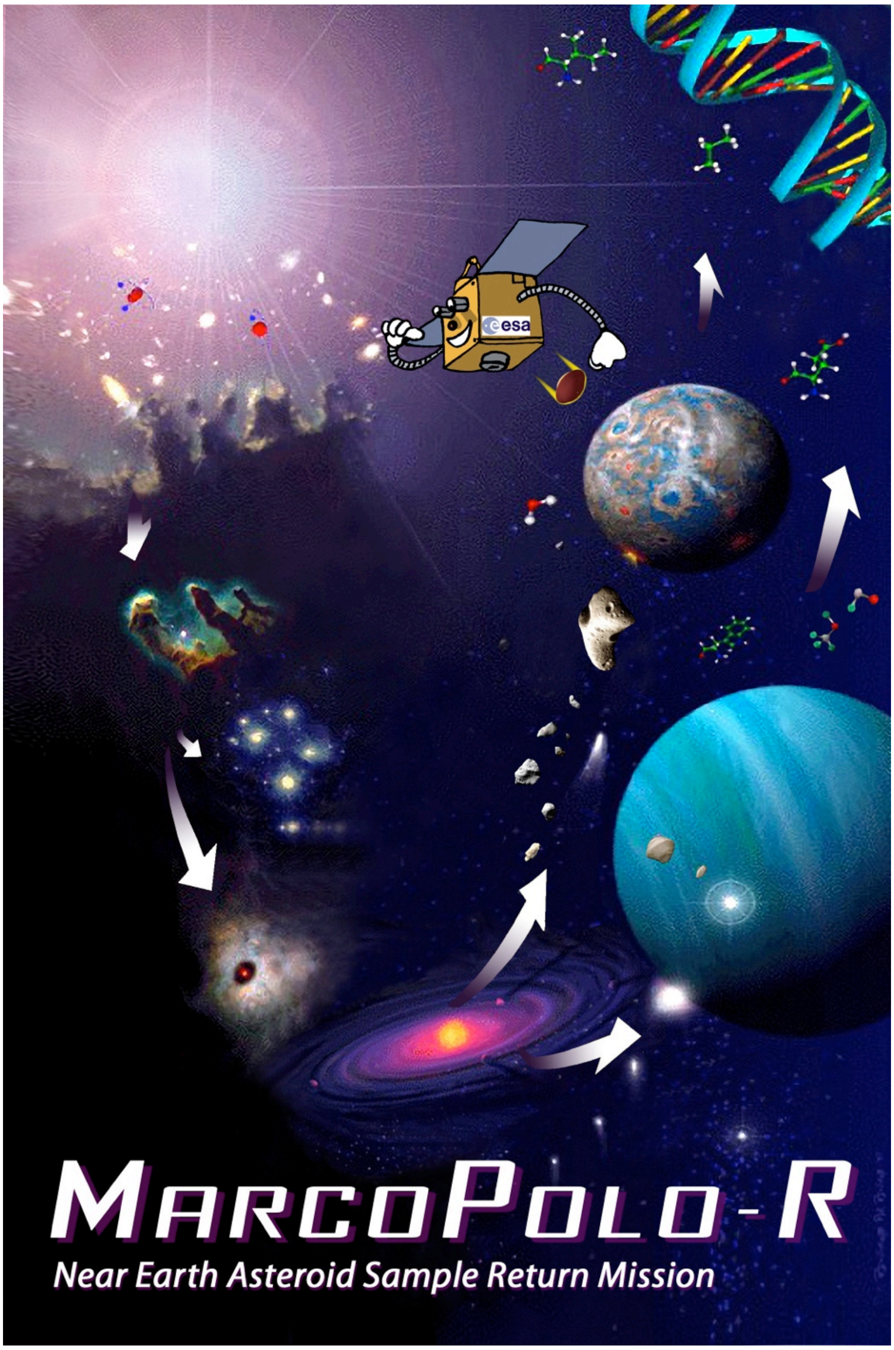
ESA/SRE(2013)4
December 2013

MarcoPolo-R

An Asteroid Sample Return Mission



Assessment Study Report

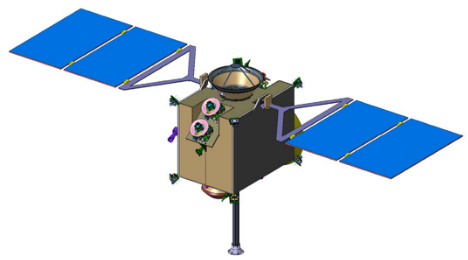
European Space Agency

The front page shows an artistic view of the 14-billion-year-long chain of events from the birth of the Universe at the Big Bang through the formation of chemical elements, galaxies, stars, planets, asteroids and comets, the mixing of chemicals and energy that cradle life on Earth, to the earliest self-replicating organisms – and the profusion of life. The MarcoPolo-R spacecraft is shown travelling through time to investigate the birth of our planetary system (Modified from an original image by NASA/JPL-Caltech).

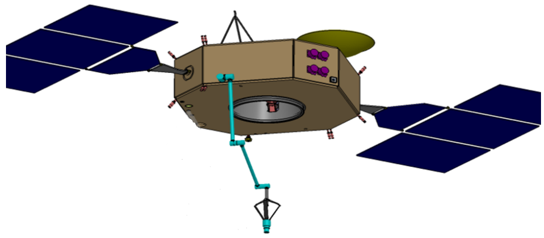
MarcoPolo-R Assessment Study – Mission Summary	
Key scientific goals	**MarcoPolo-R will return a sample from a near-Earth asteroid (NEA).** *MarcoPolo-R aims to answer the following key questions:* 1. What was the astrophysical setting of the birth of the Solar System? 2. What is the origin of material in the early Solar System and how did it evolve? 3. What are the physical properties and evolution of the building blocks of terrestrial planets? 4. How do organics in primitive NEAs relate to the origin of life on Earth?
Reference core payload	MaNAC - Narrow Angle Camera CUC - Close-Up Camera MaRIS - Visible and near-infrared imaging spectrometer THERMAP - Mid-infrared spectro-imager RSE - Radio Science Experiment VISTA2 - Volatile In-Situ Thermogravimetry Analyzer
Overall mission profile	• Launch into direct escape by Soyuz-Fregat 2-1b from Kourou, Dec 2022, to the NEA 2008EV5, backup launches in December 2023 and 2024, main spacecraft + re-entry capsule • Earth swing-by in 2023, rendezvous with NEA in Jan 2025 • 180 days stay at NEA - asteroid characterisation and collection of a sample of the order of 100 g • Jun 2025 departure to Earth • Earth Re-entry Capsule returns to Earth in Woomera, Australia, in Jun 2027 • Sample curation, preliminary characterisation, and initial distribution • Preserve part of the sample for future generations of scientists

Spacecraft modules	Main spacecraft	Earth re-entry capsule
Stabilisation	3-axis	spin
Specific capabilities	• Descent strategy: combination of ground-based and autonomous navigation relative to the surface aided by altimetry and camera, • Sampling strategy: touch and go sampling; grab bucket or brush-wheel sampler; transferred to Earth Re-entry Capsule (ERC) via touch and go arm • Electrical propulsion for transfer; Chemical for asteroid proximity operations	• Direct re-entry from hyperbolic trajectory • No parachute • Passive capsule, recovery via optical and radar tracking
Sizing case power	3 kW (during electric propulsion transfer)	
Telecommunications	X-Band high gain antenna (+ low/medium)	passive
Science data production	120 GB	None (passive)
Payload mass	33 kg	Order of 100 g of sample
Dry mass (incl. margins)	1100 kg	45 kg
Spacecraft launch mass:	**1554 kg**	

Astrium Ltd. (Option A)



Thales Alenia Space (Option B)



Foreword

Figure 0.1: *The logo of the study of MarcoPolo-R in the Concurrent Design Facility*

Returning a sample from a primitive asteroid is an extraordinary enterprise and the benefits for Europe will be invaluable. This document gives an overview of the many years of scientific preparation and the engineering activities that went into building the foundations of this endeavour. It originates from a proposal to ESA for the M1/M2 Cosmic Vision slot for an asteroid sample return mission called Marco Polo. The mission was proposed again, with a revised focus, for M3. The new name reflects this - MarcoPolo-R.

This 'Yellow Book' gives the science case for the mission. It was not only developed by the core Science Study Team, but is based on the input of many members of a wide science community, which demonstrates the multi-disciplinary aspect of the mission (cosmochemistry, astrophysics, astrobiology, planetary science). Many members of this community participated in various working groups that developed different aspects of the mission science.

The Yellow Book also introduces a baseline mission scenario developed by devoted industrial teams whose work and motivation are highly appreciated. During the study, a call for payload proposals brought on board the future mission PIs, which helped greatly in defining the science and of course contributed the relevant sections for their instruments on board the spacecraft.

Many thanks to all of those who worked so hard in putting together this document.

The MarcoPolo-R Science Study Team.

Authorship, acknowledgements

This report has been prepared by the MarcoPolo-R Team listed below.

ESA Science Study Team (SST)		
Name	*Affiliation*	*City, Country*
Maria Antonietta Barucci (lead proposer)	LESIA/Paris Obs., CNRS, UPMC, UPD	Paris, France
Patrick Michel (Co-lead proposer)	Univ. Nice, CNRS, Cote d'Azur Obs.	Nice, France
John R. Brucato	INAF/Obs. of Arcetri	Florence, Italy
Elisabetta Dotto	INAF/Obs. of Rome	Rome, Italy
Pascale Ehrenfreund	Univ. Leiden	Leiden, NL
Ian A. Franchi	Open Univ.	Milton Keynes, UK
Simon F. Green	Open Univ.	Milton Keynes, UK
Luisa M. Lara	IAA/CSIC	Granada, Spain
Bernard Marty	CRPG/CNRS Univ. Lorraine	Nancy, France
Instruments		
Tom Andert (PI, RSE)	Bundeswehruniversität München	Munich, Germany
Maria Antonietta Barucci (PI, MaRIS)	LESIA/Paris Obs., CNRS, UPMC, UPD	Paris, France
Gabriele Cremonese (PI, MaNAC)	INAF/Obs. Padova	Padova, Italy
Olivier Groussin (PI, THERMAP)	LAM	Marseille, France
Jean-Luc Josset (PI, CUC)	Space Exploration Institute	Neuchatel, Switzerland
Ernesto Palomba (Lead, VISTA2)	INAF/IAPS	Rome, Italy

The ESA Team supporting the activities is composed of:

ESA study team		
David Agnolon (Study Manager)	ESA/ESTEC	Noordwijk, The Netherlands
Remy Chalex (System Engineering Support)	ESA/ESTEC	Noordwijk, The Netherlands
Detlef Koschny (Study Scientist)	ESA/ESTEC	Noordwijk, The Netherlands
Patrick Martin (Science Operations Study Manager)	ESA/ESAC	Madrid, Spain
Jens Romstedt (Study Payload Manager)	ESA/ESTEC	Noordwijk, The Netherlands
ESA Coordinator		
Luigi Colangeli	ESA/ESTEC	Noordwijk, The Netherlands

The support of both scientific and engineering individuals and the industrial study teams in the preparation of this report is highly acknowledged.

