Ongoing Projects in the Radio Science Laboratory

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with contributions from the RSL Team

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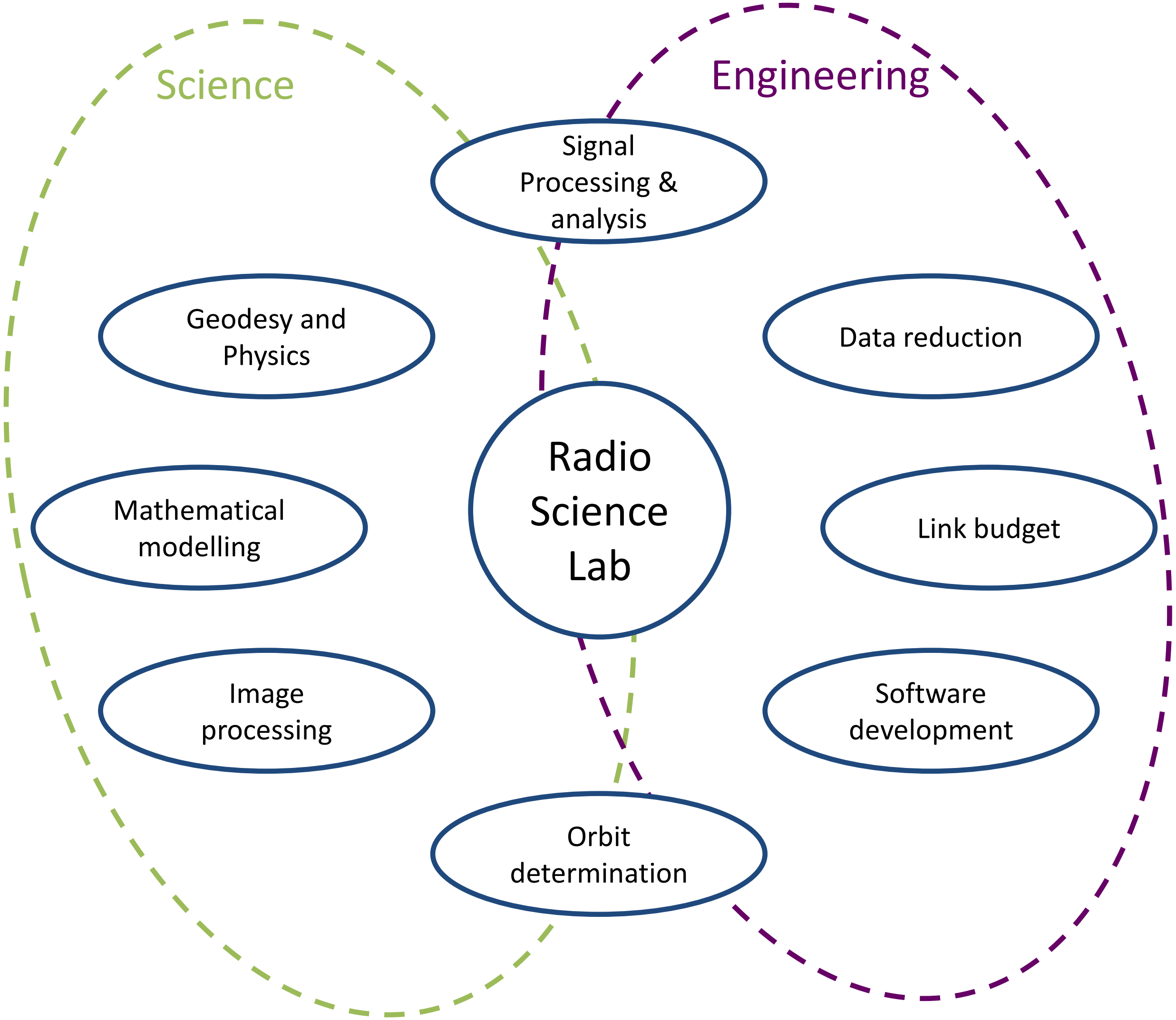
RSL activities



Funding Info

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Contracts as PI-Principal Investigator or Study Lead (2005-now)

Year	Title	Funding Agency
2005	Design and Development of a SW Correlator for Deep Space Tracking Support	ESA
2006	Attività Scientifiche fase A/B1 BepiColombo MORE	ASI
2006	Enhancement of the S/W Correlator for Deep Space Tracking Support	ESA
2007	Enhancement of the S/W Translator for Deep Space Tracking Support	ESA
2009	Cassini-Huygens Fase E2 – Attività scientifiche	ASI
2009	Radio Scienza per BepiColombo e Juno fasi B2/C/D	ASI
2010	Enhancement of the ΔDOR Software Package	ESA
2011	Interdisciplinary Study on Enhancement of End-to-End Accuracy for Spacecraft Tracking Techniques	ESA (GSP Programme)
2013	Studio degli strumenti scientifici per la missione JUICE – 3GM	ASI
2013	Improving Data Return in Ka-Band by Use of Weather Forecast	ESA
2014	Improvement of Delta-DOR Performances for 1 nrad Accuracy for Precise Landing Support	ESA
2015	Radio Scienza per BepiColombo e Juno fasi B2/C/D - Addendum	ASI
2016	Partecipazione italiana alla fase A della missione VERITAS	ASI

Funding Info

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As Group Lead of a subcontractor unit (after 2007)

Year	Study/Contract	Agency	Prime Contractor
2008	Radiocomm Signals: a "New Way" of Probing the Surf of Planets	ESA	GMV
2009	Radio Tracking of a Landed Spacecraft: Determination of the Spacecraft Position and the Ephemeris and Orientation in Space"	ESA	GMV
2014	HERO: High performance time and frequency link: microwave	ESA	WISER
2014	End-to-End Mission Performance Simulators for Space Science Missions	ESA	GMV
2015	Flexible and Autonomous TT&C Transponders for Multi-Mission Applications	ESA	Thales Alenia Space Italy
2015	CUBATA for Asteroid Impact Mission Cubesat Opportunity Payloads (COPINS)	ESA	GMV

Ongoing Research Projects

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- RSL participation and activities in deep space missions:
  - Cassini
  - BepiColombo
  - Juno
  - JUICE
  - VERITAS (phase A – preselected by NASA)
  - CUBATA (S2S tracking cubesats for ESA's AIM mission)
  - Europa Deep Geophysics Explorer (concept for NASA Europa mission)
  - …

- Tracking systems
  - Error budget analysis
  - New tracking systems architectural design
  - ESA Delta-DOR software development
  - Same Beam Interferometry
  - RadioMetOp (closed – collaboration with DIET)
  - Precise time and frequency transfer

Radio Science – Planetary Geodesy

Sapienza Università di Roma

Radio science investigations have been historically diverse and include:

- determination of planetary masses and mass distribution;
- tests of relativistic gravity;
- determination of planetary and satellites rotational state;
- measurements of planetary atmospheres, ionospheres and rings;
- estimation of planetary shapes;
- investigation of the solar wind.

In our lab we focus here (first three items)

Radio science experiments, depending on the phenomena being investigated, involve measurements of the amplitude, phase and polarization (over a large variety of time scales) of the EM wave used in the space-to-ground radio link.

In deep space communications and radio science experiments, signals use well defined frequency bands in the microwave region of the electromagnetic spectrum

Band	Uplink Frequency (MHz)	Downlink Frequency (MHz)
S	2110-2120	2290-2300
X	7145-7190	8400-8450
Ka	34200-34700	31800-32300

MISSIONS

Testing General Relativity

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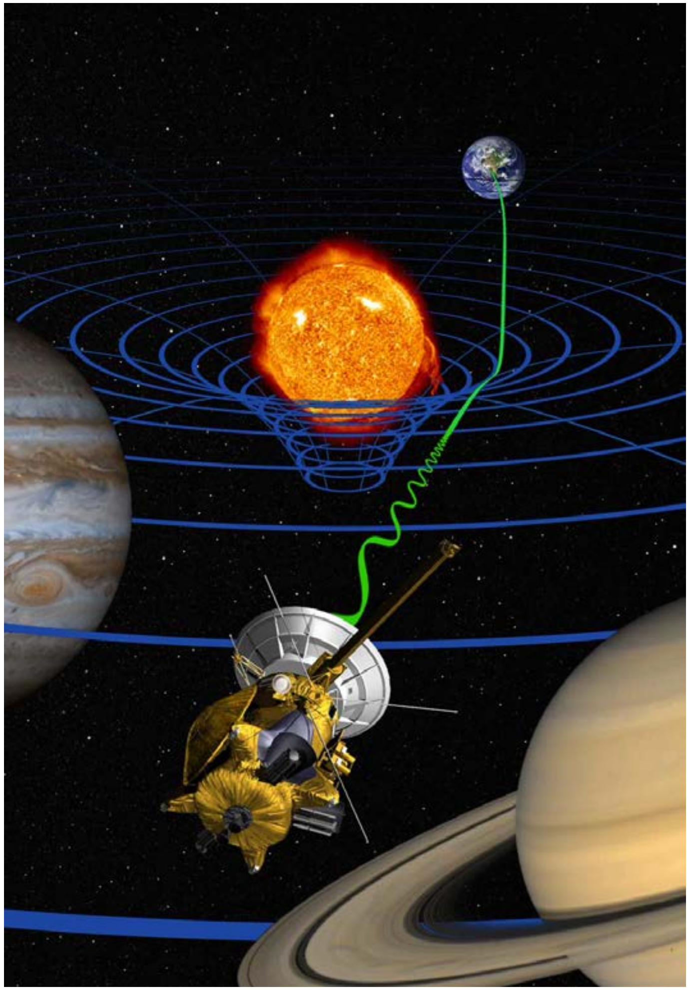


Bertotti, B., Iess, L., Tortora, P., 'A test of general relativity using radio links with the Cassini spacecraft' *Nature*, 425, 374, (2003)

- Deflection of light rays, time delay and frequency shift are different manifestation of the solar gravitational potential. In the PPN formalism these effects are controlled by the parameter γ

