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MarcoPolo-R near earth asteroid sample return mission

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Abstract MarcoPolo-R is a sample return mission to a primitive Near-Earth Asteroid (NEA) proposed in collaboration with NASA. It will rendezvous with a primitive NEA, scientifically characterize it at multiple scales, and

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return a unique sample to Earth unaltered by the atmospheric entry process or terrestrial weathering. MarcoPolo-R will return bulk samples (up to 2 kg) from an organic-rich binary asteroid to Earth for laboratory analyses, allowing us to: explore the origin of planetary materials and initial stages of habitable planet formation; identify and characterize the organics and volatiles in a primitive asteroid; understand the unique geomorphology, dynamics and evolution of a binary NEA. This project is based on the previous Marco Polo mission study, which was selected for the Assessment Phase of the first round of Cosmic Vision. Its scientific rationale was highly ranked by ESA committees and it was not selected only because the estimated cost was higher than the allotted amount for an M class mission. The cost of MarcoPolo-R will be reduced to within the ESA medium mission budget by collaboration with APL (John Hopkins University) and JPL in the NASA program for coordination with ESA's Cosmic Vision Call. The baseline target is a binary asteroid (175706) 1996 FG3, which offers a very efficient operational and technical mission profile. A binary target also provides enhanced science return. The choice of this target will allow new investigations to be performed more easily than at

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a single object, and also enables investigations of the fascinating geology and geophysics of asteroids that are impossible at a single object. Several launch windows have been identified in the time-span 2020–2024. A number of other possible primitive single targets of high scientific interest have been identified covering a wide range of possible launch dates. The baseline mission scenario of MarcoPolo-R to 1996 FG3 is as follows: a single primary spacecraft provided by ESA, carrying the Earth Re-entry Capsule, sample acquisition and transfer system provided by NASA, will be launched by a Soyuz-Fregat rocket from Kourou into GTO and using two space segment stages. Two similar missions with two launch windows, in 2021 and 2022 and for both sample return in 2029 (with mission duration of 7 and 8 years), have been defined. Earlier or later launches, in 2020 or 2024, also offer good opportunities. All manoeuvres are carried out by a chemical propulsion system. MarcoPolo-R takes advantage of three industrial studies completed as part of the previous Marco Polo mission (see ESA/SRE (2009)3, Marco Polo Yellow Book) and of the expertise of the consortium led by Dr. A.F. Cheng (PI of the NASA NEAR Shoemaker mission) of the JHU-APL, including JPL, NASA ARC, NASA LaRC, and MIT.

Keywords Astrobiology · Near-Earth Asteroid · Origin · Primitive material · Sample return mission · Re-entry capsule

1 Introduction

Small bodies of the solar system are believed to be the remnants - either fragments or “survivors”- of the swarm of planetesimals from which the planets were formed. They are thus primitive leftover building blocks of the solar system formation process that can offer clues to the chemical mixture from which the planets formed some 4.6 billion years ago. Indeed, most asteroids and (dormant) comets, primarily due to their small sizes, experienced less internal heating and so are believed to have retained a record of the original composition of our solar system’s proto-planetary disk. In addition, they retain material that predates the solar system and contains evidence for interstellar processes and its original formation in late-type stars. Current exobiological scenarios for the origin of life on Earth invoke an exogenous delivery of organic matter: abundant within the inner solar system and the main impactors

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on terrestrial planets, small bodies may have been the principal contributors of the water and organic material essential to create life on Earth. They can therefore be considered to be equivalent to DNA for unraveling our solar system's history, offering us a unique window to investigate both the formation of planets and the origin of life. Moreover, collisions of Near-Earth Asteroids (NEAs) with the Earth pose a finite hazard to life. For all these reasons, the exploration of such objects is particularly interesting and urgent.

All but the largest asteroids (diameter > ~100 km) are part of a collisionally evolved population (Fig. 1). The bulk density (porosity), shape (e.g. ellipsoidal to highly elongated), rotation rate and surface morphology (grooves, crater shapes and abundance, crater chains, slope variation) provide clues about the internal structure. This could range from monolithic/cohesive objects (mostly sizes ~ tens of meters), through fractured or shattered objects or contact/separated binaries, to true "rubble piles" of re-accumulated fragments [13] with porosities up to 40% [20]. Figure 2 shows all the small bodies (asteroids and comets) that have been imaged so far by a space probe, demonstrating their great diversity in terms of size, shape and morphology. However, it is important to point out that only one primitive (low-albedo) asteroid, namely the 50 km-size main belt asteroid (253) Malthide, has been observed by a spacecraft to date [30] and only during a brief fly-by and with limited instrumentation. Moreover, the two asteroids that were the ultimate targets of a space mission, namely the asteroids (433) Eros (NEAR, NASA) and (25143) Itokawa (Hayabusa, JAXA), are compositionally evolved. Therefore, we do not have any accurate knowledge regarding small primitive asteroids, while these are

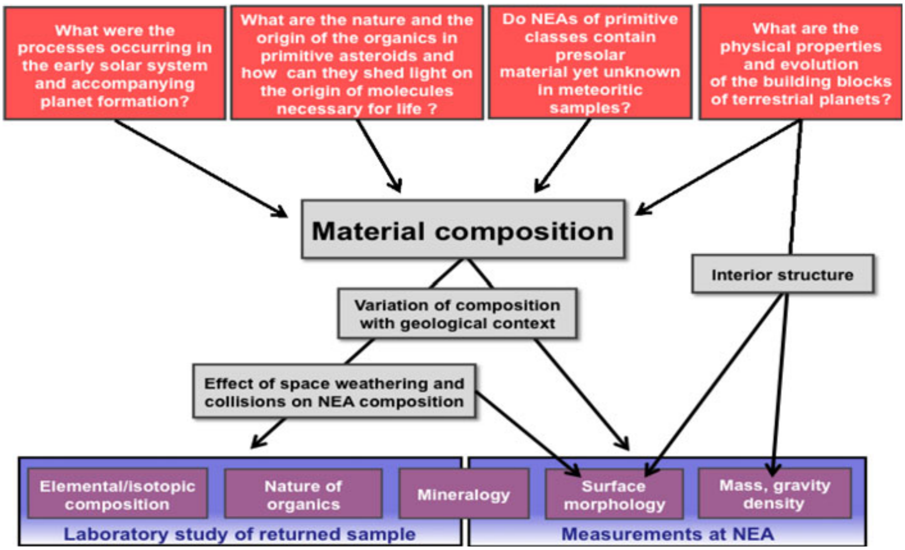


Fig. 1 Logical flow to answer to the fundamental questions

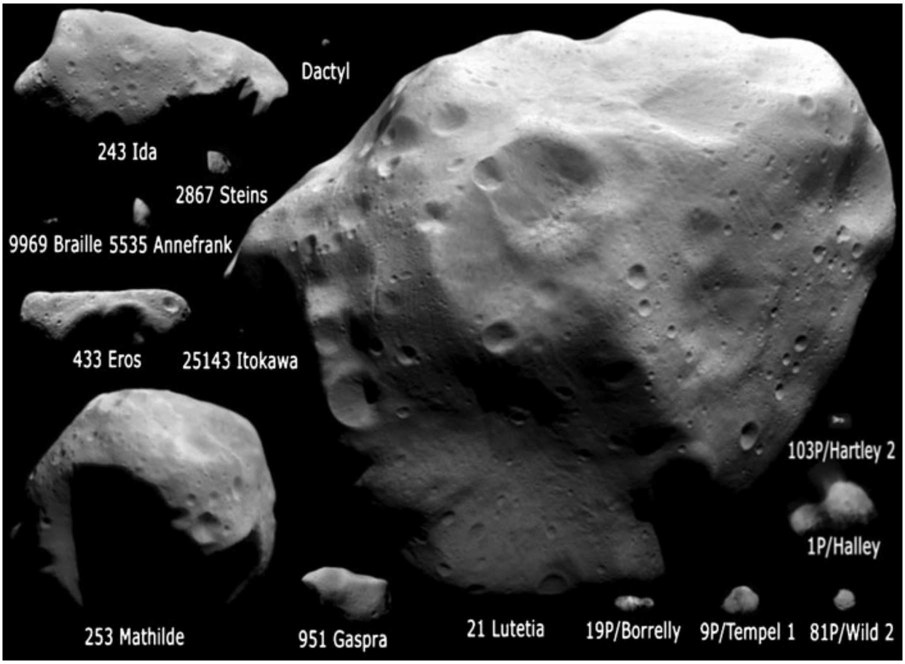


Fig. 2 Images to scale of all small bodies (asteroids and comets) visited so far by space missions, showing the great diversity in size, shape and surface characteristics. The largest body in the image is the 100 km-size Lutetia observed by the ESA mission Rosetta. The smallest object, hardly visible in the image, is the 320 m-size Itokawa visited by the JAXA mission Hayabusa. Adapted from the picture by Emily Lakdawalla (Planetary Society)

the only ones that can provide answers to the key scientific questions addressed by the marcopolo-r mission.

Near-Earth asteroids are a continuously replenished population of small bodies with orbits that come close to the Earth's orbit. Objects in near-Earth space are a precious source of information as they represent a mixture of the different populations of small bodies, i.e. main-belt asteroids and cometary nuclei, and a link with meteorites [5, 9, 15]. They have the orbital advantage of being much more accessible for scientific research and space missions than small bodies in other more distant populations (main-belt asteroids, Trojans and comets). For several tens of NEAs, the Δv required to transfer and insert a spacecraft in orbit around them is lower than that required for the Moon. Moreover, an NEA offers the particular advantage of being related to a specifically known birth region, which from dynamical studies, places most between Mars and Jupiter [6]. A space mission to an NEA therefore provides major opportunities for advancement in our understanding of some of the fundamental issues on the origin and early evolution of the solar system. NEA missions enable an entirely new approach for investigating the primordial cosmochemistry of the solar protoplanetary disk and the formation and properties of the building blocks of terrestrial planets. Moreover, considering the threat represented by those NEAs classified as potentially hazardous objects, knowledge of the physical properties of NEAs (composition and internal structure) is the first essential step towards developing efficient methods to deflect an object whose trajectory leads to a possible collision with the Earth.

The binary asteroid (175706) 1996 FG3 (1996 FG3 hereafter), baseline target of MarcoPolo-R, offers a very efficient operational and technical mission profile. A binary target (15% of the NEA population are binaries) also provides enhanced science return. Several launch windows have been identified in the time-span 2020–2024. A number of other possible primitive single targets of high scientific interest have been identified covering a wide range of possible launch windows consistent with Cosmic Vision 2.