Table of contents

1 Executive summary

MarcoPolo-R is a sample return mission to the primitive and easily reachable Potentially Hazardous Asteroid (PHA) identified as (341843) 2008 EV5. Getting a sample from a primitive body and analysing it on Earth with the most precise techniques will permit a great leap forward in our understanding of the origin of matter in the Solar System and early processes that led to the formation of planetary bodies.

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

1. *What was the astrophysical setting of the birth of the Solar System?*
2. *What is the origin of material in the early Solar System and how did it evolve?*
3. *What are the physical properties and evolution of the building blocks of terrestrial planets?*
4. *How do organics in primitive NEAs relate to the origin of life on Earth?*

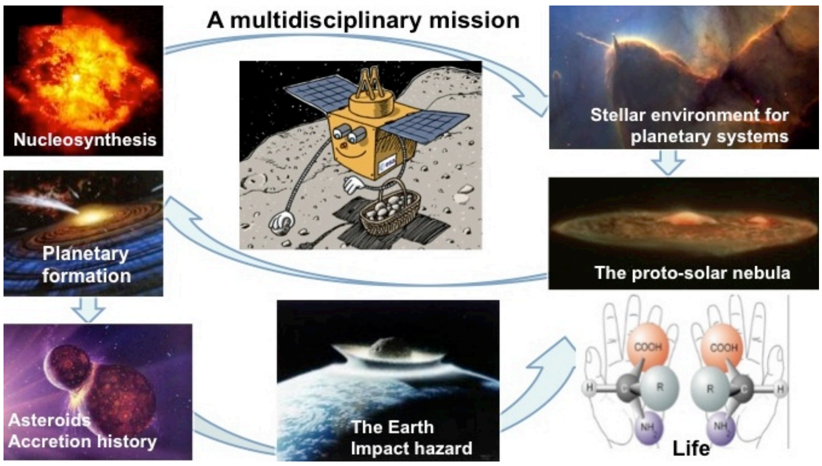
Answers to these fundamental questions require a wide array of measurements with exceptionally high precision and sensitivity. Such measurements cannot be performed by a robotic spacecraft and therefore require a sample returned to terrestrial laboratories that are unconstrained by on-board resources. The most demanding measurements are those required to date the major events in the history of a sample, and to investigate the organic components.

Small bodies, as primitive leftover building blocks of the Solar System formation, offer an un-rivalled record of the chemical mixture from which the Solar System and its planets formed some 4.6 billion years ago. The sample of mixed regolith returned by MarcoPolo-R from such a body will contain components representative of the main lithologies and components from the parent asteroid, including those that have experienced little or no parent body processing, and which would not survive atmospheric entry. Such samples are therefore of great scientific value compared to the modified materials that are meteorites, that by definition are strong enough to survive the rigours of atmospheric entry. The most pristine components provide a record of the earliest stages of Solar System formation, and even its origin. The abundance and distribution of newly synthesised short-lived radionuclides present in these earliest materials will provide a record of the nucleosynthetic events preceding the formation of the solar nebula. Insight into the nature of the molecular cloud from which the Solar System was born will be obtained from a more comprehensive understanding of pre-solar grain populations in the early Solar System, including their journeys through the Interstellar Medium (ISM). The combined pre-solar studies will provide a new picture of the astrophysical setting of the birth of the Solar System and may permit identification of the stellar event that may have triggered the collapse of the parental molecular cloud of the Solar System.

Freed from the obscuring effects of parent body processes and terrestrial contamination the mineralogy, chemical and isotopic composition of the MarcoPolo-R sample will allow characterisation of the chemical processes and the environment of the early Solar System. Pristine samples will provide unrivalled insight into the nature and origin of the large, but poorly understood isotopic fractionations observed in many important elements (e.g. oxygen, nitrogen, hydrogen). Understanding of the signatures and abundances of these volatile elements will provide critical tests of models for the origin of the Earth's atmosphere and oceans. As well as providing a new picture of the processes and environments in the early Solar System, the MarcoPolo-R sample will also permit determination of the time intervals of these important events such as between the end of nucleosynthesis and agglomeration, the duration of agglomeration, time of accumulation, 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. The nature, mix and history of the pristine materials in the MarcoPolo-R sample will also provide a new window into one of the great challenges to current understanding of the early Solar System, which relates to the nature of the large-scale transport mechanisms that were clearly operating. Current exobiological scenarios for the origin of life invoke an exogenous delivery of organic matter to the early Earth: primitive bodies may have brought these complex organic molecules capable of triggering the pre-biotic synthesis of biochemical compounds on the early Earth. It is thus vital to determine the origin, diversity and complexity of organic species in a primitive asteroid for an in-depth understanding of organic chemistry processes in space and their evolutionary timescales.

In order to achieve the outstanding scientific objectives of this mission, the spacecraft will rendezvous with the asteroid, characterise its surface and gravity field to support the main mission phase: collecting and returning a pristine sample to Earth potentially unlike any known meteorite and unaltered by the atmospheric entry process or terrestrial weathering. Some of the important properties of 2008 EV5 are already known as it is always close to Earth at around 1 AU and has been observed by numerous telescopes and ground radar. It is a 400 m-diameter oblate spheroidal shape body rotating every 3.5 hours. Spectroscopic observations suggest strongly that 2008 EV5 is a particularly primitive object that may have accreted in a volatile-rich region. Its spectrum shares similarities with CI carbonaceous chondrite meteorites, such as Orgueil, believed to represent the most primitive material available on Earth. The asteroid is expected to contain water in the form of hydrated minerals, as well as organics such as amino acids, and may correspond to a transitional object between asteroids and comets. MarcoPolo-R will thereby contribute in a unique way to our better understanding of the origin and evolution of the Solar System, the Earth, and Life itself.

The global physical properties of the targeted asteroid will also be characterised with high accuracy in order to understand how collisional fragment asteroids are formed and ejected from the main belt. Such information is essential to determine the locations on the surface from where the most scientifically important samples can be found for collection and return to Earth, and to place the sample into the global geological context from which it was collected. Moreover, collisions of Near Earth Asteroids with the Earth pose a hazard to life, which was demonstrated on a small scale with the explosion of a decametre rock over Chelyabinsk in Russia in February 2013 and the consequent damage it caused. The design of efficient mitigation strategies relies on our knowledge of the physical properties of PHAs. For all these reasons, the exploration of such objects is particularly interesting and urgent.



MarcoPolo-R is a multi-disciplinary mission, pro-posed in a new era of high international interest in sample return missions to primitive asteroids. This is demonstrated by the recent selections of sample return missions by leading space agencies: OSIRIS-REx in the NASA New Frontiers pro-gram for launch in 2016 and Earth return in 2023; JAXA's Hayabusa2 for launch in 2014 and Earth return in 2020. Both missions will greatly improve our knowledge of the material composing primitive asteroids: OSIRIS-REx target is (101955) Bennu, a B-type; Hayabusa2 target is (162173) 1999 JU3, a C-type. Their spectral characteristics and low albedo (<0.06) indicate significantly different compositions and asteroid population memberships than the moderate albedo (≈0.12) of the MarcoPolo-R target 2008 EV5. The large diversity of physical properties, composition and structure of NEAs imply that different missions, with their individual sampling mechanisms and strategies, will collect asteroid samples of different amounts and with different histories.

The exceptional target of MarcoPolo-R leads to a short mission duration of 4.5 years and the cheapest sample return mission to a primitive body that can be achieved in the near future. The resulting mission offers Europe a unique opportunity to contribute in a very timely and significant manner to the international sample return and asteroid exploration activities. It will furthermore define Europe's position as equal and important player in future sample return endeavours from other Solar System bodies.

MarcoPolo-R is now a mature M-class mission with low cost-related risk, benefitting from the extraordinary properties of the mission profile to 2008 EV5 in the given timeframe. The mission starts with the launch of a relatively small spacecraft, composed of the main spacecraft and the Earth re-entry capsule on board a Soyuz-Fregat from Kourou on a direct escape trajectory. It is using the same low-cost electric propulsion system as flown on Smart-1 and more recently on Alphasat. The mission is compatible with launches from 2022 onwards up to 2024 and beyond.

In all scenarios, the asteroid proximity operations last for 180 days, including margins. Upon arrival, the asteroid surface will be fully mapped from a distance of 10 and 5 km to the asteroid with three scientific instruments: narrow angle camera, visible and near-infrared and mid-infrared spectro-imagers. The detailed gravity field will be determined with the aid of the telecommunication system at about 1 to 2 km distance.

Five sampling site candidates are then characterised with the same instruments at very high resolution at about 250 m distance to the surface. These pre-sampling operations are defined to support the selection of the most suitable and safest sampling site. Asteroid descent rehearsals will validate the sampling and spacecraft navigation system and decrease drastically the risk of the final sampling procedure. Permanent telemetry will be sent to the ground teams throughout the descent in order to confirm the health status of the spacecraft. The sampling operation itself is based on a touch-and-go technique to lower cost and risk. The spacecraft is designed to cope with surface hazards and keeps away from the surface. It performs a soft (10 cm s^{-1}) touchdown during which a robust sampling mechanism keeps in contact with the surface for 2 to 5 seconds and collects the sample, and then takes-off immediately to move into a safe position away from the surface. A close-up camera takes very high-resolution pictures of the sampling procedure and a small sensor measures volatiles. After verification of its collection, the sample is transferred to the re-entry capsule and sealed. Otherwise, additional sampling attempts can be undertaken (up to 3). Another local characterisation of the sampled site is then carried out. The spacecraft departs from the asteroid in July 2025 and returns to Earth in June 2027. The capsule is then released, re-enters the Earth atmosphere and lands at the Woomera test range in Australia. The capsule will be tracked by ground teams throughout its re-entry to be recovered as soon as possible and transported safely to the curation facility.

