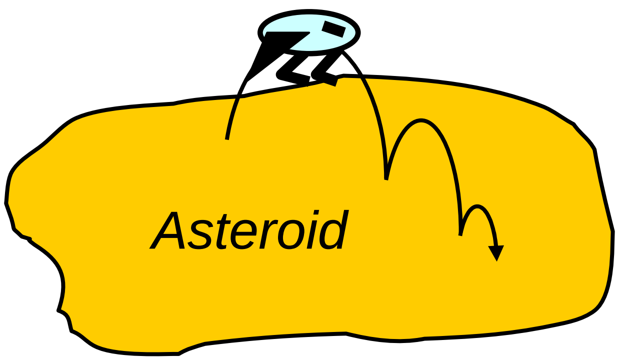
IEEE ICRA 2005
Planetary Rover Workshop

Asteroid Exploration Rover



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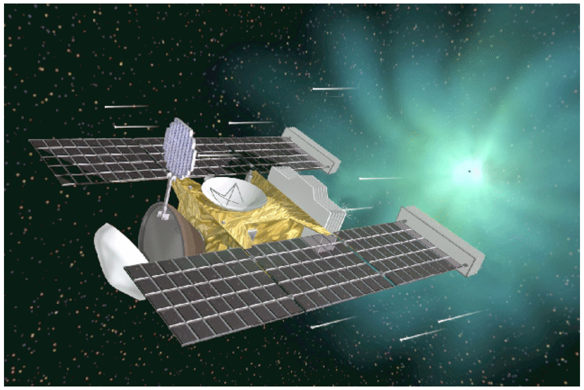
Contents

Exploration of Small Body

NEAR (NASA, 2001)

MUSES-C (ISAS, 2003-2005-2007)

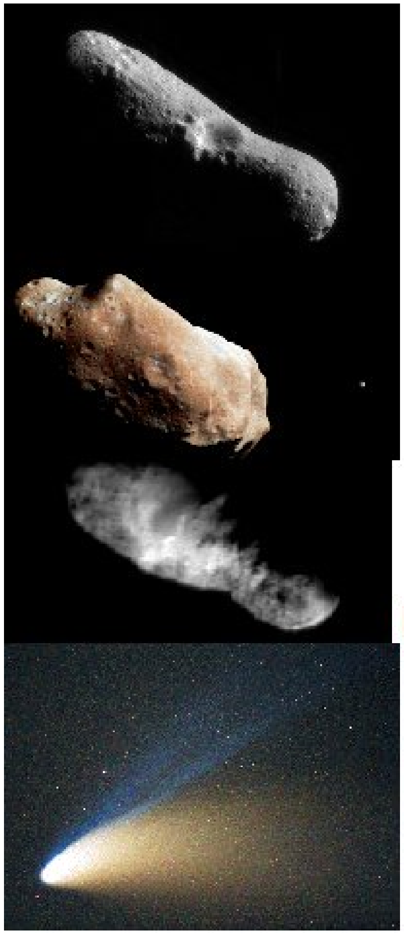
Stardust (NASA, 1997-2006)

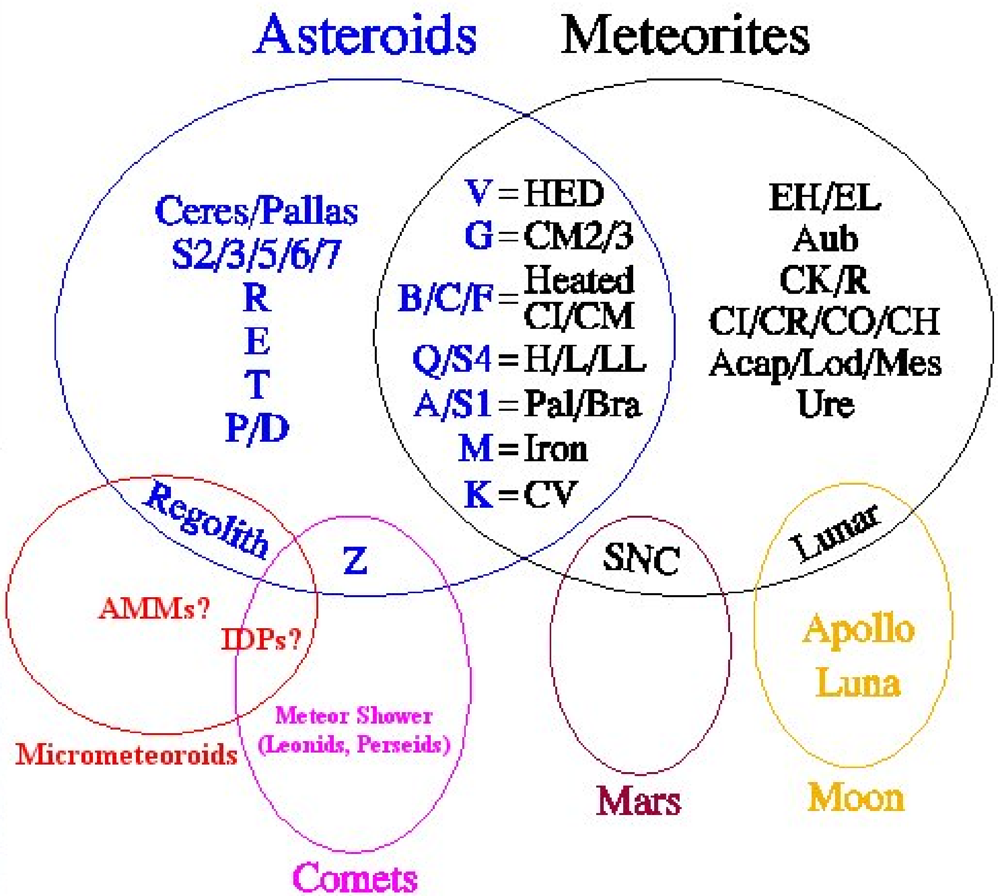


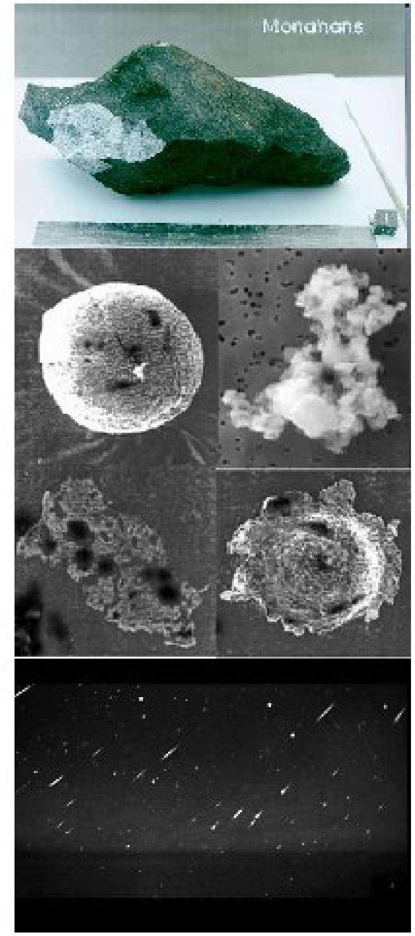
Rosetta (ESA, 2004-2006-2011)

Asteroids or comets would give us a lot of hints to throw a light on the origin and evolution of the solar system.

