INTERPLANETARY MISSION OPERATIONS

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COMET OPS Virtual Event

30th Nov 2023

Outline

I. Interplanetary missions: an overview

II. How to get there: interplanetary trajectories, orbit insertion and lander delivery

III. S/C design

IV. Mission operations

V. Mission exploitation

VI. Conclusions

I.

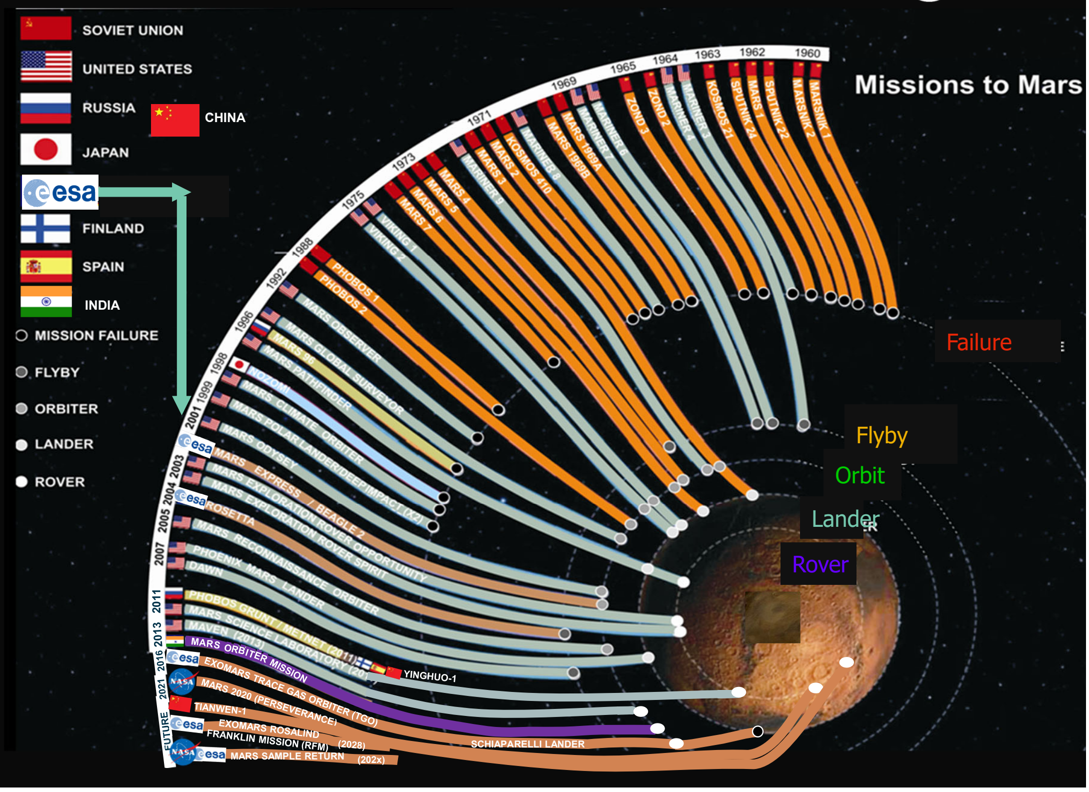
Interplanetary missions: an overview

Rosetta "selfie" taken with Philae lander camera, 50 km from the comet
7th Sept 2014

The conquest of Mars

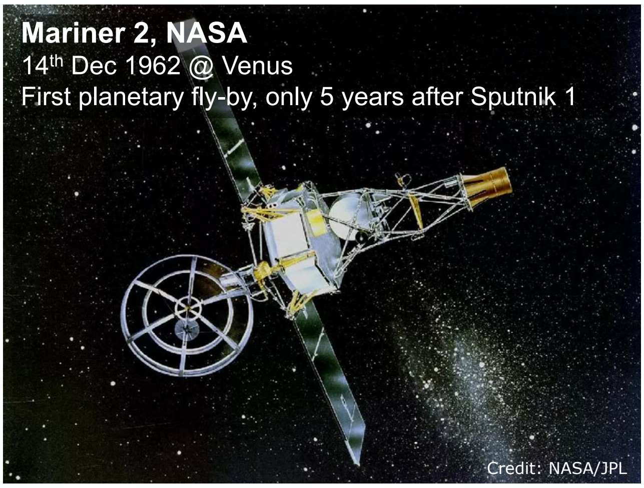
Increasing difficulty:

1. Fly-by
2. Orbiting
3. Landing



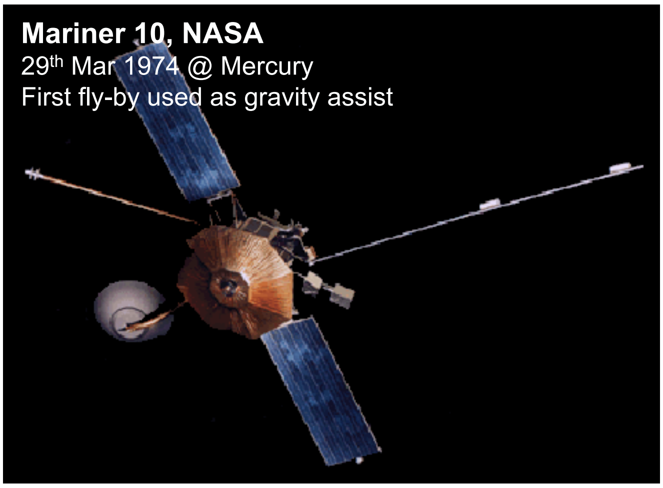
Interplanetary Missions: Fly-by

- Relatively simple vehicle design and flight dynamics
- Only a few hours in proximity of the target
- Necessary as precursors for more complex missions



Mariner 2, NASA
14th Dec 1962 @ Venus
First planetary fly-by, only 5 years after Sputnik 1

Credit: NASA/JPL

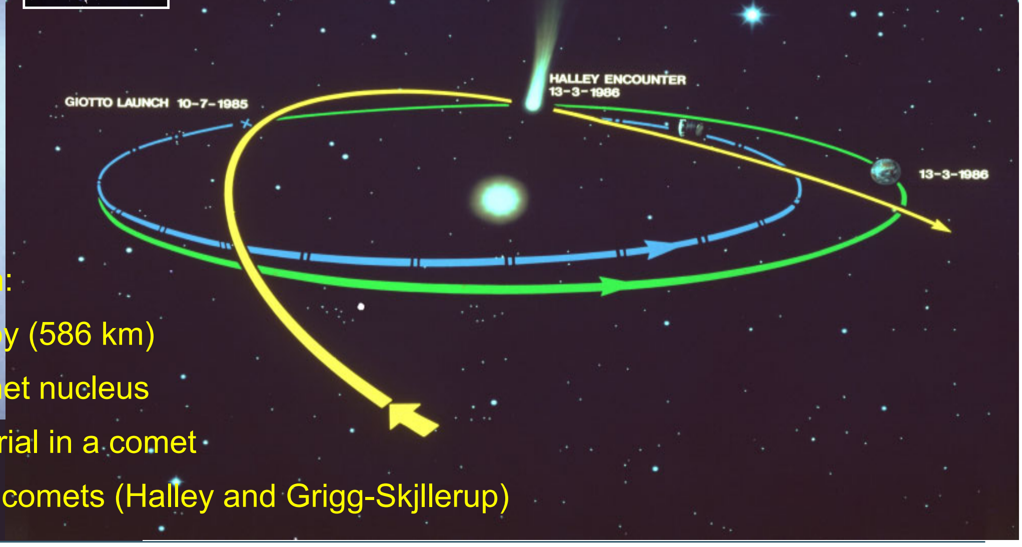


Mariner 10, NASA
29th Mar 1974 @ Mercury
First fly-by used as gravity assist

ESA's Giotto mission: close encounter with comet Halley

Credit: ESA

Launch: 2 Jul 1985, Ariane-1
Halley encounter: 14 Mar 1986
Grigg-Skjllerup fly-by: 10 Jul 1992
Status: concluded on 23 Jul 1992

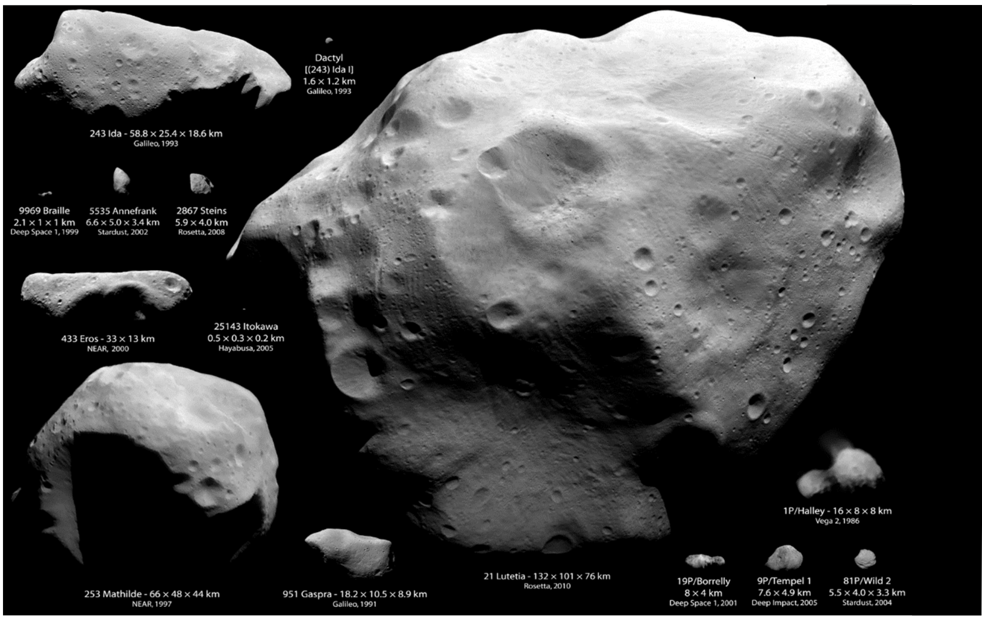


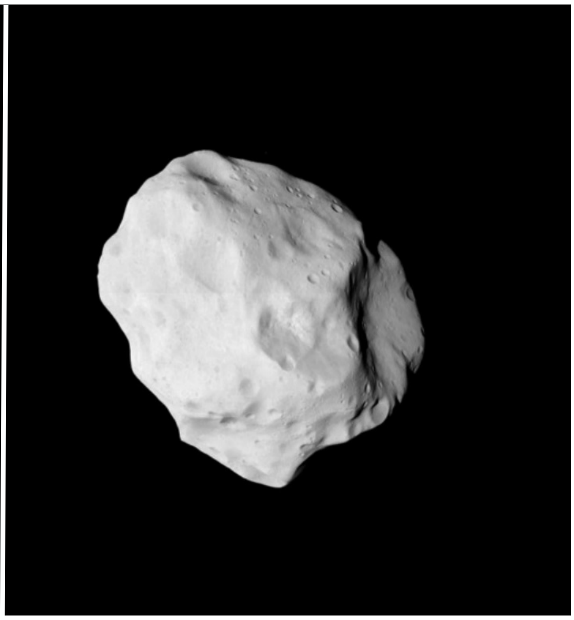
Europe's first deep-space mission:

- At the time, closest comet fly-by (586 km)
- First close-up images of a comet nucleus
- First evidence of organic material in a comet
- First mission to encounter two comets (Halley and Grigg-Skjllerup)

Asteroid flybys: ESA Rosetta over Lutetia (July 2010)

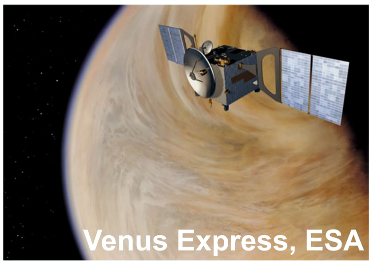
- At the time, Lutetia was the largest asteroid ever visited by a probe (ca. 100 km in length)
- Rosetta flew at 3160 km distance with a relative speed of 15 km/s
- Dawn now has the record (Vesta 500 km and Ceres 1000km)