A programme for handling and curating planetary material returned by space missions will be developed for the first time in Europe. European laboratories have already developed expertise in this field by handling and analysing samples returned by previous NASA and JAXA missions, and Europe is the home of many of the leading manufacturers in advanced analytical instrumentation. The benefits of MarcoPolo-R will extend far beyond the field of planetary science. The selection of MarcoPolo-R will be a major stimulus to propel European laboratories and industry to the forefront in analytical capability, integrating remote handling in ultraclean facilities with the preparation of samples for investigation by a large array of analytical techniques at the micro- and nano-scale. The curation facility will guarantee the preservation of the samples in their pristine condition, avoiding as best as possible alteration of materials by the terrestrial environment. A preliminary characterisation of each fragment will be performed within the facility to provide sufficient information to allocate appropriate samples to the scientific community (e.g. organic rich material may be prioritized for organic studies, low aqueous alteration for interstellar grain and early Solar System studies, etc.). Portions of the MarcoPolo-R samples will be made available (subject to peer review) to laboratories worldwide for detailed analyses. A fraction (nominally 30 %) of the returned sample will be stored in the facility for future generations of scientists and advances in analytical instrumentation. The 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 and for new techniques that are developed by new generations of scientists decades after its return from the asteroid.

In addition to addressing these major science goals, the MarcoPolo-R mission also involves innovative European technologies for which technology development programmes have achieved major breakthroughs since the previous Marco Polo mission studies (ESA/SRE (2009)3). As a result of the industrial phase A study, ESA designed a remarkably cost-effective and robust mission scenario. The key sample return capabilities, i.e. asteroid navigation, touch and go, sampling mechanism and the re-entry capsule have all been simplified with respect to the previous Marco Polo studies, are less costly and have reached an advanced design and validation status to enter implementation phase. The selected scientific instruments are based on flight-proven technologies.

MarcoPolo-R involves a large community in a wide range of disciplines and is the ideal platform to (i) demonstrate innovative capabilities such as: planetary sampling, Earth re-entry capsule, sample return operational chain; (ii) prepare mitigation technologies; (iii) prepare the next generation of curation facilities for extra-terrestrial sample storage and analysis; (iv) pave the way as a pathfinder mission for future sample returns from high gravity surface bodies. In addition to space agencies, great interest by private industry has arisen in recent years in order to better understand asteroids for their eventual use for resources and for human exploitation. MarcoPolo-R will enhance our understanding of the diversity of the asteroid population, in particular their surface properties, required to achieve these objectives. As a demonstration of the international interest, both NASA and JAXA expressed officially their interest in contributing to the mission.

MarcoPolo-R will also generate tremendous public interest. The outreach possibilities of MarcoPolo-R are considerable because of the enormous fascination for asteroids in general and challenges such as touching a planetary body, and bringing samples back from an alien world.

2 Scientific objectives

2.1 Scientific overview

In the beginning… The birth of the Solar System took place in a cradle of young stars, as a small portion of a giant molecular cloud collapsed gravitationally. The material incorporated into this collapsing disk was formed by the accumulation and mixing of nuclear debris from myriads of previous generations of stars. This matter, comprised of gas, dust, ice and complex organic molecules, was energetically mixed by stellar winds in the molecular cloud. However, we know that some grains survived, recording detailed information about specific nucleosynthetic events (Zinner 2005). Similarly, the decay products of short-lived radionuclides leave tantalising clues about the creation of elements shortly before the birth of the Solar System (Connelly et al. 2008; Dauphas & Chaussidon 2011).

As the solar accretion disk grew, increasing energy, pressure and temperature led to a multitude of processes affecting the chemical, isotopic and mineralogical nature of the mix of gas and dust. High temperatures in the inner parts of the disk led to high levels of isotopic homogenisation, setting a time frame from which to measure the age of subsequent events (Wetherill 1975). Cooling of the disk led to condensation of gases and aggregation of the dust. Further out from the proto-Sun the disk was dominated by ices together with a vast array of different organic compounds, surviving from the molecular cloud and/or synthesised within the cooler parts of the disk. But the accretion disk was far from a quiescent place – with turbulent mixing stirred by the energetic young Sun re-distributing newly formed phases throughout the disk leading to high levels of re-cycling and re-processing of material through the wide range of conditions and environments present (Shu et al. 1997).

As the turbulent disk cooled, aggregation of the dust continued, forming larger and larger grains that accreted into increasingly larger bodies, ultimately forming the minor bodies and planets that now make up our Solar System (Safronov & Ruskol 1994). The huge amount of energy associated with the formation of planets means that they experienced extensive homogenisation, which in most cases continues to this very day, such that any records of the events dating back more than 4.5 billion years to when the Solar System was born are completely obliterated. The minor bodies in the asteroid belt are known to have exhausted their internal energy sources shortly after they formed, preserving some of the material that originally accreted from the disk. However, most reflect fractionated samples of the solar accretion disk, with compositions distinct from that of the bulk solar value, and even in their short “lives” experienced periods of heating and internal modification (Baker et al. 2005).

The rare carbonaceous chondrite meteorites with compositions that are relatively unfractionated from bulk solar composition, contain components formed during the earliest stages of Solar System formation and even rare grains from the molecular cloud, as well as abundant organic molecules and other volatiles, originally accreted as ices (Wasson 1974). However, these rocks still constitute a biased sample, as the formation process of meteorites on the parent asteroids are required to make them strong enough to survive atmospheric entry. Creation of meteorites requires processes such as heating, fluid-rock interaction or shock-processing from impacts to turn the dust and fine material from the solar accretion disk into rocks capable of surviving largely intact to the surface of the Earth. Such processing further masks the detailed history of the early Solar System, over-printing geochemical signatures of accretion disk processes, re-setting isotope chronometers, destroying pre-solar grains, modifying and synthesising organic molecules.

Even after the parent asteroids cease to be actively driven from internal processes, they continue to evolve from external influences. Their orbits are controlled by the giant planets, which if they had migrated in an earlier epoch, may have greatly modified the original orbits of these bodies. Understanding the distribution of different types of asteroids, and how these populations have evolved dynamically offers great insight into the origin of the planets. However, only subtle differences can be observed in the spectra of the abundant, but dark primitive classes of asteroids. Impact events between asteroids would have led to disruption and re-assembly processes, modifying the surface, which itself is continually evolving under the influence of the radiation environment that airless bodies experience in space.

The random delivery of meteorites to Earth results in exposure to the terrestrial biosphere, leading to contamination from volatile elements and organic compounds. Even if only exposed for short periods of time, the record of astrobiologically important signatures is inevitably ambiguous. Furthermore, alteration and degradation of the primitive material (e.g., the matrix of carbonaceous chondrites that contains volatiles and pre-solar grains) by the terrestrial environment lead to severe loss of information. Despite the observation that < 5% of meteorite falls are carbonaceous chondrites (Sears & Dodd 1988), there is strong evidence that the major fraction of accreting extraterrestrial material consists of organic rich matter. Indeed, carbon-rich asteroids dominate the asteroid belt population (Gradie et al. 1989, Gaffey et al. 1993), most xenoliths in meteorite regolithic breccias resemble carbonaceous chondrites (Anders 1978), the lunar regolith is known to contain 1–2% of carbonaceous debris (Keays et al. 1970), and micrometeorites which represent the major extraterrestrial flux to Earth share similarities with carbonaceous chondrites (Engrand & Maurette 1998).

Attempting to peer through the combined "fog" of meteorite formation processes on asteroids and the effect of the exposure to the terrestrial environment results in our understanding of the birth of our Solar System remaining incomplete on many fronts. Obtaining a sample from a known, well-characterised body that contains material with a clear record of the earliest stages of Solar System formation, free from the mechanical requirements that it must survive atmospheric entry and terrestrial contamination will open a new window on our origins. The key science goals that will be addressed by MarcoPolo-R are:

1. *What was the astrophysical setting of the birth of the Solar System?*
2. *What is the origin of material in the early Solar System and how did it evolve?*
3. *What are the physical properties and evolution of the building blocks of terrestrial planets?*
4. *How do organics in primitive NEAs relate to the origin of life on Earth?*

Each of these science goals is introduced in the following section, and for each goal there are a number of primary objectives that are outlined.

2.1.1 Fundamental Science Goals of MarcoPolo-R

2.1.1.1 What was the astrophysical setting of the birth of the Solar System?

***Figure 2.1**: A massive star-forming region in the Large Magellanic Cloud. Credits: NASA, ESA, and F. Paresce (INAF-IASF, Italy), R. O'Connell (Univ. Virginia), and the Wide Field Camera 3 Science Oversight Committee.*

The Solar System is believed to have been born within a typical star-forming region (Figure 2.1), where many stars are created from a collapsing giant molecular cloud (Montmerle et al. 2006). Stars much more massive than our Sun have had much shorter life spans, consuming their nuclear fuel and ending in explosive nucleosynthetic events, recycling large amounts of new elements back into the molecular cloud. Some of the new elements condense to form grains in the expanding, cooling circumstellar shells, retaining detailed information about the chemical and isotopic signatures of their parent stars. Unfortunately, the stars born and dying around the young Sun are long since dispersed, as are all vestiges of the molecular cloud from which they came (Hester et al. 2004). However, the study of primitive meteorites has revealed a wide diversity of dust grains formed around these stars. Carbon-rich grains (carbides, graphite, diamonds), oxides (rutile, spinel, corundum), nitrides, and silicates (olivines, pyroxenes, GEMS) with huge enrichments in rare isotopes characteristic of specific nuclear reactions record details of many different nucleosynthetic events (e.g., Zinner 2005). But the record is limited to the objects we have in hand - the undifferentiated meteorites that fell on Earth. It is clear that most of these grains, robust as they are to have survived the formation of the Solar System, are highly susceptible to processes on the meteorite parent bodies, e.g. the most common pre-solar grains, the silicates, are only found in the least modified of all the meteorites. The ratio of crystalline to amorphous pre-solar grains in meteorites is very high, indicating either re-processing in the disk (without apparently interacting with the nebula gas?) or that the amorphous grains abundant in the Inter-Stellar Medium (ISM) are preferentially destroyed. Therefore, from samples of a primitive asteroid that has not experienced the meteorite-forming processes, we have the possibility ***(A) to determine whether primitive NEAs contain pre-solar grains previously unknown in meteorites, and the stellar environments in which these grains formed.***

The journey from circumstellar shell to solar accretion disk was long and complex, with the grains experiencing galactic cosmic rays and shock waves as they journey through the ISM. Implantation of new isotopes and the associated structural damage recorded the nature of these events. These grains act as catalytic surfaces for complex chemistry and as nucleation sites for the condensation of ices, other volatiles and organic molecules. While some aspects of these processes can be inferred from astronomical observations of interstellar material, details are largely unknown and therefore we aim ***(B) to investigate the interstellar processes that have affected the pre-solar grains.*** While grain mantles are undoubtedly more fragile than the grains themselves, evidence for such mantles have been found in the most pristine meteorites (Bernatowicz et al. 2003), i.e. those that have experienced the least amount of parent body processing indicating that these mantles are particularly susceptible to parent body processes. Collecting a sample of a primitive NEA that contains material that has experienced little or no asteroidal processing will open up a new area of detailed investigation of ISM processes, one that will provide unique information on the nature of the local star-forming region immediately prior to the birth of the Solar System.

