to 300MIPS.
- RTOS Vx-Works .
- Online software maintenance.
- Interface : Digital IOs / Analog inputs (ADC) / Open Collector (OC) / CAN / UART
- Mass memory and processing (Mother satellite) :
  - Input rate ≤400Mbps, Output rate ≥ 30Mbps,
  - Capacity→ 512Gbits up to 2Tbits;
- Power Distribution :current feedback on all switched lines ,all switches lines can be commanded On and Off by user.
- 3.3V single supply voltage, power consumption≤9W(Mothership) / 3W(Daughter satellite);

Concept Design---Power

- Mothership with two swing solar panels to provide 1200W in solar lighting time, daughters with surface paste solar panel to provide 10W .
- Solar panel: GaInP2/GaAs/Ge, Cell mass:7.2kg/m2.
- Lithium Ion batteries: Efficiency 96%, Energy density 125Wh/kg, Depth of battery discharge 40%
- Power management and distribution system



Concept Design---Thermal Control

- Influencing factor: mission objective, thermal requirements, orbit and attitude, structure configuration, power and weight constraints, operation modes, design life, etc.

Lunar Orbit Environment

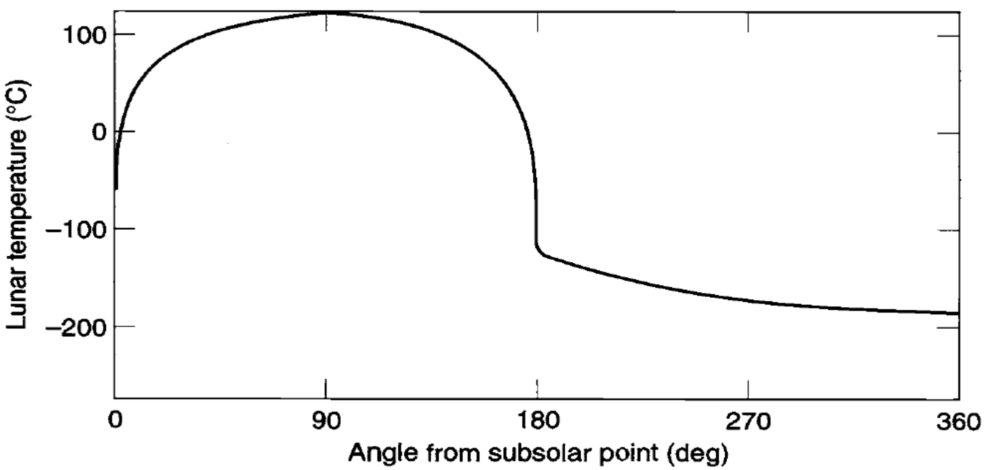
Direct Solar	Albedo	Planetary IR	
		Subsolar Peak	Dark Side
1323～1414W/m^2	0.073	1226～1314W/m^2	5.2 W/m^2

Lunar Surface Temperature

Reference Temperature	-175～+130℃

Important Thermal Requirements

Payload	Temperature Requirements	potential areas of concern
Wide-Band Matching Network	allowable temperature change <1℃, measure precision 0.1℃	1℃ Stabilization
Receiver		
Star Sensor	-20～+40℃	-20℃
Thruster	10～+50℃, Operation	10℃



Thermal Constraints

	Constraint Values	
	DSL Mother Satellite	DSL Daughter Satellites
Mass	6kg	1kg
Power	12W	1W

Concept Design---Thermal Control

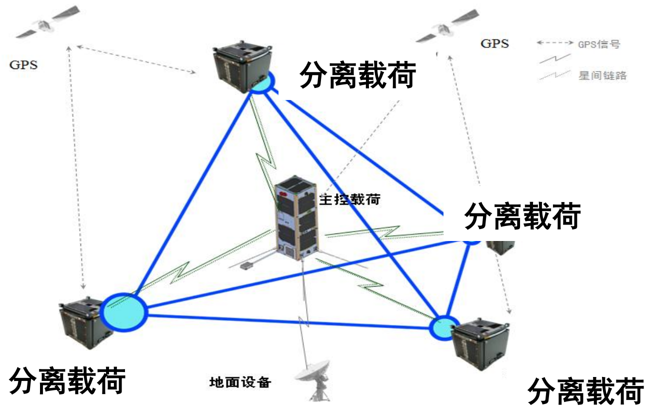
- Combinations of passive and active thermal control techniques
  - Black coating on payloads and satellite supporting structures.
  - MLI blankets fully covered on the backside of the satellite cover panels.
  - Thermal isolators at the interfaces between panels and the main support frame.
  - Payloads conductively mounted on the main support frame.
  - Patch heaters and sensors mounted on the main support frame near temperature sensitive payloads.
  - PID controlled patch heater and precision temperature sensors, MLI and carefully sized Isolators are used to maintain the temperature changes of Wide-Band Matching Network within the range of 1℃, Wide-Band Matching Network will be maintained at a relatively high temperature level.