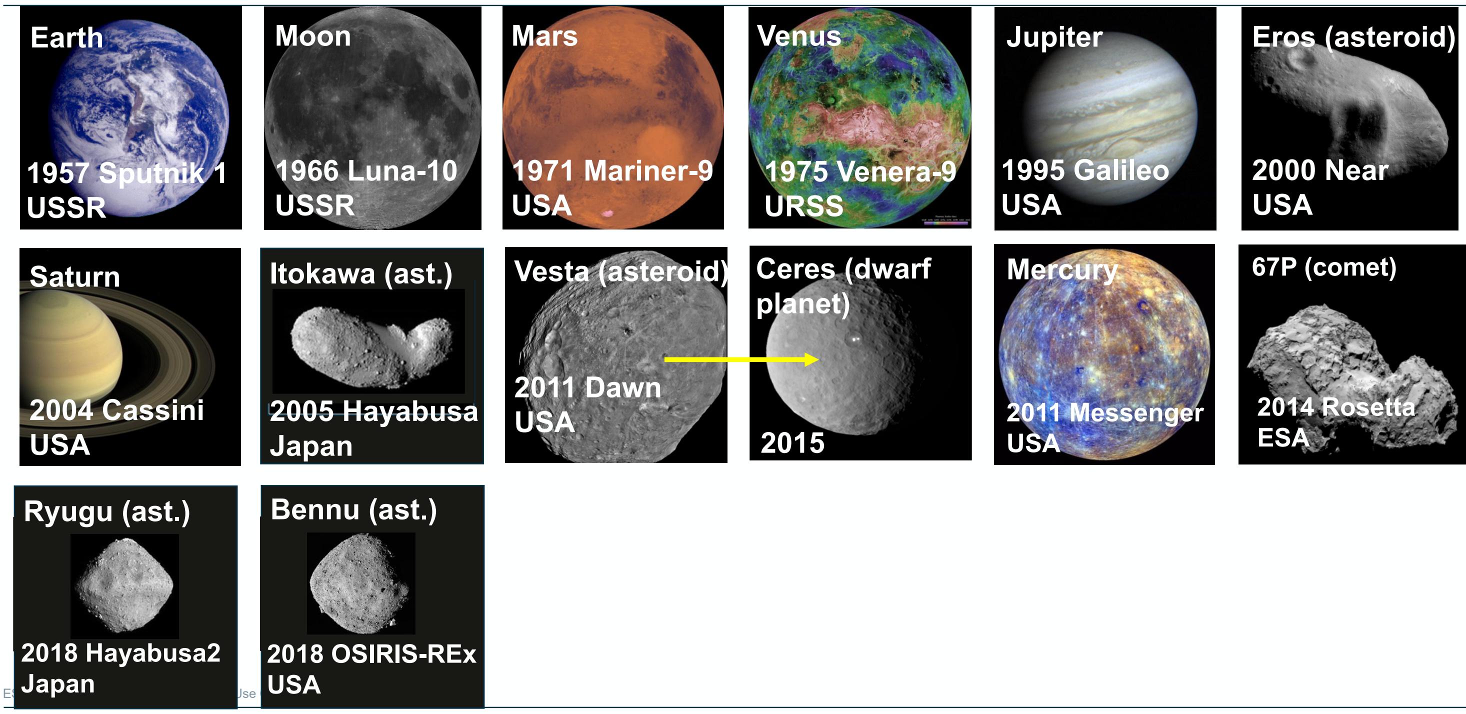


Interplanetary Missions: Orbiters

- Require more orbital energy
- Complex flight dynamics
- Complex and critical operations
- Large scientific return: typically several years in proximity of the target



Orbited Solar System Objects

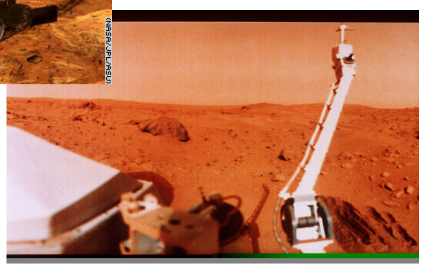


Interplanetary Missions: Landers

Maximum complexity:

- Multiple vehicles
- Extremely complex dynamics of arrival and landing
- Unique, critical and complex operations

Maximum scientific return (in situ observations and analysis)

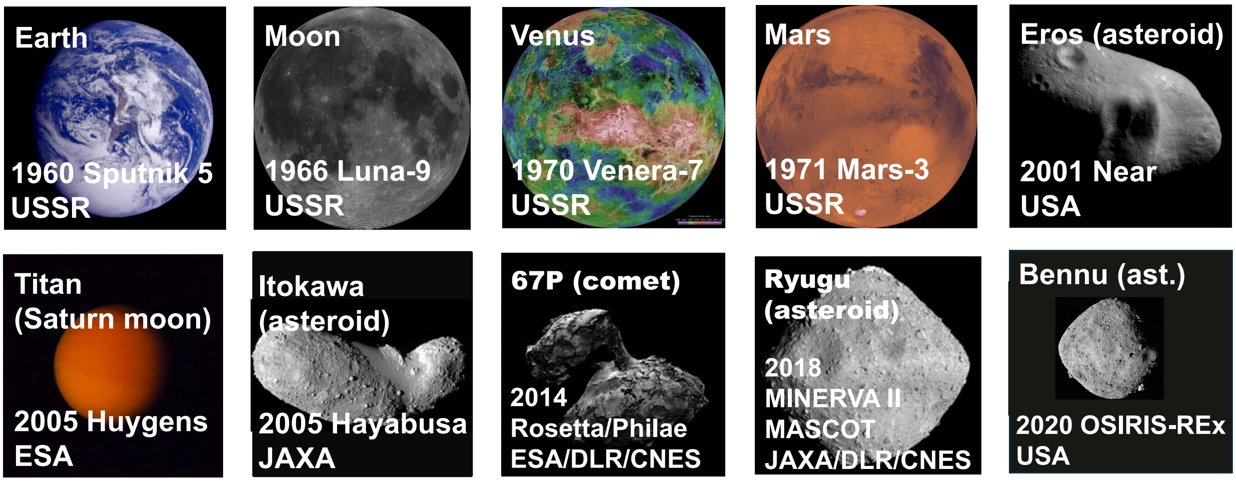


Spirit, Viking, NASA

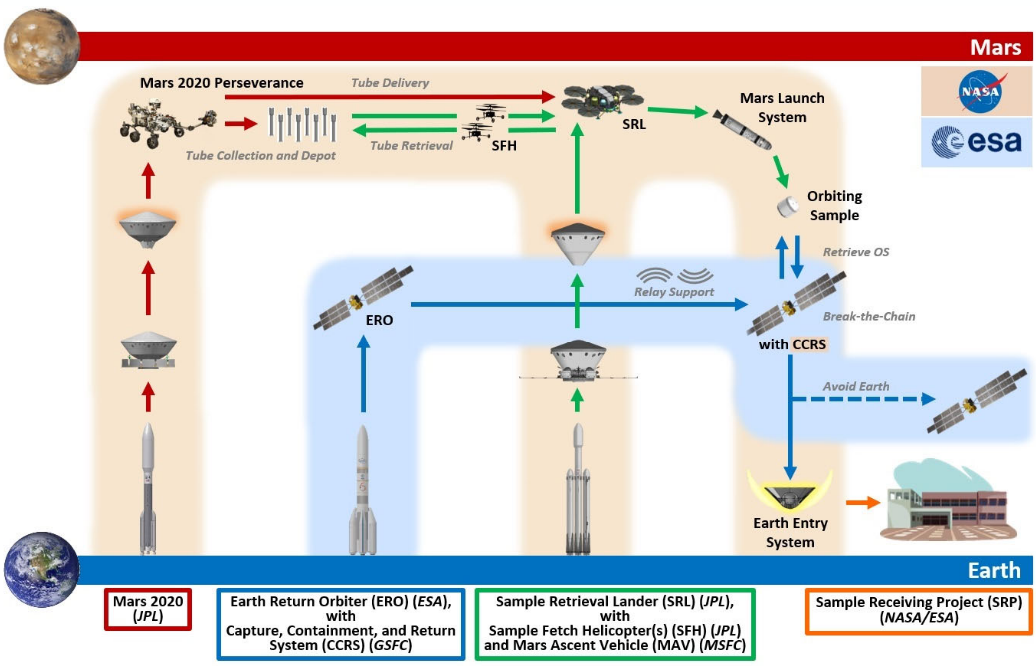
Venera, USSR

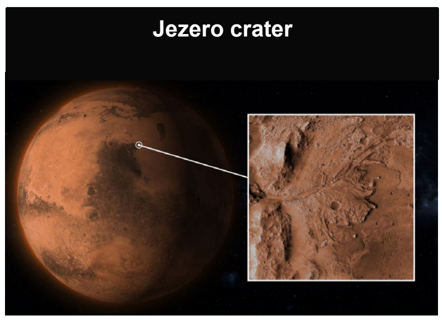
Cassini-Huygens, NASA/ESA

Landings on Solar System Objects

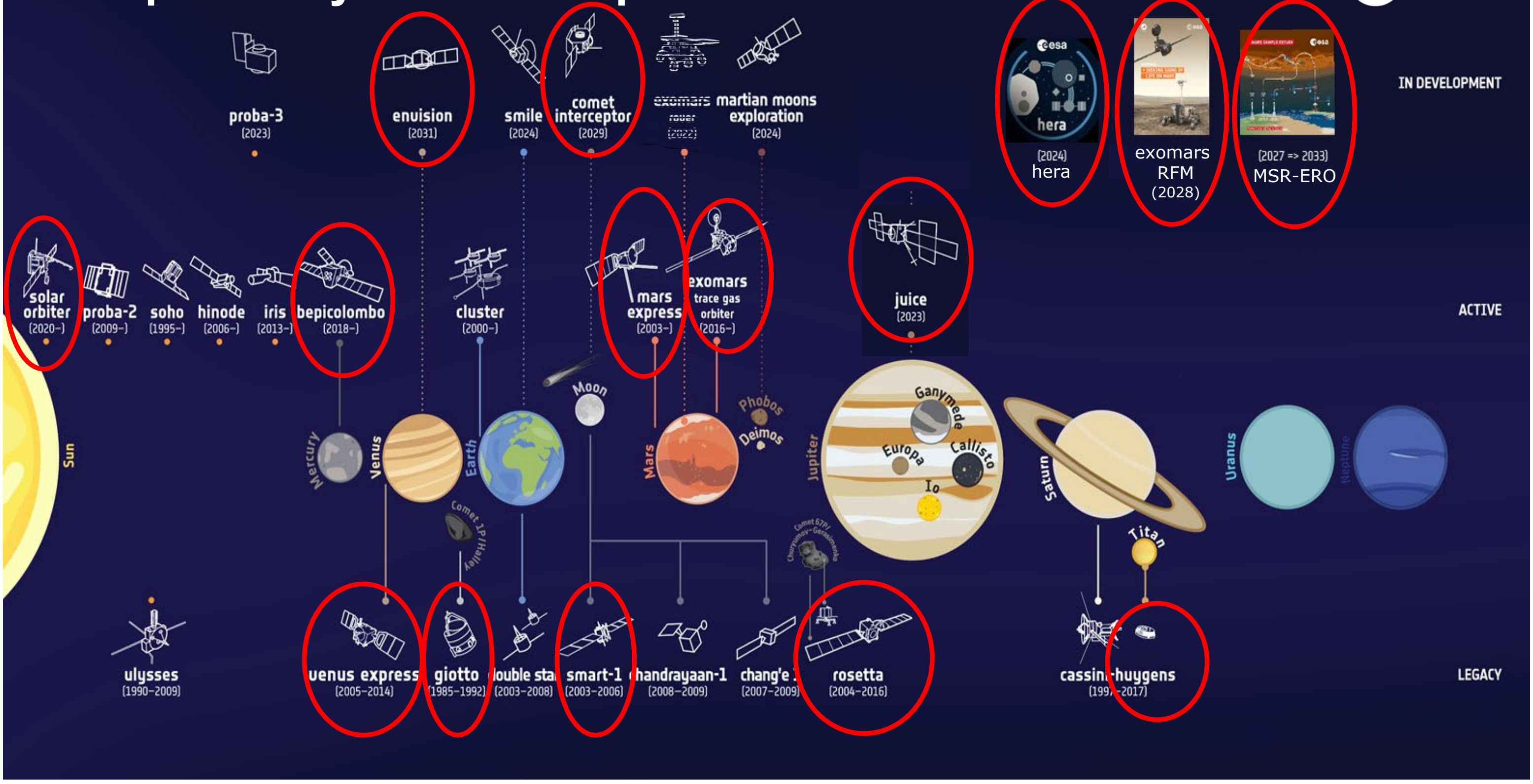


Mars Sample Return (MSR): Overview





Interplanetary Missions operated at ESOC



Challenges of Interplanetary Missions

Basic principles for S/C operations (e.g. procedure-driven operations execution, no trial-and-error) apply as well for interplanetary missions – they're just made more challenging by a number of factors:

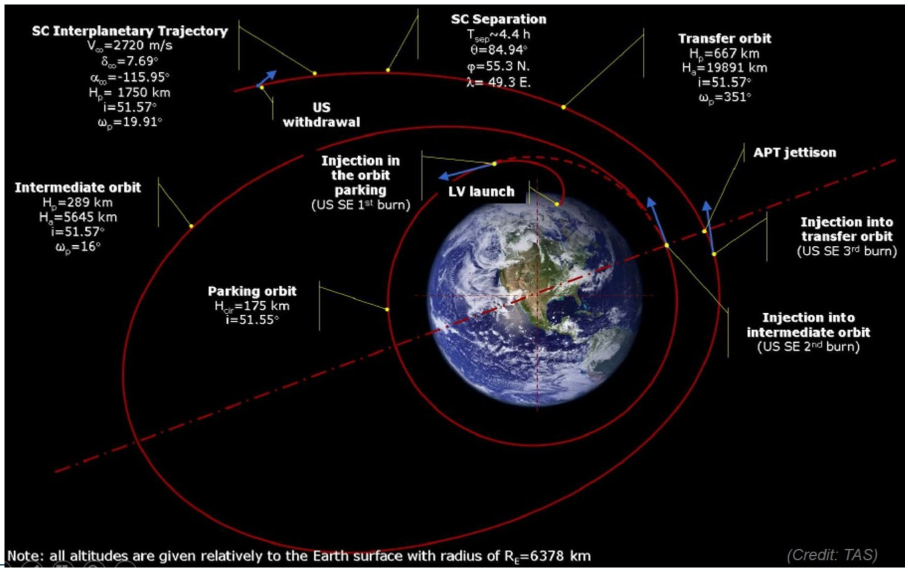
- Large distances, pt. 1: communications with the S/C
- Large distances, pt. 2: determining and controlling the S/C orbit
- Large distances, pt. 3: real time control not practical given long propagation delays
- Flight into the unknown: limited knowledge of the target body and its environment
- S/C needs to cope with big changes of environmental conditions
- S/C typically carries sophisticated suite of scientific instruments, requiring complex mission planning
- Highly variable mission profile:
  - Mission exploitation may only start after a long cruise phase
  - Long periods of low activity in cruise interleaved with highly critical, "1 shot" activities (e.g. planetary swingby, or orbit insertion at target body)

II.