Amongst the debris from the nucleosynthetic events and processes in the star forming region prior to the formation of the Solar System would have been isotopes with half-lives considerably shorter than the age of the Solar System. Radionuclides such as ^{41}Ca (half life ~ 0.1 Myr), ^{36}Cl (0.3 Myr), ^{26}Al (0.7 Myr), ^{10}Be (1.4 Myr), ^{60}Fe (~2 Myr) and ^{53}Mn (3.7 Myr) no longer exist but determining the abundance of their daughter elements in primitive materials offers potentially magnificent chronometers of the first instants of Solar System formation (e.g., Bizzarro et al. 2007; Dauphas & Chaussidon 2011). However, there is a burning debate about the origin of these so called "extinct" radionuclides. Do they originate from the galactic background through the continuous creation and destruction of stars that seed the local universe in exotic isotopes? Do they reflect the explosions of stars in the proximal environment of the protosolar nebula? To answer these questions we need ***(C) to understand the nucleosynthetic events that contributed to provide short-lived radionuclides to the Solar System.*** The local collapse of the giant molecular cloud that ultimately created the Solar System may have been triggered by a nearby supernova (Clayton 1978; Gounelle & Meynet 2012). Combining constraints from the short-lived radionuclides with the more complete understanding of pre-solar grain populations in the early Solar System, including the journey through the ISM of each population recorded in the grain mantles, may permit identification of the stellar event that could have triggered the collapse of the parental molecular cloud.

It may be that some short-lived radionuclides were produced from spallation reaction during irradiation of Solar System material by the nascent Sun (McKeegan et al. 2000), and therefore such isotopes may retain a record of the early irradiation environment and its bearing on the birth of planets. Understanding the contribution of these processes, and how the radioisotopes were distributed in the early Solar System also has important consequences on their applicability as chronometers, and is therefore critical to developing our understanding of the early Solar System.

2.1.1.2 What is the origin of material in the early Solar System and how did it evolve?

Due to the combined effects of loss of angular momentum and gravity, a fraction of a giant molecular cloud started to coalesce, forming a disk, with the central part soon starting nuclear burning. A star was born, circled by a disk of gas and dust (e.g. Cameron & Pine 1973; Nakagawa et al. 1981; Fig. 2.2). This primary architecture has long been thought to have shaped a thermal and chemical gradient: solids in the inner part of the disk formed at a temperature high enough to prevent condensation and accretion of volatile species, whereas in the outer region, more distant from the proto-Sun, ices and giant gaseous planets could form (Lewis 1974). The record of these processes has been essentially lost in the making of the terrestrial planets, which experience heating leading to extensive melting and thorough mixing of this early material. In contrast, asteroids, which comprise material that never went through the cycle of planetary formation, have retained unique information on the early Solar System processes involving condensation, heating, mixing, etc. Thus, sampling of a pristine asteroid and isolating the samples from contact with the terrestrial environment will permit us ***(D) to characterise the chemical and physical environment in the early solar nebula.***

During the condensation sequence, Solar System material started to accrete and to form mm- to cm-sized clumps glued by surface (electrostatic) forces (Figure 2.3). The next step to m- to hundreds of m-sized bodies, required processes that are not well understood - gravity would still not be efficient enough, and collisions and random agitation would have resulted in continuous destruction of larger bodies. Turbulence generated by magneto-rotational instability may help to concentrate particles representing approximately meter-sized boulders in large-scale high-pressure regions, and thus lead to local gravitational instabilities and planetesimal formation (Johansen et al. 2011). The timing of this construction sequence – from the duration of the dust epoch through the creation of planetesimals, and the processes that occurred as they accreted to form asteroids, planetary embryos and ultimately the planets - is also not well determined. Sampling an asteroid that was halted in its evolution part way through this sequence will unlock a window into the earliest stages of Solar System formation that will permit us ***(E) to determine the timescales of solar nebula and accretional processes.*** The isotope systems used in the age determinations are readily disturbed by processes involved in meteorite formation on the asteroid parent bodies, i.e. heating, aqueous alteration, shock. Therefore samples of an asteroid unaffected by these processes will constitute materials with less complex histories that will preserve undisturbed isotopic ratios and therefore better opportunities to provide highly accurate age determinations.

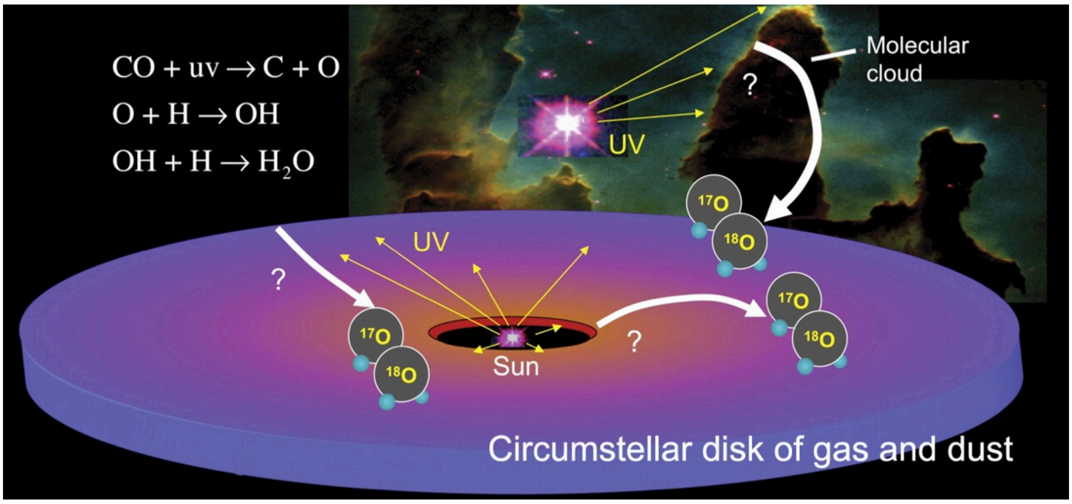


***Figure 2.2**: The Sun surrounded by a disk of gas and dust. The photolytic decomposition of CO molecules by UV light and self-shielding in a molecular cloud or circumstellar disk leads to heterogeneity in oxygen isotope compositions. Three suggested locations for this process are depicted here. Heterogeneity is preserved by the formation of isotopically labelled water ice that freezes on dust grains (after Rumble et al. 2011).*

Elements that were present mainly in a gaseous state in the protosolar nebula like H, C, N and O display large, sometimes extremely large, variations in the abundance ratios of their stable isotopes. While there may be hints that some of the observed ratios vary as a crude function of the heliocentric distance (e.g. D/H ratio; Alexander et al. 2012), any structure is complex, and details are poorly understood. These isotopic signals are of great use to understand relationships between Solar System bodies and reservoirs. In particular, the isotopic compositions of these elements are powerful tracers of the origin(s) of volatile elements and planetary atmospheres (e.g., Robert 2003; Marty et al. 2011; McKeegan et al. 2011), and of many of the key molecules necessary for the development of life. However, the causes of such variations are unknown. The oxygen that is found in the terrestrial planets and most components within meteorites are enriched by over 5% in both ^{17}O and ^{18}O relative to the bulk Solar System composition, inferred from the solar wind sample returned by the NASA Genesis mission (McKeegan et al. 2011). That both minor isotopes are enriched equally indicates that the process responsible fractionated the oxygen isotopes independently of mass. Similarly, the changes in nitrogen isotopic ratio are larger than can be readily accounted for by mass dependent fraction associated with known processes and conditions, including those operating in cold molecular clouds (e.g. Weiler et al. 2006). The origin of these large, mass independent fractionations could be linked to interactions between radiation and gas in the early Solar System by a process referred to as self-shielding (Clayton 2002). In such scenarios UV light driving photo-dissociation of abundant molecules (CO in the case of oxygen isotope effects) is efficiently attenuated at wavelengths specific to molecules containing ^{16}O. High CO column densities in the proto-solar disk may then result in large portions of the disk, only experiencing photo-dissociation of the minor isotope bearing CO molecule. This will liberate large enrichments in the heavier isotopes of oxygen to react with H and ultimately the metals (e.g. Si, Fe, Mg, etc.) that were accreted as oxides to form the planetary materials. Such fractionation mechanisms remain very speculative, with no consensus whether they occurred close to the proto-Sun (Clayton 2002), on the limbs of the disk (Young 2007) or in the molecular cloud (Yurimoto & Kuramoto 2004); see Figure 2.2. Direct evidence for this fundamental process, potentially applicable to many of the major elements, remains lacking. The meteorite Acfer 094, which is arguably the most primitive meteorite, contains a few fragments of a component that may record some of the extreme isotope ratios expected from such processes (Sakamoto et al. 2007) highlighting the fragile nature of protoplanetary disk material in the meteorite forming processes on asteroids. Samples from a primitive asteroid that include material that has escaped the meteorite forming processes will provide a unique opportunity ***(F) to determine the origin of large isotopic variations in early Solar System materials.***

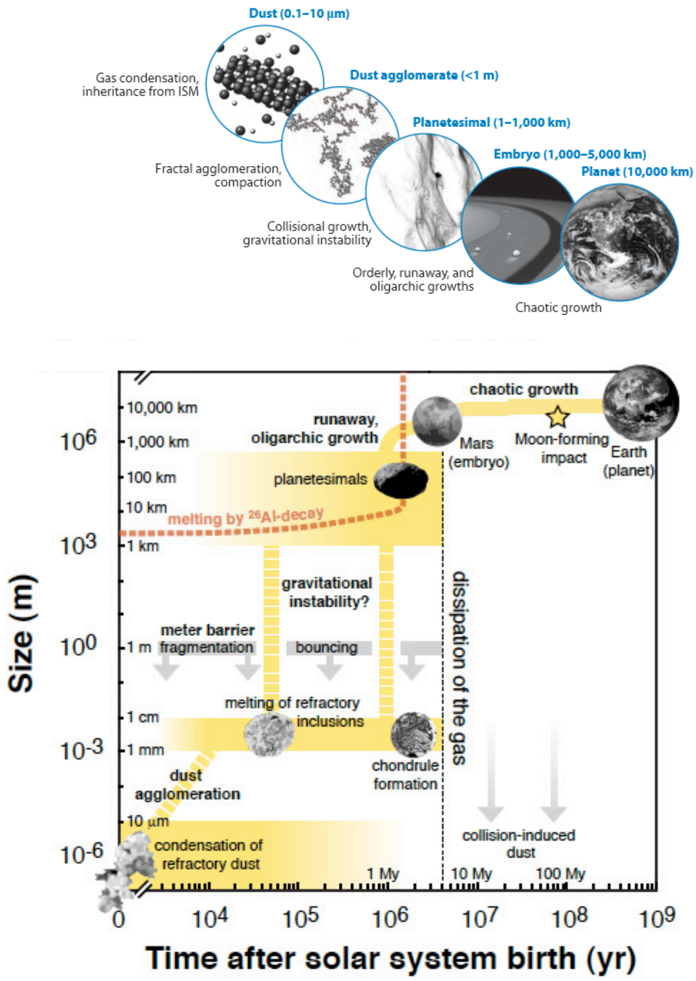


Figure 2.3*: Top: The different stages leading to the formation of planets. Bottom: Formation of the Solar System from a series of short-lived radionuclide systems (e.g.* ^{26}*Mg-*^{26}*Al) and long-lived chronometers (e.g. Pb-Pb). Time zero is marked by the condensation of refractory dust. As the disk cools, continued condensation, agglomeration and flash heating leads to the formation of mm to cm-sized CAIs and then silicate-rich chondrules, the main constituents of primitive meteorites, over a few* 10^6 *yrs. The step to form planetesimals and embryos from grains is largely unknown and may have been contemporaneous with chondrule formation. The gas dissipated after a few* 10^6 *yrs, by which time Mars sized objects had formed. The Earth, and Moon, took their definitive shape after the Moon forming impact, with the oceans and atmosphere possibly created by volatile-rich impactors. (Figures from Dauphas & Chaussidon 2011).*