For their high scientific interest, asteroids and comets have been targets of interest for proposals and missions for over three decades. Fly-bys provided the first close-up views of these objects and led to major advances in our knowledge of their physical properties and evolution. However, remote sensing gives only the most superficial information on the surface composition, and even in-situ measurements that could be made by a lander are severely limited by the resources available. Only in the laboratory can instruments with the necessary precision and sensitivity be applied to individual components of the complex mixture of materials that forms an asteroid regolith, as well as to determine their precise chemical and isotopic composition. Such measurements are vital for revealing the evidence of stellar, interstellar medium, pre-solar nebula and parent body processes that are retained in primitive asteroidal material, unaltered by atmospheric entry or terrestrial contamination. It is no surprise therefore that sample return missions are considered a priority by a number of the leading space agencies.

Cosmic Vision 2015–2025 roadmap lays out four fundamental questions to be addressed by ESA's mission programme [10]. For the second of these, "How does the Solar System work?", it states: "The natural next step in ESA's exploration of small Solar System bodies would be a sample return mission of material from one of the near-Earth asteroids." Sample return from a primitive NEA also addresses the Cosmic Vision question "What are the conditions for life and planetary formation?". A first sample return mission proposal, Marco Polo, was submitted to the first call of M-class missions [3] and selected for the Assessment Phase in 2007 (see ESA/SRE (2009) 3, Marco Polo Yellow Book).

The JAXA Hayabusa spacecraft made touch-and-go sampling attempts from the NEA Itokawa in 2005 [11] and the return capsule was successfully recovered in Australia in June 2010. Tiny grains, with total mass $<<1$ mg, have been recovered and appear to be of a highly processed S-type asteroid, with composition consistent with that of thermally-processed ordinary chondrite meteorites [18]. A follow-up mission, Hayabusa 2, is proposed to the primitive NEA 1999 JU3 for launch no later than 2015.

A number of NEA sample return mission concepts have been proposed to NASA's Discovery and New Frontiers programmes. OSIRIS-REx is one of three missions shortlisted for selection in late spring 2011 for a New Frontiers launch in 2016 to the primitive NEA 1999 RQ36.

Despite this strong international interest and activity, as of early spring 2011 there is no asteroid sample return mission that is selected for flight. We propose a European-led mission, MarcoPolo-R, based on the former Marco Polo mission study, but with a revised approach that allows access to a unique target, the primitive binary NEA 1996 FG3. The cost to ESA will be reduced within the medium-class mission budget by collaboration with an international partner. A consortium led by Dr. A.F. Cheng (PI of the NASA NEAR Shoemaker mission) of the Johns Hopkins University-Applied Physics Laboratory, including JPL, NASA ARC, NASA LaRC, and MIT, has formally responded to the NSPIRES solicitation #NNH11ZDA005J (NASA Coordination with ESA's Cosmic Vision Call for Proposals).

The proposed NASA contribution to MarcoPolo-R comprises the following mission elements:

- *Sample acquisition and transfer*, including active sample acquisition devices and robotic mechanisms to transfer samples reliably into a canister;
- *Earth re-entry capsule* (ERC), including sample canister.

These elements provide a well-defined interface with a European spacecraft and save to ESA development costs of a Earth re-entry capsule and sampling mechanism.

In this paper we provide an overview of the new MarcoPolo-R mission and the scientific objectives that can be addressed using the combination of returned samples and in-situ measurements.

2 Science case

2.1 Scientific objectives, motivations and requirements

2.1.1 Scientific objectives

The main goal of the MarcoPolo-R mission is to return unaltered NEA material for detailed analysis in ground-based laboratories. The limited sampling provided by meteorites does not offer the most primitive material available in near-Earth space. More primitive material, having experienced less alteration on the asteroid, will be more friable and would not survive atmospheric entry in any discernible amount. Moreover, the small sample successfully returned by the JAXA mission Hayabusa is confirmed as coming from a highly processed S-type asteroid [18].

MarcoPolo-R will allow us to study the most primitive materials available to investigate early solar system formation processes. Moreover, MarcoPolo-R will provide a sample from a known target with known geological context. Direct investigation of both the regolith and fresh interior fragments is also impossible by any means other than sample return.

MarcoPolo-R will provide scientific results that are crucial to answer the following key questions:

1. What were the processes occurring in the early solar system and accompanying planet formation?
2. What are the physical properties and evolution of the building blocks of terrestrial planets?
3. Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?
4. What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?

Answers to these fundamental questions require measurements with exceptionally high precision and sensitivity. Such measurements cannot be performed by a robotic spacecraft and therefore require a sample returned to terrestrial laboratories, which are unconstrained by mass, power, stability etc. The most demanding measurements are those required to date the major events in the history of a sample, and to investigate the organic components. Laboratory techniques determine the time interval between the end of nucleosynthesis and agglomeration, the duration of agglomeration, the time of accumulation, the crystallization age, the age of major heating and degassing events, the time of metamorphism, the time of aqueous alteration, and the duration of exposure to cosmic radiation.

MarcoPolo-R will answer the fundamental scientific questions listed above and outlined in Fig. 1.

The MarcoPolo-R mission to a primitive NEA (dark C, D, and similar spectral classes) will provide crucial elements to answer the key questions expressed above. In the following, we shortly indicate why MarcoPolo-R can provide fundamental elements to answer those questions.

> What were the processes occurring in the early solar system and accompanying planet formation?
>
> The solar system formed from a disk of gas and dust orbiting the Sun. Primitive objects are expected to include the earliest condensed material (Calcium-Aluminium Inclusions (CAIs) and chondrules) and material made and/or modified by stellar outflows, the Inter-Stellar Medium (ISM), and the solar protoplanetary disk, as well as by parent-body processing (e.g. thermal metamorphism). MarcoPolo-R, by returning primitive material from a small body and knowing the geological context in which it was residing, offers the possibility of distinguishing between effects of solar-nebula processing and effects of alteration from asteroidal parent-body processing. Primitive material also permits determination of the abundance of a number of short-lived radionuclides present at the time of formation of a variety of early solar-nebula components that

are essentially free from the concerns of partial re-setting or secondary process effects. They therefore offer a clear insight into the timing of the formation of these components and their origin, whether it is local (e.g. irradiation and ejection by X-wind) or remote (e.g. stellar nucleosynthesis). The abundance of the various short-lived nuclides provides an important constraint on possible triggering mechanisms for the collapse of the proto-solar molecular cloud.

What are the physical properties and evolution of the building blocks of terrestrial planets?

The current physical and chemical properties of an asteroid have been shaped by its evolution since the condensation and agglomeration that formed its parent planetesimal in the asteroid belt. This evolution includes some or all of: thermal metamorphism, aqueous alteration, collisional disruption, re-accumulation, regolith processing and space weathering. For the most primitive asteroids, the effects of these processes are expected to be minor, or even minimal, and will not obliterate the record of early nebular conditions at formation. The sample of mixed NEA regolith returned by MarcoPolo-R will likely contain components displaying varying degrees of asteroidal processing that must be accounted for to permit study of the earliest stages of solar system formation, but will also allow detailed investigation of the evolution of the solar system from its formation to the present day. In particular, it will offer a unique opportunity to follow the effects of progressive aqueous alteration, that are supposed to have been undergone by 60% of C-class main belt asteroids [2], on the mineralogy and organic inventory of a suite of rocks. This will also provide further insight to the abundance and isotopic signatures of water originally accreted at 3–5 AU and will allow checking the possibility that primitive asteroids are responsible for the abundance of water now present on Earth that is so essential for all life.

Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?

Primitive material is expected to contain pre-solar grains, in particular silicates. The latest and potentially the most important group of grains identified in meteoritic material is the one composed of interstellar silicates. MarcoPolo-R will offer the opportunity to investigate the abundance of pre-solar grains accreted in the parent body and to search for new, less robust grains which have not survived the meteorite formation processes. Moreover, by their very nature, the rims or mantles of those grains are likely to be particularly susceptible to modification or destruction during meteorite formation on the parent body. Primitive material collected from the surface of an NEA offers the best opportunity for obtaining pristine grains.

> What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?
>
> Current exobiological scenarios for the origin of life invoke an exogenous delivery of organic matter to the early Earth. It has been proposed that carbonaceous chondrite matter (in the form of planetesimals down to cosmic dust) could have imported vast amounts of complex organic molecules capable of triggering the prebiotic synthesis of biochemical compounds (e.g. Maurette [12] and references therein). Current investigations of the most primitive organic materials available from samples such as the Stardust cometary samples, interplanetary dust particles (IDPs) and micrometeorites are limited to a few techniques – i.e. those offering exceptional spatial resolution or sensitivity, but due to the very small sample size, lacking detailed abundance and isotopic information available from the meteorite samples. A sample of mixed regolith from a primitive NEA containing a number of components with varying degrees of aqueous alteration would give definitive answers on the formation processes of carbonaceous matter in interplanetary material. It would help to determine the origin of compounds such as the amino acids – by monitoring how the abundance of the amino acids, and their possible precursor, evolves with the degree of aqueous alteration (as determined by mineralogy). By returning a sample free from terrestrial contamination, any ambiguity created by life on the Earth is eliminated.

2.1.2 Why a sample return?

Many of the science questions we are attempting to resolve stem from detailed knowledge obtained from high-precision and high-sensitivity measurements of meteorites. However, since only the strongest material reaches the Earth, it is not known whether meteorites are representative of the dominant material in space. In fact, various clues point to an abundance of material that does not survive atmospheric entry. For instance, the C-class asteroids account for about 75% of all main belt asteroids, and their nearest meteoritic equivalents, the somewhat friable carbonaceous chondrites, are present in our meteorite collections at the level of less than 5%.

Furthermore, interpretation of all remote observation data will be greatly enhanced by "ground truth" analysis. A significant complication in this interpretation comes from space weathering which can alter the surface properties of airless bodies. The effects of space weathering are very difficult to simulate in the laboratory, but have been studied in great details using returned lunar samples. However, the composition of the space environment at the lunar surface is quite different from that of asteroids. Laboratory reflectance spectra of individual components from a returned sample of a primitive NEA can be compared with telescope spectra. The level of space weathering each component has experienced can also be determined mineralogically and geochemically (e.g. noble gas studies), by comparison with the mineralogy and chemistry of known meteorite types. Only on the basis of MarcoPolo-R sample analysis will it be possible to apply the knowledge obtained from meteorites to the vast amount of information available from asteroid observations.