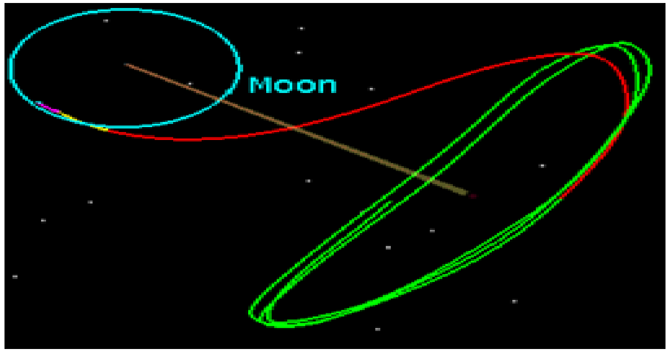
Key Techniques

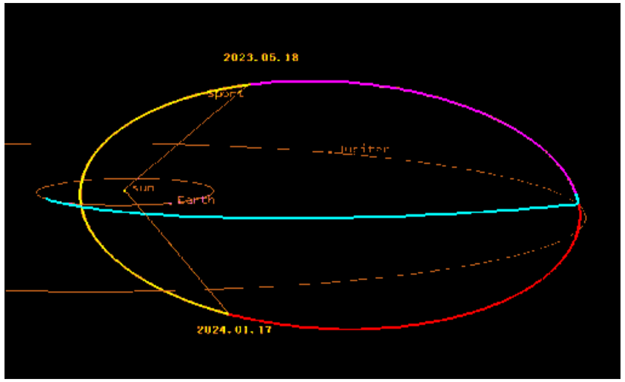
- Transfer orbit and Moon Capturing Orbit Design with low energy transfer trajectory design using invariant manifolds and electrical propulsion
- Formation Flying Fleet Autonomous Control
- High data rate communication and processing on board
- Reliable fastening and releasing mechanism between mothership and daughter satellites

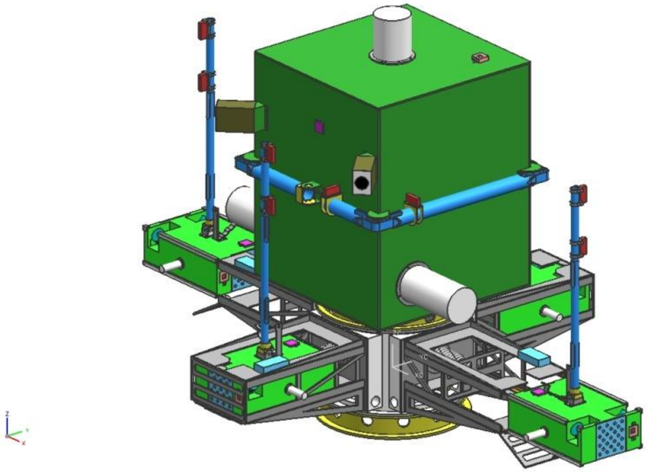
Heritage from previous studies/missions

- National Space Science Center, CAS
  - Long-term technical accumulation in Low Energy orbit dynamics, orbit design, and formation flying autonomous control.
  - With the founding support , we are developing the demonstrator of cube satellite.