Comets contain minerals formed at very high temperature (~1800 K) and ices that condensed at <100 K (Brownlee et al. 2006), demonstrating that lateral transfer of matter was widespread in the nascent Solar System, fuelled by the early activity of the proto-Sun (Shu et al. 1997). Extrasolar planetary systems clearly demonstrate that giant, gaseous planets can move from their more distant formation regions to very close to the central star (Mayor & Queloz 1995). Such observations have led to increasingly sophisticated modelling resulting in extraordinary predictions for our own Solar System, with Jupiter penetrating deep into the inner Solar System, triggering bombardment of the inner Solar System by bodies formed well beyond the orbits of the most distant planets (Walsh et al. 2011). Some of these predictions are indeed supported by observations and cosmochemistry, but others await analytical confirmation, and remnants of these events could be stored in the regolith of asteroids and recorded in the isotopic compositions of the stable isotope ratios of light elements (Hartogh et al. 2011; Robert 2003), and/or of isotopes formed by interactions with the solar irradiation as ^{10}Be or ^{7}Be (McKeegan et al. 2000, Chaussidon et al. 2006). Sampling asteroidal regolith may supply key information allowing us ***(G) to characterise the large scale mixing processes in the protoplanetary disk.*** Size distributions of the different dust components within samples of pristine protoplanetary material from a primitive asteroid will provide unique information on gas and dust movement in the inner portions of the disk.

Central to this problem of mixing is the relationship between the icy cometary bodies, originating from the outer Solar System, and the so-called primitive asteroids (that are primarily composed of the rocky remnants of planetary formation) preserved in the asteroid belt. The traditional view of a snow line separating the two formation regions is questioned, with increasing evidence that there exists a continuum in the composition of these classes of objects. Indeed, some of the primitive meteorites could have originated from nuclei of now extinct comets. Having access to material from bodies being intermediate in composition between "classical" asteroids and comets will permit exceptional insight into the composition of the most primitive bodies of the

Solar System and the structure and conditions of the solar accretion disk. The ground truth provided from the returned samples will also resolve many of the unanswered questions about the provenance of the diverse collection of the most primitive materials currently available in our collections (e.g., chondrites, interplanetary dusts) some of which may even originate from comets or a population of transitional bodies**.**

The volatile elements (e.g. hydrogen, carbon, nitrogen, oxygen, the halogens, etc.) created the environmental conditions necessary for the development of life on Earth. However, how the Earth came to possess such a substantial inventory of these elements remains unknown. Late accretion of comet-like bodies has been advocated, but the isotopic compositions of most cometary volatiles are not consistent with such an origin (Hartogh et al. 2011), although recent observations found that the D/H ratio in the Jupiter-family comet 103P/Hartley 2, which originated in the Kuiper belt, is close to that of ocean water (Hartogh et al. 2011). In contrast, some primitive meteorites from asteroids contain hydrogen and nitrogen with isotopic compositions more closely matching those of the atmosphere and the oceans (Marty et al. 2011; Marty 2012; Alexander et al. 2012). However, because of atmospheric entry selection effects, it is unclear how representative the meteorites are of the asteroidal bodies from which they came in terms of isotopic composition or volatile abundance. Therefore, a range of samples from a well characterised primitive asteroid is required ***(H) to establish the abundance and signature of water and other volatiles – a possible source for the Earth's oceans and atmosphere*** and to constrain the other signatures such bodies would impart on the Earth (e.g. siderophile elements). The volatile-rich environment at the Earth's surface means that meteorite samples are highly susceptible to contamination by these species. Therefore, samples of pristine asteroidal matter, carefully protected from exchange or contamination with the terrestrial environment, will allow an accurate determination of the potential volatile inventory of such bodies. This work extends to testing the origin of the volatiles on Mars and Venus, for which atmospheric compositions have been documented by dedicated space missions (Viking, MSL, Venera...) and by the analysis of volatile elements trapped in Martian meteorites. Debate continues about the origin of Jupiter and other giant planets, whether by accretion of icy bodies or collapse of a local solar-like atmosphere. Understanding the volatile inventory of primitive asteroids will inform this debate.

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

All but the largest asteroids (diameter > ~100 km) are part of a collisionally evolved population. Their bulk density (porosity), shape (*e.g.,* ellipsoidal to highly elongated), rotation rate, morphology (grooves, crater shapes and abundance, ridges, slope variation) as well as the gravitational properties provide clues about their internal structures. These could range from monolithic objects (mostly sizes ~ tens of m), through fractured or shattered objects or contact binaries, to true "rubble piles" of re-accumulated fragments with porosities up to 60 % (Richardson et al. 2002). In order to understand how collisional fragment asteroids are formed and ejected from the main belt it is necessary ***(I) to determine the global physical properties of an NEA.*** Such information is essential to determine the locations on the surface from where the most scientifically important samples can be found for collection and return to Earth, and to place the sample into the global geological context from which it was collected.

Given that the collisional lifetime of an asteroid decreases for decreasing size of the object, it is likely that the small NEA target of a sample return mission is a collisional fragment of a larger body, which was then transported from the main belt to the Earth-crossing region by being placed into an unstable zone such as a mean motion resonance with Jupiter. However, the evolution of the asteroid surface would have continued to the present day, due for instance to small impacts, tidal forces during planetary close approaches, changes in rotational properties, thermal effects and space weathering. Space weathering, the physical and chemical alteration of materials exposed to the space environment, starts to affect the surface layers of NEAs as soon as the surface is exposed by collisional disruption or subsequent surface movements. The effects are most apparent on the extreme surfaces of grains (solar radiation and particle flux) and can significantly affect the light scattering properties. In order to determine the formation and structure of the asteroid and to understand the geological context of the sample collected it is necessary ***(J) to determine the physical processes, and their chronology, that shaped the surface of the NEA.*** Dating of disruption or resurfacing events is possible via sample analysis (exposure ages derived from more deeply penetrating cosmic rays; or re-set radio-isotope ages) and asteroid imaging (crater counts).

Following the initial accretion of the parent asteroid, energy from the accretion process together with heat from the decay of short-lived radionuclides would result in melting of any water ice likely to have accreted along with organics and silicate dust at heliocentric distances beyond the snow line around 3 to 5 AU. Some of the water would have escaped directly to space, but a portion would have been sufficiently contained to remain in liquid form and permit reaction with the surrounding rocks. Aqueous alteration of rocks consists essentially of low temperature chemical reactions driven by the liquid water that acts as both a reactant and a solvent to mobilise materials. The products of aqueous alteration are secondary minerals such as phyllosilicates, sulphates, oxides, carbonates, and hydroxides and play a major role in the modification and synthesis of organics. Related spectral features, found for several meteorites and low-albedo main belt and outer belt asteroids, indicate that liquid water was present during some previous epoch.

About 60 % of the C-class asteroids, at heliocentric distances between 2.5 and 3.5 AU, are thought to have undergone some kind of aqueous alteration process (Barucci et al. 1998). While D-class bodies have no clear relation with any kind of meteorites (with the tentative exception of Tagish Lake), C-classes appear to be related to carbonaceous chondrite meteorites, which are the best-preserved available witnesses of the early phases of the Solar System formation. The baseline target of MarcoPolo-R, (341843) 2008 EV5 (see Section 2.1.5), shows a spectral feature at 0.48 mm that is attributed to the presence of magnetite. Accounting for the otherwise generally featureless spectra of the target asteroid, the magnetite appears most comparable to the abundant secondary magnetites observed in the most primitive, CI type, carbonaceous chondrites that show evidence of extensive aqueous alteration (e.g. Brearley 2006). The sample of mixed regolith returned from an NEA by MarcoPolo-R will allow us ***(K) to characterise the chemical processes that shaped the NEA composition*** as it will undoubtedly contain a range of components sampling portions of the parent asteroid with different geological histories, that were re-accreted to form the escaping NEA and subsequently thoroughly mixed within the regolith. Such a sample will thus offer a unique opportunity to follow the effects of progressive aqueous alteration on the mineralogy and organic inventory of a suite of rocks where we can be confident that the starting materials had homogeneous properties.

The effects of space weathering are different according to the heliocentric distances of the bodies and their surface composition. In particular, it is important to study the effects of space weathering on an NEA because those effects can give hints on how surface spectral properties are altered in the space environment. Such a study will provide ground truth for astronomical observations of reflectance and thermal emission. The visits to S-class asteroids by the missions NEAR and Hayabusa showed evidence of alteration of spectral properties by space weathering, which creates redder slopes and weaker mafic absorption bands. Results from the Sloan Digital Sky Survey suggest the opposite colour trends for C-class asteroids than for S-class asteroids (Nesvorny et al. 2005), although this is contradicted by other studies (Lazzarin et al. 2006). These results are very intriguing and highlight the difficulty of attempting to interpret the very subtle features in the spectra of dark, primitive objects in the Solar System. While there is a vast amount of remote observations of asteroids, it is now essential to return samples from well characterised primitive material from different population of asteroids in order ***(L) to link the detailed orbital and laboratory characterisation to meteorites and interplanetary dust particles (IDPs) and provide ground truth for the astronomical database***.