The anticipated scientific advances with the new sample from a primitive asteroid, will only be achievable with the level of analytical capability provided by laboratory instruments. MarcoPolo-R will collect at least 5 orders of magnitude more material than Stardust, permitting more sample-specific selection from the expected complex mixture of asteroid regolith. Most importantly, MarcoPolo-R will be able to collect the sample such that its physical/chemical content is not modified during its collection. Moreover, contrary to the sampling strategy of Stardust and similarly to Apollo missions, the sampling area will be selectable after inspection from orbit. There will also be a strong control on any possible contamination, particularly by and for the organics. It is clear that in order to answer the science questions that MarcoPolo-R seeks to address, laboratory analysis of a sample of a primitive asteroid is required. The great added benefit of sample return is that the analyses can be refined to account for unexpected features of the sample, and that material is available to address new scientific questions which may arise or for new techniques that are developed during the long lead time up to the return of the sample in such a mission.

The study of the MarcoPolo-R sample within the larger context of extraterrestrial primitive materials will greatly advance the understanding of the nature and origins of primitive materials in the solar system.

2.1.3 Scientific requirements

MarcoPolo-R will provide fundamental elements to answer the key science questions indicated in the previous subsection and reported in Table 1 together with the related scientific objectives.

To reach these objectives, the main goal is: *to return a sample from a near-Earth asteroid belonging to a primitive class* that will allow the analysis of asteroid material in ground-based laboratories to study the formation of the solar system and its planets, the characterization of an NEA as a representative of a primitive solar system body, and contribute to the field of astrobiology.

The sample provides a legacy for future generations of scientists with the potential for application of new analysis techniques and instrumentation to address as yet unexplored aspects of planetary science.

In addition, in-situ observations, and possible surface measurements shall be made to provide local and global geological and physical context for the returned sample.

2.2 Target selection

A *primitive asteroid* is considered to be a low-albedo object of spectral class B, C, D, P or T including sub-classes, according to the taxonomic classification by Barucci et al. [1] and Bus and Binzel [7, 8].

Table 1 Science questions and objectives, with measurements and methods to be used to address them

Science questions	Science objectives	Measurements	Method
What were the processes occurring in the early solar system and accompanying planet formation?	Characterize the chemical and physical environment in the early solar nebula	Bulk chemistry	Sample analysis
	Define the processes affecting the gas and the dust in the solar nebula	Mineralogy, petrology	
	Determine the timescales of solar nebula processes	Isotopic chemistry in inclusions (e.g., chondrules or CAIs), matrix; pre-solar grains and volatiles, water	
What are the physical properties and evolution of the building blocks of terrestrial planets?	Determine the global physical properties of an NEA Determine the physical processes, and their chronology, that shaped the surface structure of the NEA Characterise the chemical processes that shaped the NEA composition (e.g. volatiles, water)	Volume, shape, mass Surface morphology and geology Mineralogy, petrology Isotope geochemistry & chronology Weathering effects Thermal properties	Imaging Laser altimetry[a] Radio Science Visible and Near-IR spectrometry Sample analysis Neutral particle analysis Mid-IR spectrometry
	Link the detailed orbital and laboratory characterization to meteorites and interplanetary dust particles (IDPs) and provide ground truth for the astronomical database	Radar absorption[a] Seismic waves[a]	LIBS[a] Penetrating radar[a] Seismic Exp.[a]
Do NEAs of primitive classes contain pre-solar material yet unknown in meteoritic samples?	Determine the interstellar grain inventory	Bulk chemistry	Sample analysis
	Determine the stellar environment in which the grains formed	Mineralogy, petrology	
	Define the interstellar processes that have affected the grains	Isotopic chemistry in inclusions (e.g., chondrules or CAIs), matrix; pre-solar grains and volatiles, water	
What are the nature and origin of organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life?	Determine the diversity and complexity of organic species in a primitive asteroid Understand the origin of organic species Provide insight into the role of organics in life formation	Abundances and distribution of insoluble organic species Soluble organics Global surface Distribution and identification of organics	Sample analysis Visible and Near-IR Imaging-spectrometry

[a] Optional

The primitive C-type binary (175706) 1996 FG3 has been chosen as the baseline target of MarcoPolo-R, primarily because it is a relatively accessible binary NEA. Indeed, the science return is maximised by choosing a binary as in this case, there is also the possibility of observing evolutionary processes still in action as well as striking geophysical effects, such as regolith motion (as suggested for the binary 1999KW4 observed by radar; [22]). Moreover, one can better understand the potential outcome of YORP spin-up (the YORP effect is a thermal effect that can slowly increase or decrease the rotation rate of irregular objects) and test models of formation of a system that represents a non-negligible fraction (15%) of asteroid populations. Relevant to MarcoPolo-R objectives, one of the most important implications of the model of binary formation by YORP spin-up [28] is that the pole of the primary should be composed of fresh material that was originally at some depth in the progenitor. In effect, when spun-up, the material of the pole of the progenitor migrates to the equator and when the centrifugal force exceeds the gravity of the body, this material escapes from the surface to form the secondary. Collecting samples from the pole of the primary can therefore provide a means of obtaining material that was originally inside the body without having to drill into it.

Thanks to its binary nature, the sizes, mass and orbit pole direction of the system can be estimated from Earth-based observations. This knowledge of basic physical parameters will enhance navigation accuracy and lower mission risk during the rendezvous; it will reduce the time required for initial characterization before entering into close-in, bound orbits.

The current orbit of 1996 FG3 ranges from 0.69 to 1.42 AU from the Sun. A probabilistic model [6] of its orbital evolution shows a 93% probability that it entered near-Earth space via the $\nu 6$ resonance after forming in the 2.1–2.5 AU region of the main asteroid belt. Optical lightcurve observations reveal its binary nature [16, 19, 23], with a 16 hour mutual orbit period and a 3.6 hour primary rotation period. 1996FG3 will closely approach Earth in November 2011, when an extensive campaign of radar imaging is planed. This should significantly improve our understanding of the physical properties and the orbital parameters. Table 2 summarizes the main known physical properties of 1996 FG3.

In addition to 1996 FG3, other primitive asteroids can be considered as appropriate back-up targets that are easy to reach and that altogether offer

Table 2 Physical properties of the baseline binary target (175706) 1996FG3

Primary diameter	1.9 ± 0.5 km[a]
Primary geometric albedo	0.035
Primary spin period	3.595 ± 0.002 h
Primary density	1.4 ± 0.3 g cm^{-3}
Primary taxonomic type	C
Secondary to primary diameter ratio	0.28 ± 0.02
Secondary orbital semimajor axis	3.1 ± 0.5 km
Secondary orbital eccentricity	0.1 ± 0.1
Secondary orbital period around primary	16.14 ± 0.01 h

All properties are available on the E.A.R.N. website
[a] From Mueller et al. [17]

a wide range of launch opportunities. All are single objects that can allow us to achieve the science objectives of a sample return mission to a primitive asteroid, except the additional ones specifically linked to binaries.

2.3 Sample requirements

There is a vast array of analytical tools for the characterization of returned materials encompassing many techniques spanning the principal approaches of microscopy and spectroscopy/spectrometry. These are shown in Table 3, together with the mass of selected material for a given measurement and an estimate of the mass of original sample required.

The required mass has been derived in such a way as to guarantee the scientific success of the mission. Different aspects have been taken into account to evaluate the returned mass, specifically: the probability that an amount of each sample component is sufficient for analysis was estimated; a statistical analysis of the returned sample has to be done in the laboratory (e.g. at least three different measurements in three different laboratories have to reproduce the same results); and finally 1/3 of the returned mass has to be stored for an indefinite time in the Curation Facility for future analysis. A few tens of grams of sample will guarantee the scientific success of MarcoPolo-R.

In almost all cases no single measurement, or type of measurement, will provide the complete answer to any of the questions. Instead, our understanding will be derived from the results of many analyses of different components of the returned sample, and by a plethora of techniques.

2.4 Remote sensing analysis

The scientific requirements and associated measurements at the asteroid are structured in three phases: *‘global characterization’*, *‘local characterization’*, and *‘sample context measurements’*:

- *‘Global characterization’* means to measure the properties of the whole NEA, on a global scale;
- *‘Local characterization’* is the characterization of dedicated areas which are identified as potential sampling sites;
- *‘Sample context measurements’* are measurements being performed at the actual sampling site.

The global characterization of the body is required to obtain as complete a picture as possible of the physical nature of the NEA in order to relate the properties of the sample to those of the parent body. Moreover, for the overall success of the mission, the global characterization will allow the selection of a number of surface areas as potential locations for the intended surface sampling.

Table 3 Scientific information obtained from analysis of various types of materials expected in the returned sample, sample requirements to achieve the scientific result, and estimate of the required mass for a given measurement

Component	Scientific aspects			Measurement requirements			
	Goal	Objective	Theme	Measurement type	Techniques	Required mass	Single analysis mass
Chondrules, refractory inclusions, inclusions, matrix	1	C	Age	Isotopic abundances	SIMS, LA-ICPMS, MC-ICPMS, TIMS	Gram	10 s pg (SIMS) to 10 s mgs (TIMS) per analyses
	1	B	Disk dynamics	Mineralogy & mineral chemistry chemistry	EMPA, SEM, TEM, XRS, FTIR, Raman, SIMS, LA-ICPMS	Gram	ng (EMPA) to μgs (LA-ICPMS) per analysis
	1	A	Volatility fractionation	Elemental and isotopic abundances	SIMS, LA-ICPMS, GS-MS, NG-MS	100 s mgs	10 s pg (SIMS) to 100 s μgs (NG-MS) per analyses
	1	B	Processing	Elemental and isotopic abundances	SIMS, LA-ICPMS, MC-ICPMS, GS-MS, NG-MS	Gram	10 s pg (SIMS) to 10 s mgs (MC-ICPMS) per analyses
	1	B, C	Thermal history	Mineralogy and mineral chemistry	EMPA, SEM, TEM, XRS, FTIR, Raman, SIMS, LA-ICPMS	Gram	ng (EMPA) to μgs (LA-ICPMS) per analysis
	1	A, B, C	Accretion dynamics	Mineral chemistry	EMPA, SEM, TEM, XRS, FTIR, Raman, LA-ICPMS, SIMS	Gram	ng (EMPA) to μgs (LA-ICPMS) per analysis
	2	L	Interstellar processes	Elemental and isotopic abundances	SIMS, CS-GS-MS, NMR, GC-MS, XANES, STXM, μL^2MS	10 grams	10 s ag (GC-MS) to gram (NMR) per analyses
Organics	1	A, B	Early solar-system processes	Chemical analyses, elemental and isotopic abundances	SIMS, GS-MS, NMR, Raman, XANES,	Several grams	10 s ag (GC-MS) to gram (NMR) per analyses
	3	K, L	Asteroidal processes	Chemical analyses	NMR, Raman, XANES, HPLC, GC-MS, μL^2MS	100 s mgs	10 s ag (GC-MS) to gram (NMR) per analyses
	3	K, L, M	Origin of life	Chemical analyses	Laser GSMS, NMR, Raman, XANES, HPLC, GC-MS, μL^2MS	Several grams	10 s ag (GC-MS) to gram (NMR) per analyses
	3, 4	D, L	Collisional history	Mineral composition	EMPA, SEM, TEM, XRS, FTIR, Raman	100 s mgs	10 s pg (Raman) to ngs (EMPA) per analyses