Small Body Exploration

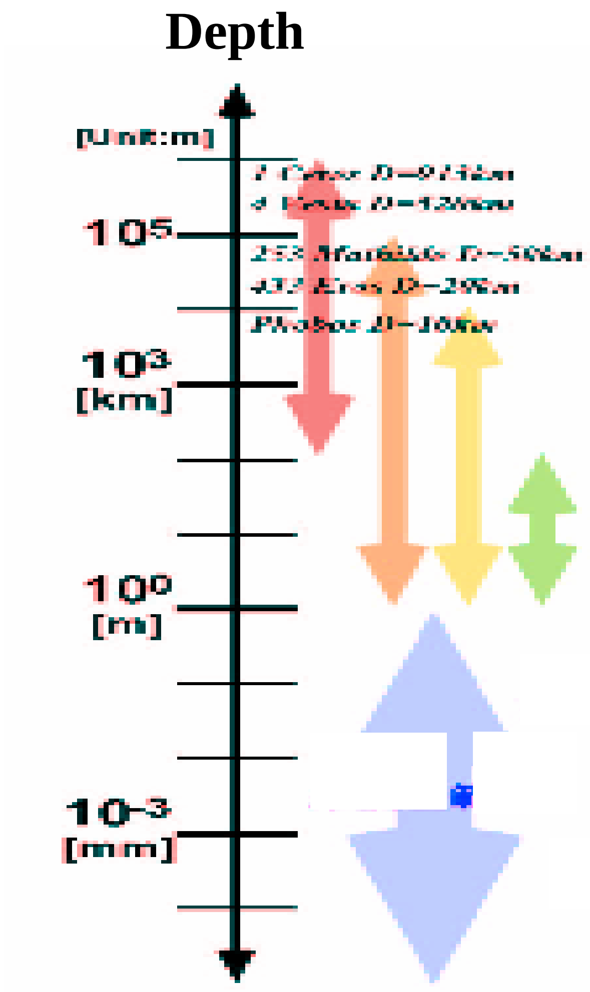






Sample return missions make it possible to make the composition and origin of a number of small bodies clear.

Minorbody Investigation



Vesta Crater Exploration

Family Asteroid Exploration

Radar Sounder /Tomography

Seismic Network, Landing Radar

Boulder or Groove Rover *In-situ*

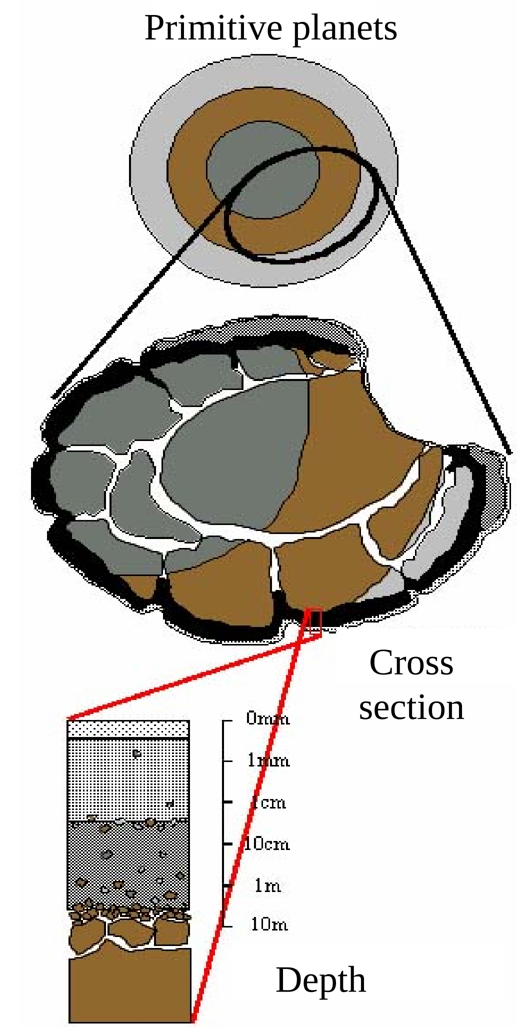
Fixed Lander *In-situ*

Sample Return (Core Boring)

Sample Return (Regolith)

In-Situ Microscopic Camera

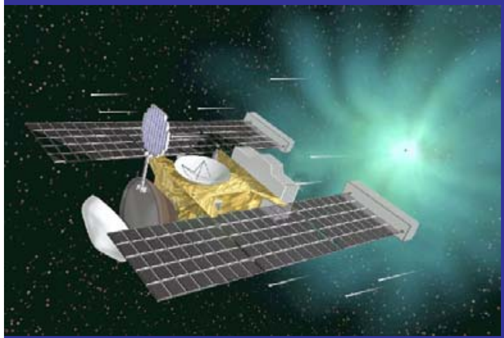
Micro-tomography



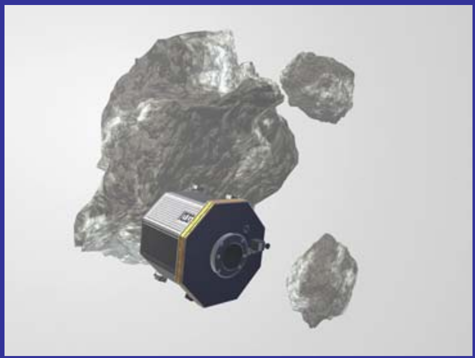
Subsurface exploration is the key way to know the evolution process.

Small Body Exploration Missions

1999 **2002** **2003**



Stardust （USA）
Comet FB&SRx1(2006)

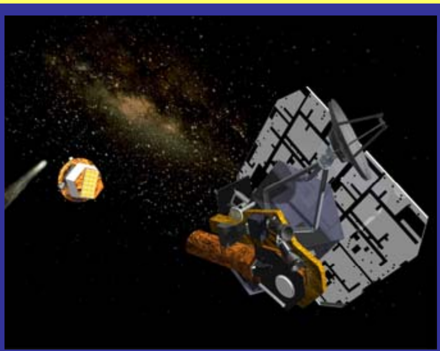


CONTOUR （USA）
Comet FBx2(2003, 6)

MUSES-C （Japan）
NE Asteroid R&SRx1 (2007)

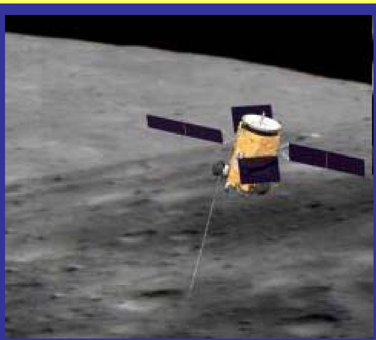
Rosetta （Europe）
MB Asteroid FBx2(2006,8)
Comet R&Lx1(2011)

2004 **2006**



Deep Impact （USA）
Comet FB&Ix1(2005)

Dawn （USA）
MB Asteroid Rx2(20010,14)



Hera (Proposal) （USA）
NE Comet R&SRx3(2010)

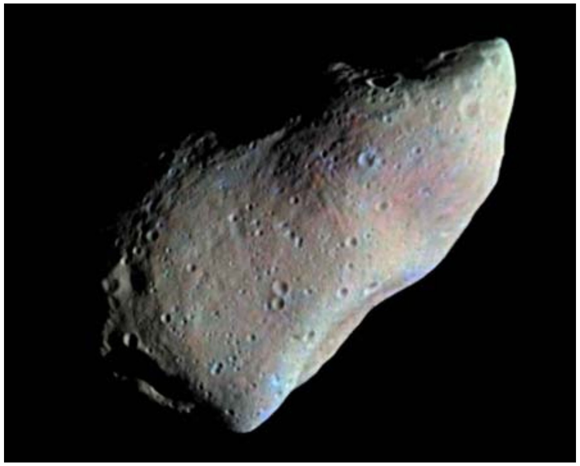
FB= Fly-by
SR=Sample Return
R=Rendezvours
L=Landing
I=Impactor

Red=Surface Contact
Italics=Asteroid Visit
NE= Near Earth
MB= Main Belt

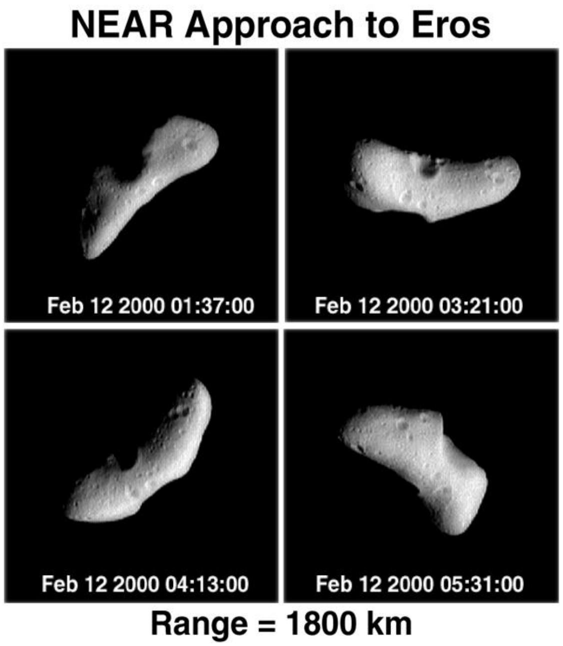
Observed Asteroids

Ida

Gaspra



Mathilda



MUSES-C Mission

MUSES-C Mission (ISAS)