How to get there: Interplanetary Trajectories, Orbit Insertion and Lander Delivery

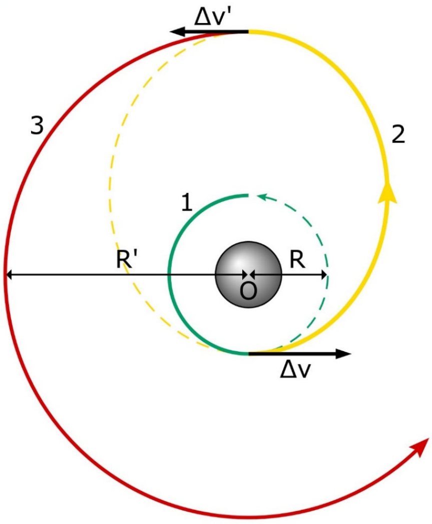
Trajectory Dynamics: Leaving the Earth

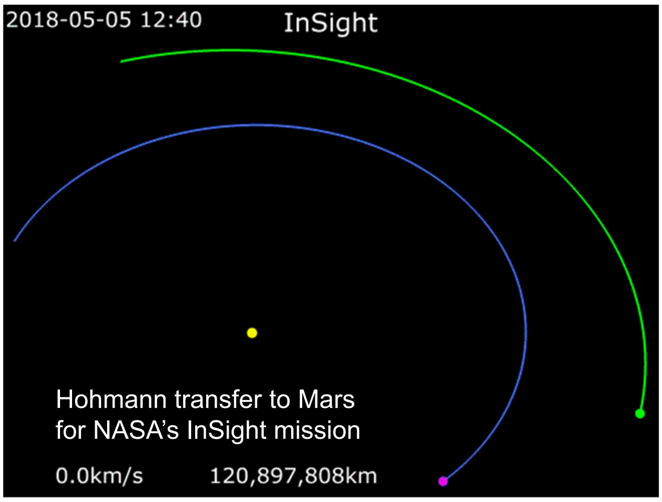
- Escape velocity of 11.2 km/s needed to leave the Earth
- S/C may be put directly on a hyperbolic escape trajectory by the launcher, or first into a parking orbit and then accelerated to escape velocity (e.g. reignitable launcher upper stage or dedicated propulsion module)
- Complex example: ExoMars TGO (2016)



Trajectory Dynamics: Hohmann Transfer

- Hohmann transfer: fuel efficient transfer on orbit 2 go from circular orbit 1 to circular orbit 3, requiring 2 impulsive manoeuvres and good timing to arrive at the target body
- Can require a lot of deltaV and a long time => use of planetary swingbys





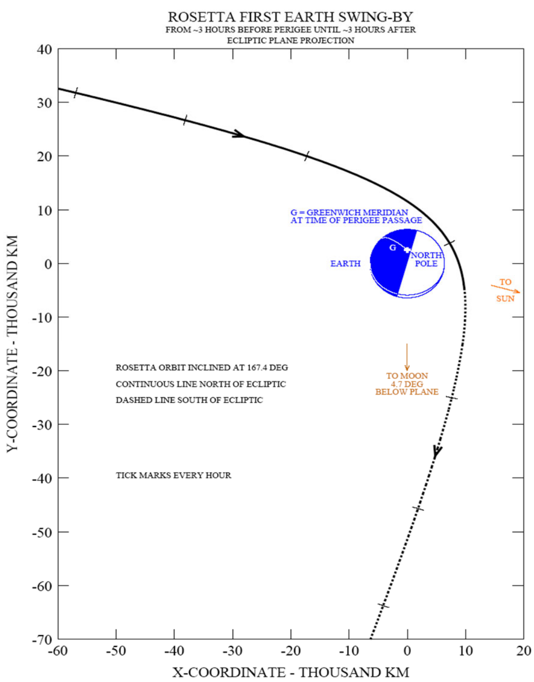
© Animation_of_InSight_trajectory.gif' by Phoenix7777, 2018

Target	Orbital radius [AU]	Δv to enter Hohmann orbit [km/s]
Mercury	0.39	7.5
Venus	0.72	2.5
Mars	1.52	2.9
Jupiter	5.2	8.8
Saturn	9.54	10.3
Uranus	19.19	11.3
Neptune	30.07	11.7
Pluto	39.48	11.8

Trajectory Dynamics: Gravity Assist

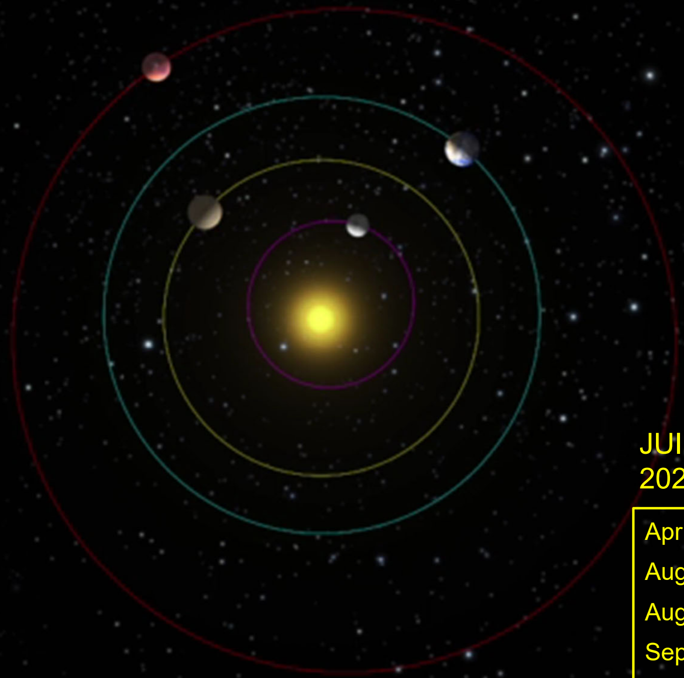
- Also known as "gravitational slingshot" or "planetary swing-by"
- Use gravity of planetary body to alter the S/C trajectory (net change of delta-V relative to the Sun "for free")
- Precise navigation required to achieve intended trajectory change
- Typically flight to Venus or Mars as direct transfer, while missions to other planets require series of gravity assists

	Rosetta	BepiColombo
Number of swingbys	4 3 Earth + 1 Mars	9 1 Earth + 2 Venus + 6 Mercury
Swingby delta-V (km/s)	19.75	18.2
Propulsion delta-V (km/s)	2.2 (chemical)	2.731 (electric)



Jupiter Icy Moons Explorer (JUICE): 2022 Trajectory

esa



Jun 2022	Launch
May 2023	Earth swingby #1
Oct 2023	Venus swingby
Sep 2024	Earth swingby #2
Feb 2025	Mars swingby
Nov 2026	Earth swingby #3
Oct 2029	Arrival at Jupiter

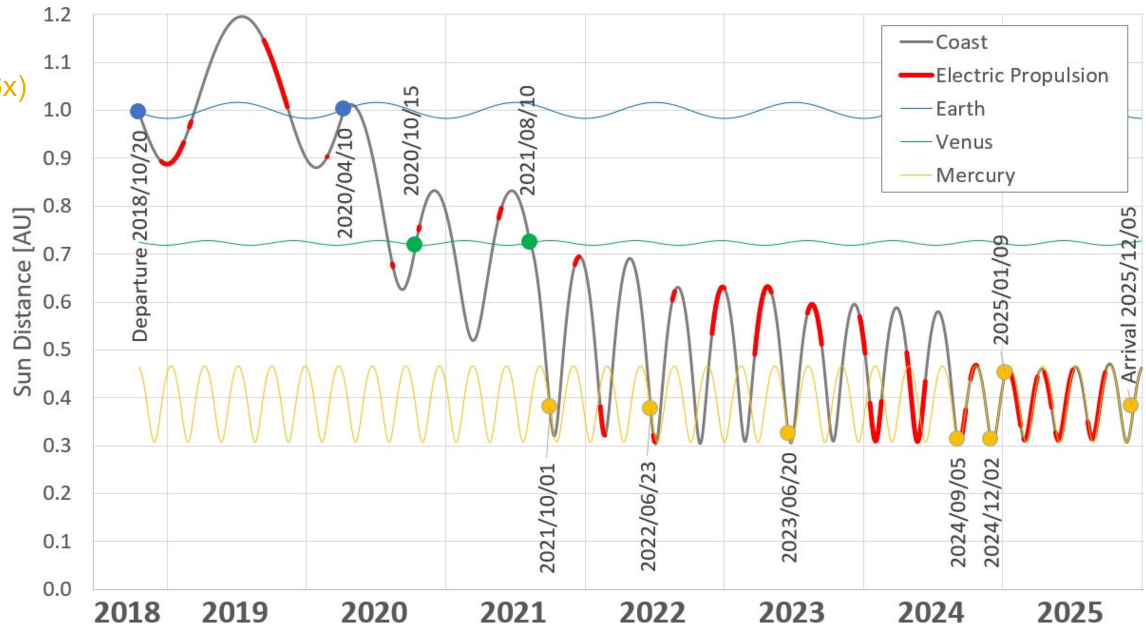
JUICE launched only on 14 April 2023 => new trajectory design!