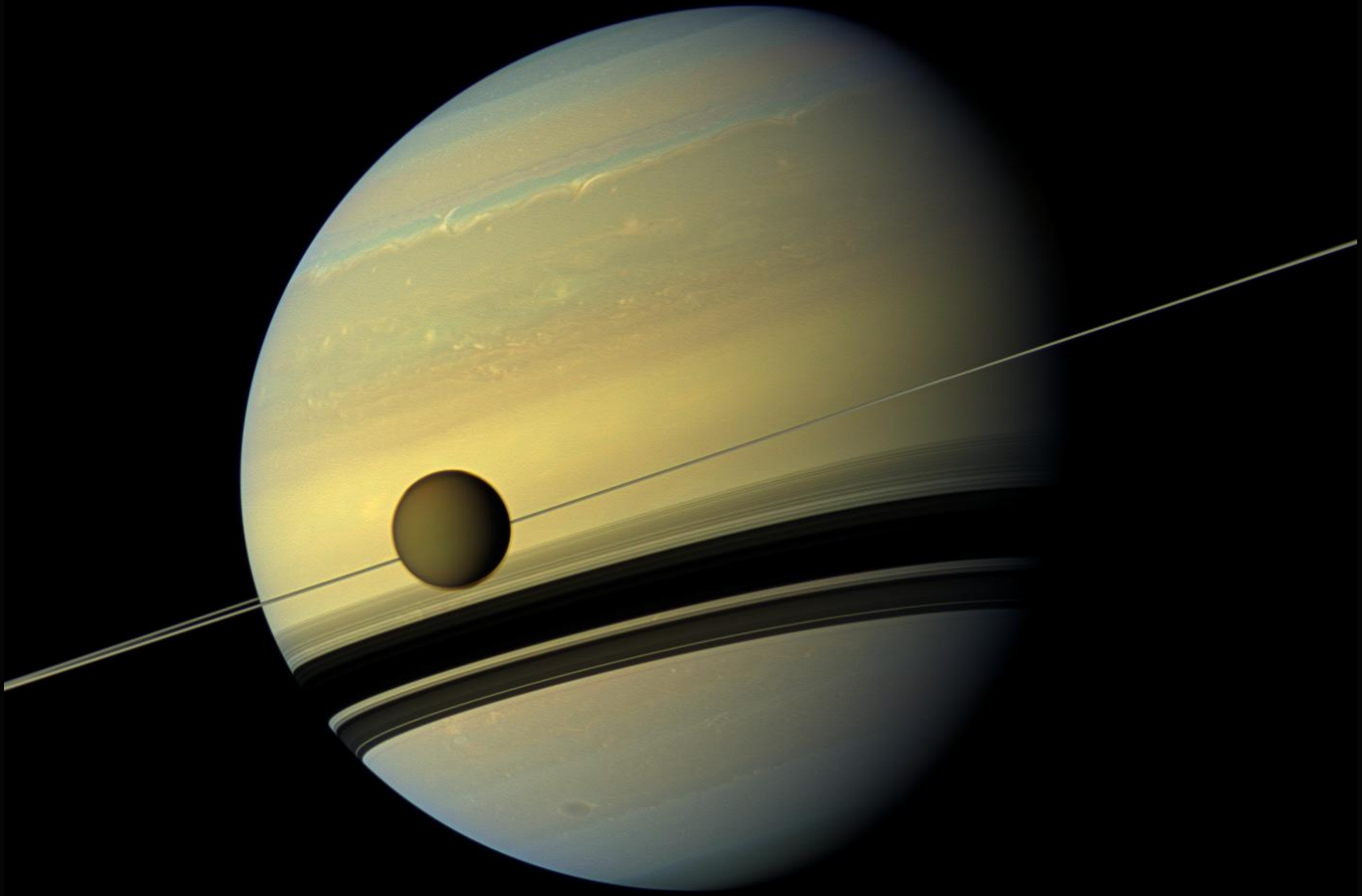
- Cassini Solar Conjunction Experiment (SCE1) allowed for range-rate residuals accurate to 1.1 µm/s @ 1000 s integration time
  - Multi-frequency link to obtain plasma-free observables
  - Calibration of wet troposphere by Advanced Water vapour radiometers

- x 50 improvement in the estimation of γ

$$\gamma_{Cassini} = 1 + (2.1 \pm 2.3) \square 10^{-5} \quad (2003)$$

$$\square_{Viking} = 1.000 \pm 0.001 \quad (1979)$$

Cassini at Saturn

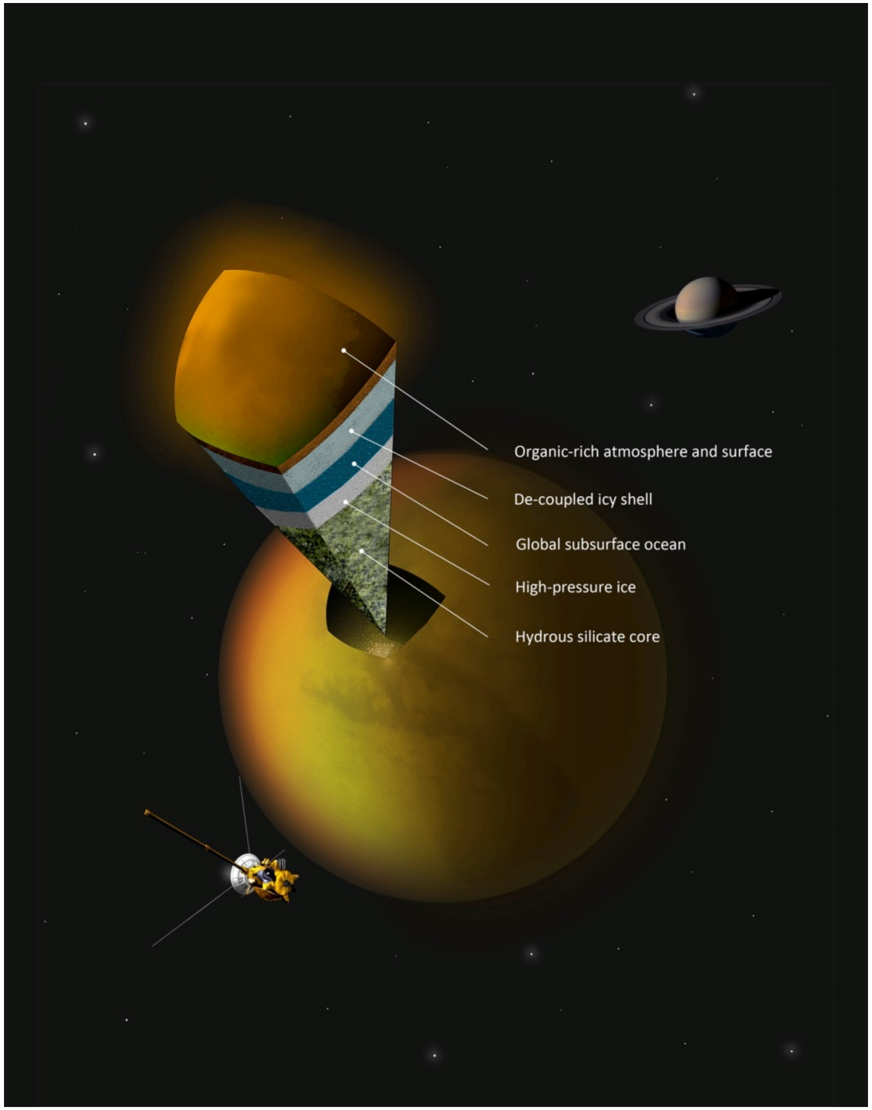


The Geysers, Lakes and Oceans
of the Saturnian Moons

Titan Geodesy

Determination of the gravity field and its tidal variations provide crucial information to describe:

- Shape (reference ellipsoid)
- Internal structure (Geoid heights, Moment of inertia and Love number)