Engineering test spacecraft
for sample and return Technologies

aiming at demonstrating four key technologies

- **Electric Propulsion for Interplanetary Cruise**
- **Autonomous Optical Navigation and Guidance**
- **Automated Sampling Mechanism**
- **Direct Reentry of Recovery Capsule**

MUSES-C Mission (ISAS)

also demonstration of other new technologies

- **Hopping Rover Exploration**
- **Multi-Junction Solar Cell**
- **Lithium Ion Re-chargeable Battery**
- **Duty Heater Control**
- **Bi-Propellant Small Thruster RCS**
- **X-band Up/Down Communication**
- **CCSDS Packet Telemetry**
- **Wheel Unloading via Ion Engines**
- **PN-Code Ranging, etc.**

MUSES-C Spacecraft Launch

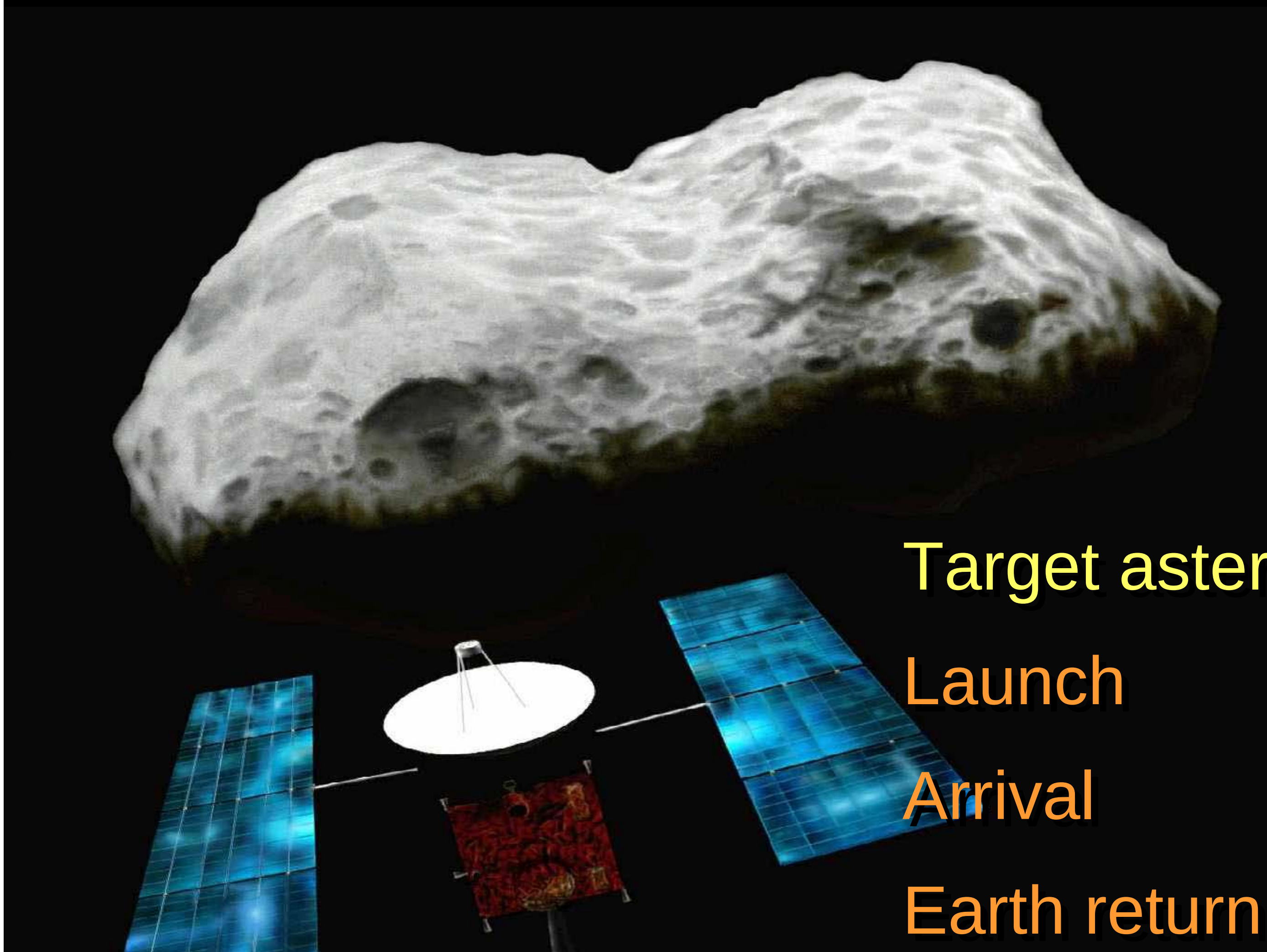
MUSES-C Spacecraft was launched at Kagoshima Space Center on May 9th 2003 by ISAS M-V rocket.

MUSES-C Spacecraft [*Hayabusa*]

隼

Falcon

MUSES-C Mission (ISAS)



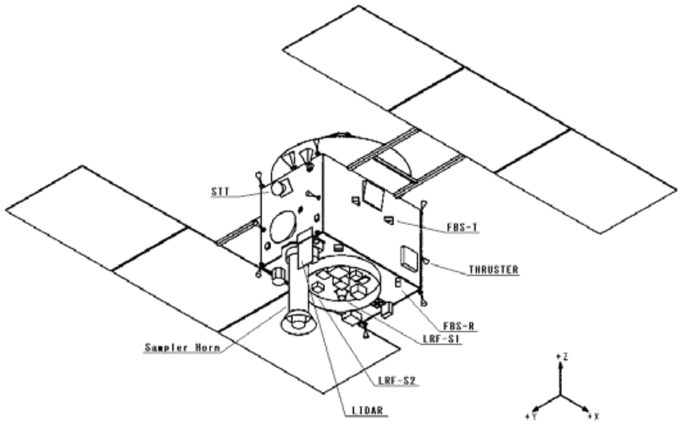
Target asteroid : 1998SF36

Launch : 2003.5.9

Arrival : 2005.9.

Earth return : 2007.6.

MUSES-C Spacecraft



- Launch weight : 510kg
  Chemical Fuel : 67kg
  Xenon propellant : 66kg
- Attitude Control : three-axis stabilize
- Communication : Xband (max:8kbps)
- Solar Cell Paddle : 2.6 kW at 1 AU
- Chemical propellant : 12 RCS (Isp:290sec)
- Electric propellant : 4 IES (Isp:3200sec)
- Payloads
  Telescope cameras, Near Infra-red Spectrometer,
  X-ray Spectrometer, Sampling Mechanism,
  Laser Altitude-meter, Reentry Capsule, Small Rover

Asteroid Exploration Rover

Small Body Exploration Rover

In-situ surface observation by robots would be a promising method to explore the target body.