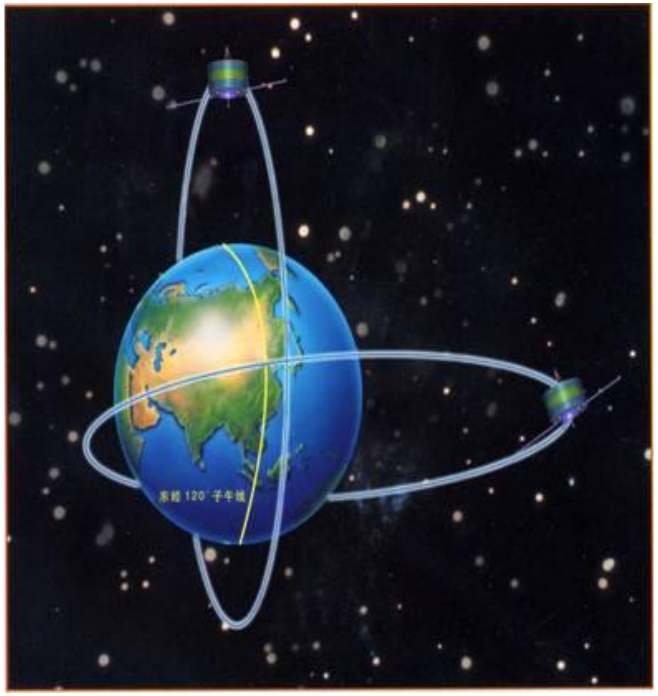


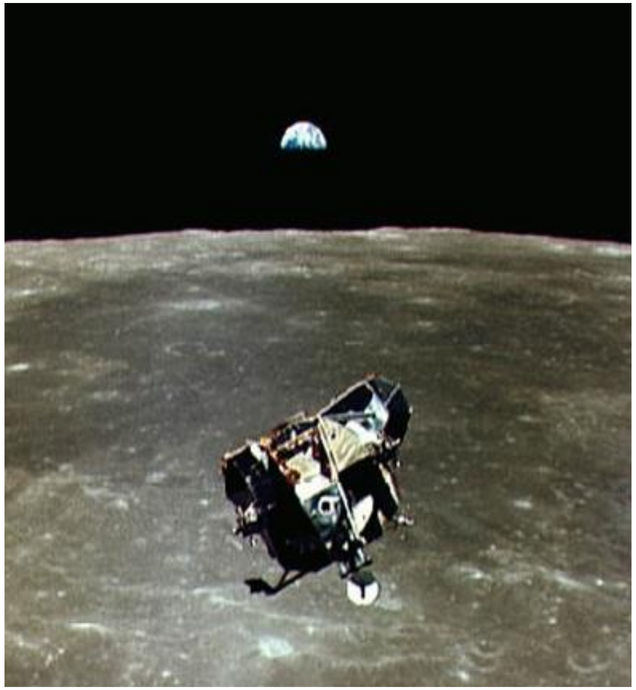




Heritage from previous studies/missions

- National Space Science Center, CAS
  - Data Handling and Processing are derived from with heritage in satellites projects such as Double Star Exploration Program, Chang’e Lunar Probe Program and YH-1 Martian Space Environmental Exploration.