2.1.1.4 How do organics in primitive NEAs relate to the origin of life on Earth?

Carbon is a key element in the evolution of prebiotic material (Henning & Salama 1998). Our understanding of the evolution of organic molecules and their journey from molecular clouds to the early Solar System and Earth provides important constraints on the emergence of life on Earth and possibly elsewhere (Ehrenfreund & Charnley 2000). Carbon is found in space in all its allotropic forms: diamond, graphite, and fullerenes (Cataldo et al. 2004; Cami et al. 2010). In the denser regions of interstellar space, the so-called interstellar clouds, active chemical pathways form simple and complex carbon molecules from carbon atoms (Herbst & van Dishoeck 2009). Astronomical observations have shown that carbonaceous matter is actually ubiquitous in our own as well as distant galaxies. Moreover, a significant number of molecules that are used in contemporary biochemistry on Earth is found in interstellar and circumstellar regions as well as Solar System environments. The ice mantles of tiny dust particles in those cold environments contain a variety of simple carbonaceous molecules, including CO, CO_2, CH_4, H_2CO and many others. During the formation of the Solar System, interstellar organic material was chemically processed and later integrated in the pre-solar nebula from which planets and small Solar System bodies formed. The remnant planetesimals in the form of comets and asteroids impacted the young planets in the early history of the Solar System (Gomes et al. 2005; Walsh et al. 2011). It is therefore vital ***(M) to determine the origin, diversity and complexity of organic species in a primitive asteroid*** for an in-depth understanding of organic chemistry processes in space and their evolutionary timescales. Existing samples of meteorites have all experienced extensive processing on the parent asteroid, masking earlier organic material formation mechanisms in the ISM and protoplanetary disk. The MarcoPolo-R sample is expected to provide a range of components from a primitive asteroid, including largely unaltered material. Most critically, the random delivery of these meteorites to Earth always leads to contamination from the extensive terrestrial biosphere. Such contamination is difficult, and in many cases, impossible to resolve from indigenous components. The sample of 2008 EV5 will be collected under very strict contamination controls that will provide an unprecedented opportunity to investigate the pre-biotic organic chemistry of the early Solar System.

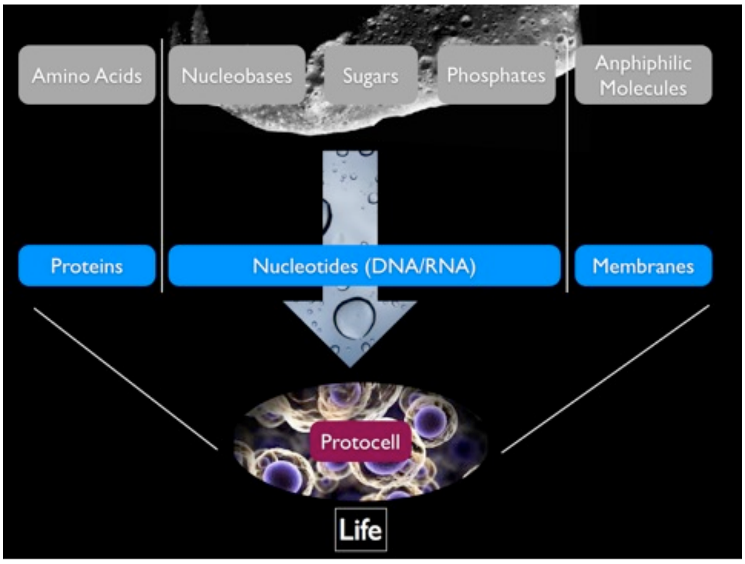


***Figure 2.4**: The composition of a contemporary cell. Most of the precursors are detected in carbonaceous meteorites. Amino acids are the building blocks of proteins. Nucleobases, ribose and phosphate are the building blocks of nucleotides (which are the building blocks of RNA and DNA). Amphiphilic molecules are known to spontaneously self-assemble into vesicles in water (i.e. into primitive cell membranes).*

Extraterrestrial material delivered to young planetary surfaces may have played an important role in life's origin (Chyba & Sagan 1992; Ehrenfreund et al. 2002). Before life could arise on a planet, atoms have to organise themselves into complex biological molecules such as proteins, RNA, or DNA. Such elaborate structures cannot appear spontaneously. Instead they result from a complex chemical evolution. These may have been crucial for the establishment of the first living systems on Earth. There is a possibility that a combination of exogenous and endogenous sources has provided the first precursor molecules for life on the young Earth. These simple molecules reacted and assembled on catalytic surfaces (such as minerals) and formed more complex structures that later developed into primitive cells (protocells).

Four groups of organic compounds are considered to be crucial for the chemical evolution from which life may have arisen (Figure 2.4). Those co-called "prebiotic" molecules include amino acids (which are the building blocks of proteins), nucleobases, sugars and phosphates make up nucleotides (the building blocks of DNA and RNA). Additionally, amphiphilic compounds are required with a soluble head and an insoluble tail as building blocks of membranes. Each of these families of organic compounds could have been synthesized under specific conditions on the primitive Earth (for a review see Martins 2012). Alternatively these organic compounds may have been brought to the primitive Earth by exogenous delivery of comets, asteroids and their fragments (i.e. meteorites, micrometeorites and Interplanetary Dust Particles (IDPs)). In fact, they have all been detected in meteorites (e.g. Martins et al. 2008; Callahan et al. 2011; Shearer et al. 2011).

High molecular diversity and exciting new results concerning the analysis of prebiotic compounds in carbonaceous meteorites emphasise the importance of analysis of pristine returned samples from asteroids. The question of how life originated on the Earth and whether it exists elsewhere in our Solar System has captured human imagination for centuries. How prebiotic building blocks could self-assemble and produce a minimal living system is one of the most experimentally challenging research areas. Life is generally believed to have emerged on Earth in a form functionally similar to current biochemistry but could have been based initially on much simpler compounds (Ehrenfreund et al. 2006). Identifying biologically important molecules in meteorites is always problematic due to ever-present terrestrial contamination. Therefore a sample of primitive asteroid collected under strict contamination control is vital to assess the sources of prebiotic material available to the young planets and will allow us ***(N) to provide insights into the role of organics in life formation.***

In the following sections, we describe the rationale for a sample return mission to the primitive Potentially Hazardous Asteroid (341843) 2008 EV5 and the measurements required both in the laboratory and at the asteroid to achieve the science goals (see Figure 2.5).

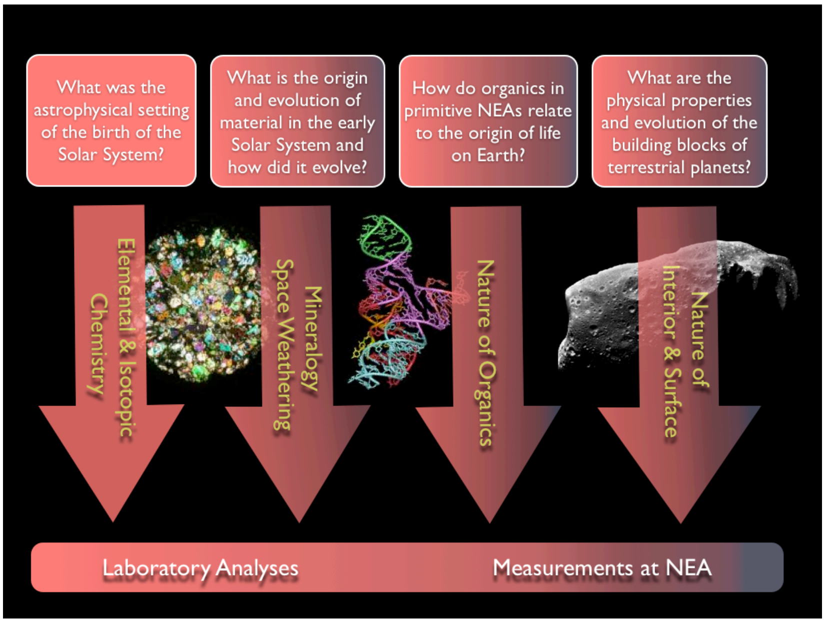


***Figure 2.5**: MarcoPolo-R will address the four fundamental goals through laboratory analyses of the returned samples and the data returned by the scientific payload on board the spacecraft.*

2.1.2 Why sample return?

2.1.2.1 The era of sample return

Some of the major challenges in planetary science have been tackled by ground- or space-based telescope observations, or by dedicated space missions that performed in-situ measurements. However, such approaches inevitably face limits in what can be achieved, either from the quality of information that can be obtained by telescopes or constraints in power, mass and environmental stability available in space missions. As the scientific challenges increase as we move beyond exploration, the quality of data required increases. In the case of MarcoPolo-R, deciphering the history of the Solar System, determining the isotopic composition of protosolar nebula components and the origin of biologically important organics molecules, all require high precision analyses of matter at the micro- and nano-scale, which can be achieved only by measurements in the laboratory.

One of the major goals of MarcoPolo-R is to provide a detailed understanding of the chronology of early Solar System events, which we know to span only a few million years from the analysis of meteorites. In order to perform these measurements, isotopic ratios of trace elements in a complex matrix must be performed with a precision of better than one part in a thousand. This demands exceptional levels of stability (power, vibration, thermal) as well as the opportunity to ensure that the instrument is optimised perfectly for the required measurements through repeated calibrations and tests. In the laboratory, these are demanding measurements, requiring specialist facilities, housing large (2-3 m) instruments (e.g. TIMS, MC-ICPMS), often with >1000 kg magnets, to achieve the necessary stability and mass resolution. Perhaps even more challenging to consider for a robotic mission is the need to select specific components from within the sample for such chronology measurements and to undertake a thorough characterisation. That way it is possible to ensure their formation history is understood and it is clear what it is that is actually being dated. This involves a series of mineralogical (e.g. spectroscopy, SEM/TEM), chemical (e.g. EPMA, LA-ICPMS, SIMS) and other isotopic measurements (e.g. SIMS, MC-ICPMS, GS-MS) providing high precision data, with a spatial resolution at the micron scale. This invariably requires very exact preparation of the samples – typically providing samples with a very flat (polished) surface.

Organic analyses require a wide array of techniques, many based on the use of liquid solvents, to extract key life-implicated compounds such as amino acids and nucleobases. Detection of some key compounds could be performed using space flight instruments (e.g. SAM on MSL). However, precise isotopic measurements of individual compounds, necessary for determining origins and relationships, are far more demanding, requiring instruments with performance approaching those used for chronology. Detailed investigation of the insoluble organic macromolecules requires harsh acid demineralisation of the sample and the use of NMR (with large super-conducting magnets) and synchrotron radiation (e.g. FTIR, XANES), neither of which could ever be envisaged for space flight.