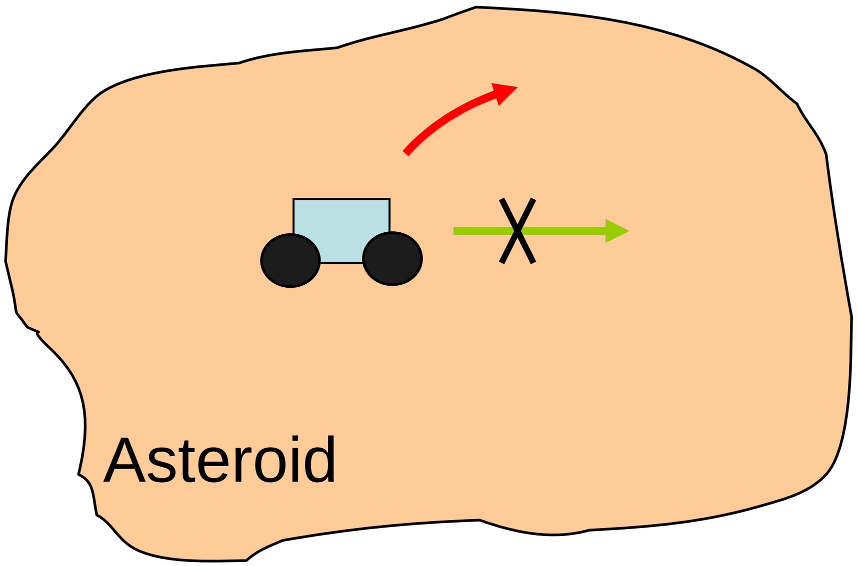
Gravity acceleration → very small

$10^{-3} \sim 10^{-7}$G

Mobility system of robot is important

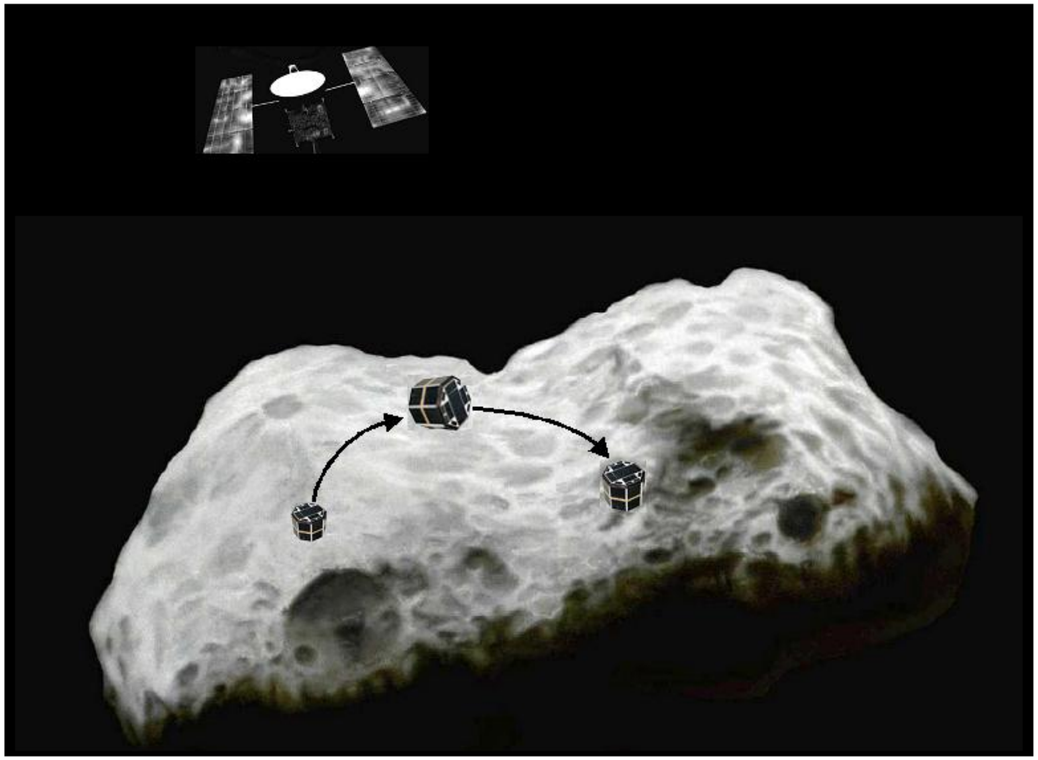
Asteroid Exploration Robot

Surface gravity：0.0001G～0.000001 G



Wheeled type robot cannot move on the surface of small body, because it is easy to lift-off.

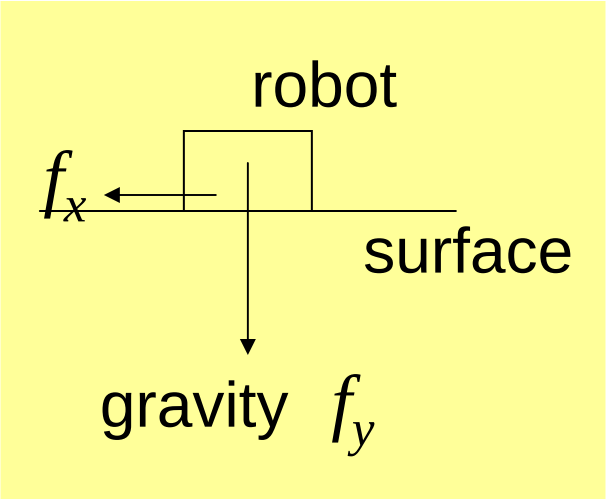
Asteroid Exploration Robot



Why hopping mechanism?

Suppose the asteroid size of about 1[km] (diameter),
its surface gravity would be 10-100[μ G],
its escape velocity from the surface would be 20-80[cm/s]

(1) easily away from the surface



(2) extremely low speed

$$f_x = \mu \ f_y$$

f_x : traction to move horizontally
f_y : contact force
μ : friction coefficient

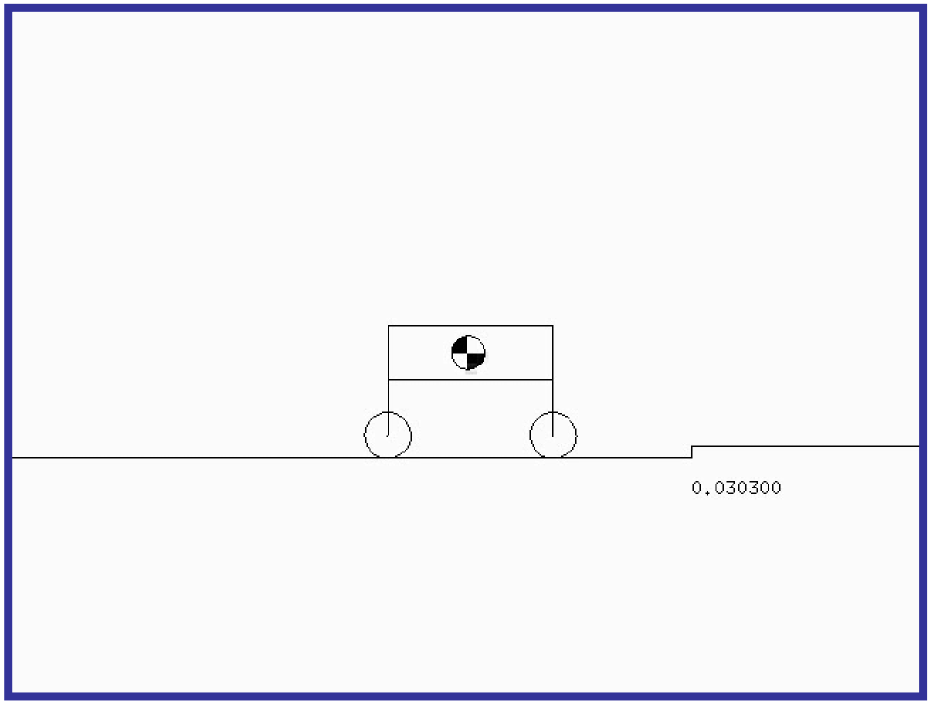
To make f_x larger, either f_y or μ has to be increased

μ : can not be controlled.