Apr 2023	Launch
Aug 2024	Lunar/Earth swingby #1
Aug 2025	Venus swingby
Sep 2026	Earth swingby #2
Jan 2029	Earth swingby #3
Jul 2031	Arrival at Jupiter

BepiColombo Trajectory to Mercury

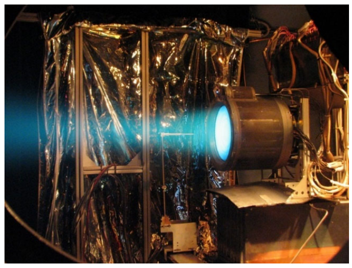
esa

- 7 years cruise with flybys at Earth (1x), Venus (2x), Mercury (6x)
- Electric propulsion usage (**thrust arcs**)
- Total EP deltaV for trajectory: 2731 m/s



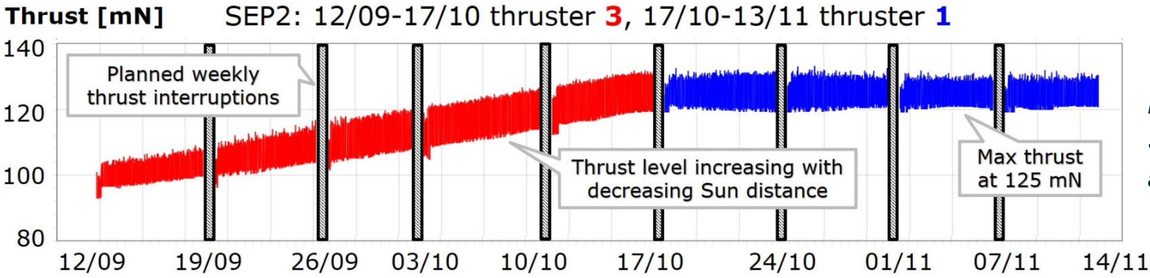
Electric Propulsion

- EP mission compared to ballistic mission:
  - Low thrust (BepiColombo 250 mN max, MSR-ERO: 750 mN max), high efficiency
  - Increased operations complexity (EP system continuously running for days/weeks/months)
  - Increased mission flexibility (no critical “1 shot” ballistic manoeuvres)



- Implications on operations and S/C design:
  - Specific autonomy/FDIR for EP subsystem
  - Regular thrust interruptions (typically weekly) for orbit determination

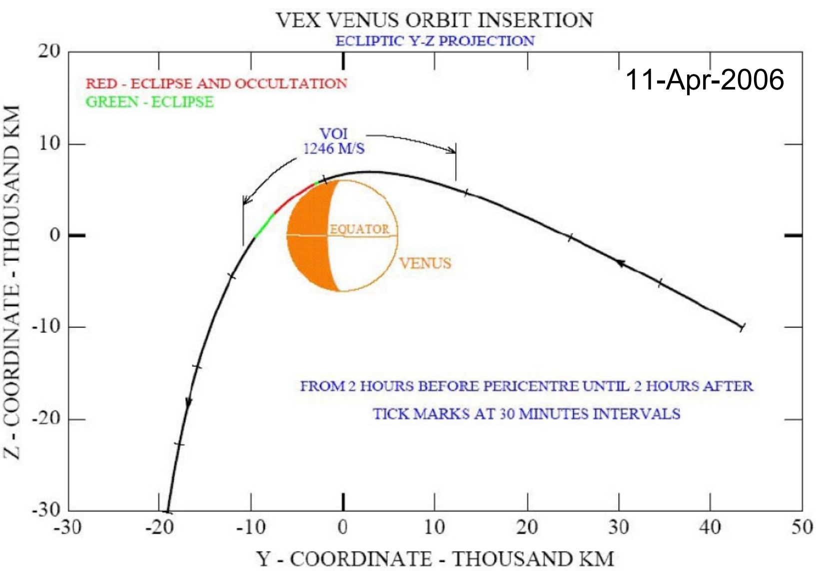
    Recently, a new way of performing OD without interruptions (relying on frequent DDOR passes) is being used on BepiColombo
  - High power demand (BepiColombo: up to 11 kW, MSR-ERO: up to 34 kW) => S/C power budget constrains EP thrusting
  - BepiColombo: attitude constraints and SA performance in extreme thermal environment leading to additional constraints



BepiColombo SEP2 arc from Sep to Nov 2019: thrust level and thrusters used

From Probe to Orbiter: Orbit Insertion (Venus Express)

- Critical ballistic manoeuvre to achieve Mars orbit insertion: no second chance, mission failure if manoeuvre fails
- *“A Launch in reverse – where the spacecraft operators fire the rocket”*

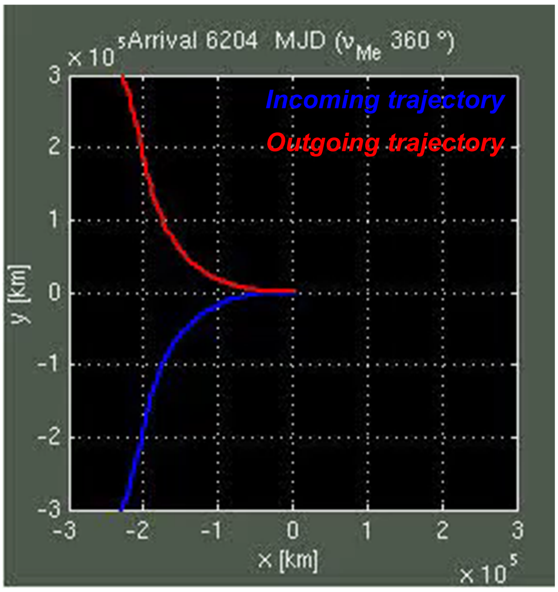


Specifics:

- S/C configuration for unique event: e.g. configure on-board fault management to reduce likelihood of critical burn not executing
- Navigation campaign (starting >1 month prior) with dedicated targeting manoeuvres
- Main insertion burn: critical operations phase with extended teams and station coverage
- Dedicated simulations campaign to train the operations teams for the event

Alternative Orbit Insertion: Weak Stability Boundary

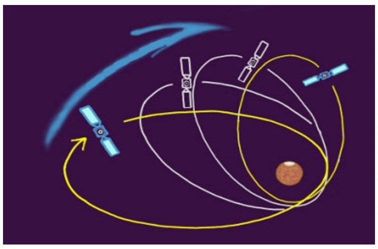
- Also known as “low energy transfer” – bring S/C on a trajectory that will lead to it being captured by the target body:
  - No single point failure at insertion (avoid critical insertion burn)
  - Constrains arrival date
- Will be used for planetary insertion at Mercury for BepiColombo in 2025

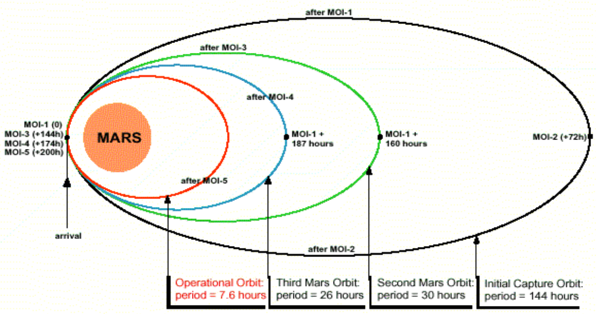


BepiColombo trajectory as a function of Mercury arrival date: only for a subset of dates the incoming trajectory is “open” and the outgoing trajectory is “closed”, i.e. the S/C can come in from heliocentric orbit and come out “bound‘” into Mercury orbit

Orbit Changes after Orbit Insertion

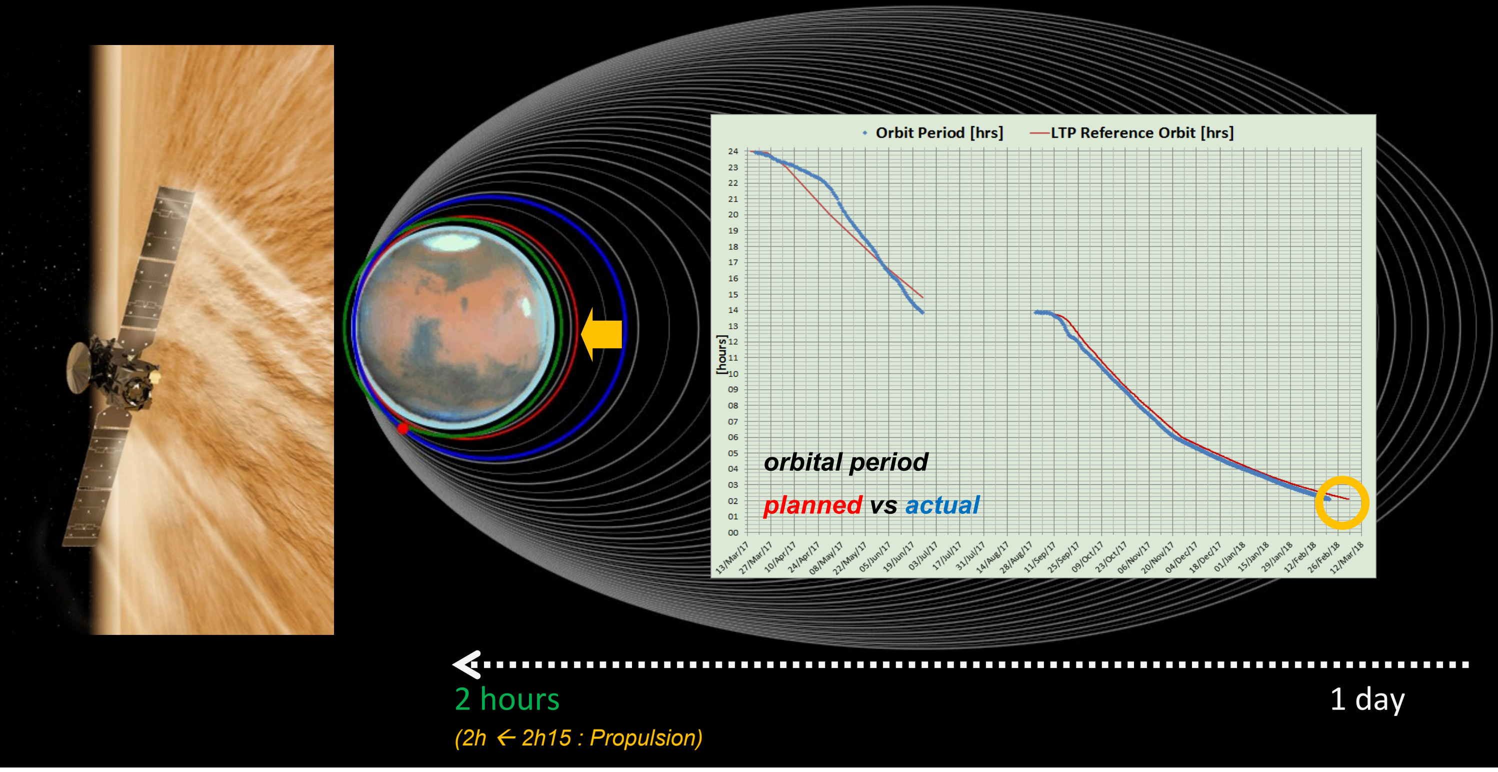
- Orbit needs further adjustment following the critical insertion burn
- Mars Express: series of ballistic manoeuvres in order to..
  - Turn orbit plane to make it polar
  - Shorten orbit period from 7 days to 7 hours





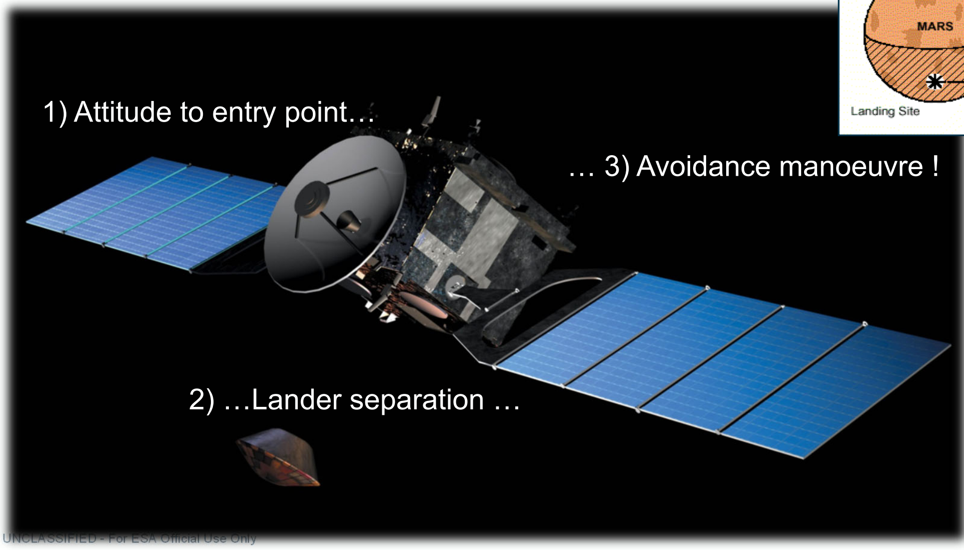
- Aerobraking:
  - No use of propellant, but takes longer and is operationally complex (needs extensive ground station coverage and S/C safing autonomy due to highly variable atmospheric density)
  - Used so far at Mars and at Venus
  - At Mars: used since 1997 by NASA orbiters (MGS, Odyssey, MRO) to lower and circularise the orbit
  - ESA ExoMars TGO: 2017/2018, 1 year, 1000 passes: orbit period reduction from 24h to 2h
  - At Venus – ESA Venus Express in 2014: “aerodrag” experiments to improve Venus atmosphere knowledge and gain ops experience – orbit period reduction from 24h to 22h15mn (55 aerobraking passes in 2 months)