Table 3 (continued)

Component	Scientific aspects			Measurement requirements			
	Goal	Objective	Theme	Measurement type	Techniques	Required mass	Single analysis mass
Lithologies & breccias	4	F	Aqueous alteration	Mineralogy	EMPA, SEM, TEM, XRS, FTIR, Raman, GS-MS, SIMS	Several grams	10 s ag (GC-MS) to 100 s μgs (GS-MS) per analyses
	4	D	Shock processes	Mineralogy	EMPA, SEM, TEM, XRS, FTIR, Raman	Several grams	10 s pg (Raman) to ngs (EMPA) per analyses
	4	F, L	Thermal alteration	Mineralogy	EMPA, SEM, TEM, XRS, FTIR, Raman, SIMS, GS-MS	Several grams	10 s ag (GC-MS) to 100 s μgs (GS-MS) per analyses
	4	F, G, L	Space weathering	Mineralogy	EMPA, SEM, TEM, XRS, FTIR, Raman, Opt. spectro., ESR, NG-MS, SIMS, GS-MS, susceptometer	Gram	10 s pg (SIMS) to mgs (susceptometer) per analyses
	4	D	Physical properties	Strength, porosity, thermal diffusivity	Helium pycnometer, differential scanning calorimeter	Gram	mgs (differential scanning calorimeter) to 100 s mgs (Helium pycnometer)
	4	D, L	Age	Mineralogy & isotopes	EMPA, SEM, TEM, XRS, FTIR, Raman, SIMS, NG-MS, ICPMS	Gram	10 s pg (SIMS) to 10 s mgs (ICPMS) per analyses
Pre-solar grains	2	H, I	Nucleosynthesis	Elemental and isotopic composition	SIMS, NG-MS, TEM, SEM	Several grams	10 s pg (SIMS) to 100 s μgs (NG-MS) per analyses
	1, 2	B, H, I	Circumstellar processes	Mineralogy and mineral chemistry	SEM, TEM, Raman, SIMS, Auger spectr.	Gram	10 s pg (SIMS) to 100 s μgs (NG-MS) per analyses
	2	H, J	Interstellar processes	Isotopes and mineralogy	SEM, TEM, Raman, SIMS, Auger spectr.	Gram	ags (Auger) to 10 s pgs (SIMS)
	1, 2	C, I, J	Age	Isotopes	SIMS, NG-MS	Several grams	10 s pg (SIMS) to μgs (NG-MS) per analyses

For each science area, the range for the minimum amounts of consumed material is shown in column 'single analysis mass'

3 Mission profile

There are a wide range of options available when defining a mission profile for an asteroid sample return mission. Mission design choices have to be made taking into account the main constraints and design implications, which for MarcoPolo-R are summarised below:

- Preferred target: the binary 1996 FG3
- Launch vehicle: Soyuz/Fregat
- Minimum stay time at the asteroid: 3 months
- Maximum entry velocity: 15–16 km s^{-1}, limited by the ERC heatshield material capabilities.

3.1 Launcher requirements

For the preferred target and selected launch vehicle, feasible missions can be found using chemical propulsion by launching into Geosynchronous Transfer Orbit (GTO) and using two space segment stages. The use of a GTO launch with a large propulsion capability enables more mass to be delivered to the asteroid and therefore a feasible return mission. A direct injection trajectory was ruled out to meet the Δv requirement for the target 1996 FG3. Electric propulsion may offer attractive alternatives to the chemical one (lower escape velocity, no planetary assist) though at higher cost. A staged space segment, adopted during the preliminary assessment, has shown that the inclusion of a separate propulsion module to perform the escape manoeuvres from GTO and the outbound transfer leads to a lower launch mass and therefore greater launch margin.

3.2 Orbit requirements

An initial assessment of the transfer opportunities to 1996 FG3 has been carried out (Table 4) and several potential mission scenarios were identified within the 2020–2024 launch timeframe. Earlier launch windows (e.g. in 2018) also offer good opportunities. The mission will be launched from Kourou

Table 4 Possible baseline mission scenarios

Launch	Mission duration (years)	Stay time (months)	Δv (km s^{-1})	Entry v (km s^{-1})
10.03.2020[a]	6.98	10.5	2.07	12.0
10.03.2020[a]	4.70	3.5	1.9	15.0
23.02.2021[a]	9.09	13.7	2.93	12.0
24.04.2021	**7.99**	**16.1**	**2.81**	**13.6**
09.01.2022	**7.28**	**9.3**	**2.88**	**13.6**

As defined according to the designs of OHB/GMV and Astrium. Prime and backup baseline mission scenarios are indicated in bold

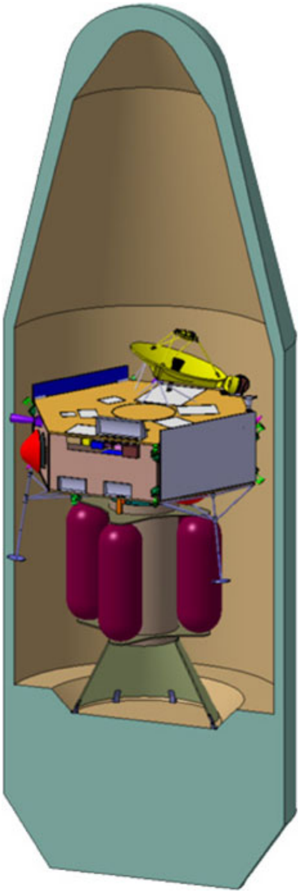
[a] Defined according to the designs of OHB/GMV

on board a Soyuz/Fregat launcher (Fig. 3). Figure 4 shows an overview of the baseline mission. The propulsion module will provide the Δv to inject the composite into an interplanetary transfer that would include planetary (Venus or Venus-Earth) fly-bys. This is followed by the asteroid approach phase during which the propulsion module will be jettisoned, with the science module performing the targeting manoeuvres required to rendezvous with the asteroid.

When the spacecraft is close enough to the asteroid, the interplanetary cruise ends and the approach phase begins. An on-board star sensor or narrow angle camera is used to detect and track the NEA. Some braking manoeuvres are executed to reduce the approach velocity and increase the knowledge of the spacecraft relative state with respect to the asteroid. This phase is similar to the Rosetta approach phase, that typically lasts one month.

When the spacecraft is at a few tens of km from the asteroid, the proximity operations start. The first sub-phase of the proximity operations is Far Station Keeping. The on-board Guidance Navigation Control/Attitude and Orbit Con-

Fig. 3 Mission composite in Soyuz Fairing (Astrium design)



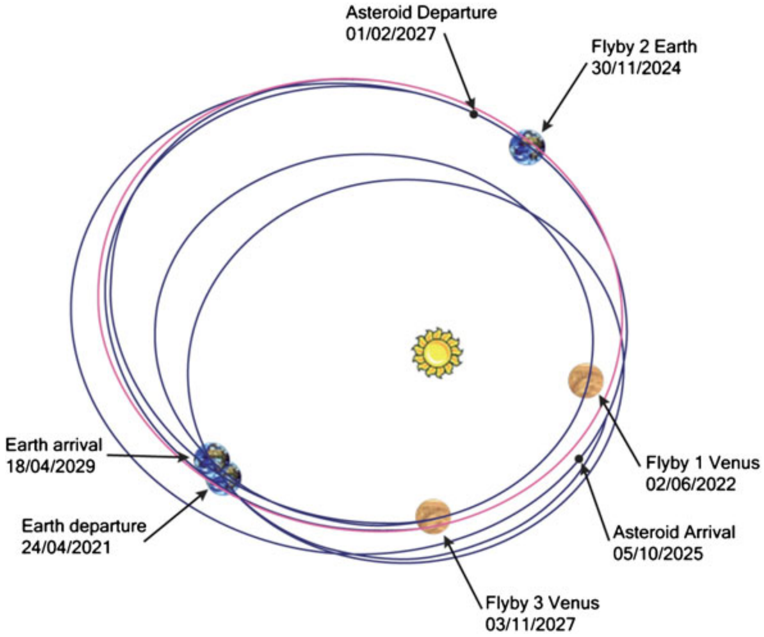


Fig. 4 Example of MarcoPolo-R overall trajectory with launch in 04/2021 (from Astrium)

trol System/Failure Detection, Isolation and Recovery (GNC/AOCS/FDIR) system has been developed in a Technology Research Program activity at ESA led by GMV company (called NEO-GNC).

This technique assures safe station keeping using a wide angle camera. Only light curves taken from ground observatories (prior to launch) and refined using on-board observations during the approach phase are needed.

During this phase, a known landmark database is built. Enough time to observe a large portion of the surface of the asteroid should be allocated ($\sim$1 month). To ensure good visibility of the asteroid, the Far Station location should be close to the Sun-asteroid line. Several station positions at closer distances are foreseen, that allow a robust identification of landmarks on the surface and eventually a more precise estimate of the gravity parameters of the asteroid.

When the distance is close enough, the spacecraft can be injected into a Self-Stabilised Terminator Orbit (SSTO), which requires very sparse manoeuvres for perturbation control. The duration in this phase shall allow for radio science experiment and for identification of the landing site. Remote sensing activities are performed, characterizing the asteroid in different levels of detail and determining its main gravitational, thermal and topographic characteristics. Local characterization shall be performed for some selected potential landing sites.

After a landing site is selected, the Descent & Landing phase (D&L) can start. Up to three sampling attempts are considered. The D&L can be preceded by some rehearsals, which are essentially a D&L procedure stopped at a certain altitude. The spacecraft will follow a predefined descent profile that fulfils all constraints to achieve safely the required landing accuracy. At a given altitude, the D&L phase shall be performed by the spacecraft autonomously.

After touch-down, the surface operations shall start, beginning with the spacecraft stabilization, then execution of the sampling phase, transfer of the collected material to a canister inside the ERC and the ascent phase, which ends when the spacecraft is in the desired safe haven (a station position or a SSTO). From this point, the mission can perform additional science observations and prepare for the return flight (inbound trajectory).

The spacecraft will be injected on to the return trajectory, which may include a Venus fly-by, ending with ERC release and Earth atmospheric entry.

Back-up missions have been identified for alternative targets 1999 JU3 and 1999 RQ36.