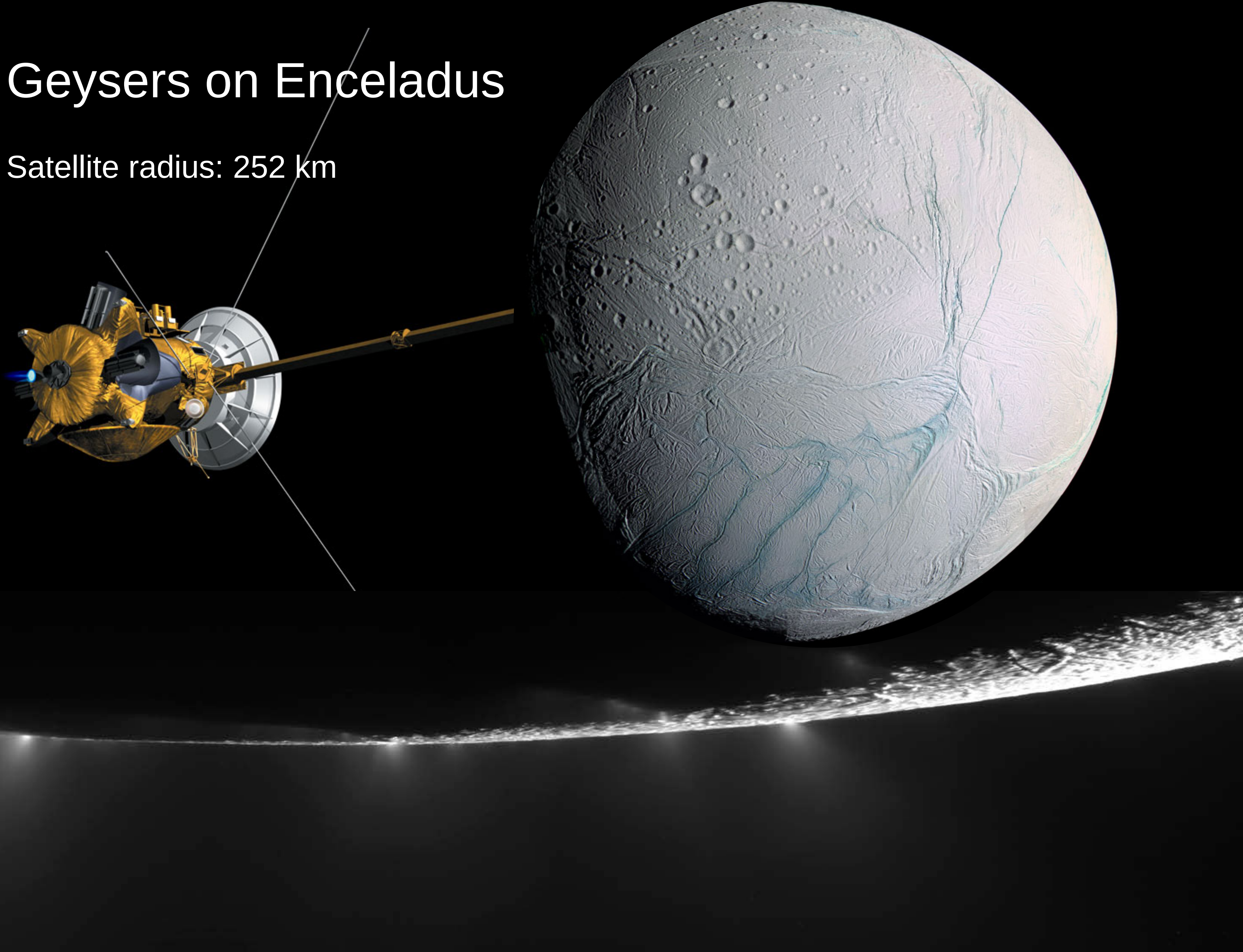


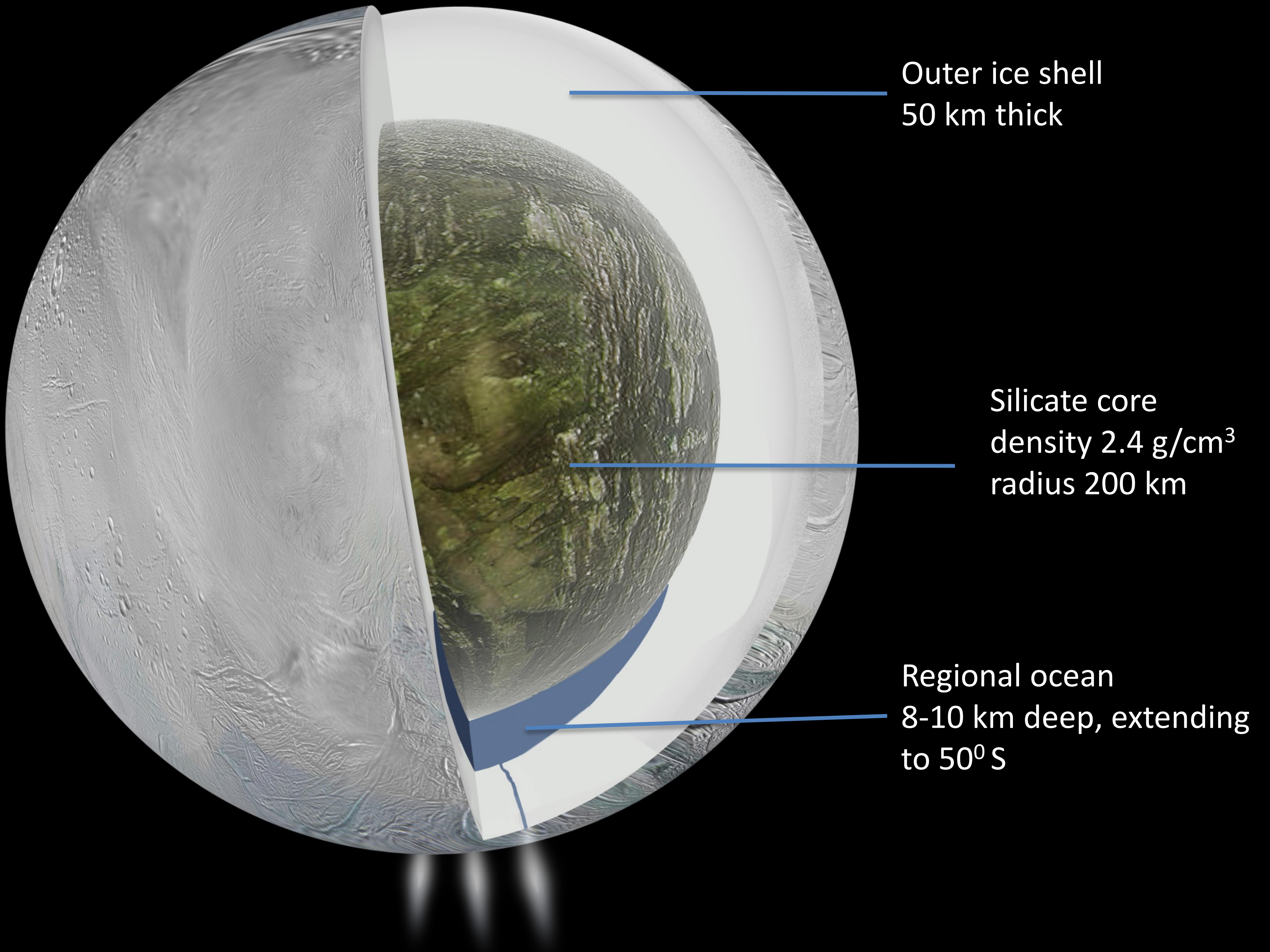
Publications:

- Iess, L., Jacobson, R.A., Ducci, M., Stevenson, D.J., Lunine, J.I., Armstrong, J.W., Asmar, S.W., Racioppa, P., Rappaport, N.J., and Tortora, P., “The Tides of Titan”, Science, 337, 457, 2012
- Iess, L., Rappaport, N.J., Jacobson, R.A., Racioppa, P., Stevenson, D.J., Tortora, P., Armstrong, J.W., Asmar, S.W., “Gravity Field, Shape, and Moment of Inertia of Titan”, Science, 327, no. 5971, 1367 – 1369, March 2010

Geysers on Enceladus

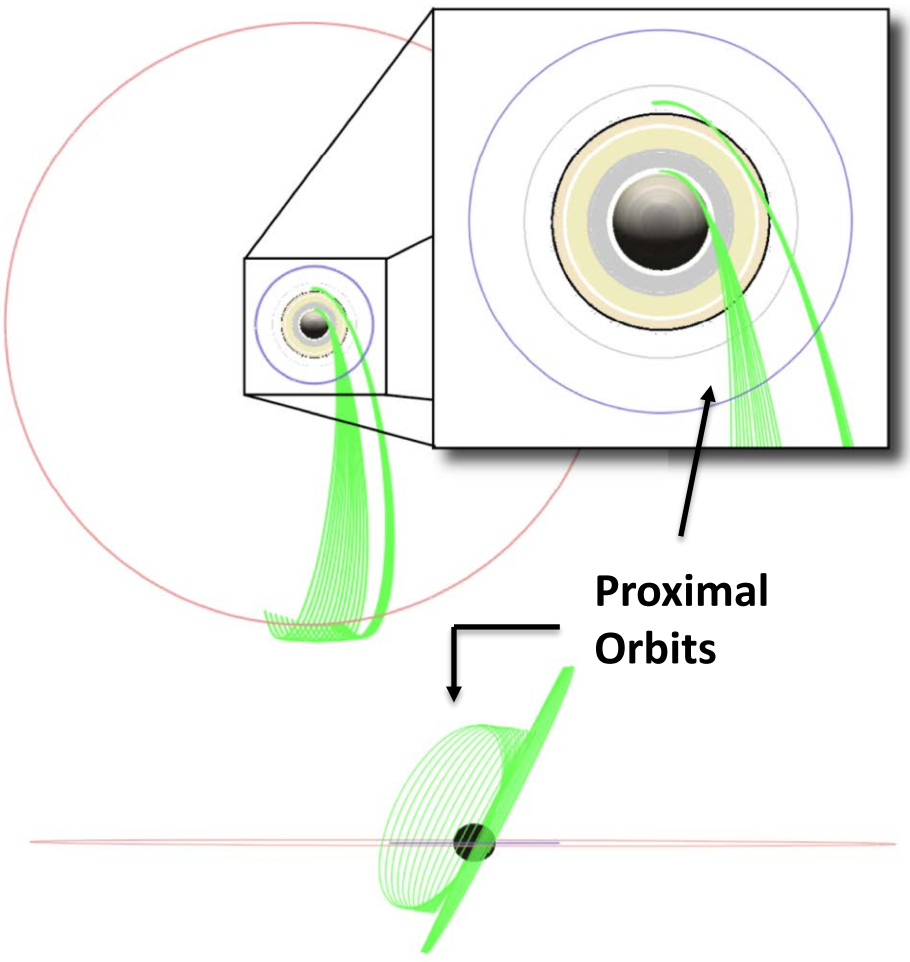
Satellite radius: 252 km




Outer ice shell
50 km thick
Silicate core
density 2.4 g/cm^3
radius 200 km
Regional ocean
8-10 km deep, extending
to 50^0 S

Saturn Gravity

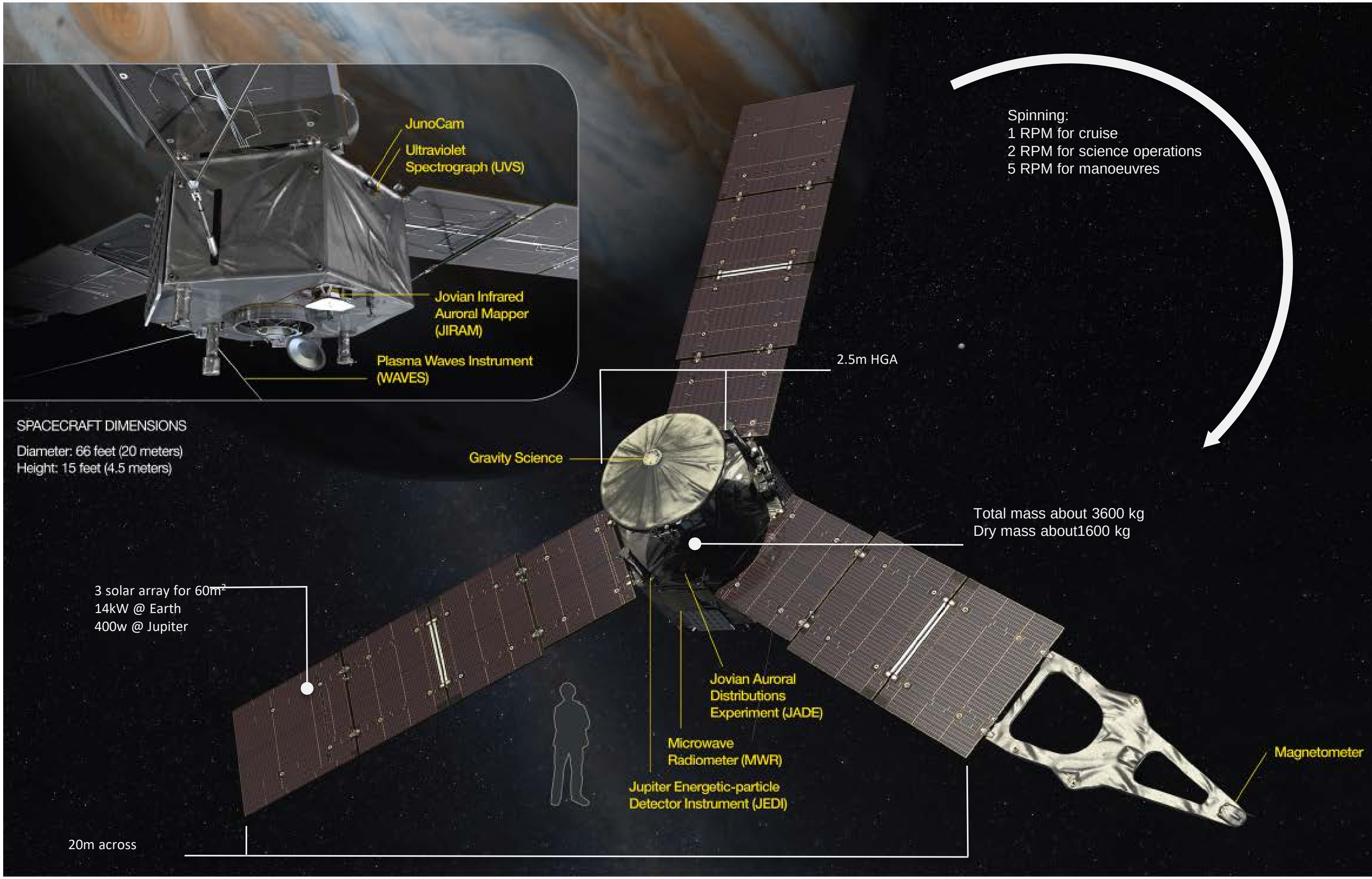
The best configuration to probe the Saturn gravity field is during the **PROXIMAL ORBITS** phase during which the spacecraft will pass between the planet and the rings.