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. There have been five sample return missions (or programmes in the case of the early lunar exploration). Each of these missions produced a step change in our understanding of the origin of Solar System material, and in several cases not in a manner that was expected. The exploration of the Moon four decades ago returned to Earth almost 400 kg of lunar rocks and soils, heralding a giant leap not only for mankind but also for planetary sciences. These samples revealed many new discoveries, including that the Moon is lifeless, that it is as old as the Earth, that it records how planetary bodies formed by accretion, that magma oceans existed early in the history of the Moon. Importantly, dating of these events led to a start in establishing a comprehensive chronology of planetary formation. It is not an exaggeration to say that planetary sciences were not the same after the Apollo era. Furthermore, thanks to a careful curation policy, those returned lunar samples are still available for present day studies. Analytical techniques have evolved since the Apollo samples were returned, with gains in sensitivity of up to 10^6 while analytical precision increased by 10^2 to 10^4. Our understanding of the universe has also evolved, but the samples of the Moon returned over four decades ago still remain an important research tool providing major advances of knowledge in the past ten years (~600 papers from Apollo and Luna missions since 2004; Crawford 2012).

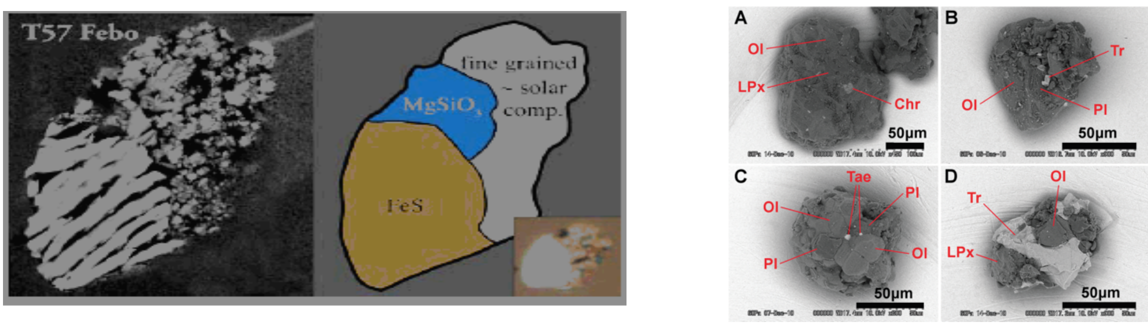


***Figure 2.6**: Left: Stardust 8-μm particle from comet 81P/Wild 2 showing the presence of sulphide pyrrhotite, enstatite grains and fine-grained porous aggregate material with chondritic composition (Brownlee et al. 2006). Therefore, in a single particle, materials that formed in different regions in a protoplanetary disk can co-exist. Right: Backscattered electron (BSE) images of four particles from the asteroid Itokawa showing the complexity of the mineral assemblages and the effects of space weathering (from Nakamura et al. 2011).*

The Genesis mission had a very simple goal: to determine the composition ("genesis") of the protosolar nebula from which planets were formed. Despite an accidental hard landing upon return in April 2004, the main goals could be achieved thanks in part to the sensitivity of the analytical systems developed specifically for this mission but also to the adaptability of ground based approaches to un-foreseen eventualities. The results are astonishing: for instance, they demonstrate that the Earth does not possess a typical Solar System isotopic ratio in certain key elements (e.g. oxygen, McKeegan et al. 2011, and nitrogen, Marty et al. 2011) and that all models henceforth must start from a solar composition, in a dramatic move from a Ptolemaic to a Copernican view. The analysis of the samples returned by the NASA Stardust mission from comet 81P/Wild highlights the wealth of information that can be achieved by sample return from a small body (Brownlee et al. 2006). Several thousand micron-sized dust particles from the coma were trapped in aerogel during a high-speed (6 km s^{-1}) fly-by and returned to Earth in January 2006. The collection velocity resulted in considerable modification of the samples. Nevertheless, identification of high-temperature minerals that formed in the hottest regions of the solar nebula resulted in a complete revision of our understanding of the early solar nebula, providing unexpected evidence for extensive radial mixing (Figure 2.6; Brownlee et al. 2006; Zolensky et al. 2006). The JAXA Hayabusa mission returned at least about 2000 particles of dust up to 300 μm in size from the surface of the evolved S-type Near-Earth Asteroid Itokawa in June 2010. Sample analyses demonstrated for the first time directly the link between the spectra of an evolved asteroid (S type) and meteorites (thermally metamorphosed LL chondrites) found on Earth (Nakamura et al. 2011), and permitted new insight into the regolith gardening of dust on the surface of an asteroid (Tsuchiyama et al. 2011; Ebihara et al. 2011) and the irradiation history of such small bodies (Noguchi et al. 2011).

The benefits of MarcoPolo-R will extend far beyond the field of planetary science. As a result of the Apollo programme, new instrumentation was developed to address the questions and challenges that these samples created. This process has continued with recent sample return missions (Genesis, Stardust, Hayabusa). European laboratories played a major role in the study of all returned sample collections, and Europe is the home of much of the leading industries in advanced analytical instrumentation (e.g. electron microscopes, mass spectrometers, ion probes). The selection of MarcoPolo-R will be a major stimulus to maintain European laboratories and industries at the forefront in analytical capability, integrating remote handling in ultraclean facilities with the preparation of samples for investigation by a large array of analytical techniques at the micro- and nano-scale. Such technical developments invariably find new applications in the wider analytical sciences.

2.1.2.2 Why can't meteorites answer the MarcoPolo-R key science questions?

Approximately 45,000 meteorites now exist in collections across the world (including large collections from Antarctica and the hot deserts), although the number of individual falls is much lower – reflecting the presence of unidentified shower falls and mechanical break up of single bodies into numerous fragments. However, even after correcting for such effects, we have strong indications that our terrestrial record is biased and an abundance of material does not survive atmospheric entry. The C-class asteroids account for ≈75 % of all main belt asteroids. While largely located in the mid/outer asteroid belt, their nearest meteoritic equivalents, the somewhat friable carbonaceous chondrites are present in meteorite collections at the level of <5 %. Although CM meteorites are by far (~35 %) the most numerous of the carbonaceous chondrites, it is possible that they come from one asteroid only (Morbidelli et al. 2006).

Since only the strongest material reaches the Earth, it is not known whether this material is representative of the dominant material in space. The measured compressive strength of the Murchison meteorite is 50 MPa (Tsuchiyama et al. 2008), about ten times higher than the compressive strength of porous materials on the Earth. This could explain the apparent over-representation of metamorphosed ordinary chondrites in the meteorite collections compared to dominant interplanetary matter inferred from populations of asteroid classes.

The strength of meteorites is the result of metamorphism and/or aqueous alteration on the parent asteroids – with effects that extend well beyond the mechanical properties of the meteorites as they mobilize elements and isotopes within and between minerals, re-set radio-isotope chronometers, destroy and modify primitive materials, and synthesize and redistribute organic compounds. In contrast, IDPs display mineralogical, chemical and isotopic signatures not found in meteorites, indicating formation and/or residence in the ISM or solar accretion disk. Such primitive material must have been stored somewhere for the past 4.5×10^9 years. On a more macroscopic scale, the Tagish Lake meteorite is perhaps the most friable carbonaceous chondrite recovered to date. Recovery of useful amounts of material was only possible as the fall was witnessed and happened over a frozen lake. In some respects it appears to be a particularly primitive meteorite, with high carbon content and unusual organic inventory. It has been linked with the very primitive D-class asteroids (e.g. Hiroi et al. 2001), but the high levels of aqueous alteration affecting this meteorite are not consistent with the fact that water features in D-class spectra are rarely observed (e.g. Kanno et al. 2003).

In October 2008, a small asteroid with a primitive F-type reflectance spectrum, 2008 TC3, entered the atmosphere and exploded over the Nubian desert, depositing material in a strewn field in Northern Sudan (Jenniskens et al. 2009). Searches to date have recovered >600 fragments (Shaddad et al. 2010), but still indicating that 99% of the original mass of the asteroid was lost in the atmosphere. These materials are collectively named Almahata Sitta (AHS), and represent the first recovered meteorite from a spectrally observed asteroid. The ensuing wave of work on AHS (see special issue of MAPS, October, 2010) revealed a huge diversity of components, including typical differentiated ureilitic material (petrology, oxygen isotopes, geochemistry) but ~30 % of the recovered samples are a diverse array of chondrite types (ordinary, enstatite, and Rumaruti types). It appears that asteroid 2008 TC3/AHS was a new type of breccia, unlike any meteorite known to date. It records a complex collisional and dynamical history for ureilitic material that is not immediately apparent in either polymict or main group ureilites, and has far-reaching implications for the dynamics and evolution of planetesimals in the early Solar System, impact fragmentation, and delivery of meteorites to Earth (Jenniskens et al. 2010; Herrin et al. 2010; Hartmann et al. 2011). Most importantly, none of this complexity was predicted from the remote spectral observations of the asteroid in space.

These rare events demonstrate that mechanically weak material does exist in significant quantities within the inner Solar System and that the existing meteorite collection is strongly biased towards heavily processed material. Sampling the regolith of a disrupted primitive C-type asteroid will include many lithologies and components from the parent asteroid including those that have experienced little or no parent body processing, but which would never survive atmospheric entry.

2.1.3 Why Near-Earth Asteroids?

2.1.3.1 Accessible samples of primitive material

NEAs, in orbits with perihelion distances $q < 1.3$ AU, periodically approach or intersect the Earth's orbit. They are the most accessible targets containing primitive materials for scientific research. Starting from the classical definition of "accessibility" in terms of the velocity change (Δv) to be applied to an already free-flying spacecraft, rendezvous with some NEAs is easier than with the Moon (Perozzi et al. 2001).