4 Model payload

4.1 Overview of proposed payload

As requested for an M class mission, the proposed instruments (Table 5) are based on existing/under development technologies (TRL $\geq$ 4), and have already been assessed as a result of the assessment study phase of the former Marco Polo Mission in 2008–2009; details of the payloads can be found in the resulting Payload Definition Document (PDD, ESA/ESTEC, SCI-PA/2008/002/Marco-Polo PDD). Some optional payloads have also been considered (see Sections 4.2.8 and 4.3). The possibility to have further optional payloads will be analyzed during the assessment study.

4.2 Summary of each instrument's key resources and characteristics

4.2.1 Wide Angle Camera (WAC)

Images provide important information on the morphology and topography of the NEA surface and are necessary to choose the landing site. WAC imaging will provide the data:

- To obtain the first bulk characterization of the NEA (size, shape, rotational properties) during cruise phase
- To map the entire surface
- To identify the landing site (elaboration of a Digital Elevation Model)
- To map the secondary of the baseline target or search for moonlets in the other cases
- To support spacecraft navigation.

Table 5 Overview of the nominal payload complement and main resource budgets

	Wide Angle Camera (WAC)	Narrow Angle Camera (NAC)	Close-Up Camera (CUC)	Visible Near Infrared spectro. (VisNIR)	Mid-Infrared spectro. (MidIR)	Radio Science Experiment (RSE)	Neutral Particle Analyser (NPA)
Mass [kg]	2.0	8.92	0.82	3.6	3.0	Contained in the resources of the radio subsystem	2.2
Volume [mm]	237 × 172 × 115	520 × 380 × 197 250 × 170 × 120	364 × 78 × 68	270 × 110 × 90 150 × 180 × 82	160 × 220 × 370	Contained in the resources of the radio subsystem	200 × 200 × 100
Power [W] average	11.5	13.5	12.5	18	2		11
Data volume single measur.	67 Mbit	67 Mbit	67 Mbit	0.45 Mbit	360 Mbit	Data recorded in the ground station in real time	0.72 kbit
Heritage	Rosetta, ExoMars, ISS, Bepi Colombo	Rosetta, ExoMars, ISS, Bepi Colombo	Rosetta, ExoMars, ISS, Micro-rover (ESA)	Mars/Venus Express, Rosetta	SMT, TechDemSat		Bepi Colombo

The WAC is a small-aperture camera for the visible wavelength range providing wide angle low resolution images of the target (or other fields).

4.2.2 Narrow Angle Camera (NAC)

The asteroid is intrinsically a dark object. The low contrast resulting from the low albedo makes it difficult to obtain high contrast images that are necessary to study the regolith properties well. A high contrast image can be obtained only if the optical contrast performance of the camera, including the residual diffraction contribution, is very high. One of the main scientific objectives of the NAC is the generation of the Digital Terrain Model (DTM) of specific regions, in particular of the potential and the actual sampling area. The NAC optical design is based on an off-axis three mirror anastigmatic configuration which follows the heritage of the OSIRIS cameras for the Rosetta mission. According to preliminary calculations it is not necessary to have a panchromatic filter covering the entire spectral range. One filter with broad-band coverage of 100 nm, and up to seven filters with bandwidths of 5–10 nm provide coarse spectral resolution for composition/colour diagnostics. Their central wavelengths will be selected according to specific scientific simulations.

4.2.3 Close-Up camera (CUC)

Images acquired with a close-up camera are needed to perform the local characterization of the sampling site. Images must be taken before the sampling to study the surface structure (i.e. the arrangement of larger and smaller particles and dust). The structural property of the surface will likely be destroyed during the sample acquisition. Images of the sampling site after the sample collection will allow an estimate of the friction coefficient of the regolith from observations of slumping of material. The CUC is a compact imaging device for the 400–900 nm wavelength range designed for microscopic resolution (better than 100 nm).

4.2.4 Visible Near-Infrared Spectrometer (VisNIR)

Spectroscopy in the VisNIR range is a powerful technique for the characterization of the chemical and mineralogical surface composition. The proposed instrument (Fig. 5) is a classical slit imaging spectrometer composed of a reflecting telescope imaging the scene at the entrance slit of the spectrometer.

On a 2D detector, this kind of imaging spectrometers records a 1D image and a full spectrum of each point of the 1D image. Either the motion of the spacecraft with respect to the asteroid or a scanning mirror is needed to recover the second spatial dimension.

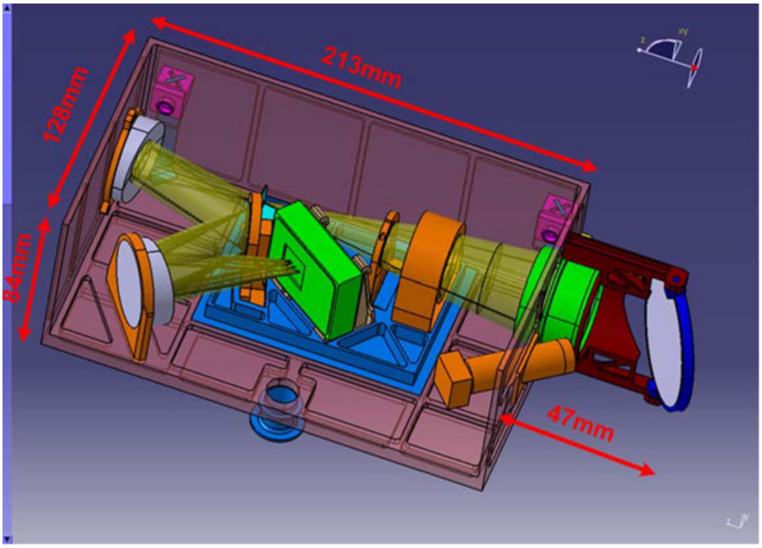


Fig. 5 VisNIR spectro. optomechanical scheme

4.2.5 Mid-Infrared Spectrometer (MidIR)

The Mid-Infrared spectrometer analyses the thermophysical properties of the surface (thermal inertia) by measuring changes in thermal emission due to the day/night temperature cycle. It provides information on surface mineralogical and chemical composition and the combined results are important in addressing sample site selection.

The proposed instrument is an imaging Fourier transform mapping spectrometer utilising a beam-shearing interferometer to generate a set of spatially resolved interferograms that are imaged onto a detector array. This allows spectral image cubes of the target body to be measured. The instrument uses a mid-infrared beam splitter and all reflective optics to image the interferogram onto a 640 × 480 micro-bolometer array.

4.2.6 Neutral Particle Analyser (NPA)

The NPA is designed to detect neutral particles released from the asteroid's surface and to investigate the effect of space weathering. Discrimination of the major components of the escaping flux will add important information also on surface composition. Detecting and characterizing neutral atoms in the energy range of interest, <1.0 eV to 1.0 keV, in an environment of photon, electron and ion fluxes, requires (1) highly effective suppression of photons, electrons, ions, and (2) two sensors for particles above and below 10 eV. The incoming radiation made by neutrals, ions and photons impinges upon an aperture. The ions and electrons are deflected by an electrostatic lens before the entrance. The neutral particles pass through an entrance of about 1 cm^2 divided for detecting both low energies and higher energies separately.

4.2.7 Radio Science Experiment (RSE)

Radio Science will use the radio subsystem of the main spacecraft for its observations. The goal is to derive the mass of the target body and if feasible low order gravity harmonics by observing the Doppler shift of two downlink radio carrier frequencies at X-band and Ka-band caused by the perturbation of the spacecraft motion.

4.2.8 Optional laser altimeter

A Laser altimeter measures, with high precision, the distance of the spacecraft from the surface of the NEA. The instrument can measure the two-way travel time of a pulse between the instrument and the surface. A topographic profile along the ground track of the spacecraft can be produced from which a global shape model can be derived (in conjunction with WAC and NAC images). By measurements of pulse amplitude and shape, the reflectivity of the surface, as well as slope and surface roughness (within the footprint of the laser) can be modelled. A laser altimeter also provides information on the gravity field and the position of the centre of mass.

The suggested instrument is based on BELA (BepiColombo Laser Altimeter) but with performance parameters specifically designed for MarcoPolo-R. This reduces the size, total mass, and required power compared to BELA.

4.3 Optional Lander and associated payloads

4.3.1 Lander

The Lander package, with a total mass of about 10 kg, has the means to characterize physical properties (e.g. electrical, magnetic, thermal) of the landing site, as well as the surface and subsurface fine structure and composition (elemental, mineralogical, molecular). The lander does not aim at collecting samples, however complementary data from a lander science package can address questions such as: are the returned soils and rocks representative of the bulk of the parent body? What are the macroscopic physical properties of the terrain from which the samples have been extracted?

A Lander could also act together with the spacecraft to support the global characterization of the asteroid, e.g. by microwave sounding, and thus, enhance our understanding of the formation process of the target.

The proposed surface package would be based on the MASCOT design, currently foreseen as payload for the Hayabusa 2 mission and supporting about 3 kg of scientific instruments. Such a design is scalable to some extent (allowing trade-off between mass of lander and orbiter instruments). The package would be delivered by the mother spacecraft to the asteroid surface. During cruise it would be connected via an umbilical for power supply and communications link. This strategy is applied e.g. for Philae, the Rosetta Lander [27].

Delivery to the asteroid surface is planned by a fairly simple spring ejection (Δv in the 5 cm s^{-1} range), no velocity adjustment (as for Philae) nor spin eject needs to be applied. The "impact speed" of the lander must be well below the asteroid's escape velocity (actually all velocities involved are low and consequently accelerations and shock loads are non-critical from a structural point of view; however bouncing is an aspect to be considered). Communications will be relayed via the spacecraft (no direct link to Earth).

4.3.2 Lander payloads

A lander in the 10 kg mass range could support a scientific payload of up to about 3 kg, including:

1. *Camera system*—A wide angle camera would provide the geological and general context for the MarcoPolo-R lander environment in addition to supporting the system (orientation, localisation, navigation during hopping). Surface features of the landing site from the mm (close up) to m (horizon) size would be investigated.
2. *Laser Induced Mass Spectrometer (LIBS)*—A LIBS measures the abundances of elements of the asteroid surface and would allow rock-type as well as mineral identification. Element concentrations from a few ppm to 40 wt.% can be measured with a lateral resolution of 50 μm. The instrument does not require particular sample preparation and is, by its design, capable of removing dust layers prior to the actual measurement. Laser ablation even allows depth profiling to a certain extent (down to a few 100 μm).
3. *Infrared/visible microscope*—An instrument imaging over an area of a few millimetres with an optical microscope as well as a hyperspectral IR imager (0.5 to 2.6 μm) will characterize rocks and minerals with a spatial sampling of a few micrometers.
4. *Thermal Probe*—Characterization of the thermal properties of the asteroid surface material is important in comparison between in-situ and returned samples and have implications for the quantification of Yarkovsky and YORP thermal effects.
5. *Bi-static Radar Tomographer*—Using tomography techniques a radar can provide information on the target internal structure (monolithic/rubble pile/stratigraphy). Radiowaves are transmitted between lander and spacecraft. During an orbit (or asteroid rotation underneath the hovering spacecraft) the asteroid is scanned. Several such scans will allow three-dimensional modelling of the asteroid. The instrument consists of one unit aboard the lander plus a similar unit on the spacecraft.