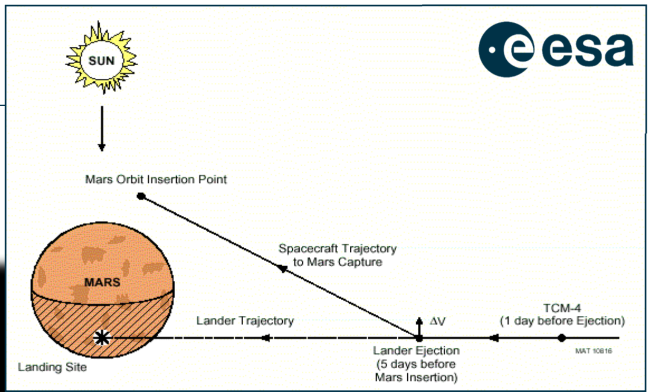
Exomars TGO Aerobraking 2017/2018



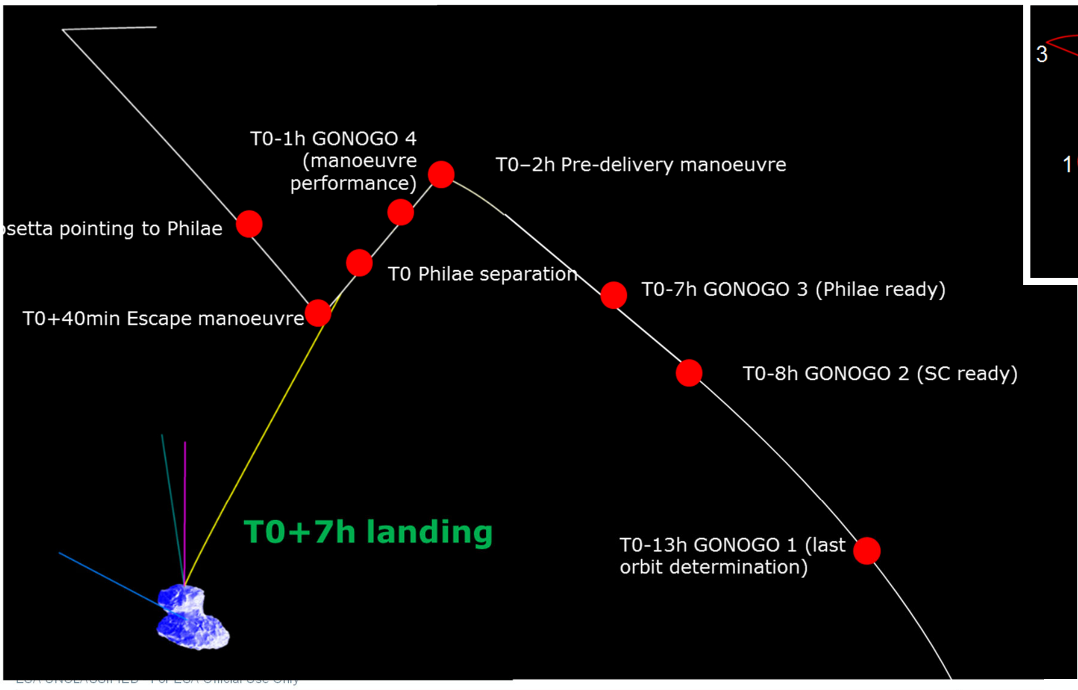
How to deliver a Lander

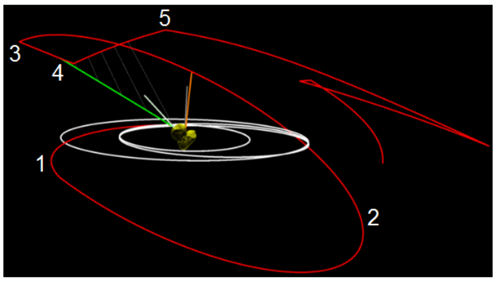
- By a carrier: standalone mission (MER, MSL)
- By the orbiter from the orbit (Viking, Rosetta)
- By the orbiter before arrival (Mars Express, ExoMars TGO)

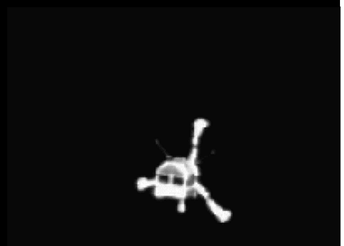




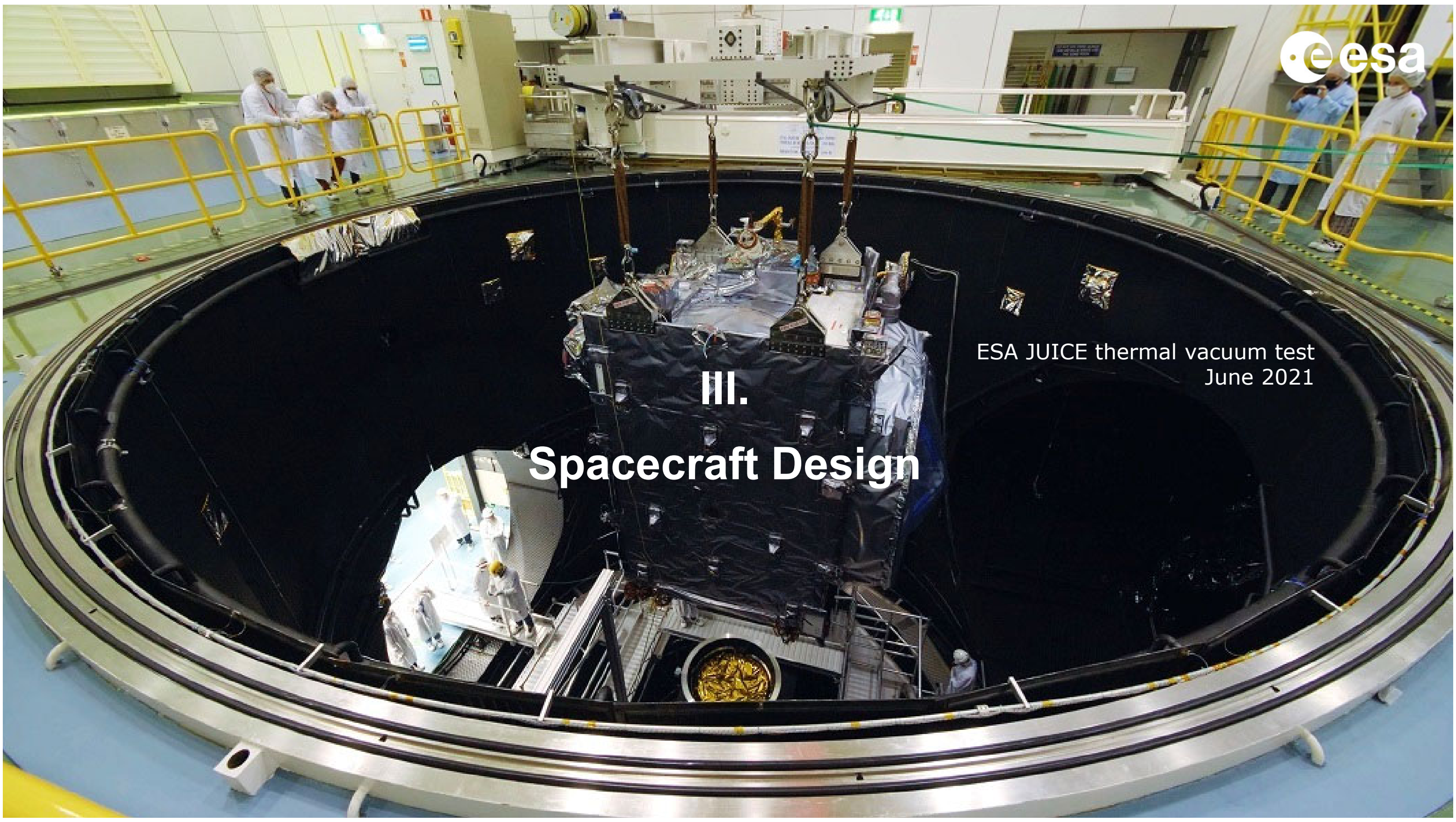
How Rosetta’s Philae lander was delivered







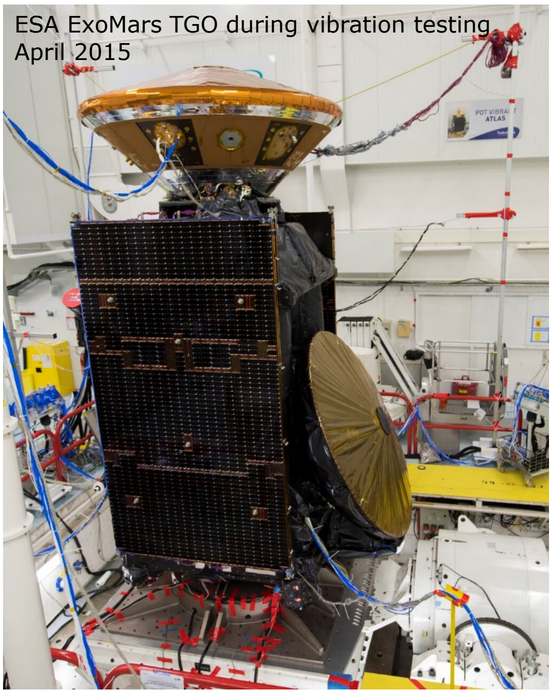
Parting shots of Philae lander after separation by OSIRIS camera
12th Nov 2014



ESA JUICE thermal vacuum test
June 2021

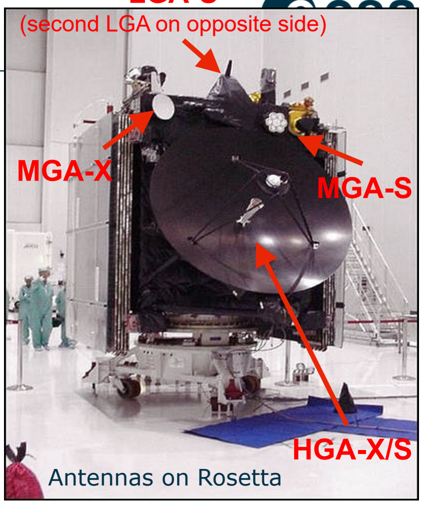
Interplanetary S/C Design Specifics Overview

- Complexity may vary greatly depending on the mission, but there are some typical specifics for interplanetary S/C:
    - Communications (large distances)
    - Power generation (Sun distances much different from 1 AU)
    - Thermal (wide range of thermal conditions different from Earth orbit)
    - Increased need for autonomy (large propagation delays, long outages e.g. during solar conjunctions)
    - Complexity of payload suite
- ESA interplanetary S/C design heritage:
    - Several European S/C Primes have gathered extensive experience with interplanetary S/C design in the last 20 years (start of new wave of interplanetary missions with Rosetta)
    - Technology reuse among the missions (e.g. ROS/VEX/MEX, BepiColombo / Solar Orbiter)
    - Successful autonomy features / concepts keep being refined and reused (also driven by operations requirements, ref. later slide)


ESA ExoMars TGO during vibration testing April 2015

Communications

- Frequency Bands: S-band (2 GHz), X-Band (7-8 GHz), Ka-Band (26.5-40 GHz)
    - S: use in backup modes on Rosetta/MEX/VEX, not used by more recent S/C
    - X: used in routine and also for backup modes of recent S/C
    - Ka: use on BepiColombo and JUICE to increase scientific return (but more susceptible to weather conditions at ground station)
- On-board antennas:
    - 2 Low-gain antenna (LGA) when close to Earth or for emergency in deep space (offer omnidirectional coverage)
    - Medium-gain antenna (MGA) typically for use in backup modes (less precise pointing required than for HGA)
    - High-gain antenna (HGA) for use in routine
    - MGA/HGA steerable or fixed (depends on needs of mission)
- On-board RF power 20-100W (!), data rates typically from few bps to several hundred kbps (depending on Earth distance, S/C mode and antenna used)

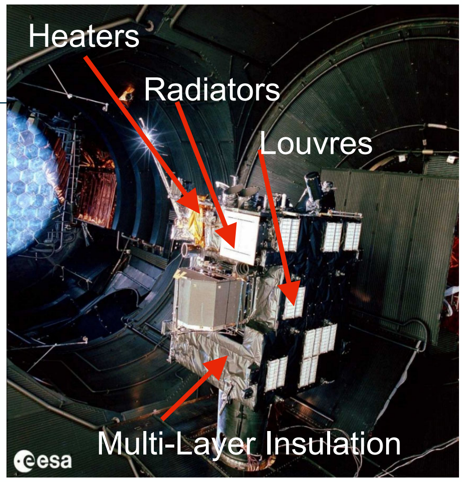


Antennas on Rosetta

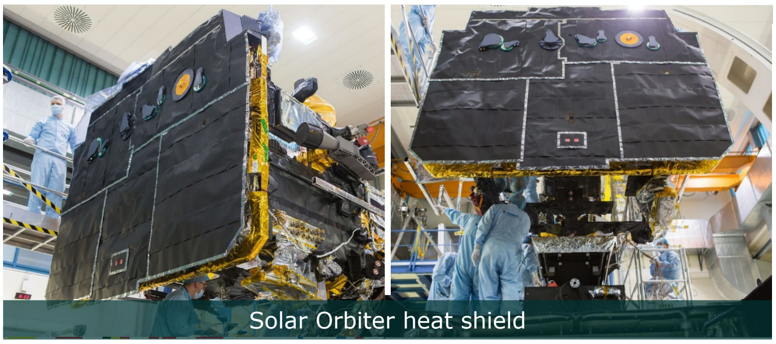
Steerable antennas Y or N?