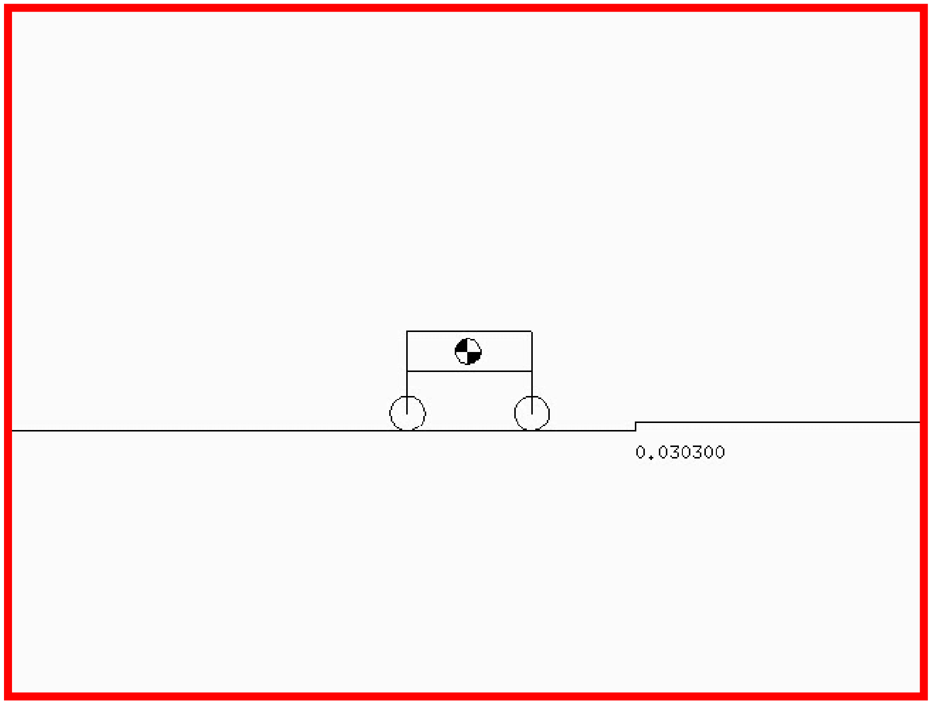
f_y : can be increased by artificially pushing force of hopping mechanism

Simulation Study

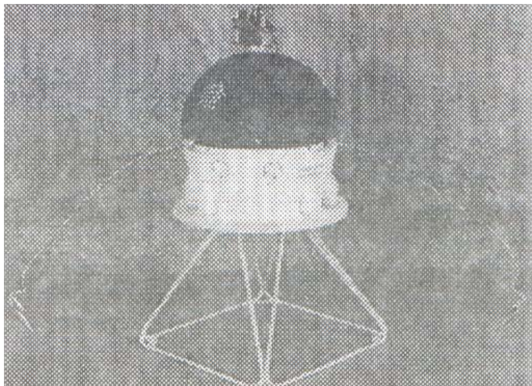
Gravity=1G



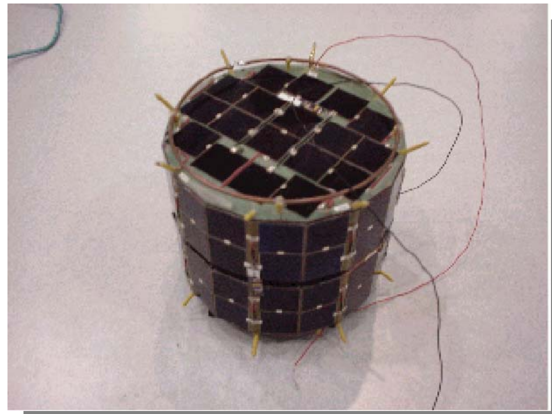
Gravity=0.0005G



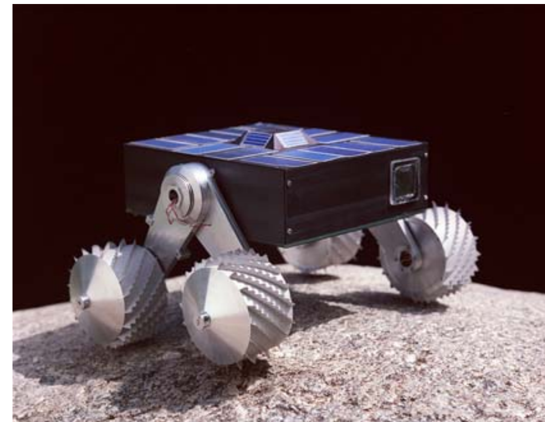
Proposed Hopping Robots



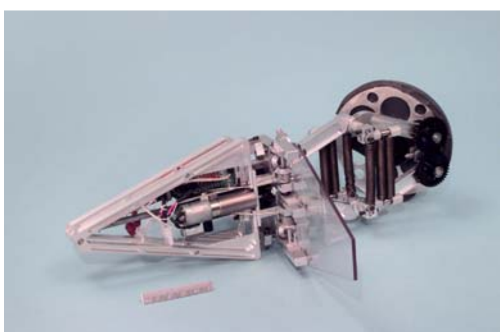
PROP-F
(Soviet Union)



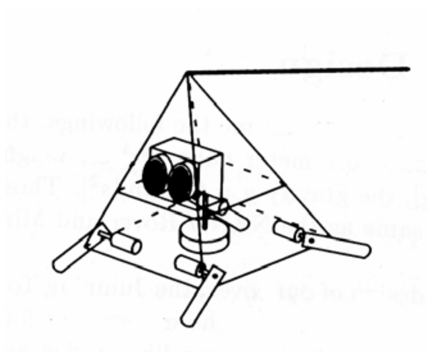
MINERVA
(ISAS/JAXA)



SSV
(NASA/JPL)

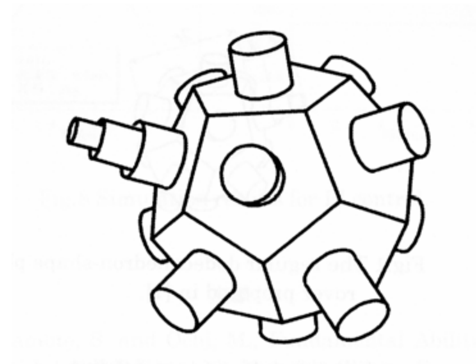


Frog type
(NASA/JPL)



Legged type
(Tohoku Univ.)

Iron-Ball type
(Univ. of Tokyo)

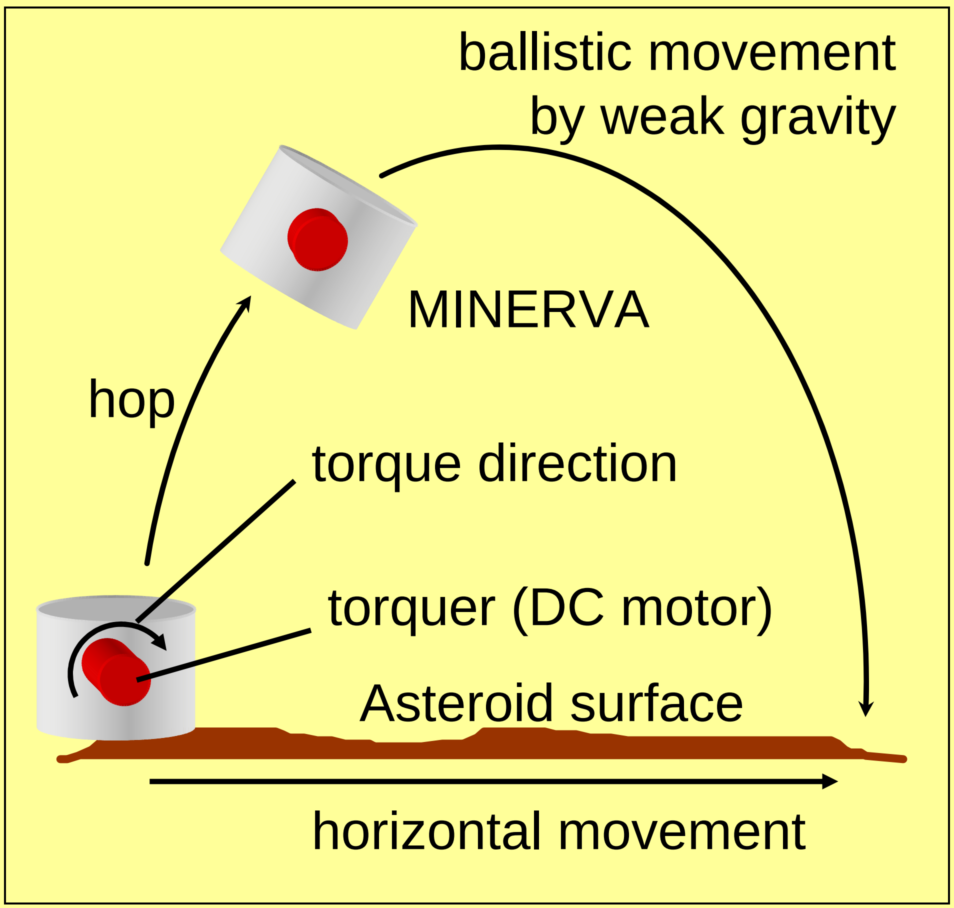


Legged type
(Kyushu Univ.)