4.3.3 Optional seismic experiment package

The interior of the target asteroid can also be studied by an active and passive seismic experiment. The experiment is designed with a single type of sensor but in two configurations. The first seismic sensor can be deployed and serviced by the MarcoPolo-R lander. Note that in this case, a lander of about 14 kg is necessary to host both the payloads described in Section 4.3.2 and the seismic sensor. It will perform long term monitoring during the lander's life time.

This seismic sensor can be deployed jointly with thermal sensors and can use a deployment spike. The second type of seismic sensor can be mounted onboard a small autonomous "egg" that is released from the orbiter to the asteroid surface. This egg has a mass of about 3.5 kg, with a battery power system compatible for one day of cumulative operations, transmitting the data to the orbiter. It is ejected from the orbiter by a spring device for a free fall onto the asteroid surface. It includes a charge of about 250 g that will be activated upon command to generate an active seismic source. The activation is done by electrical discharge, the latter being inhibited prior to eggs deployment and performed by a timer activated at the separation. The total mass is about 7.5 kg.

The science goals of the seismic investigation are:

- To characterize the seismic efficiency and quantify the mass of ejecta through measurement of the amplitude of the ground acceleration;
- To constrain the efficiency of seismic shaking (e.g. [21]) and improve asteroid surface age determination;
- To provide information on the deep interior and shallow surface of the asteroid.

4.3.4 Current heritage and TRL of optional payloads

The TRL of the MASCOT lander is 3 (completed phase A) and all its instruments described in the previous section have TRL between 5 and 6. All components of the seismic experiment are based on high TRL: sensor electronics are based on the SEIS-Humboldt electronics (TRL > 5), geophones sensors are qualified for harsh environments (including launch) and are furthermore in qualification process for radiation (TRL > 4), batteries have flown e.g. on Rosetta and the UHF system has flown on small nanosats (TRL > 6).

4.4 Curation facility

While spacecraft operations end once the ERC has safely returned the samples to the surface of the Earth, a major phase of the overall mission remains before the sample science phase in the community can commence. Many different laboratories across Europe and around the world will be required to undertake the full range of studies necessary to answer the scientific questions MarcoPolo-R seeks to address. This demands that carefully selected portions of the returned material are identified and distributed to appropriate laboratories. In order to achieve this, a sample Receiving and Curation Facility is an essential element of the mission, and is required for the long term archiving of such a valuable resource.

First and foremost, the facility must guarantee to preserve the sample in its pristine condition, avoiding chemical and physical alteration of materials by the Earth environments in order that none of the key analyses are compromised, ensuring the highest scientific return. The key activities of the facility are to provide:

- Secure and appropriate long term storage,
- Preliminary characterization of the sample,
- Preparation and distribution of sub-samples,
- Accurate documentation of the samples

Security The returned samples will command very high scientific and public interest. Therefore, high levels of protection against natural events and theft are essential aspects of the Curation Facility. However, the location and security must also permit ready access for visiting scientists, required to aid sample characterization and selection. No bio-containment of the sample is required as MarcoPolo-R will only be a COSPAR designated "unrestricted" sample return mission.

Contamination control In order to preserve the samples in the same condition as when collected, it is essential to strictly limit the addition of terrestrial materials through the selection of materials and control of the ambient environment the samples experience. Key parameters that must be controlled are exposure to particulate material, volatile organics and moisture. All storage and initial handling and characterization of materials will need to be conducted in Class 4 (ISO 14644-1) environments under moisture-free inert gas atmospheres (Ar or N_2) and low levels of volatile organic compounds. In order to provide the appropriate environments for all the activities, a suite of clean laboratories are required for sample receiving, handling, and storage, as well as support labs for preparation and additional characterization.

A range of continuous monitoring and witness plates are required to ensure that the environment conditions are maintained.

Sample storage A fraction of the returned sample will be preserved for posterity—which can be best achieved under high vacuum. The remainder of the sample will be stored in a clean environment with a controlled atmosphere composed primarily of inert gas (argon or nitrogen). As multiple operations on any one sub-sample will likely be common, an integrated sample storage and handling area is required in order to ensure that samples are not cycled through different conditions. In order to access the large number of sub-samples that will result from a sample of NEA regolith and stored under inert gases, robotic handling of the sample is required in the main storage area.

Sample characterization The returned sample will be heterogeneous, containing a variety of different lithologies from the parent asteroid. Prioritization of analysis sequences for any one sub-sample, or even if a sub-sample may be appropriate for any specific analysis, requires some knowledge of its mineralogy and composition (e.g. organic rich material may be prioritized for organic studies, low aqueous alteration for interstellar grain and early solar-system studies, *etc.*). Non-destructive and non-contaminating analytical tools will be required within the cleanest areas of the sample Curation Facility:

- Optical microscopes—for initial overview;
- FTIR/Raman spectrometer microscopes—for characterizing mineralogy and organics;
- High precision balances—for sample mass.

Additional analytical facilities (FIB-ASEM, GC-MS and XPS) will be required within the Curation Facility to support aspects of the sample preparation and operation of the facility:

Sample preparation Many of the analytical techniques employed by the scientific community demand special preparation of the sub-samples—e.g. polished sections, homogenized powders, electron transparent sections. Preparation of such samples must be performed within the Curation Facility in order to ensure optimum use of materials and control of contamination.

Documentation Detailed descriptions of each fragment within the sample will be generated by the Curation Facility for distribution to the scientific community in order to facilitate sample requests. The facility will be required to document all activities for each part of the sample, including all movements and processes within the facility and to track and monitor usage and movement once allocated. A database will manage the vast amount of information associated with these tasks, and feed a sample catalogue that will be readily accessible to the scientific community.

Sample analyses It is anticipated that virtually all scientific studies of the samples will be conducted by the dispersed analytical laboratories in Europe and around the world. However, a number of important analyses are particularly susceptible to terrestrial contamination—particularly those involving biologically important molecules likely to be present in low abundance in the samples and those relating to the nature of any aqueous alteration the samples may have experienced. In such cases some additional sample preparation and/or analyses should be undertaken within the sample Curation Facility to minimize sample contamination. Examples include:

- Extraction and concentration of some soluble organics (e.g. amino acids, nucleobases);
- Analyses of some soluble organics (upgraded of support GC-MS systems);

- Isotopic measurements (O and H) of alteration products (requires isotope mass spectrometer);
- Characterization of alteration mineralogy (TEM).

Considerable expertise exists within Europe for the curation and distribution of sensitive extraterrestrial samples – e.g. numerous large national meteorite collections (e.g. London, Paris, Vienna, Berlin), Antarctic meteorite collections (e.g. Milton Keynes, Siena) and cosmic dust collection programs (e.g. Paris, Aix-en-Provence, Siena).

Presently, no single facility exists within Europe that has the capability to curate, characterize and distribute returned samples in the way required for this mission. In addition to the samples from the NEA, the Curation Facility will act as a repository and distribution centre for a further two sets of material that will be important in confirming that the samples have not been affected by contamination. The first set is of materials collected during the construction of the spacecraft that may contribute volatiles or directly contact the sample. The second set is of witness plates recording the sample collection process and sample storage that will be returned by the ERC along with the NEA sample.

The new ESA centre at Harwell (UK) contains a proposed sample receiving facility (as part of Mars sample return), although a decision on whether this will go ahead (or indeed if it is appropriate for an asteroid sample return) has not yet been finalized and alternative sites within Europe may be equally viable.

5 System requirements and spacecraft key issues

5.1 System requirements

The MarcoPolo-R system requirements and drivers are derived from the mission science objectives:

- Sample-return mission: the key science driver is to return a sample of at least a few 10 s of grams; this drives the mission profile, specifically the number of mission phases and their type.
- Target: the selected asteroid will drive the trajectory and Δv required for the mission and also impact the power and communications system design, with the corresponding implications in terms of equipment selection, mass and cost.
- Asteroid characterization: the required remote sensing activities drive the operations schedule, observation orbit selection, data volume and thus communications subsystem sizing.
- Sampling: the selected sampling collection and transfer concept will drive the spacecraft design and operations. The need to perform landing operations is a major driver in the GNC design.

The science priorities and mission requirements for MarcoPolo-R can be met by a large number of mission architecture options which will need to be carefully analysed and traded-off to select the optimal baseline. A preliminary analysis based in part on the results of the previous Marco Polo assessment study has led to a feasible reference solution. Spacecraft designs suggested by Astrium and OHB are shown in Fig. 6 (see Marco Polo Yellow Book, ESA/SRE (2009)3 for details of proposed designs, including a third by Thales Alenia Space).

5.1.1 Space segment mass budget

For the prime and backup missions (2021 and 2022 launch years, see Table 4) proposed to 1996 FG3 the space segment requirements are very similar. A preliminary mass budget for the worst case back-up mission, including a propulsion module, is of 3,010 kg (including 20% margin). Considering the launch vehicle (Sozyuz) capability of 3,200 kg to GTO, a launch margin of 190 kg (6%) is available.

Another mission design (OHB) leads to a different mass budget, that does not involve necessarily a propulsion module. Although an accurate analysis cannot be provided at this stage, the design is similar to that proposed for Marco Polo (see ESA/SRE (2009)3, Marco Polo Yellow Book).

The assessment study will improve the accuracy of the whole mission design.

For the baseline target 1996 FG3, differences with the former Marco Polo scenario concern essentially the required Δv, re-entry velocity, and mission duration, as well as a mass increase that remains within the launcher capability, including margins.