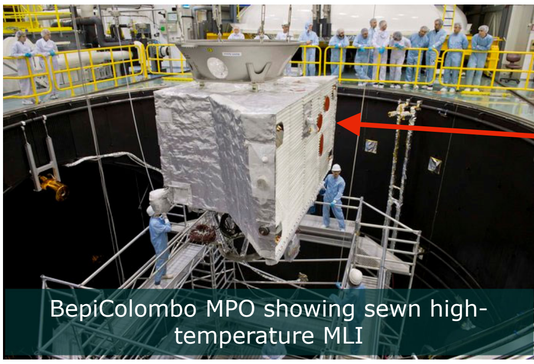
Mission	MGA	HGA
MEX/VEX	n/a	N
Rosetta	N	Y
ExoMars TGO	n/a	Y
BepiColombo	Y	Y
Solar Orbiter	Y	Y

Thermal



- Large variation of thermal conditions during mission lifetime, e.g.
  - BepiColombo at Mercury: 10x solar irradiance at Earth
  - JUICE at Jupiter: 4% of solar irradiance at Earth
  - ..yet these S/C have to function at Earth distances (JUICE even at Venus)!
- **Outer Solar System: keep the heat – Inner Solar System: get rid of it**
- Inner solar system missions: strict attitude constraints to avoid overheating, dedicated high temperature technology
- Heaters: typically electrical, Radioisotope Heater Units (RHU) for some missions in outer solar system or on planet surface


Solar Orbiter heat shield


BepiColombo MPO showing sewn high-temperature MLI

Radiator side: may never face Sun or Mercury!

Power: Solar Electric

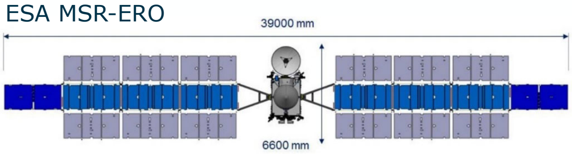
ESA Rosetta

- Solar electric generators as prime means
- Outer solar system – low solar flux a limiting factor:
  - Sun distance record with solar panels: NASA Juno (72 m^2, yielding about 500W at Jupiter), 832 million km from Sun
  - Previous record held by ESA Rosetta (64 m^2), still this was not enough to go through aphelion, requiring S/C hibernation in spin-stabilised mode Jun 2011 - Jan 2014
  - ESA JUICE to Jupiter: 85 m^2
- Inner solar system – plenty of power..?
  - Not really, high temperatures decrease solar array efficiency
  - ESA BepiColombo: offpoint arrays to avoid overheating
- Electric propulsion systems with high power demand, driving SA sizing (BepiColombo: up to 11 kW, MSR-ERO 144 m^2!: up to 34 kW)


ESA JUICE

	Distance [AU]	Mean solar flux [W/m^2]
Mercury	0.31-0.47	9066
Venus	0.72-0.73	2601
Earth	1.0	1358
Mars	1.38-1.67	586
Jupiter	4.95-5.45	50
Saturn	9.0-10.0	15
Uranus	18.2-20.3	4
Neptune	30.0-30.3	2
Pluto	29.5-50	1

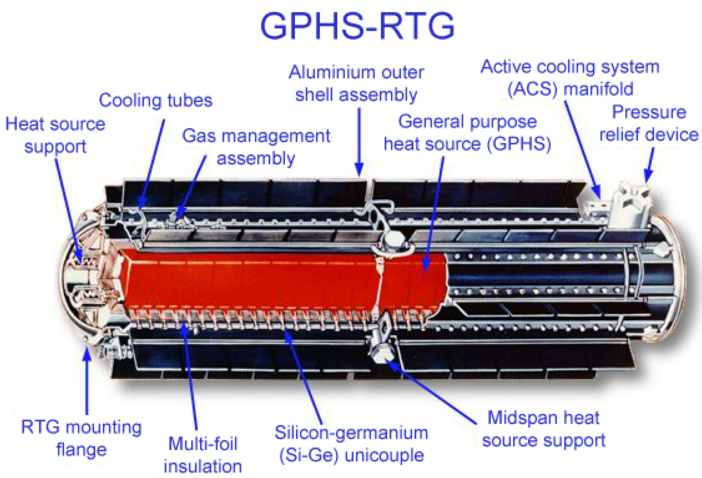
ESA MSR-ERO




ESA BepiColombo

Power: RTGs

- Radioisotope Thermoelectric Generator (RTG): “nuclear battery”, converts heat released by decay of radioactive material into electricity by the Seebeck effect
- All missions to outer planets so far have used RTGs (except NASA Juno and ESA JUICE)
- RTGs used very restrictively by NASA
- ESA-funded RTG development programme for possible eventual use on deep space missions



General-purpose heat source - radioisotope thermoelectric generator (GPHS-RTG) used on NASA Cassini

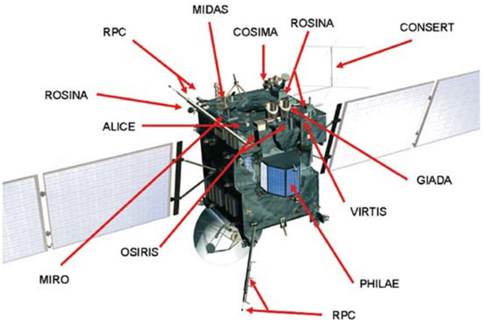
Autonomy and Fault Detection, Isolation & Recovery

- Why is autonomy important?
  - Long signal propagation delays (e.g. round trip time for S/C at Mars up to 44 min, at Jupiter up to 107 min)
  - No ground contact may be possible for extended durations (typically up to 1 month), e.g. due to solar conjunction events (interference from the Sun when S/C is “behind the Sun” as seen from Earth)

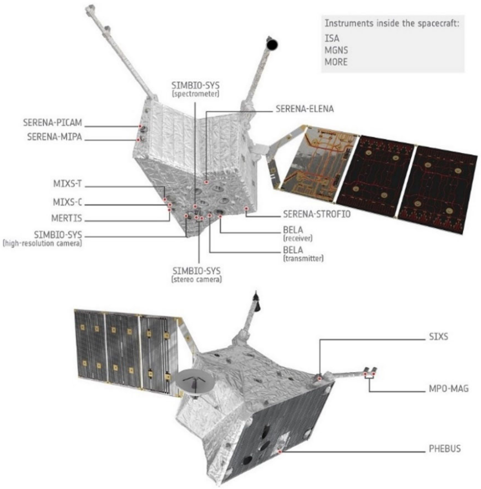
    [Extreme case of Rosetta: 2.5 years hibernation for power reasons, with no ground contact and S/C almost entirely switched off]
  - If done right, more autonomy means less overhead on ground and hence less cost / achieve more with same cost
- FDIR for interplanetary S/C:
  - Layered fault management allowing to autonomously go through series of configurations before “giving up”
  - “TC link monitor” FDIR functionality: S/C starts undertaking recovery measures with escalating severity if it hasn’t heard from ground for a configurable amount of time
- AOCS autonomy features supporting the complex attitude and orbit control (e.g. custom attitude and antenna guidance profiles, optical navigation modes)
- Significant configurable autonomy features (e.g. mission timeline, on-board control procedures, file-based operations) to ease operations of interplanetary S/C

Payload Suite

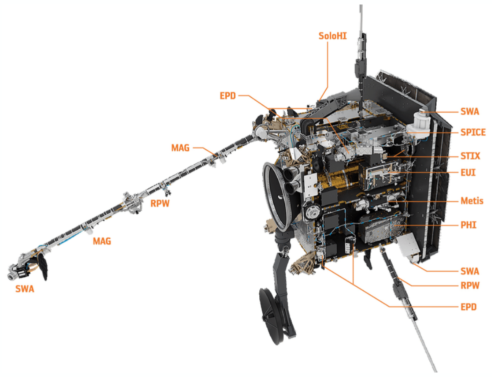
- While some missions are very specialised (e.g. MSR-ERO for return of Mars samples), interplanetary S/C typically carry a significant number of scientific instruments covering a wide range of measurements
- => High complexity of S/C integration & testing, interface with principal investigators, science operations planning



ESA Rosetta payload suite



ESA BepiColombo payload suite



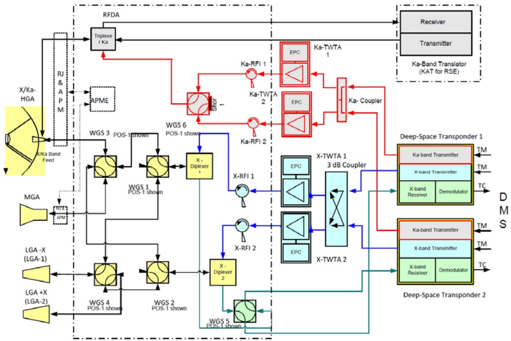
ESA Solar Orbiter payload suite

ESA Interplanetary S/C: OPS involvement in Design

- S/C development followed from early on (operations team built up gradually starting in phase B)
- OPS-provided, mission-specific Operations Interface Requirements Document (OIRD) becomes part of S/C system requirements, containing..
  - Functional requirements based on a tailoring of ECSS-70-11C Operability Standard
  - Tailoring of Packet Utilisation Standard “PUS” (PUS compliance is key)
- Extensive test slots allocated with the S/C (and engineering model prior to launch): typically 30 days of SVTs on the S/C, leading to thorough understanding of S/C design and early discovery of potential operational issues
- Same approach for other ESA missions controlled at ESOC e.g. in Earth Observation, but particularly important for interplanetary due to the high operational complexity of these missions

Increased S/C complexity: BepiColombo Safe Mode #2 and High-Gain Antenna (HGA) mispointing

- Safe mode #2, 22nd Nov 2018:
    - Pre-launch NCR 702 on AOCS design problem with restart rotation slew after electric propulsion mode exit
    - 9th Oct (L-11d): workaround in place (parameter patch)
    - L+2w: industry notifies workaround incomplete, 2nd param needs tuning
    - Implemented, but not considered in pre-prepared products for EP manoeuvre => safe mode on 22nd Nov due to guidance inconsistency
- Unit B-sides in use after safe mode
- Move back from MGA to HGA as part of safe mode recovery:
    - TM, but poor signal strength, impossible to get RX locked
    - Commanding via backup LGA to go back to MGA
- Root cause:
    - 2.8 deg mispointing of HGA due to incorrect parameter setting in redundant antenna electronics
    - Difficulty of testing antenna pointing on ground under gravitational loads, differences between PFM and EQM..
- If S/C hadn't been close to Earth (11.6 Million km), recovery in the blind would have been needed..



ESOC Main Control Room

Mission Control Drivers

Specifics of Interplanetary Flight:
- Large signal propagation delays
- Long duration missions
- Minimisation of contact in cruise
- Long periods of low activity, followed by short, highly critical phases
- Complex, variable navigation and attitude control operations
- High S/C vulnerability (navigation, power, comms, thermal)
- Scarce knowledge of target

Impact on Operations Concept:

→offline operations approach

→extensive pre-validation of ops and procedures

→staff profile, training, knowledge management

→on-board autonomy

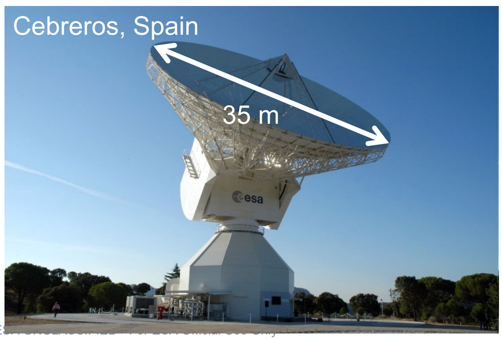
→intense coordination Flight Dynamics / Flight Control