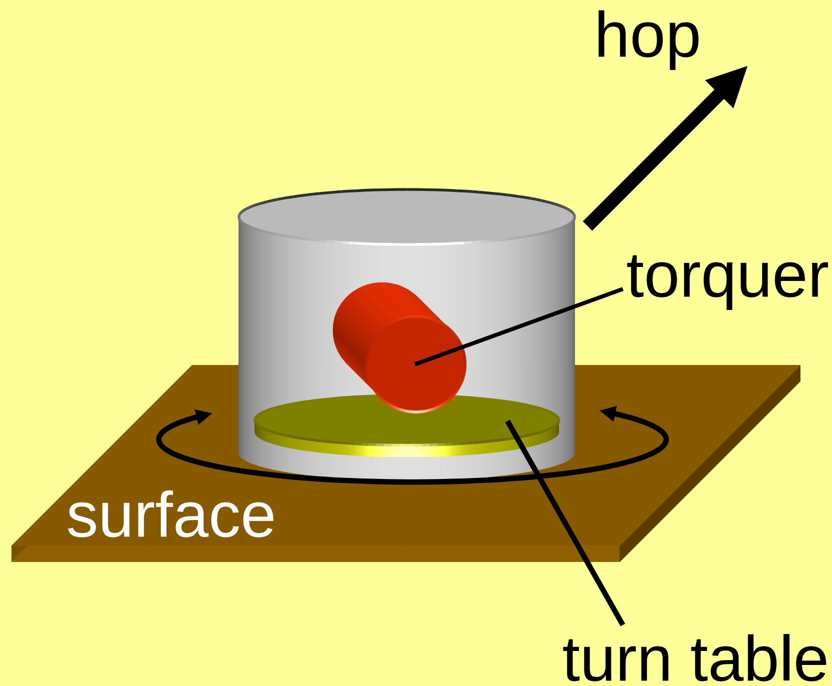
Novel Hopping Mechanism

Hopping Mechanism by Torquer

No actuator outside

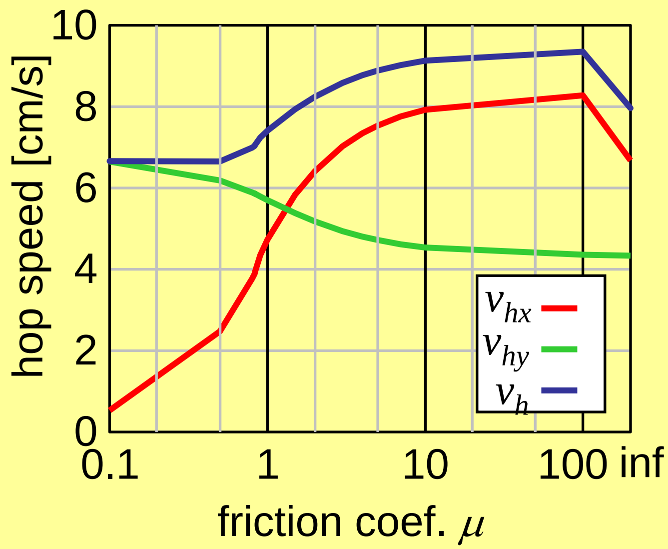


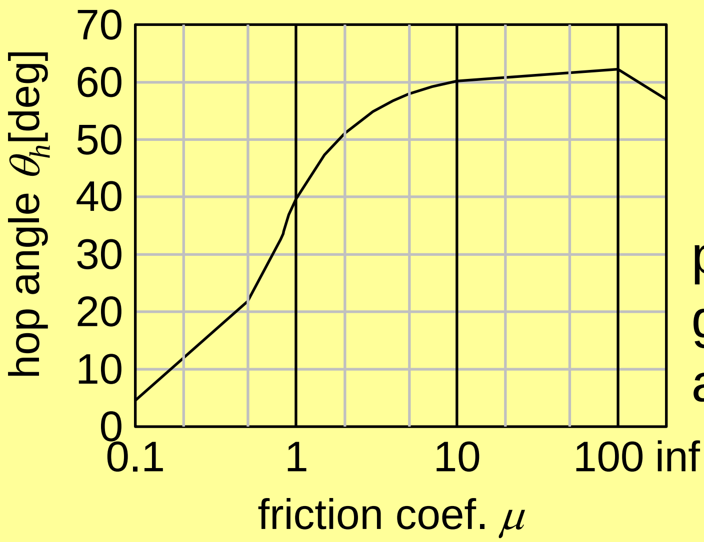
2-DOF Actuators
(1) Torquer(DC motor)
(2) Turntable



rotate turn table to
decide hop direction

Simulation Analysis





protoflight model used
gravity equals to zero
accelerated in 100%

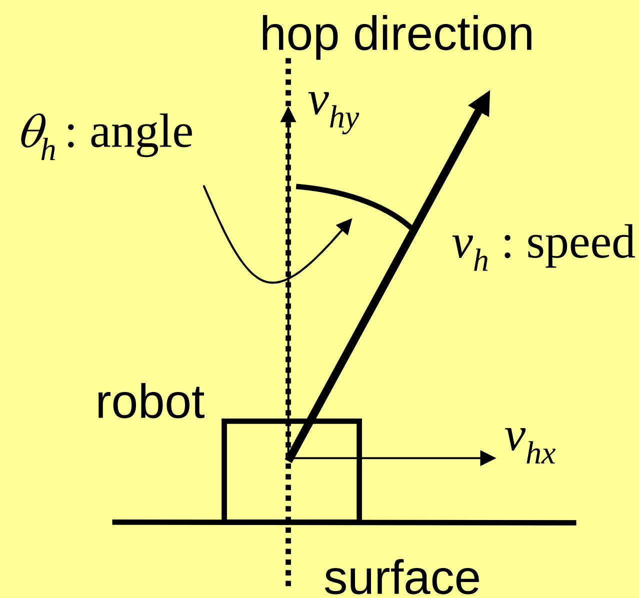
Hop speed is affected by

torque > friction coef. >> microgravity

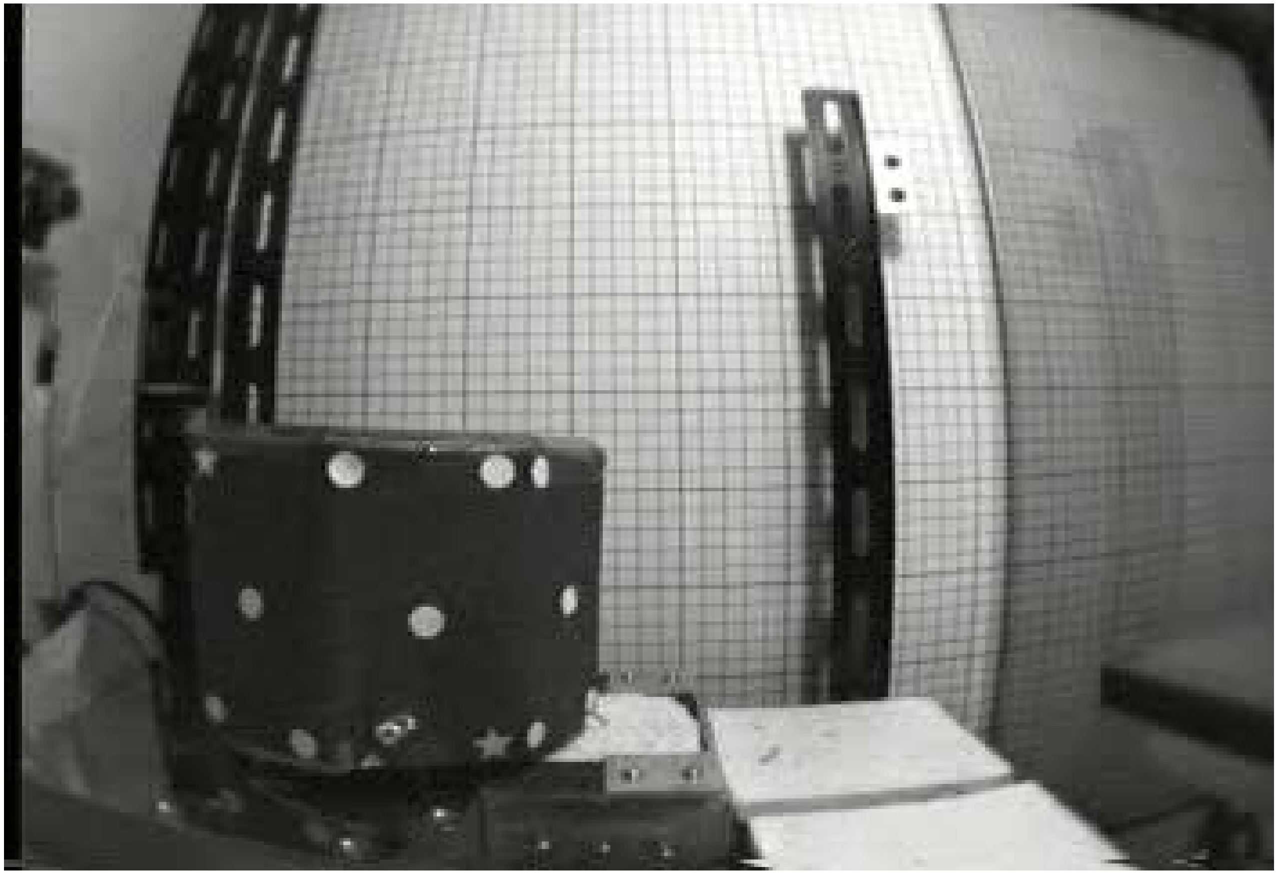
Hop angle(direction)