Proximal orbits:

- 22 highly elliptical orbits
- Eccentricity ~ 0.9
- Inclination ~ 62° (on Saturn equator)
- C/A latitude ~ -5.5° to -7.5°
- Altitude : 4000 km – 2000 km
- Sun-Earth-Probe angle 90° to 130° (important for Doppler noise)

Juno



JunoCam
Ultraviolet Spectrograph (UVS)
Jovian Infrared Auroral Mapper (JIRAM)
Plasma Waves Instrument (WAVES)
SPACECRAFT DIMENSIONS
Diameter: 66 feet (20 meters)
Height: 15 feet (4.5 meters)
Gravity Science
2.5m HGA
Spinning:
1 RPM for cruise
2 RPM for science operations
5 RPM for manoeuvres
Total mass about 3600 kg
Dry mass about1600 kg
3 solar array for 60m²
14kW @ Earth
400w @ Jupiter
Jovian Auroral Distributions Experiment (JADE)
Microwave Radiometer (MWR)
Jupiter Energetic-particle Detector Instrument (JEDI)
Magnetometer
20m across

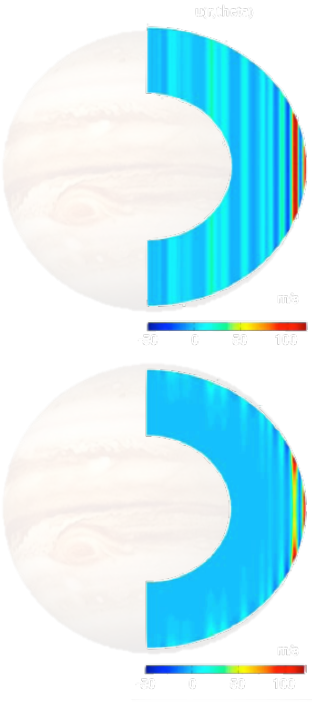
Juno Science Goal

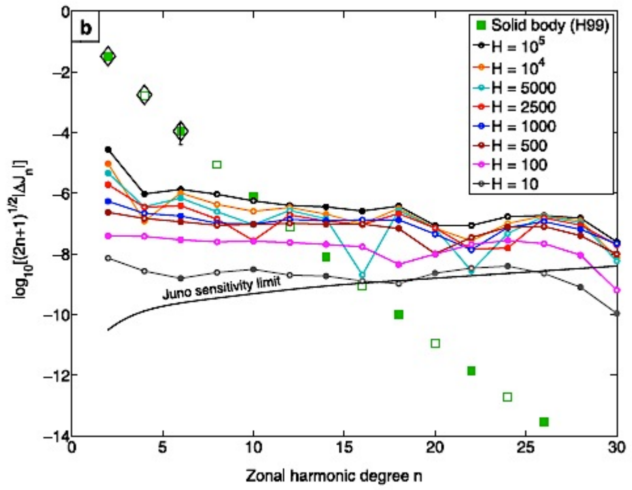
Explore the interior structure by mapping the gravity field

- What is the structure inside Jupiter?
- Does Jupiter rotate as a solid body, or is the rotating interior made up of concentric cylinders?
- Is there a solid core, and if so, how large is it?

Solid body rotation

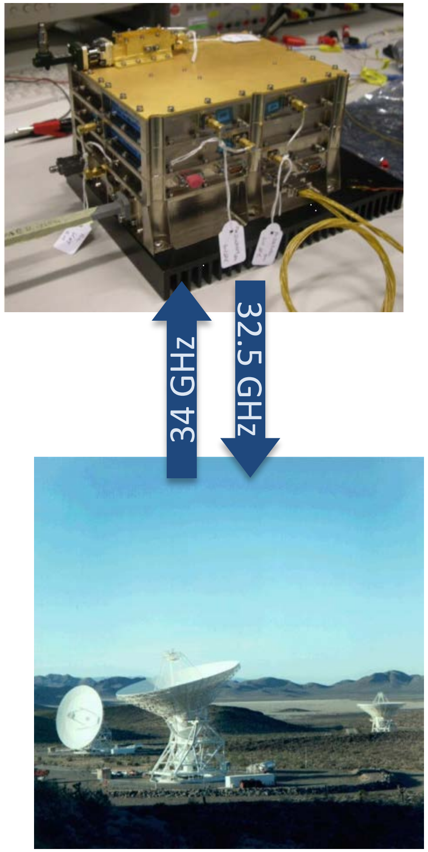
Deep Zonal winds

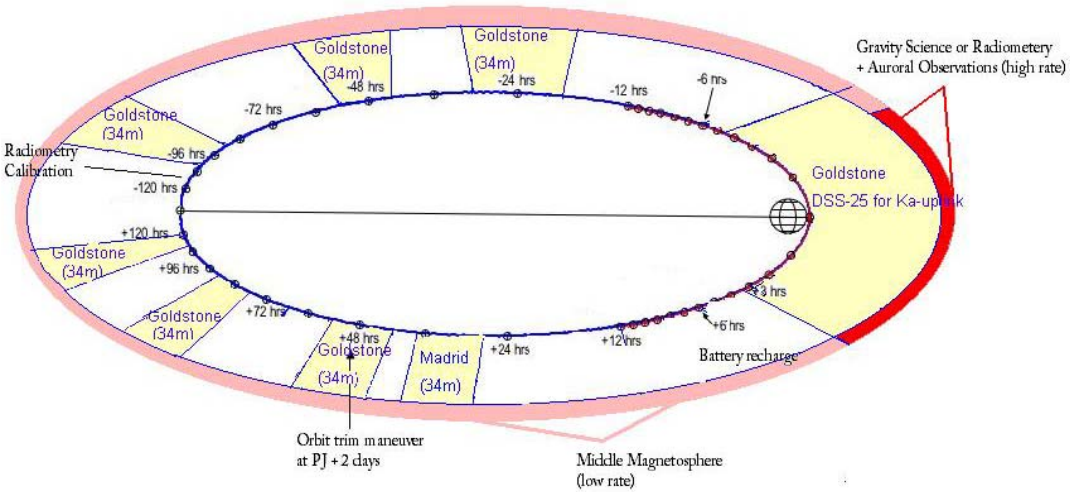




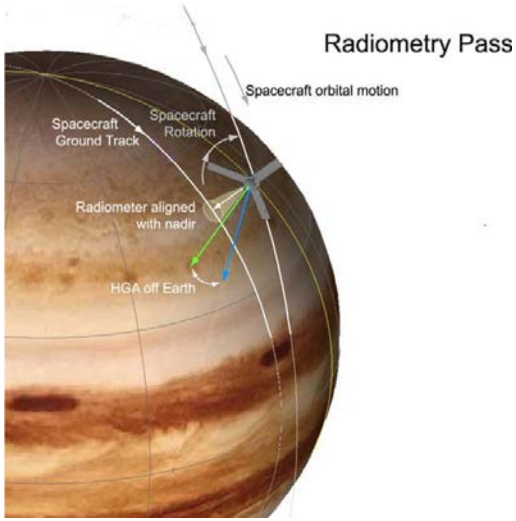
Juno tracking system

Instrument	KaTS
Manufacturer	Thales Alenia Space - Italia
Allan Deviation	4×10^{-16} @ 1000s
Observables	2-way Doppler
Link	Ka/Ka (34Ghz up / 32.5 GHz down)
Tracking Station	DSS25 34m BWG – Goldstone DSN
Tracking Schedule	C/A +/- 3h
Pass	25 out of 32
Allan Deviation	$< 10^{-14}$ @ 1000s end to end





Juno science orbit



Polar orbit

satisfies science objectives and provides lower radiation environment, continuous solar power, and minimal operational requirements

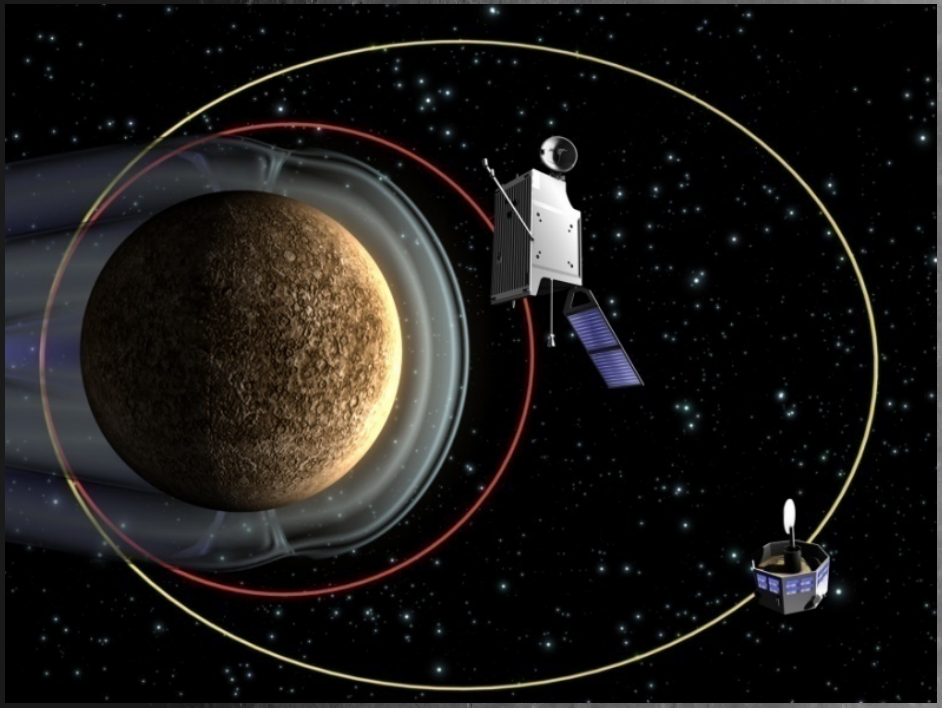
- 33 orbits
- C/A about 5000 km
- High eccentricity (e=0.947)
- Period 11 days
- Orbit is face-on

Pericentre drift ~ 0.93° per orbit

the apsidal rotation causes the radiation dose to increase significantly as the mission evolves

$$\dot{\omega} = \frac{3nR^2 J_2}{4p^2}\{4 - 5sin^2(i)\}$$

MMO & MPO on dedicated orbits



- ✓ MMO orbit optimized for study of magnetosphere
- ✓ MPO orbit optimized for study of planet itself

- ➢ High-accuracy measurements of interior structure
- ➢ Full coverage of planet surface at high resolution
- ➢ Optimal coverage of polar area
- ➢ Resolve ambiguities
  - exosphere
  - magnetosphere
  - magnetic field