5.1.2 Communication

The ground system assumed for the mission uses the ESA-DSN. A 35 m ground station is baselined for nominal operations with availability for eight hours per day during proximity operations. A 70 m ground station can be made available in case of emergency. The requirements for the MarcoPolo-R communication subsystem include: telemetry and telecommand during all mission phases; peak data downlink during the remote sensing phase; navigation

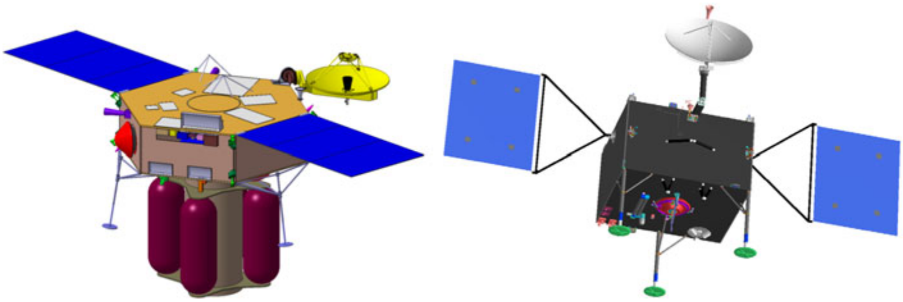


Fig. 6 Main Spacecraft designs from Marco Polo assessment study by Astrium (*left*, with propulsion module) and OHB (*right*)

images during characterization and proximity operations and in-situ instrument data. The remote sensing phase is the most demanding in terms of required data rate. Therefore, the sizing of the communication subsystem is driven by the data rates and volume of that phase (see Table 6). For the appropriate range of distance of the spacecraft to the Earth, during the proximity operations, assuming an High Gain Antenna (HGA) of diameter 1.36 m and a high output power transponder, a data-rate of 22 kbps can be sustained in X band. The baseline communication hardware includes a prime and redundant Low Gain Antenna, providing omni-directional coverage for Low Earth Orbit phase, a steerable HGA, responsible for the main data transmission, and a Medium Gain Antenna, providing useful telemetry during descent and landing and emergency communication in safe mode.

5.1.3 Power

The distance to the Sun during the proximity operations phase is between 0.7 and 1.42 AU, with the solar constant ranging between 2,794 and 698 W m^{-2}. This leads to a significant solar array area of $\sim$10 m^2. There is no credible alternative to solar arrays in Europe in the mission timescale, so a large area of solar arrays will have to be accommodated. This will have implications for the spacecraft configuration.

Lithium Ion batteries are selected as the baseline. The sizing case (descent, sampling and ascent manoeuvres) leads to an energy requirement of 750 Wh resulting in a total battery mass of approximately 10 kg.

5.1.4 Thermal system

The thermal environment of the spacecraft is influenced by radiation from the Sun and the asteroid (and Venus during the transfer phase). The most demanding phase for the thermal system is the landing phase where the spacecraft could need to operate on a surface at 190°C. The proposed thermal design makes use of Multi-Layer Insulation to isolate the spacecraft from the hot thermal environment, with some radiators to dissipate heat in particular from exposed components. Heaters are also needed to maintain the spacecraft temperature when in a cold environment or to compensate for any equipment which is not operating.

5.2 Landing, sampling and transfer systems

There are a number of options for the landing and sampling systems and the selected option has a strong influence on the overall spacecraft design.

For the landing, a simple leg design is proposed with a crushable damper integrated into each of the three legs, which corresponds to the design proposed by Astrium during the former Marco Polo assessment study phase (ESA/SRE (2009)3, Marco Polo Yellow Book). The current design for the landing gear is simple with the majority of components off the shelf with a TRL of 9. Some

Table 6 Example of remote-sensing data rates and volume for a campaign of 27 weeks over the asteroid

	Total compressed data volume [Mbit]	Total compressed data volume [Gbit]	Duration of campaign [weeks]	Duration of campaign [days]	Average production data rate [kbit/s]	Average data rate [kbit/s] for 10 h/day G/S availability	Average data rate [kbit/s] for 8 h/day G/S availability	Average data rate [kbit/s] for 6 h/day G/S availability
Far characterization	5311.2	5.3	2	14	4.39	10.54	13.17	17.56
Global characterization	380222.7	380.2	12	84	52.39	125.74	157.17	209.56
Local characterization	6279.4	6.3	5	35	2.08	4.98	6.23	8.31
Gravity field campaign	9004.3	9.0	8	56	1.86	4.47	5.58	7.44
Remote sensing total	400817.58	400.82	27.00	189.00	24.55	58.91	73.64	98.18

development activity is needed however for the crushable dampers which absorb the landing energy and to test the overall performance of the system under representative conditions.

The Sampling, Transfer and Entry (STE) subsystem is responsible for the acquisition, verification, transfer, and containment of the sample from the asteroid to the surface of the Earth. The key elements of the STE are: (1) two block redundant arms with Brush Wheel Sampler (BWS) end effectors and (2) an ERC. All of the STE hardware is mounted on a single panel of the spacecraft as seen in Fig. 7.

The ERC is comprised of a vault in which the sample canister is inserted prior to Earth return, and a capsule which facilitates a safe sample return during Earth entry and landing. The ERC is mounted to the spacecraft via a Hinge Latch device that allows the ERC to be opened for sample canister insertion by both of the block redundant arms with the SAS.

All components are secured to the spacecraft via pyrotechnic launch locks and are released after the launch. The 3-DoF robotic arm is reconfigured to its nominal deployed position (Fig. 7b) in preparation for sampling operations. A contamination shield is jettisoned from the BWS before landing.

The arms are made of aluminum and designed to tolerate surface contact and ascent burn plume impingement. Electrostatic discharge problems during contact will be mitigated by standard practices such as using conductive and grounded exterior spacecraft surfaces, and sampling in sun-light, where photoelectron emission will reduce potential differences to a few volts, well below the electrostatic discharge threshold.

Once the sampling process is complete, the arm rotates to verify sample acquisition via cameras on the panel supporting the ERC. The BWS head is jettisoned after confirmation that the required sample has been acquired. This jettison event locks the canister, containing the sample, in a rigid axially aligned position on the end of the arm ready for insertion into the vault.

The ERC-mounted vault is based on the JPL-designed Genesis mission container and sealing design. A door on the canister is used only to ensure that the sample stays in the canister. The vault seal controls the contamination of the canister and sample once the canisters are inserted and the vault is sealed shut for Earth return. The vault is an integral part of the ERC and serves as the structural tie between the fore and aft-bodies. When the spacecraft is ready to

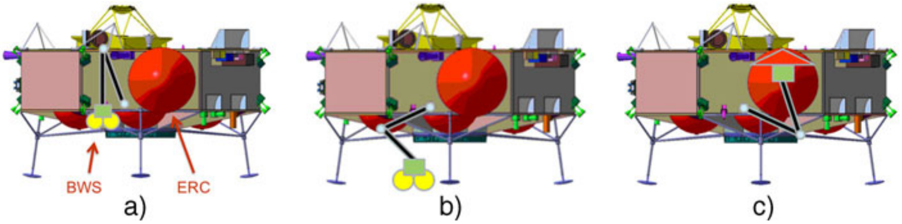


Fig. 7 **a** Arm, ERC, and BWS in stowed position; **b** BWS in deployed position for sampling; **c** canister insertion into vault

release the ERC, a pyrotechnic cable cutter severs the electrical connections between the spacecraft and the ERC. Once the ERC is disconnected, a spring is able to transfer its preload to the whole ERC. This release mechanism allows the spin-up of the ERC to 1 to 2 rpm and a separation velocity of 25 ± 2.5 mm s^{-1}.

The Sample and Acquisition System (SAS) is part of the STE subsystem and performs sample acquisition, verification, and transfer into the ERC from LaRC. The SAS comprises two arms (from JPL), each with a BWS (from JPL), two rock chippers (from APL), a sample canister with a sample verification mechanism, and hinge latch and spin eject mechanisms (all from JPL). The STE is integrated and tested as a system at JPL. After sample collection, the BWS is jettisoned allowing insertion of the sample canister into a vault within the ERC. After the canister is inserted, the vault is sealed.

The BWS has been designed and tested to collect the required sample in less than one second. Alternative collection approaches were studied, including sticky pads, drive tube coring, augers, projectile ejecta collection (as in Hayabusa's rock chippers), cutting wheels, scoops, drag line bucket and gaseous transport devices. The BWS with pyrotechnic rock chippers was selected as the most reliable sample collection approach given uncertainties in surface properties and contact conditions (relative velocity and positioning). It is moreover amenable to high fidelity verification and validation by testing and analysis.

Before sampling, the brush wheels are spun up, and the canister door opens, allowing entry of sample. The rotating brushes, designed to comply with the surface, sweep regolith into the sample canister through a 3 cm opening. The sample canister is shaped to create a vortical flow to dissipate particle kinetic energy and trap the sample. It has an internal volume of 700 ml, for a returned mass between 0.35 and 2.1 kg, depending on sample density. If the asteroid surface is assessed to contain no loose regolith, pyrotechnic rock chippers are fired during the sampling event. This determination is made prior to sampling and activated by ground command. The canister door is shut after two seconds of asteroid contact. The BWS can be reused in subsequent sample collections.

The BWS has been tested in air and in vacuum, in Earth gravity and in low gravity on the KC-135A, with many regolith stimulants, including one using the modified lunar regolith size distribution (Fig. 8). Rock chipper testing with an operating BWS has demonstrated the capability to generate and collect 15 g of sample per single rock chipper firing into Bandelier tuff rocks (two chippers are fired during a sample collection event). Testing has shown that sample collection by the BWS is largely insensitive to both gravity and atmosphere. JPL has developed and validated numerical models of BWS particle transport and collection dynamics. Testing and analysis confirm robust sample collection in flight-like and ground test conditions. Novel application of proven components allowed the successful development and zero-g and vacuum testing of the BWS. JPL and APL internally funded R&D efforts have brought the BWS to TRL-5 and the Rock Chipper to TRL-4. Continued R&D funding will bring the integrated BWS and Rock Chipper to TRL-6 by Project Mission System Review.