friction coef. >> microgravity, torque

(Orbit after hop is dominated by microgravity)



Hopping Experiments on Rocks



Micro G test by Drop Tower

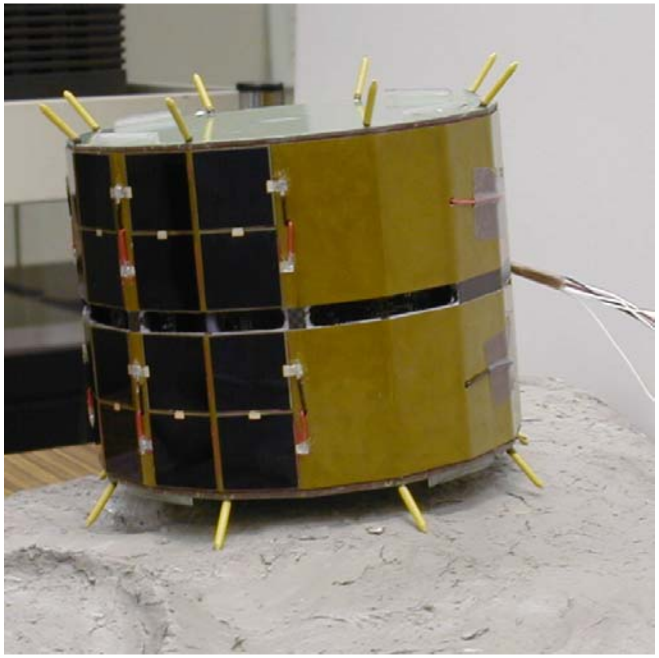
Hopping Experiments on Sand

Micro G test by Drop Tower

Asteroid Exploration Robot MINERVA

(MIcro Nano Experimetal Robot Vehicle for Asteroid)

- Asteroid Surface Explorer
- Novel Mobility
  by Hopping
- Surface Observation
  by Stereo Vision
- Temperature Measurement
- Surface Gravity Estimation
- Autonomous Behavior Functions



Flight Model of MINERVA and OME

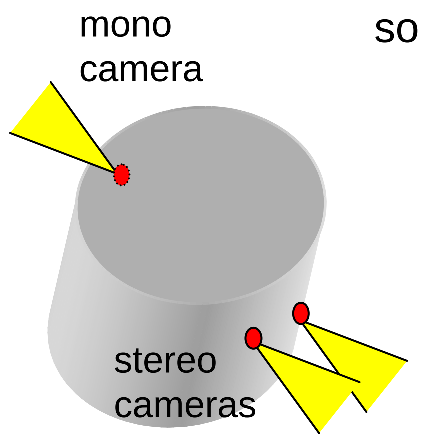
MINERVA Specification

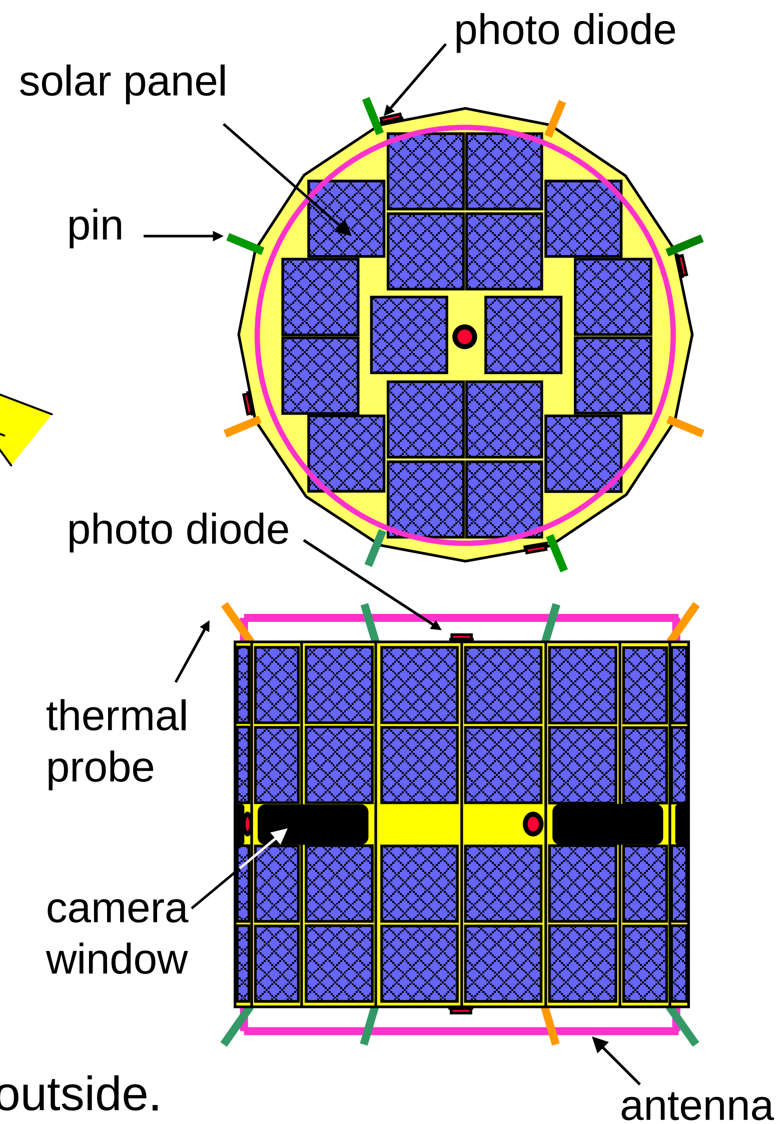
body size	Cylinder (hexadecagonal pole) Diameter: ϕ120[mm] Height: 100[mm]
weight	591[g]
actuators	two DC motors(2.6[w])
sensors	3 CCD cameras Photo Diodes Thermometers
com.	9600[bps]

Rover Onboard Sensors

(1) three CCD cameras

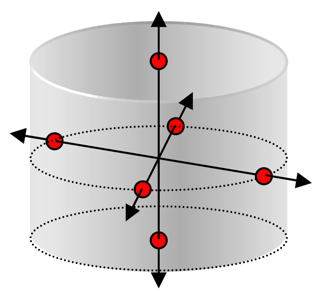
- image size: 320x240(nominal)
- image format: Y-Cr-Cb=4:2:2
- I/F: USB
- focal length
  - one of three: infinity
  - the others: short (stereo)





(2) six photo diodes (PDs)

- detect solar direction
- judge whether the rover moves or not.