MPO (ESA)

Polar orbit

Pericenter altitude = 400 km

Apocenter altitude = 1500 km

Orbital period = 2.3 h

MMO (JAXA)

Orbita polare

Pericenter altitude = 400 km

Apocenter altitude = 12000 km

Orbital period = 9.2 h

MORE

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The **Mercury Orbiter Radio-science Experiment (MORE):**

- addresses scientific goals in geodesy, geophysics and fundamental physics.
- provides crucial experimental constrains to models of the planet's internal structure and test theories of gravity with unprecedented accuracy
- Assesses the performances of the novel tracking system in precise orbit determination and space navigation

Gravity:

- Gravity field coefficients (SNR $\cong 10^4 \div 10$)
- Geoid surface (10 cm)
- Love number k_2 (SNR $\cong$ 50)

Orbit:

- Spacecraft position (10 cm – 1 m Mercury-centric; < 10 m Solar System Barycentric)
- Planetary figure (1 part in 10^7)

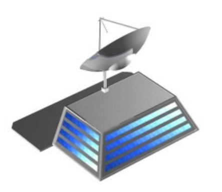
Rotation:

- Mercury's obliquity (< 1 arcsec)
- Amplitude of librations in longitude (< 2 arcsec)

Relativity:

- Post-Newtonian parameters γ, β and η
- J_2 of the Sun ($2 \cdot 10^{-9}$)
- Time variation of G ($2 \cdot 10^{-13}$ years^{-1})

Configuration of the onboard radio system

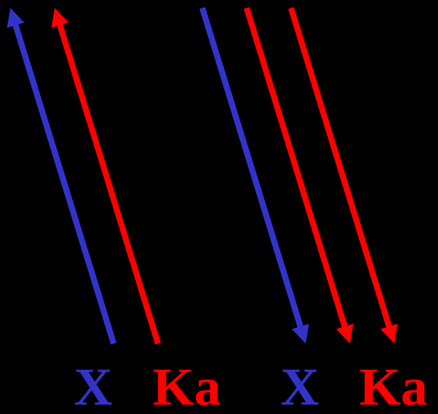


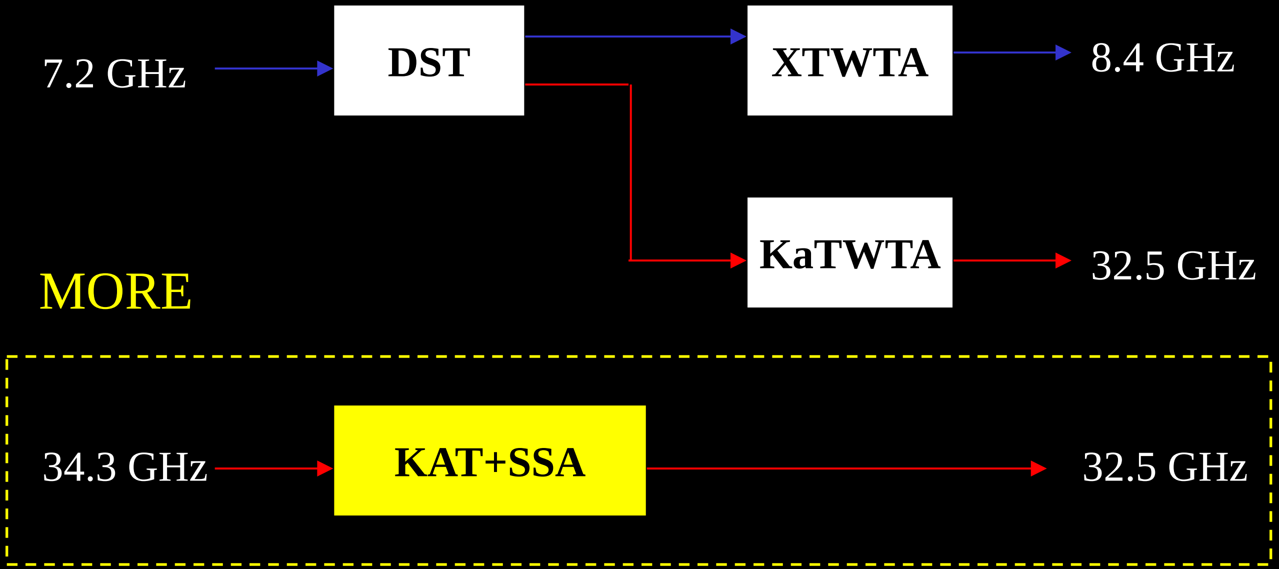
Multi-frequency radio link (two-way)

Target accuracy:

$\Delta f/f = 10^{-14}$ at 10^3-10^4s
$\Delta \rho$ = 10 cm

$\sigma_y = 10^{-14}$ is equivalent to a one-way range rate of 1.5 micron/s
The corresponding one-way displacement in 1000 s is 1.5 mm





3GM

GRAVITY AND GEOPHYSICS OF JUPITER AND THE GALILEAN MOONS

Principle Investigator:
Luciano Iess – Sapienza University of Rome

Co-Principle Investigators:
David J. Stevenson – Caltech - USA
Yohai Kaspi – Weizmann Institute - Israel

Lead Funding Agency:
Agenzia Spaziale Italiana

Juice: Overview

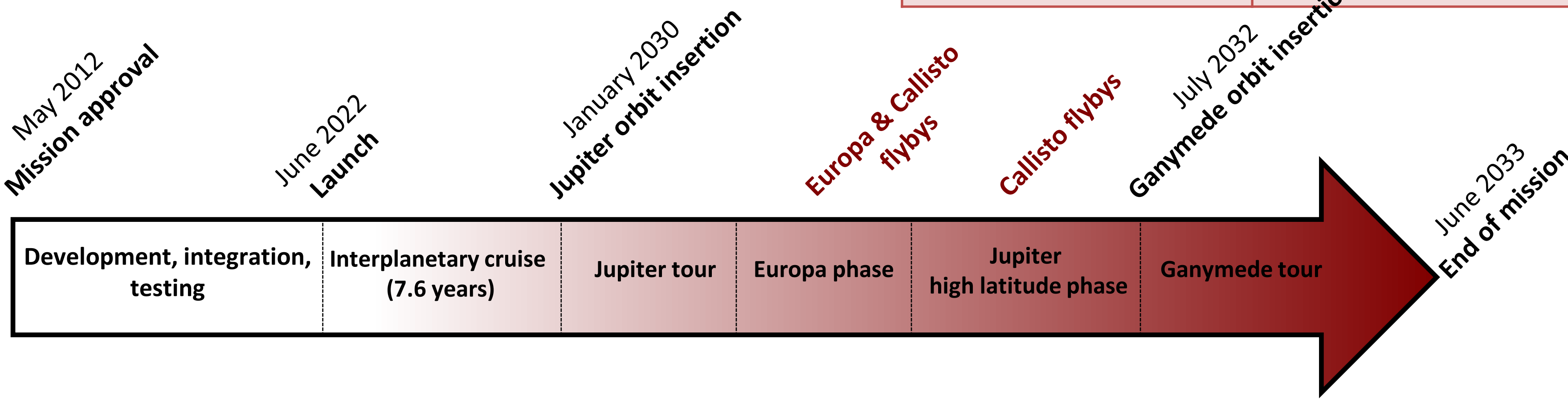
JUICE: Jupiter Icy Moons Explorer

The emergence of habitable worlds around gas giants

Its main objective is the study of the Galilean moons
ESA L-mission currently in phase A/B1

European Space Agency

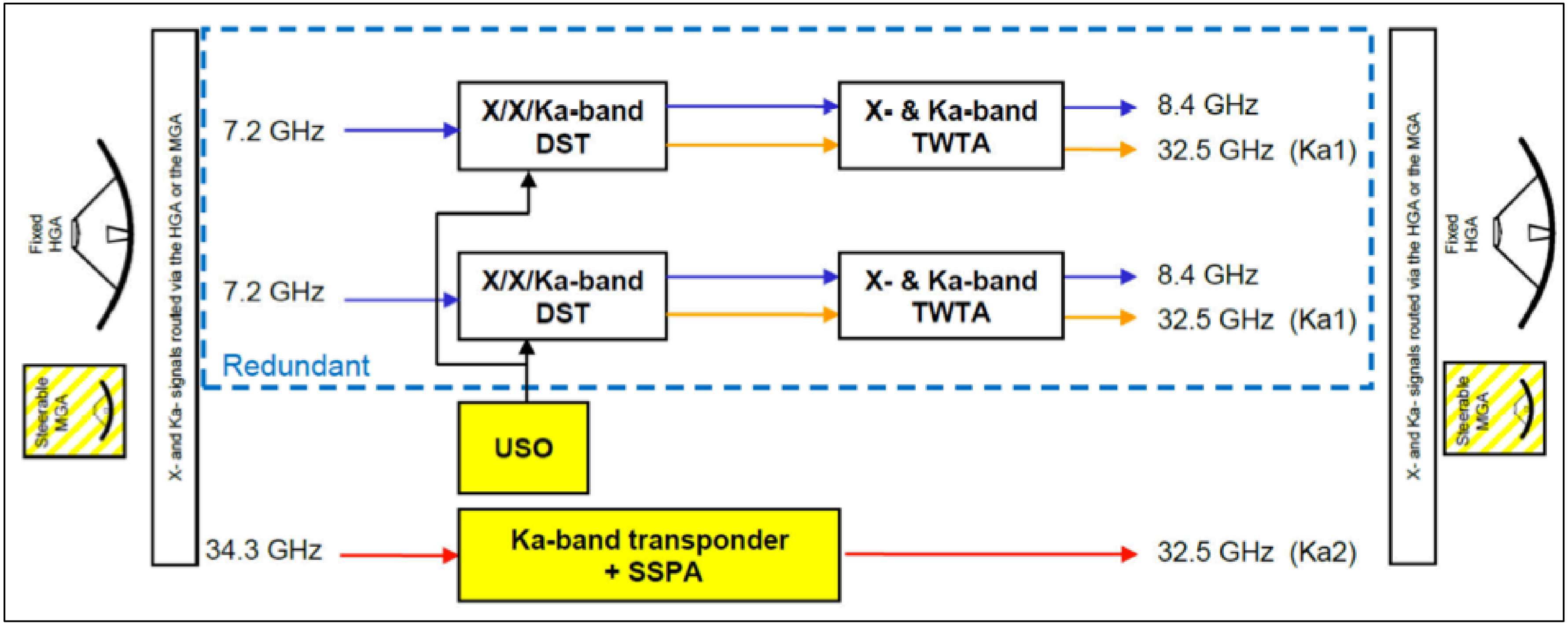
Instruments	
Narrow Angle Camera	Ice penetrating radar
Wide Angle Camera	Submillimeter Wave Instrument
Visible and Infrared Hyperspectral	Magnetometer
Imaging Spectrometer	Particle Package
Ultraviolet Imaging Spectrometer	Radio and Plasma Wave instrument
Laser Altimeter	Radio Science Instrument and Ultrastable Oscillator
Ice penetrating radar	