→on-board autonomy *(+ in-flight improvements)*

→incremental, adaptive operations concept

ESA Ground Stations Network

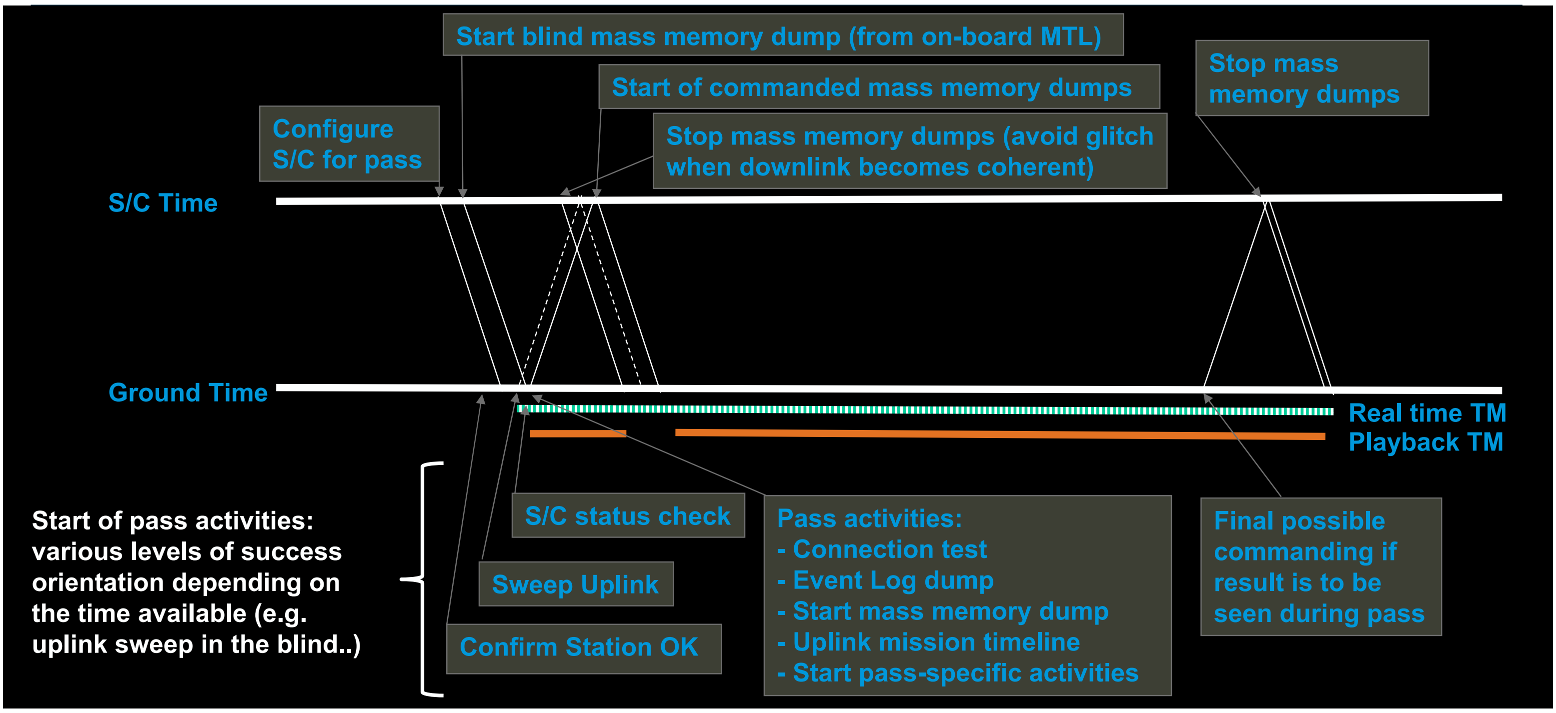
- 35m deep space stations in Cebreros, Malargüe and New Norcia (4th antenna in New Norcia to be built by 2024)
- Station cross support with partner agencies crucial for deep space (in particular ESA/NASA cross support used heavily)



Pass Activities: General Approach

- Basics:
  - Pass in deep space potentially long (10-12h), however can be cut into shorter slots in particular when in orbit around a planet (e.g. occultations, observations requiring S/C slew, constraints on antenna pointing to Earth)
  - Uplink allowed only above 10 deg (ITU regulation)
- Planned / routine activities:
  - "Offline approach": time-tagged execution from on-board Mission Timeline (MTL), minimise commanding in real time
  - Load the future mission timeline (MTL) via "all-or-nothing" command files to ensure its integrity
  - Plan operations such that S/C is safe if MTL runs out (e.g. make sure guidance profile doesn't end shortly after)
  - Be robust to one full pass failure
  - Automation of routine pass operations
- Special activities:
  - "Real time" commanding for few select cases (e.g. commissioning near Earth)
  - Consider what needs ground confirmation and what can be grouped safely for execution on-board
  - Keep in mind propagation delay (e.g. countdown from end of pass / time it takes to recover to re-establish TC link)

Pass Activities: Example

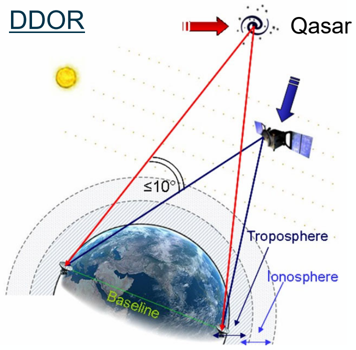


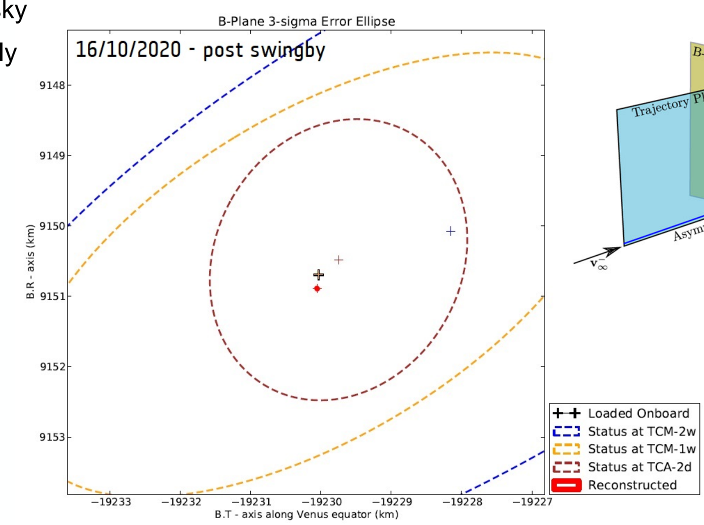
Orbit Determination

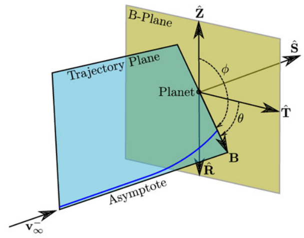
- Extreme accuracy required (know S/C position within a few km at a few hundred million km distance..!)
- Use of traditional Doppler and Ranging (use of radio signal, no GPS receiver in deep space)
- Delta Differential One-way Ranging (DDOR):
  - Determine angular location of S/C in the sky
  - Needs two stations tracking simultaneously + Qasar for calibration purposes
  - Very precise, but high overhead => used selectively for critical activities

BepiColombo Venus 1 swingby navigation – Sep/Oct 2020

DDOR

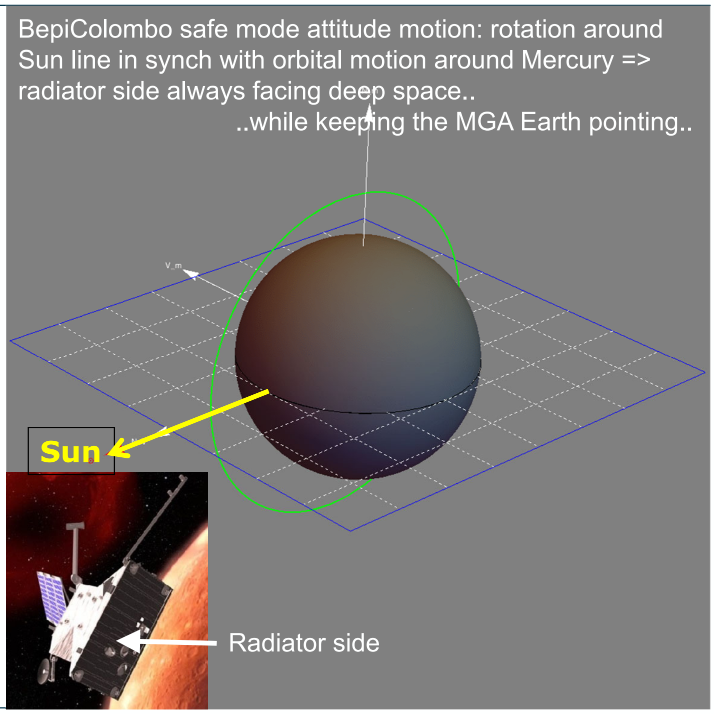




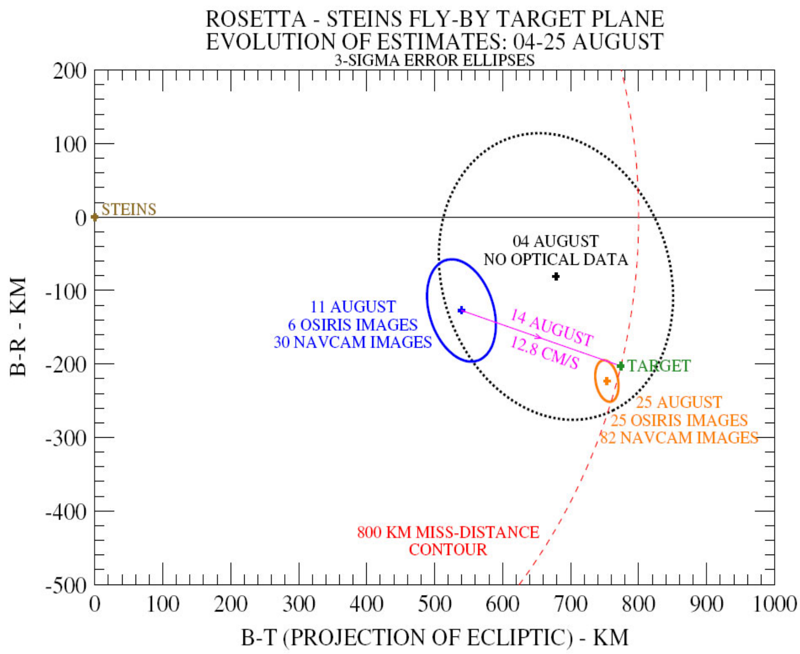


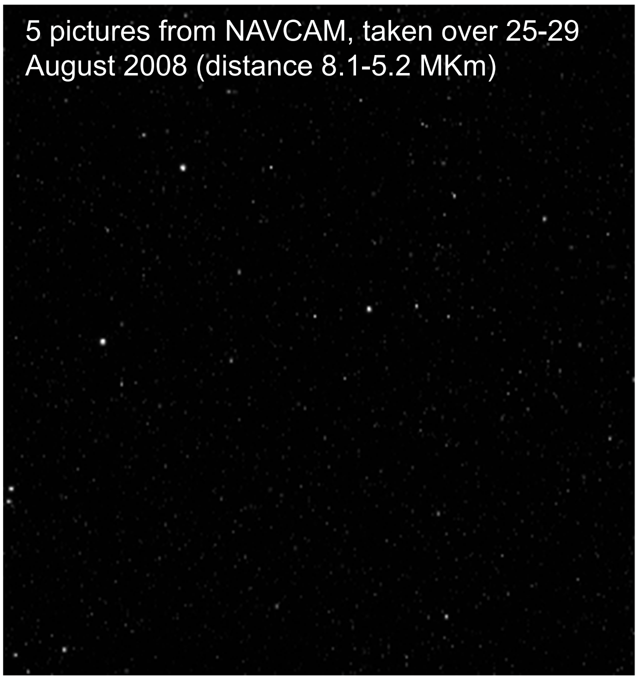
S/C Pointing and Attitude Determination

- Autonomous attitude determination using star trackers is standard nowadays – but how does the S/C know where the Earth is?
  - Correct Earth pointing critical for establishing comms with Earth – mission lost otherwise
  - Safe mode concept typically includes backup mode ("Survival mode") to cope with degraded Earth pointing performance (strobing motion with MGA)
- On-board ephemerides:
  - Providing Earth / Sun direction (plus auxiliary information)
  - Maintained by ground to keep up required accuracy
  - In protected memory, robust to main bus undervoltage



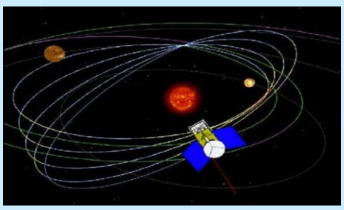
Optical Navigation: Rosetta Asteroid (Steins) Flyby





On-board Control Procedures (OBCPs)

- OBCP concept:
  - "Procedure executed on-board" with well-defined TM/TC interface to other on-board subsystems
  - Capabilities similar to ground operator, e.g. read TM, take decisions, send TC
  - First heavily used on Rosetta, standardised by ECSS-E-ST-70-01C in 2010, now a common service on ESA missions (beyond interplanetary)



Particularly adequate for interplanetary missions:

- Long missions = > likely to require changes *(← ageing)*
- Unknown environment => adaptations in flight
- Long round trip => procedures undoable from ground
- On-board software expertise not always available/affordable
- OBCPs flexible: the user is the designer (Flight Control Team)

- Experience:
  - Rosetta: >100 OBCPs at launch (key part of ops concept), extensive maintenance in flight, >30 new OBCPs in flight
  - Mars Express: 0 at Launch , 3 in 2008, 100 now. Without OBCPs, would abandon 2 instruments out of 6, operate 1 at a time, and need 3 uplink passes/day (>>1/week)
  - BepiColombo: >100 OBCPs as Rosetta, so far 3 new in flight, >40 changes to existing OBCPs

File-based Operations

- Use of files as a complementary data unit:
  - Handling of non-packetized data (e.g. memory images, OBCPs)
  - Ensure completeness of transfer and reduce latency (retransmission of missing parts)
  - Simplified end-to-end traceability and handling of data (higher level of abstraction)
- File concept gradually introduced:
  - Rosetta (and Mars Express / Venus Express): file transfer on uplink implemented using PUS service 13
  - BepiColombo: as Rosetta + file transfer on Ka-band downlink (data loss recovery)
  - JUICE: on-board file system for storing science data and other non-packetized data, service 13 on uplink, CCSDS File Delivery Protocol (CFDP) on downlink over X- and Ka-band
- Mars Express: move to file-based operations approach using existing services (TC files, OBCPs) to work around mission timeline becoming unreliable (anomaly with link between OBC and SSMM)

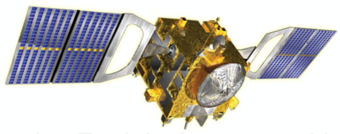
V.