PDs

(3) thermometers

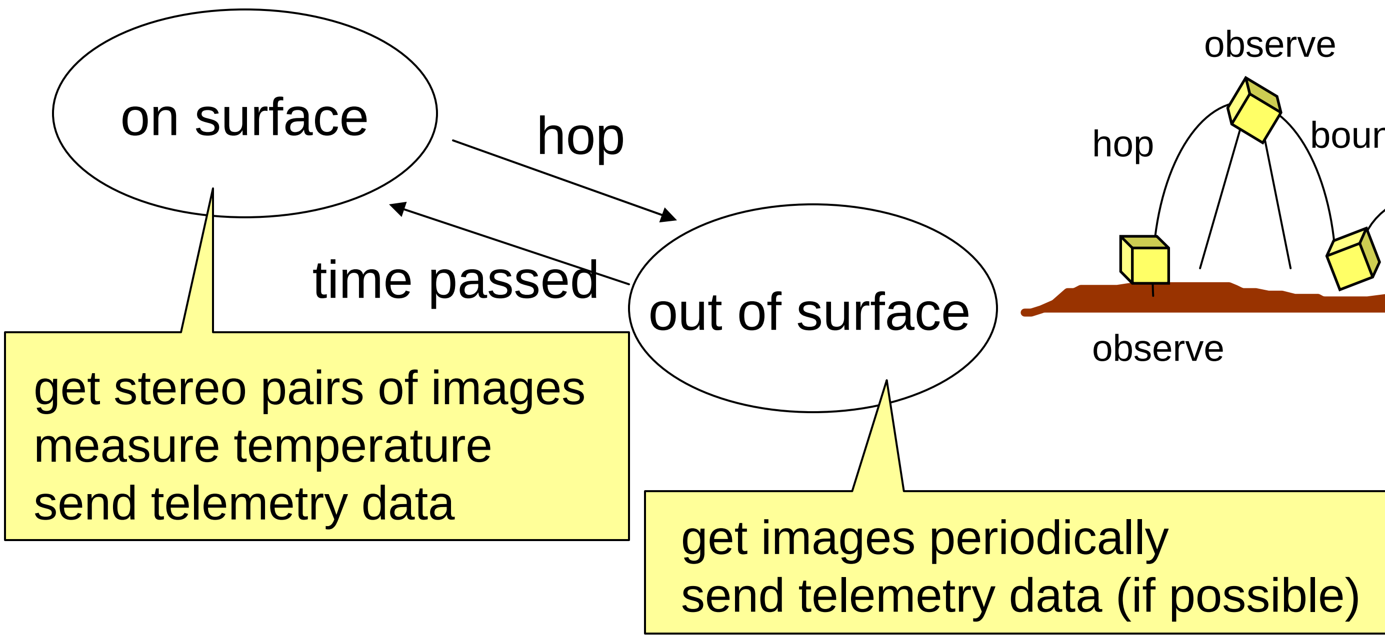
- Six thermal probes to measure the temperature outside.
- Another four thermometer are installed to monitor the temperature inside.

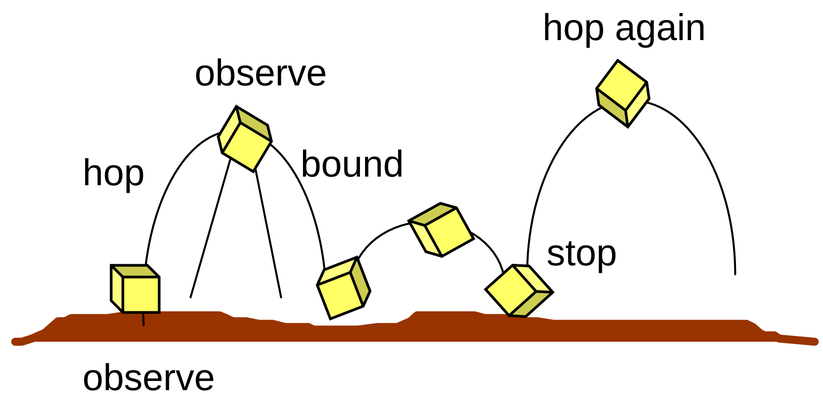
Autonomous Exploration

Navigation System

do not pursue the precise localization
do not pursue the reachablity to the specified location.
get the images/data at as many different places as possible

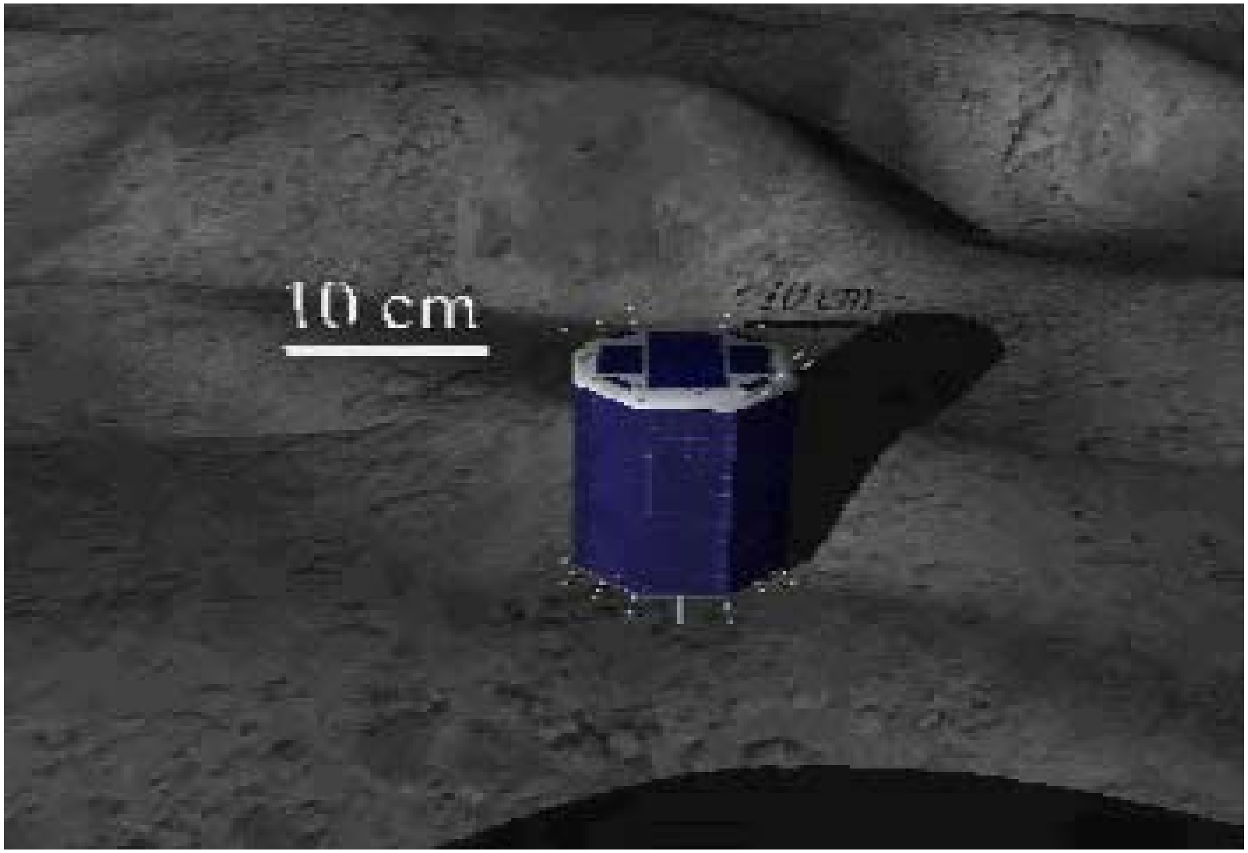
"Observe and hop" is repeated.





Hopping with 5[cm/s] in g=10[μG] will lead the rover 1000sec of travel in free space

Exploration on the Surface



Summary

- Small Body Exploration
- Outline of MUSES-C Mission
- Asteroid Exploration Rover

- Post MINERVA is under study for the next small body mission, which has localization and reachbility
- Lunar or Planetary rover is also under study in JAPAN