3GM: The radio science experiment

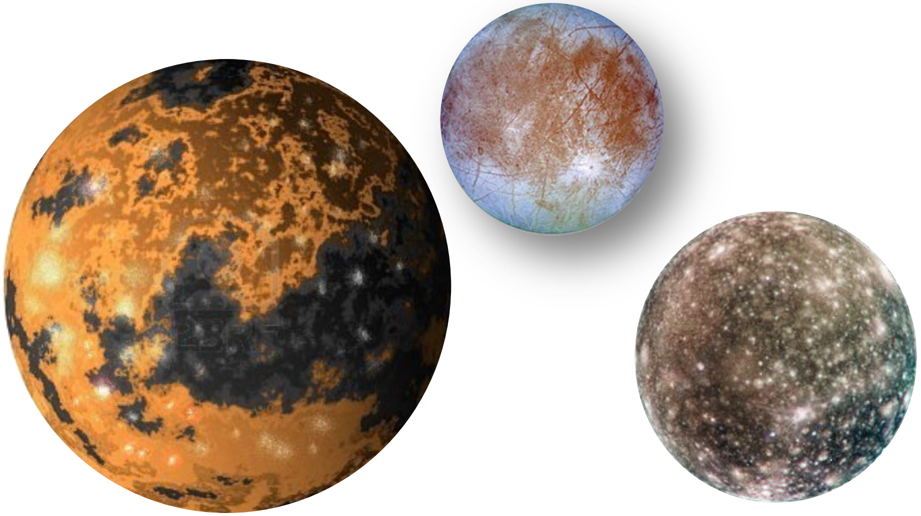
3GM experiment consists in:

- **Gravity science (range and range-rate observables)**
- **Radio occultations**

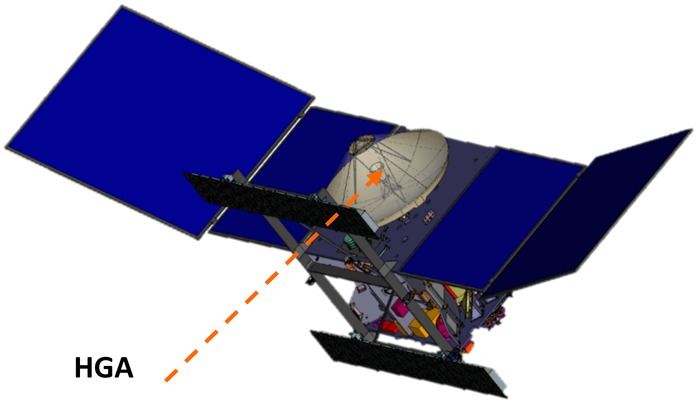


JUICE gravity science objectives

- Determination of the radial density distribution (low-degree gravity field + moment of inertia factor)
- Detection of density anomalies (high-degree gravity field)
- Detection of water sub-surface oceans and water diapirs (k_2)
- Determination of differentiation level
- Orbit reconstruction



VERITAS Gravity Instrument Quad Chart



- Two wavelength radio links (X- and Ka-bands)
- Utilize HGA and telecom subsystem

Performance Capabilities	Value	Margin
Doppler Data Quality	$5x10^{-15}$	20% Depends on calibration data
Accommodation Needs	**Value**	**Margin**
Power (W)	16/22(*)	20%
Mass (kg)	3.9	20%
Data Rate (Mbits/s)	N/A	N/A
Data Storage (MB)	N/A	N/A

(*) Depending on number of active radio links

Gravity Instrument Heritage

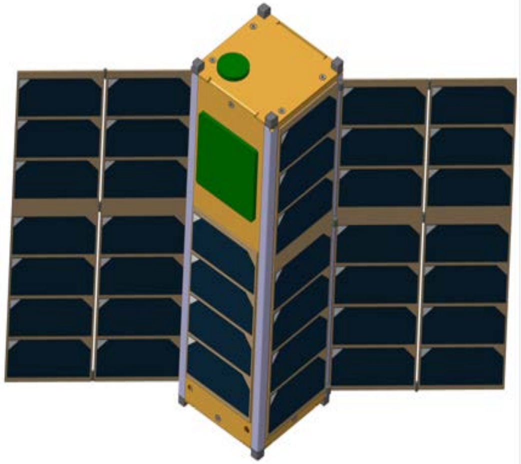
- X-band is a proven and redundant spacecraft communication system
- Ka-band has been developed and tested for the ESA mission BepiColombo to Mercury

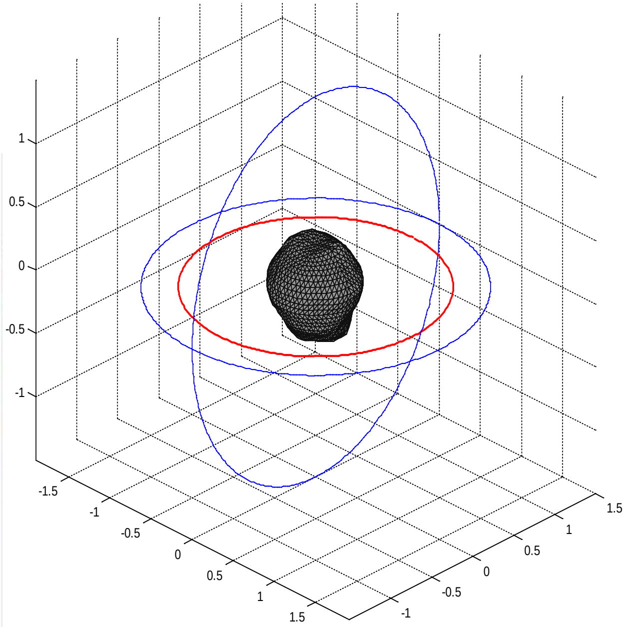
Gravity Instrument Risks

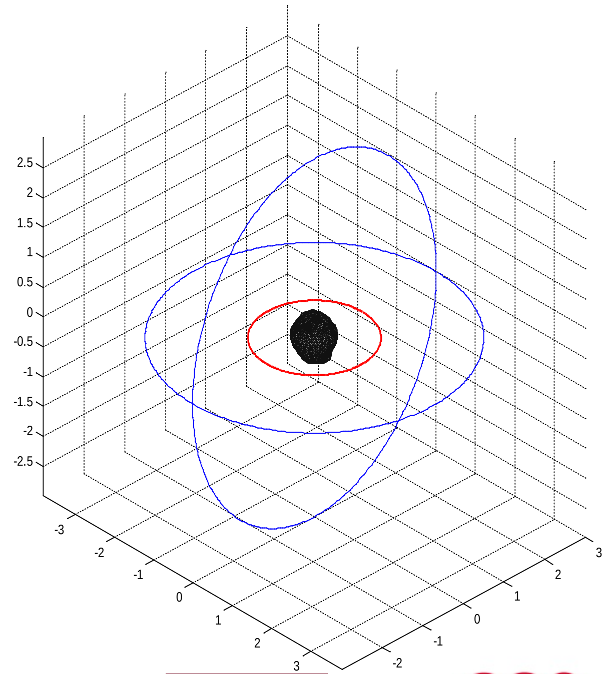
Risk Item	Mitigation
Viewing and Tracking Duration	Coverage of planet limited by times HGA is pointed to Earth; study shows very significant improvement in the minimum global resolution from 540 km to 125 km for known gravity field obtained with the baseline coverage plan; improvement from n=35 to n=150.
DSN Ka-band uplink stations	Design mission to optimize coverage over Goldstone where Ka-band uplink transmitter is available

MISSION ARCHITECTURE

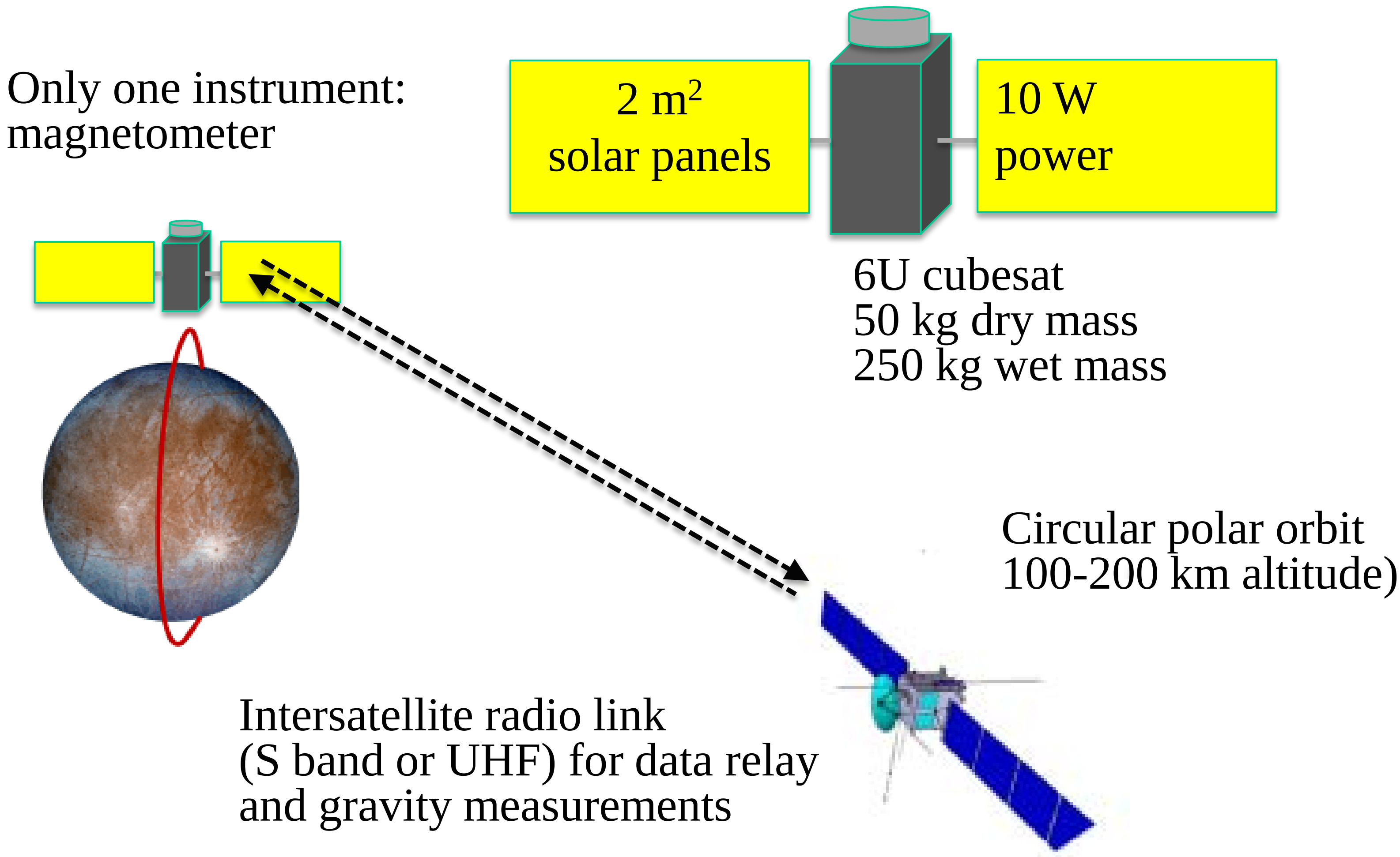
- The mission is composed of two CubeSats to be released by AIM
- The CubeSats will orbit the main body with orbital radius in the range 1.5 – 3 km (left and right figures below). Orbits shall be stable for 7 days TBC
- Orbital periods 17-48 hours
- Measurement acquisition 12hr shifts
- Transfer to dedicated orbit prior to impact
- Transfer back to observation orbit for post impact