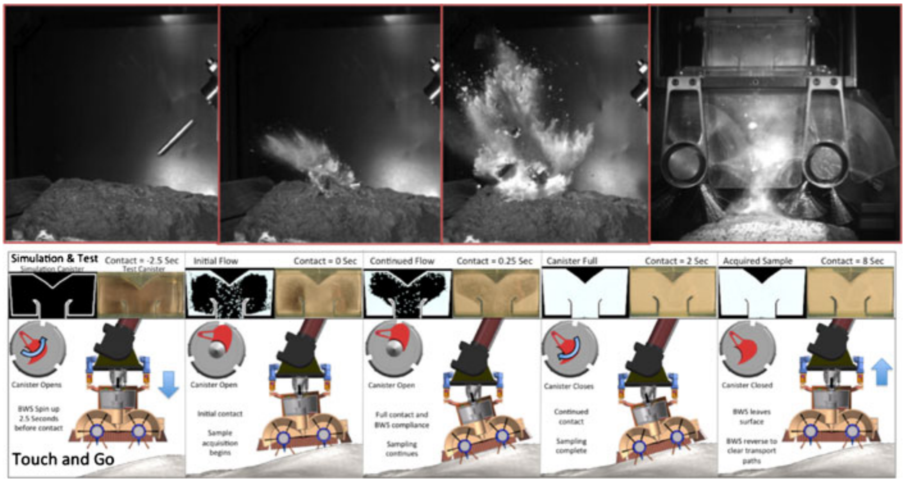


Fig. 8 Sampling mechanism. *Top* test with Rock Chipper and Brush Wheel Sampler and Bandelier tuff rocks; *bottom* test, simulation, and diagram of BWS collecting lunar regolith simulant in a few seconds (see text for details)

5.3 Earth re-entry capsule (ERC)

The MarcoPolo-R ERC is derived from a unique NASA-developed, chuteless design [14] for Mars Sample Return. This design is optimized to meet MarcoPolo-R mission needs while preserving key characteristics for high reliability. These are: the elimination of all active systems, a well-understood forebody shape, and a well-characterized flight heritage thermal protection system (TPS). NASA LaRC will be responsible for the design, development, integration, test and delivery of the ERC. NASA ARC will partner with LaRC and be responsible for the design, development, and delivery of the ERC aeroshell element (TPS and carrier structure).

The ERC (Fig. 9) has an axisymmetric external shape, and consists of a core (primary structure, impact system, etc.), TPS and carrier structure, and payload element (provided by JPL).

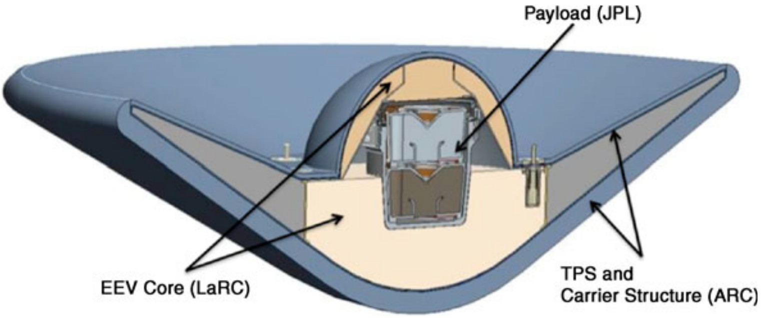


Fig. 9 Illustration of MarcoPolo-R ERC (cross section)

A completely passive design, spin-stabilized at 2 rpm with no parachute, the total diameter is 0.9 m, and the maximum expected mass (including payload) is approximately 33 kg (including 20% contingency), for a ballistic coefficient at entry of about 72 kg m^{-2}. The entry state assumed has a nominal inertial Entry Flight Path Angle (EFPA) near $-10°$ and velocity of 13.63 km s^{-1}.

The ERC core consists of the primary structure, the impact foam, which supports the payload element, thermal insulation, spacecraft attachment hardware, and a small radio beacon. This beacon is self-contained, activated at landing using a g-trigger, and acts as a backup to visual and radar tracking of the ERC to determine its location at landing.

The baseline ERC forebody TPS is unipiece PICA (Phenolic Impregnated Carbon Ablator; [25, 26, 29]) manufactured by FMI (with ARC insight and oversight) for Stardust. It was flown in 2006 at entry heating conditions twice those expected by MarcoPolo-R. The unipiece PICA TPS will be manufactured to the same specifications as Stardust, using components with traceability to Stardust, thus providing full flight heritage. After detailed analysis of the recovered Stardust PICA [24], both Orion and MSL [4] invested heavily at both ARC and LaRC to further improve the reliability of the PICA thermal response models and understand its thermostructural performance and material properties through extensive test and analysis. This gives PICA qualification heritage far beyond Stardust. If required, unipiece PICA could be manufactured up to a diameter of 1.2 m.

The design of the ERC impact system provides ample margin to the 1500-g payload impact load requirement. The thermal design provides significant thermal insulation of the payload during the entry heat pulse, as well as post landing. For example, a 2-D axisymmetric thermal soak analysis using a design similar to that of MarcoPolo-R showed the maximum temperature of the sample canister interior surface during entry or after landing never exceeded 42°C, providing 28°C margin against the 70°C science temperature requirement, thus allowing for an indefinite period of time for recovery of the ERC.

An option exists to increase the allowed ERC entry velocity from the current 13.63 km s^{-1} to about 16 km s^{-1} by replacing the ERC unipiece PICA forebody material with carbon phenolic. This effort would require a new process qualification which will be evaluated in the next proposal phase.

6 Science operation and archiving

6.1 Mission phases

Currently, the following mission phases are foreseen. For each phase, the main goals of the science operation activities are indicated:

Near-Earth commissioning and calibration phase Early operation phase will include spacecraft checkout and trajectory correction manoeuvre to remove injection error.

Cruise phase Regular instrument checkouts are planed, typically in 6-month intervals. Some science observations should be done, e.g. of star fields or bright stars for functional testing, geometric and radiometric calibration.

Asteroid phases Asteroid approach and encounter mission phases consist of: (1) approach and rendezvous leading to distant station-keeping; (2) target characterization phase from orbit around the asteroid; (3) proximity operation phase leading to touch-and-go landing (TAG). As MarcoPolo-R approaches the target system, Earth-based radar and optical observations of the asteroid will be combined with spacecraft optical navigation and radiometric data to refine the spacecraft position relative to the asteroid. These navigation observations will be used to design and execute the rendezvous manoeuvre which will be split into a series of smaller burns of decreasing magnitude, in order to control approach errors.

Target characterization phase In this phase the NEA is mapped and characterized such that the best landing site, both from an engineering and from a scientific point of view, can be selected. As 1996 FG3 is a binary system, the initial characterization refines the determination of system mass (already measured from Earth-based observations) and masses of the primary and secondary from imaging of the mutual orbit. From a station-keeping position over the dayside of the target system, the sizes, shapes and rotations of the two components will also be determined. After initial characterization, the spacecraft is injected into high inclination (to the binary orbital plane) stable orbits around the target system barycentre. From the stable orbits, the spacecraft will map the surfaces of the primary and secondary to determine morphology and topography. These data enable selection of the landing site and certification that it meets science requirements as well as safety requirements for landing.

Lander delivery phase (optional) There will be at least one rehearsal descent prior to landing for sample acquisition. The spacecraft will briefly hover at fixed low altitude and can release the lander package from that position.

"Touch and go" phase The spacecraft will approach the NEA surface and collect the surface samples. During the TAG landing, the spacecraft remains in contact with the asteroid surface for at most a few seconds before autonomous lift-off occurs. TAG landing will occur only over sunlit portions of the surface. TAG landing may occur at the surface of either member of the binary system; the choice of landing site will be made after target characterization.

Lander relay phase (optional).

In-situ measurements done by the Lander (optional) Communications to Earth will most likely be relayed via the main spacecraft.

Return cruise phase as *Cruise phase*.

Earth re-entry phase The ERC re-enters and is recovered at the US Utah Test and Training Range (UTTR). The UTTR is located where previous sample return missions like Stardust returned and were successfully recovered. The MarcoPolo-R entry strategy will be similar to that of Stardust where a series of small manoeuvres will be performed, starting 30 days before atmospheric entry, to target the entry safely within UTTR.

Sample distribution and ground measurement phase The collected samples are distributed to ground laboratories and analyzed.

6.2 Science operation architecture and proposed shares of responsibilities

The aim of the mission operations is to assure the monitoring and the control of the complete mission. The control of the MarcoPolo-R mission will take place at ESOC, in conjunction with the ESA-DSN.

The scientific data will be acquired during the NEA acquisition/approach, the near NEA phase before and during the optional lander delivery (and relay) phase, and after the sampling, during an extended monitoring phase. Some cruise science will also be done with only a very small impact on operation cost. Particularly important are the operations governing the sample collection phases, the sample transfer to ERC, the round trip cruise phases and the ERC delivery. During critical mission phases (launch, cruise, sampling, Earth return, ERC recovery), support for tracking, telemetry and command by the ESA ground stations and the NASA-DSN could be foreseen.

For the entire mission duration, ESA will provide facilities and services to the scientific experiment teams through a MarcoPolo-R Science Ground Segment (MPSGS). Its tasks will be:

- Planning and execution of scientific data acquisition, in particular the long-term scientific mission planning and experiment command request preparation for consolidation and submission to the Mission Operation Centres;
- Generating and providing complete raw-data sets and the necessary auxiliary data to the Principal Investigators. The MPSGS will make preprocessed scientific data and the long-term scientific data archive available to the scientific community after a proprietary period for the PI teams;
- Optionally, the Lander Science Ground Segment will support operations of the Lander, in particular before and after completion of the landing, sampling and relay phases.

7 Conclusion

MarcoPolo-R is a European-led mission with NASA contribution that is within the available technical and financial resources of an ESA M class mission. MarcoPolo-R is one of the four candidates selected by ESA (February, 25,

2011) in the ESA M3 Cosmic Vision 2 program to proceed for an assessment study. The assessment study will allow ESA and NASA to design the best mission scenario to reach the science objectives of the mission.

In addition to addressing the exciting science goals, as described in Section 2, the MarcoPolo-R mission also involves technologies for which technical development programmes are well under way. It is the ideal platform to (1) demonstrate innovative capabilities such as: accurate planetary navigation and landing, sample return operational chain; (2) prepare the next generation of curation facilities for extra-terrestrial sample storage and analysis; (3) pave the way as a pathfinder mission for future sample returns from bodies with high surface gravity. MarcoPolo-R will ensure that European laboratories involved in sample analysis remain world class facilities spanning the entire breadth of expertise required for the science success of the mission. MarcoPolo-R will also involve a large community in a wide range of disciplines (Planetology, Astrobiology, Cosmochemistry etc...) and will generate tremendous public interest.

The various phases of the mission are scientifically autonomous and the completion of each of them separately will lead to major improvements of our knowledge. The remote sensing data will allow us to reach an understanding of a primitive body comparable to that obtained for the more evolved bodies by previous missions. The choice of a binary asteroid as the baseline target for the first time will provide enhanced science return. The returned sample (first for ESA) will then be of an inestimable value. Until we return a sample from a primitive asteroid, which is the primary goal of MarcoPolo-R, we will never know what a primitive material is.

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The mission design takes advantages of the ESA assessment study phase of the former Marco Polo project in 2008–2009 including the related three industrial studies. For this proposal, we acknowledge the contribution of the following European industrial teams: Astrium Ltd, OHB, GMV, Thales Alenia Space. Some components are based on work by APL and JPL funded by NASA under the Science Mission Directorate Research and Analysis Programs.

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