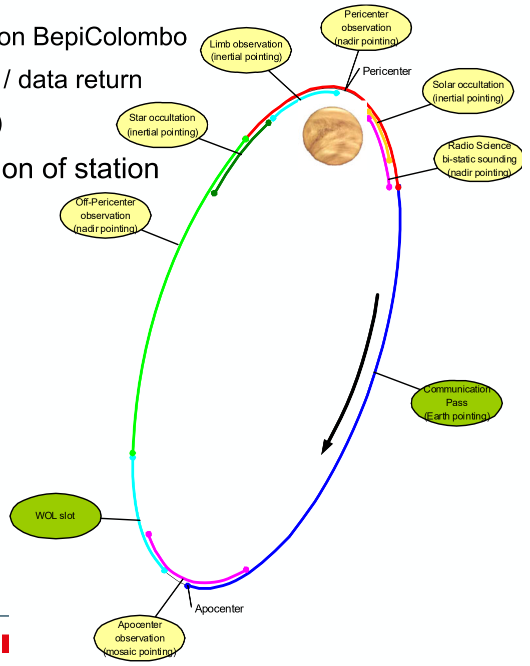
Mission Exploitation

Pictures taken of Arsia Mons Elongated Cloud with Mars Express "Webcam" (Visual Monitoring Camera VMC)
July 2020

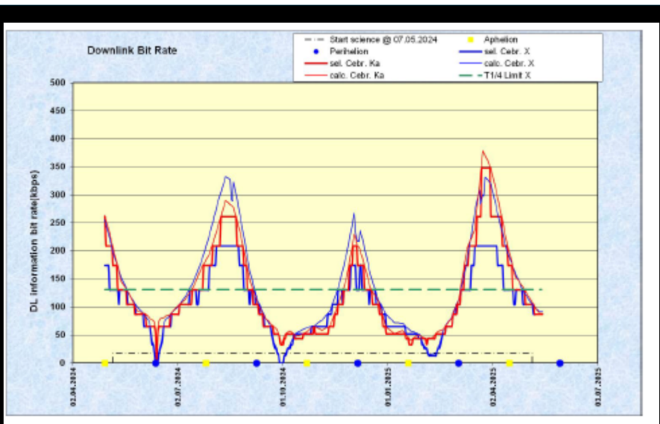
Mission Planning

- Layered planning process to reconcile science requirements with available resources
- Science observations vs. resources:
  - Hardware factors limiting science : thermal on VEX, power on MEX, both on BepiColombo
  - Pointing to Earth (comms) vs. planet (observations) => balance data take / data return
  - Seasonal variability (e.g. @ Mars: data rates 1 to 10, Sun power 1 to 1.5)
- Ground station time is a precious resource: long term planning for allocation of station time to all users
- Venus Express – a benign example:
  - 24h orbit synchronous with Earth rotation
  - All science data taken in one orbit is dumped to Earth in the same orbit
  - Fixed HGA => need dedicated slot per orbit to communicate with Earth
- Mars Express: orbit (7h) not synchronised with Earth rotation => more complex planning

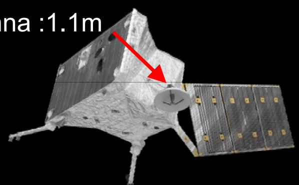




Variability of Data Return (BepiColombo)



- Radio link: X-Band (8.4 GHz) and Ka-band (32GHz)
- Diameter High Gain Antenna :1.1m

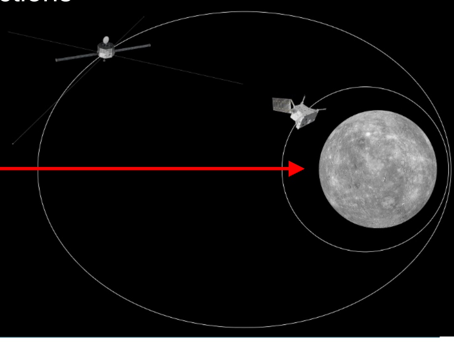


- Yearly variation of visibility hours, depends on station's Earth hemisphere
- Occultations and Conjunctions

Distance Earth-Mercury: 82.3 to 225 Mkm

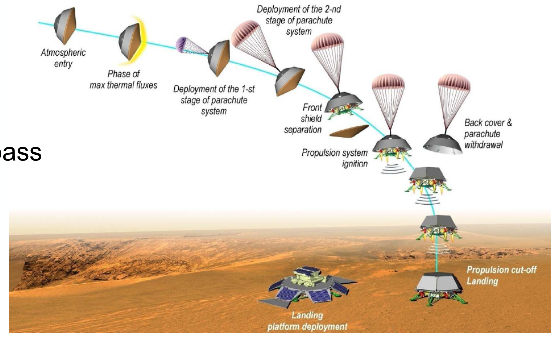
Data rate up to 700kbps

(record only what you can transmit!)



Ops Phases of a Relay Mission (@ Mars)

- Conditions:
  - NASA (resp. ESA) orbiters compatible with ESA (resp. NASA) assets
  - Relay = International co-operation
  - Inter-Agency working groups => provider/user database => inter-SC pass
- Before / During / After Landing:
  - Change orbital phase a few weeks/months ahead
  - Point towards landing asset, record signal
  - Relay to Earth, process it
- On surface:
  - Relay test every few months
  - Exercise all involved items (incl. planning) (same frequency)
  - Lander/rover require daily commanding (weekly for orbiters)
  - => provide access whether used or not (with enough margins)



Similar to operating a station network – the stations flying, the spacecraft on ground

ESA Mars Relay Orbiters

Mars Express 2004-now

3 EDL monitored

Phoenix **Curiosity** *Schiaparelli*

> 170 surface relay sessions

Spirit Opportunity Phoenix Curiosity

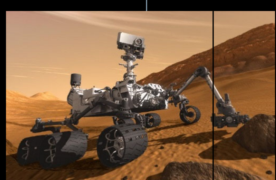
InSight **Perseverance**

Emergency Service

Upon NASA request, 3 days to replace science by Relay plan (1/day)

Curiosity InSight, Perseverance

2016-now ExoMars Trace Gas Orbiter



1 EDL monitored

Schiaparelli

Early surface passes

Perseverance

> 4756 surface relay (*since Jan 2019*)

Curiosity, *InSight*, **Perseverance**

InSight reached end of life End 2022

→ Solar Arrays are covered in dust.

TGO supports Lander search with

~4 relay sessions per week until Oct 2025

Now: MSL/NSY/M20 ~3-4 relay/day

TGO alone conveys > 50% of all Mars surface data

Future (RFM/SRL/MSL/M20): **~6-7+ relay/day**

UHF Radio Science

TGO open loop recording of MEX UHF signal during radio occultation for atmospheric science

Emergency service

Provide relay within hours to any ESA or NASA Lander

MEX and TGO provider of Services integrated to the Mars Relay Network

Challenges of (Very) Long Duration Missions

Technical aspects:

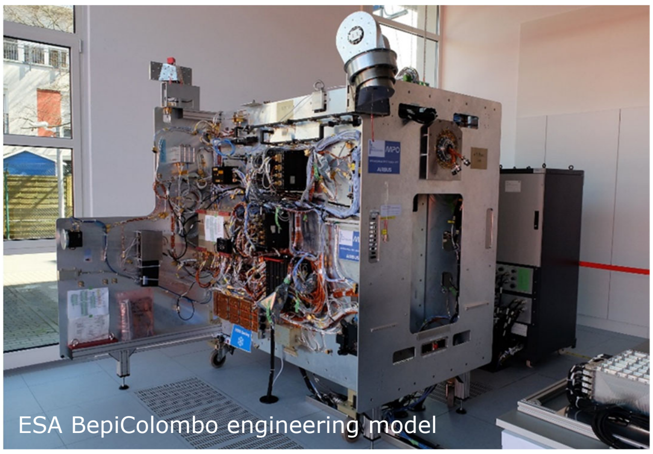
- Rehabilitate an instrument
- Work around (small) anomalies
- Add new functionality
- Redefine operations concept in flight
- Keep the mission working as long as possible

Human aspects:

- Maintain the knowledge and the motivation of the teams

Engineering Models / Benches at the Operations Centre

- Software simulator:
  - Standard for all missions operated at ESOC
  - Central platform on-board software (and select other units, e.g. mass memory) running on a processor emulator => high fidelity testing with the real on-board software
  - Other units (payloads or platform units like star trackers) only simplified models
- Engineering model:
  - For long duration interplanetary missions, engineering models and their GSE get relocated to ESOC around end of Phase E1
  - Done so far for Rosetta, BepiColombo, Solar Orbiter
  - Dedicated facilities required / complicated transport => to be planned well in advance
  - Training of Flight Control Team for bench operations
  - Highly realistic testing with real hardware: a key tool, may save a mission..



ESA BepiColombo engineering model

On-Board Software Maintenance at the Operations Centre

- For long duration missions, handover of On-Board Software Maintenance (OBSM) of the platform software (e.g. avionics, mass memory, star tracker)
- Handover around end of phase E1 (Launch + few months)
  - Transfer of all development environments
  - OBSM training of Flight Control Team
- Typical capability:
  - Implement short to medium level changes
  - Industrial support may still be needed for large changes and for revalidation of spacecraft dynamics (e.g. in case of significant AOCS change)
- OBSM capability at the centre has proven to be essential in the past:
  - E.g. implementation of “gyroless” AOCS modes on Mars Express to work around degradation of gyros following >15 years in orbit
- OBCP maintenance:
  - Handover of OBCP development environment (same approach as for OBSM)
  - Essential due to the high number of changes typically needed in flight, using OBCPs as a powerful tool for implementing workarounds, avoiding to perform OBSM

Team Readiness, Expertise, Motivation

Are you ready to.. *(while staying motivated)*

…invest a significant portion of your <u>career</u> in one mission?

…<u>be blind</u> about the SC for days, weeks, months?

…remember (manage) a problem for 10 years or more?

...learn for years, & manage for longer <u>knowledge</u> for yourself/your successors?

…invent new operations concepts while operating?

…swallow intense <u>peaks</u> of activities in between long cruise phases?

…<u>wait</u> for years until first mission results ?

…swap between <u>exploration</u> and <u>exploitation</u>?

VI.

Conclusions

Rosetta Landing Operations Mission Control Team
Nov 2014

Personal Conclusions and Outlook

- What's it like for me to work in interplanetary S/C operations?
  - Additional complexity at all levels (S/C design, operations) makes the job more interesting!
  - One spends a lot of time working on aspects that aren't even a thing on other missions – e.g. how to separate S/C modules when arriving at Mercury, how to recover a survival mode in deep space..
  - Close involvement in S/C operational design aspects from very early on is very rewarding
  - In flight, there's always something to look forward to (the next critical activity), it doesn't get boring
  - Most memorable experiences: the one-off critical activities (i.e. not only the launch, but also orbit insertions, planetary swingbys, etc.)
  - Strong component of international collaboration beyond Europe (e.g. with JAXA or NASA): super interesting, but also challenging

2003-2004	Rosetta
2004-2006	Venus Express
2006-2013	GOCE
2014-2020	BepiColombo
2020-today	MSR-ERO

- The future of interplanetary missions:
  - ..is bright – as many challenging deep space missions coming to ESA/ESOC as never before!
  - Push for becoming more efficient is present – huge improvements have been made and keep on coming (e.g. comparing the size of teams and number of interplanetary missions operated throughout the last 20 years)
  - Interplanetary flight is still an exclusive club – "competition" by more actors as an enrichment rather than a threat..

THANK YOU!

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BepiColombo 3rd Mercury swingby
June 2023