Europa Tomography Probe (ET or ETP) or Europa Deep Geophysics Explorer (EDGE)



TRACKING SYSTEMS

Advanced tracking systems

RSL has been the main contractor of a study funded by ESA for the enhancements of the agency's tracking systems

consolidation of the error budget in radio-metric and OD systems by means of a re-analysis of existing data

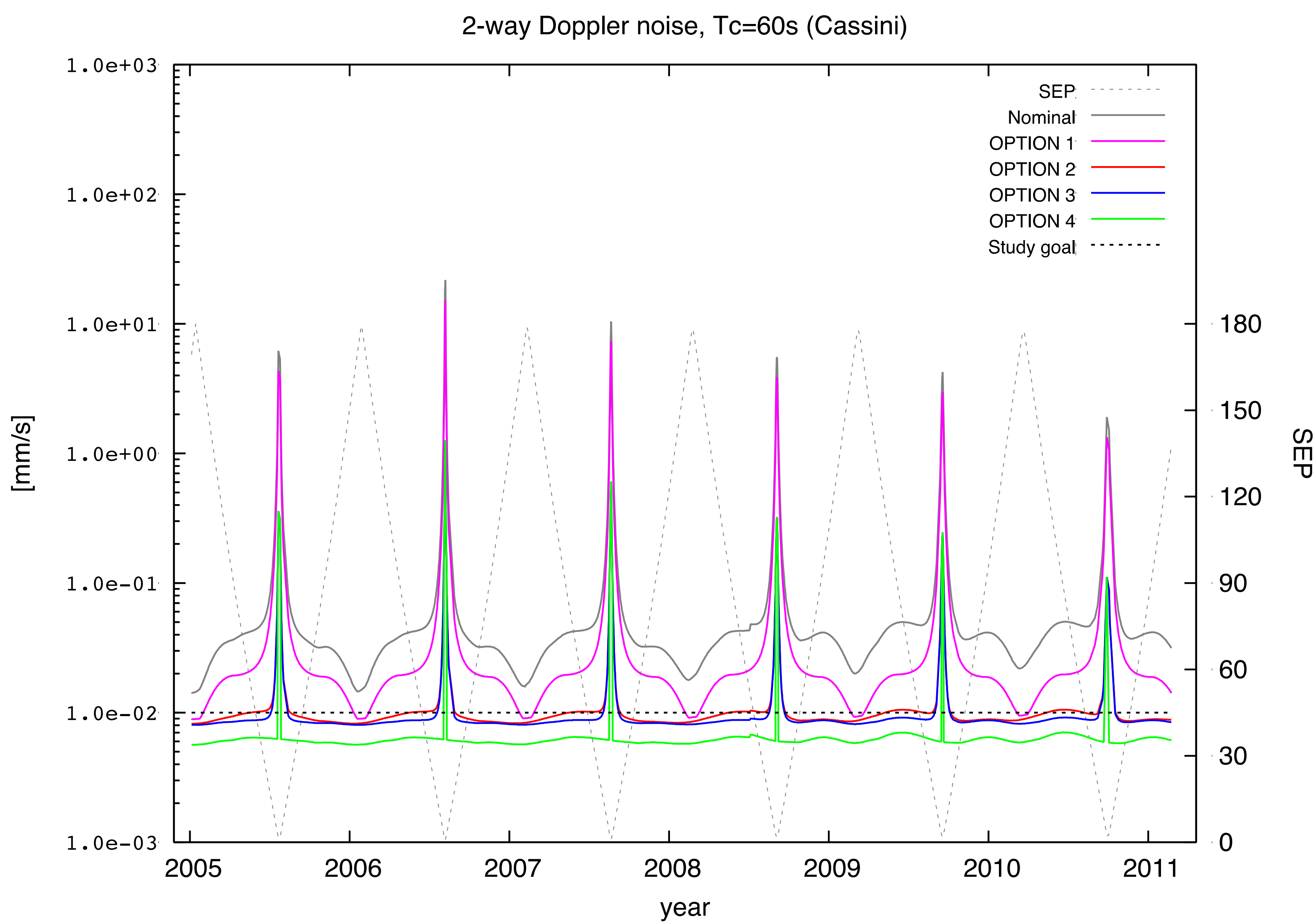
→

FINAL GOAL:

identification of the driving noise sources and outline of solutions (at architectural level) to improve current accuracies by one order of magnitude

Observable	Present accuracy (X-band)		Target accuracy
Range-rate (two-way)	0.05 to 0.1 mm/s	60 s integration time	0.01 mm/s
Range	1 to 5 m	jitter+bias	0.1 m
DDOR	6 to 15 nrad	For a spacecraft with DOR tones and NNO-CEB baseline (11650 km)	1 nrad

Doppler attainable accuracies - Cassini



European Delta-DOR system: S/W correlator

History, missions supported and results

DIPARTIMENTO DI INGEGNERIA
MECCANICA E AEROSPAZIALE

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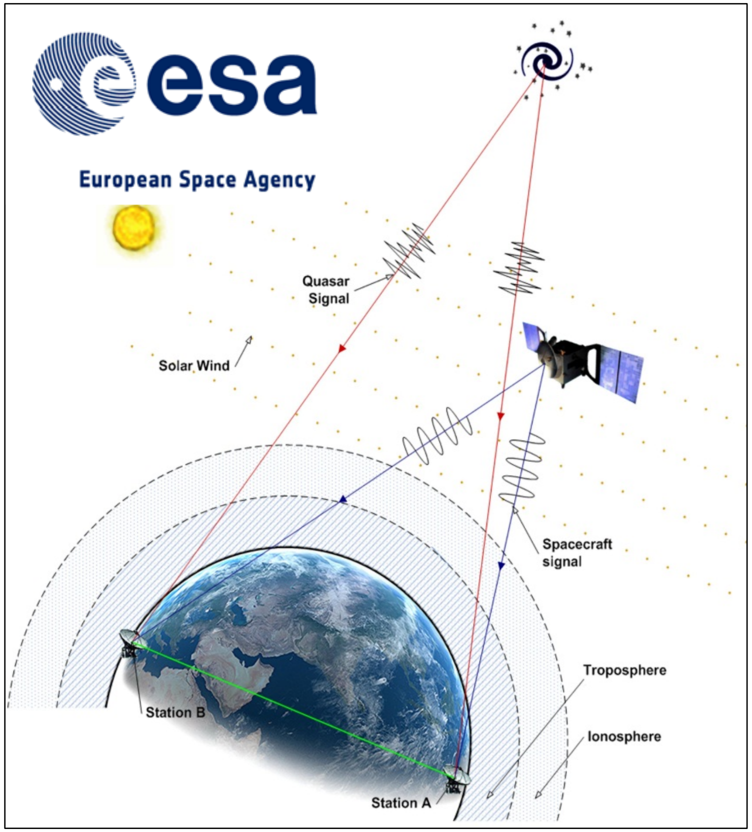
arpsoft

esa
European Space Agency

DDOR system: measurement principle



DDOR stands for **Delta-Differential One Way Ranging**

DOR is the measure of the differential phase delay of a spacecraft (S/C) signal, recorded simultaneously at two geographically separated ground stations.

The signal arrival time between two stations.

$$\tau = \frac{1}{c} B \cdot \hat{s} = \frac{1}{c} B \cos \vartheta$$

The measurement is affected by errors that prevent its use for navigation (synchronization between station clocks)

DDOR = DOR_{SC}-DOR_{QS}

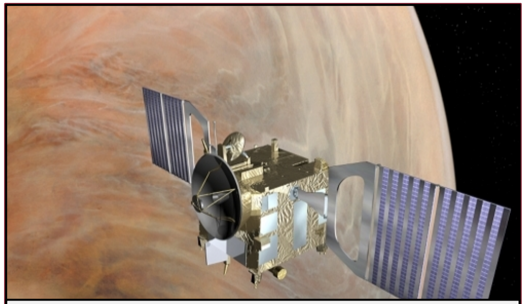
In 2006 Sapienza University of Rome received a contract by ESA to develop the DDOR raw data Format Translator in order to enhance the cross agency operability.

$$\sigma_{\vartheta} = \frac{c}{B\cos\vartheta}\sigma_{\tau}$$

- **Baseline length**
- **Hortogonality**

JPL-VSR
IFMS-ESA
VLBI- MARK V

ESA-DDOR system: history (1/2)



2006
Venus Express orbit insertion

2005
Correlator development (UNI/DIMA)

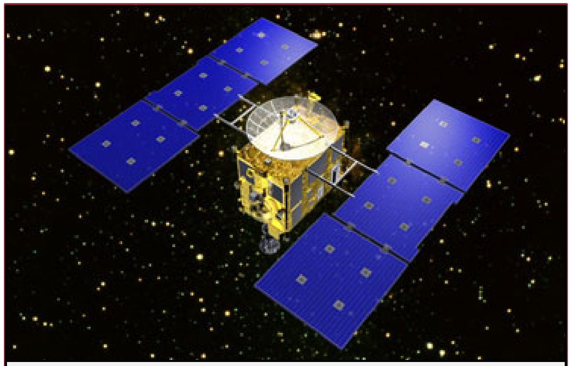
2007-2008
First enhancement: Fragmented correlation (UNI/DIMA)

2005

2005
Rosetta test

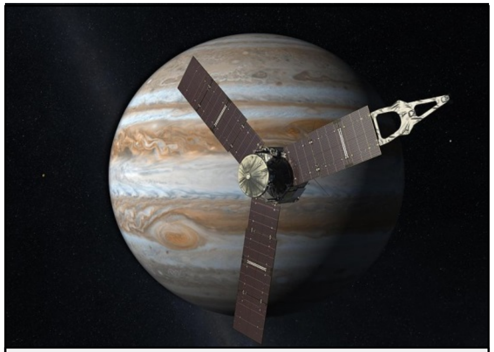
2006-2007
Translator development (UNI/DIMA)

ESA-DDOR system: history (2/2)