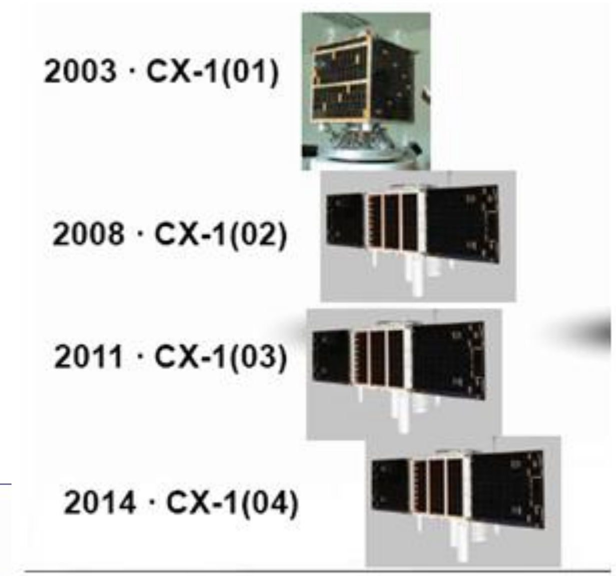


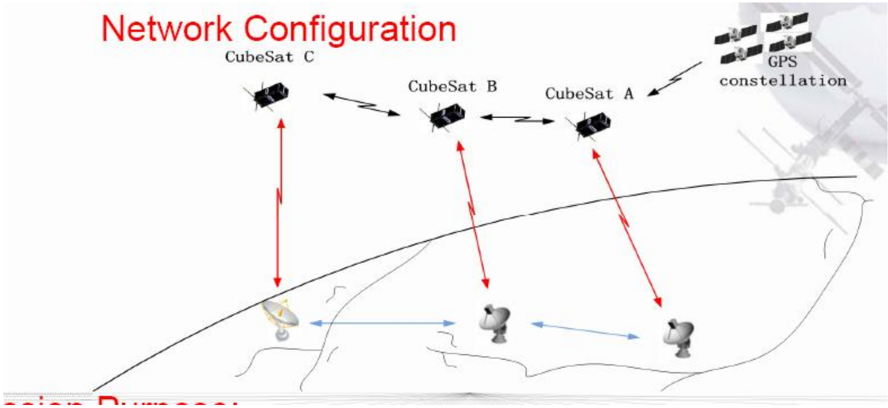
Heritage from previous studies/missions

- Research Center of Propulsion System (RCPS) of Beijing Institute of Control Engineering
  - Founded IN 1965, it's the leading manufacturer in the aerospace propulsion in China
  - In China, the RCPS designed and manufactured:
    - the first cold-gas propulsion system
    - the first monopropellant propulsion system
    - the first bipropellant propulsion system
    - the first electrical propulsion system
  - Propulsion system of RCPS have been successfully used in more than 100 satellites. RCPS has provided propulsion systems for 90% satellites in China.

Heritage from previous studies/missions

- Shanghai Engineering Center for Microsatellites
  - Founded by CAS and Shanghai city, to build a technical platform and innovation base for micro/small satellites.
  - Able to manufacture 10+ satellites simultaneously.





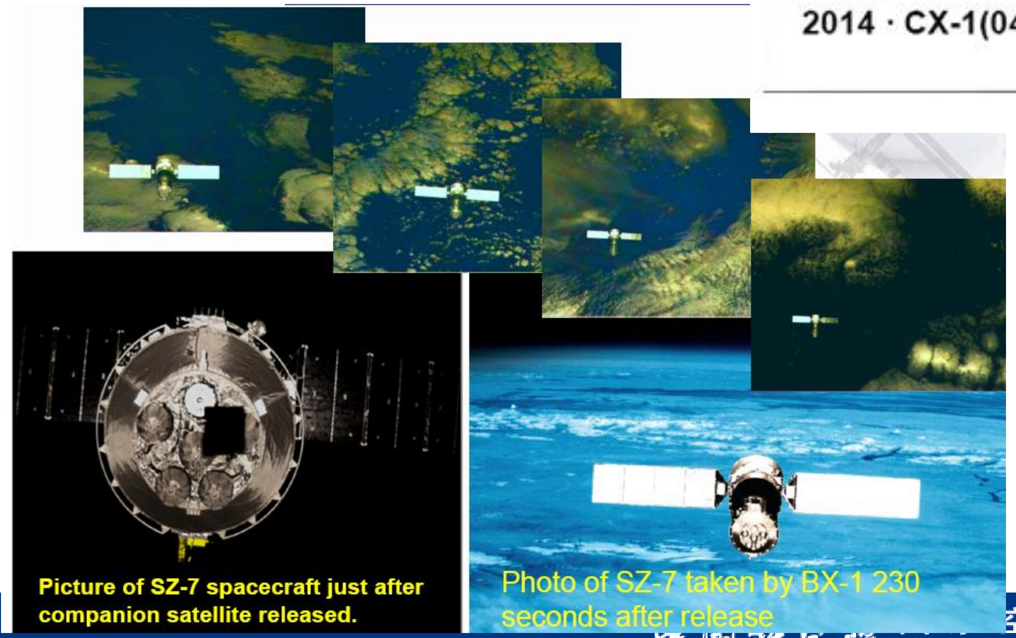

Picture of SZ-7 spacecraft just after companion satellite released.

Photo of SZ-7 taken by BX-1 230 seconds after release

Heritage from previous studies/missions

- Contribution from China Side
  - Others …

- Contribution from ESA Side
  - …

Thanks for your Attention!