2008
ESA-JAXA operability - Hayabusa

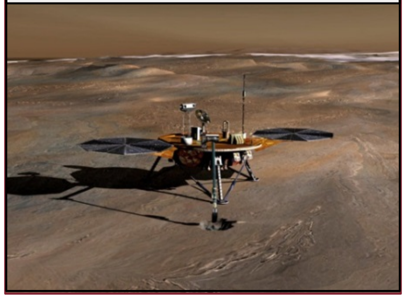
2010
Arpsoft S.r.l founded



2012
ESA-NASA WB test - Juno

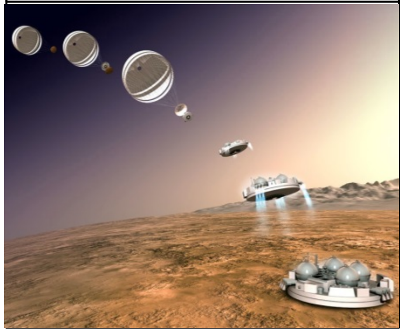
2016

2008
ESA-NASA operability
Phoenix



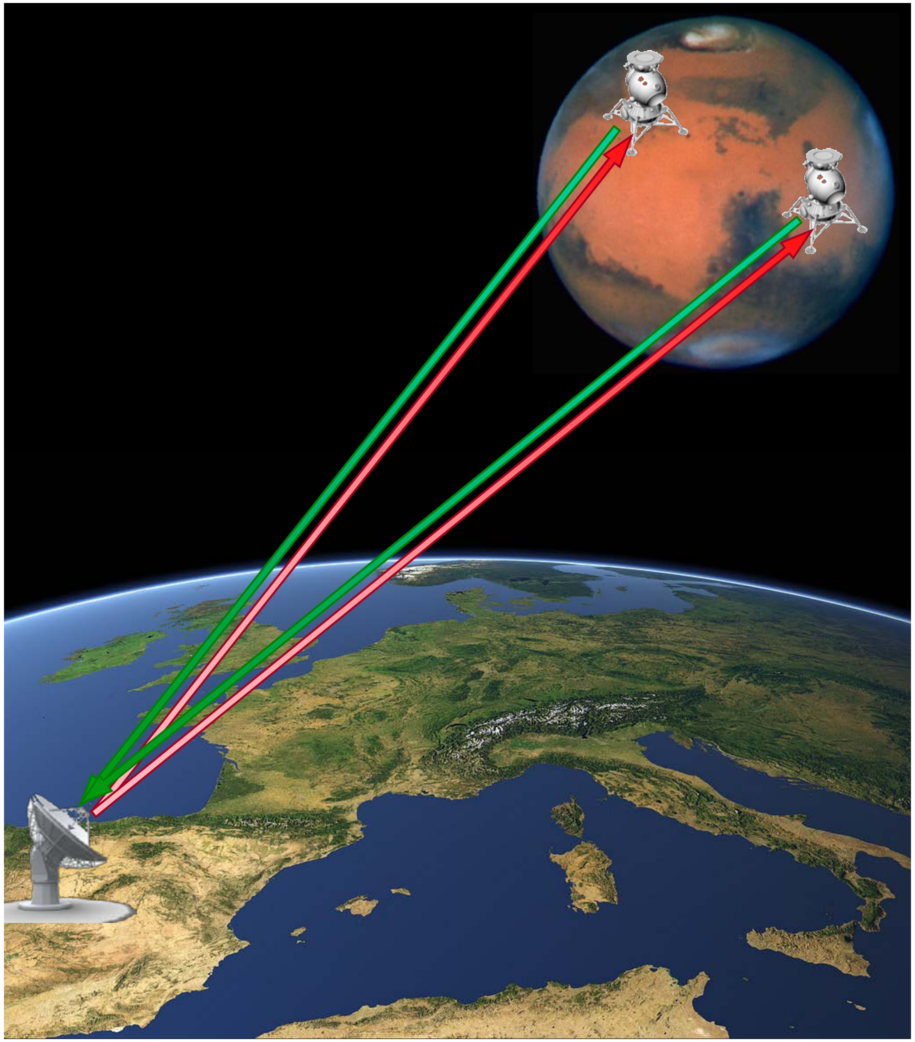
2011-2012
Second Enhancement: Wideband and Low-SNR(UNI/DIMA – ARPSOFT)

2014-2016
1 nrad for Precise Landing



ADVANCED CONCEPTS AND PERSPECTIVES

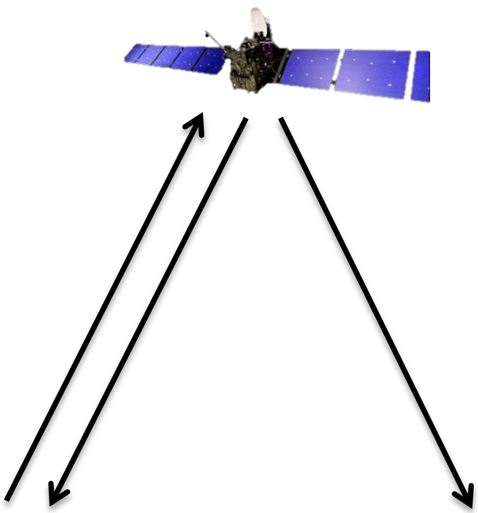
SBI Measurement Concept



- A ***single ground station*** transmits a ***Ka band*** carrier towards two or more, widely separated landers on a celestial body (e.g. Mars or the Moon)
- ***Identical digital transponders*** (KaT) onboard the landers retransmit **coherently** the ***uplink signal*** to the ground station
- The ***observable quantity is the differential phase*** between the signals from each pair of transponders

Multi-station tracking: 10x better Doppler

- Unmodeled motion of the ground antenna's phase center can be a limiting noise source if media propagation noise is calibrated (multi-frequency links and WVR)
- The antenna mechanical noise can be reduced by simultaneous tracking of the spacecraft and proper combination of two-way and three-way Doppler measurements (Armstrong et al., 2008)



$$y_2(t) = [M_2(t) + M_2(t-\mathrm{T})] + [T_2(t) + T_2(t-\mathrm{T})] + [C_2(t) - C_2(t-\mathrm{T})] + y_s \quad \text{Two-way}$$

$$y_3(t) = [M_3(t) + M_2(t-\mathrm{T})] + [T_3(t) + T_2(t-\mathrm{T})] + [C_3(t) - C_2(t-\mathrm{T})] + y_s \quad \text{Three-way}$$

$$E(t) = y_3(t) + y_3(t-\mathrm{T}) - y_2(t-\mathrm{T}) = [M_3(t) + M_3(t-\mathrm{T})] + [T_3(t) + T_3(t-\mathrm{T})] + [C_3(t) + C_3(t-\mathrm{T}) - 2C_2(t-\mathrm{T})] + y_s$$

Transmitting/Receving

Receving only

where:

- M = antenna mechanical noise;
- T = tropospheric noise;
- C = frequency standard (clock) noise;
- y_s = doppler signal;
- T = time-of-flight.

Mechanical and troposphere noise are due only to the receving antenna.

STE-QUEST: Space-Time Explorer and Quantum Equivalence Space Test

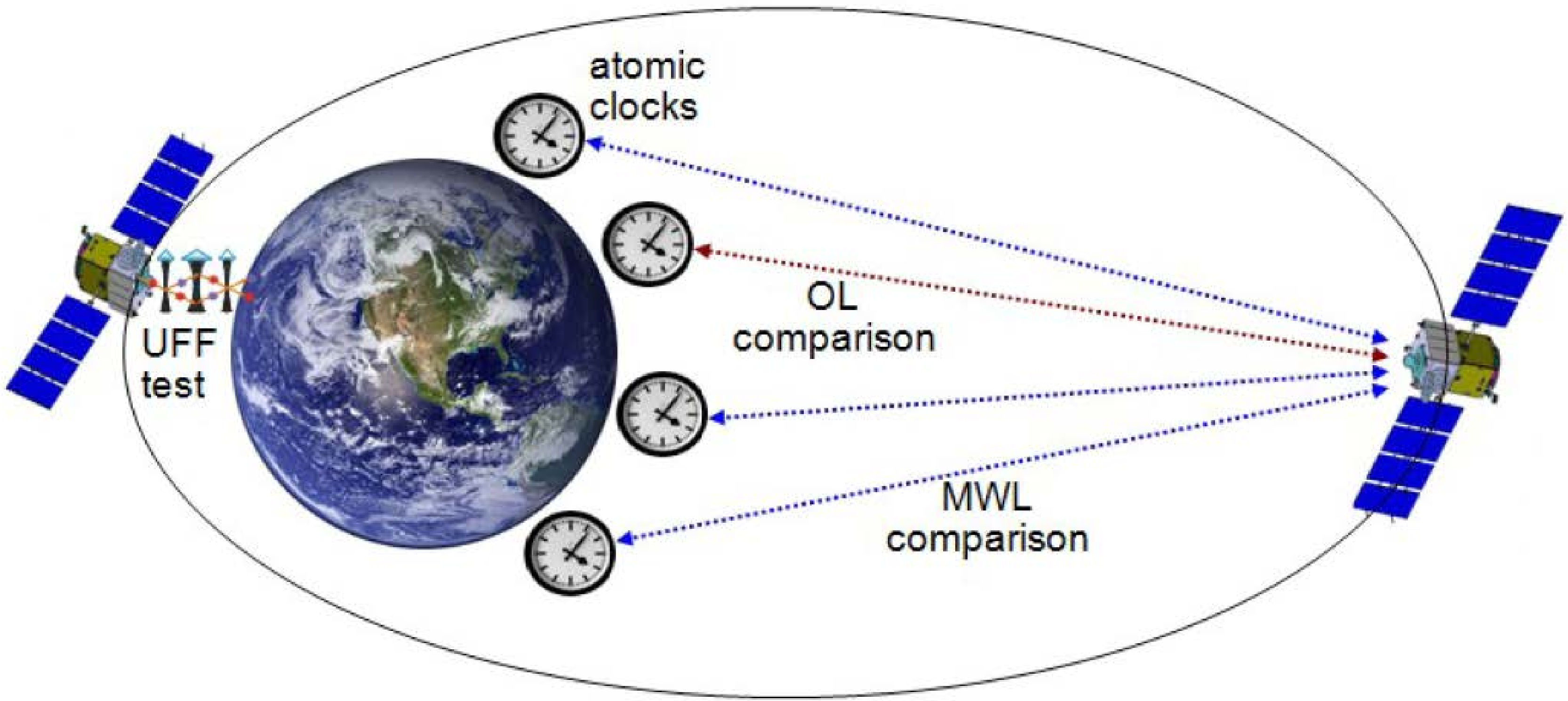


Figure B1: *General concept of the STE-QUEST mission. The clock on the satellite is compared with one or more ground clocks as the satellite orbits earth on a highly elliptic orbit. During the perigee the local acceleration of two rubidium isotopes is measured and compared.*