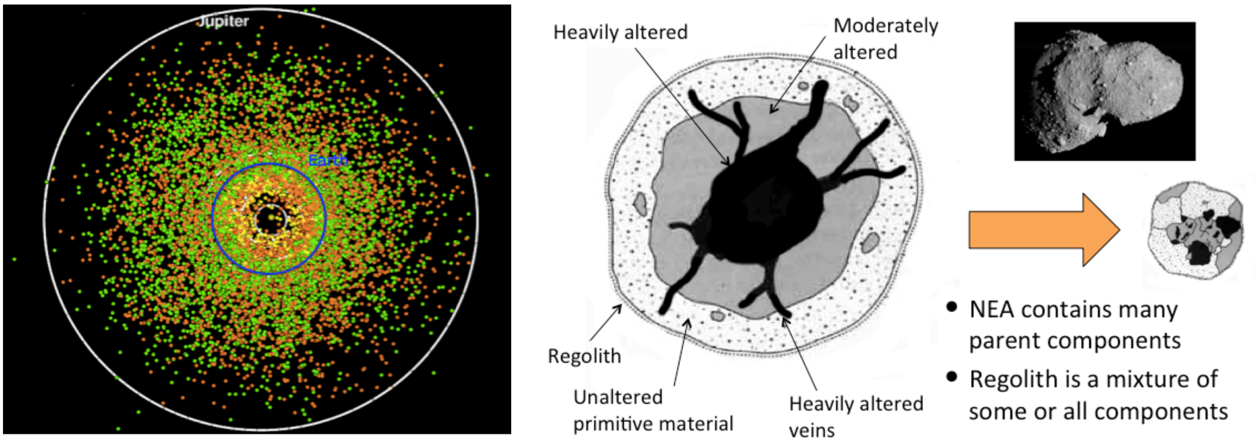


Figure 2.7: *Left: A top view of the inner Solar System depicting a snapshot of the known 10,400 NEAs at the time of submission. Different colours indicate different dynamical groups. Earth's orbit is the blue circle. Yellow dots: Atens; orange dots: Apollos; green dots: Amors. Credit: ESA/Albin. Right: NEAs are re-aggregated from disrupted parent asteroids (e.g. inset Itokawa). The surface of 2008 EV5 is dominated by primitive material, some of which will be unaltered. Image credit Itokawa: JAXA.*

More than ten thousand objects in near-Earth space have currently been discovered (Figure 2.7). Numerical studies have determined that the main sources of the near-Earth population are located in the inner Solar System (Michel et al. 2000; Bottke et al. 2002) with a small component coming from Jupiter Family Comets. It is possible to estimate the relative probability that a body with a known orbit in near-Earth space comes from a particular reservoir before its transport to its current orbit. Consequently, it is possible to relate the target from which a sample will be taken to its most likely dynamical source region in the Solar System. Such an estimate has already been made for Itokawa (Michel & Yoshikawa 2006) and 1999 JU3 (Campins et al. 2013).

2.1.3.2 The missing links

Considerable effort has been made linking asteroids with comets and meteorites. Recent observations of active main belt asteroids (Jewitt 2012) as well as observations of comets by recent space missions and new theoretical models have blurred the distinction between asteroids and comets, implying a continuum between the two kinds of bodies.

Good matches have been achieved between the reflectance spectra of the highly evolved (melted) asteroid (4) Vesta and those of basaltic achondrite meteorites, but the link becomes increasingly more tenuous with decreasing albedo (increasing organic content) and other characteristics of more primitive mineralogy. For instance, the C-class asteroid (21) Lutetia appears to be composed of a mixture of what was understood as "incompatible" materials (Coradini et al. 2011; Barucci et al. 2012). There is a discrepancy between the composition of asteroid 2008 TC3 inferred from spectral observations and analysis of meteorites recovered from the resultant Almahata Sitta fall (Jenniskens et al. 2009). Also, spectra of the E-class asteroid (2867)

Steins obtained by the ESA Rosetta spacecraft do not match any existing reflectance spectra of meteorites (Keller et al. 2010; Barucci et al. 2011).

Because of their spectral similarity in the visible and near-infrared regions, C-class asteroids have always been associated with carbonaceous chondrite meteorites (Barucci et al. 1987). However, the interpretation of the continuum of reflectance or thermal emissivity of an asteroid surface is difficult and not unique, since asteroid surfaces are composed of mixtures of minerals whose spectral properties are non-linearly combined.

A significant complication comes from space weathering which can alter the surface properties of airless bodies. Interpretation of all remote observation data will be greatly enhanced by "ground truth" analyses. Only on the basis of analyses of samples returned by spacecraft will it be possible to apply the knowledge obtained from meteorites to the vast amount of information available from asteroid observations.

2.1.3.3 Impact Hazard

It is well established that large NEAs represent a threat to the survival of living species, and that even small NEAs can be the source of local or regional damage. This was shown by the meteor that exploded in the Earth's atmosphere on 15 February 2013, over Chelyabinsk (Russia). The object, of only 15-20 m in diameter, exploded in an airburst at a height of 15 to 25 km. The explosion produced a shock wave and led to a bright flash and the production of fragmentary meteorites. The energy released is estimated to be equivalent to ≈440 kilotons of TNT (i.e. 30 times the yield of the Hiroshima bomb; Brown et al. 2013). This occurrence demonstrated that a low probability event can have major consequences. Risk assessment depends on the collision probability of potentially hazardous NEAs with Earth as a function of their impact velocity and physical properties (mass, mechanical properties; e.g. Stokes and Yeomans 2003). In addition, the technology needed to set up a realistic mitigation strategy also relies upon knowledge of the physical properties of the impacting body. Thus, knowledge of the global and local physical properties of an NEA that is required for successful sample collection, and the subsequent physical nature and composition of the returned samples measured in the laboratory, are extremely relevant for Planetary Defence objectives (Michel 2013).

The MarcoPolo-R spacecraft will, as a direct result of the mission requirements, demonstrate a number of technologies needed for the deflection of threatening asteroids in the Planetary Defence context:

- Rendezvous and navigation in close proximity to an NEA.
- Demonstration of a photo-gravitationally stabilized orbit as envisaged for the RSE experiment would be important for precise positional tracking of a deflected asteroid.
- Controlled hovering close to an asteroid surface - e.g. for a gravity tractor or an ion-beam shepherd concept, where a satellite has to be brought close to the object at a constant distance.

These points are also mentioned - with explicit reference to MarcoPolo-R - in a roadmap for future activities (Cano et al. 2013). The baseline target of MarcoPolo-R, 2008 EV5, is classified as a Potentially Hazardous Asteroid (PHA), i.e. its orbit comes very close to Earth's and it has a size large enough to cause significant damage. Although 2008 EV5 is an example of a PHA large enough to pose a threat of regional or global damage, it is, fortunately, not predicted to impact the Earth in the foreseeable future!

2.1.4 The target (341843) 2008 EV5 - property highlights

(341843) 2008 EV5 was discovered on 4th March 2008 (Larson et al. 2006) and made a close approach within 0.022 AU of the Earth in December 2008 when photometric (Galád 2009), spectroscopic (Reddy et al. 2012) and radar (Busch et al. 2011) observations were possible. The recent publication of these results, combined with its favourable orbital geometry, has led to the identification of 2008 EV5 as an exceptional target for a sample return mission.

The overall spectrum of 2008 EV5 and the presence of an absorption band at 0.48 μm (Figure 2.8; Reddy et al. 2012) attributed to magnetite, indicates similarity with Orgueil, a CI carbonaceous chondrite. This rare meteorite class is believed to represent some of the most primitive material available on Earth, with a composition that most closely matches that of the Sun and by inference the original solar nebula. They contain up to 20 % water, in the form of hydrated minerals as well as organics such as polycyclic aromatic hydrocarbons and amino acids. Their porous, volatile-rich composition and similarity with icy outer Solar System moons suggests formation in the outer asteroid belt and possible link to comets. However, this interpretation must be taken with caution because Orgueil, and other CI meteorites, are contaminated by their terrestrial sojourn (e.g. growth of sulfates; Gounelle & Zolensky 2001). Only samples returned from 2008 EV5 can provide us with the pristine composition of its primitive material. In addition, radar and optical measurements indicate that this asteroid has interestingly a moderate albedo for a primitive body (0.12 ± 0.04 for the optical albedo; Busch et al. 2011), at odds with the usual lower albedo of the majority of known primitive asteroids, including the targets of Hayabusa2 and OSIRIS-REx.

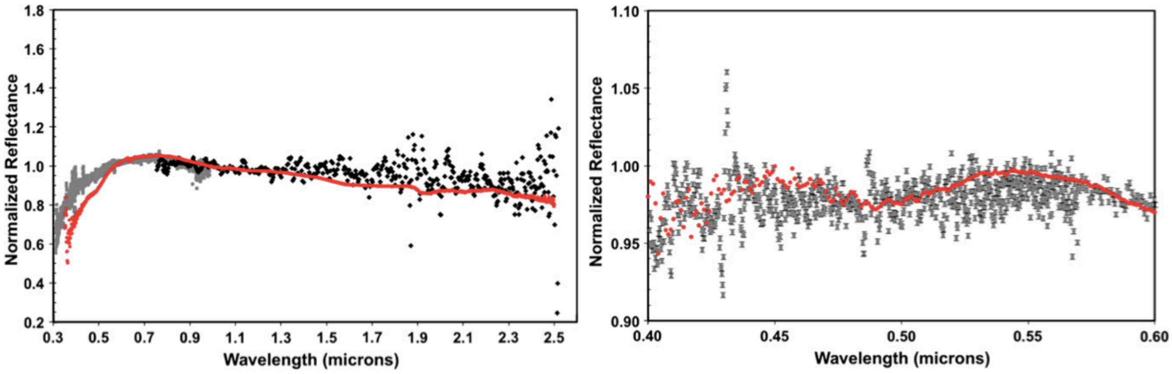


***Figure 2.8**: Left: Combined visible and near-IR spectrum of 2008 EV5 along with, in red, the spectrum of CI carbonaceous chondrite Orgueil (Gaffey 1976). The differences between the two spectra at shorter wavelengths could be due to slope variation that is phase angle dependent. Right: Continuum removed 0.48 μm feature for 2008 EV5 and CI chondrite Orgueil. The feature is likely due to a spin-forbidden Fe^{3+} absorption band (Cloutis et al. 2011). From Reddy et al. (2012).*

2008 EV5 has an overall shape like an oblate spheroid with retrograde rotation. The most prominent surface feature derived from radar observations (Busch et al. 2011) is a ridge parallel to the asteroid equator that is broken by a concavity about 150 m in diameter (see Fig. 2.9). Oblate shapes with equatorial ridges, as found for many small asteroids (e.g. (66391) 1999 KW4, Ostro et al. 2006), are characteristically produced on rubble-pile objects that reconfigure their shape due to spin up by the YORP effect (Walsh et al. 2008; Harris et al. 2009; Holsapple 2010; see Section 2.2.2.2). Busch et al. (2011) conclude also that the asteroid surface is smooth on decametre scales and interpret the concavity as an impact crater based on its morphology. A crater with a diameter roughly 1/3 the asteroid diameter and a depth-to-diameter ratio of about 0.2 do not provide any constraint on the surface porosity of the object. It is however possible that the impact that produced the crater caused shaking and later regolith redistribution that may have erased smaller features, explaining the general lack of decametre-scale surface structures. Table 2.1 lists the known physical properties of 2008 EV5. Independent measurements of the size and albedo from radar and WISE infrared data are in good agreement. The thermal inertia is typical of small asteroids and implies an average grain size of the regolith of the order of 0.5 - 1 cm (Ali-Lagoa et al. 2013, using the method of Gundlach & Blum 2013). The maximum equatorial surface temperature of less than 350 K, with much lower temperatures towards the pole and a few cm below the surface, offers a benign environment for organic material.

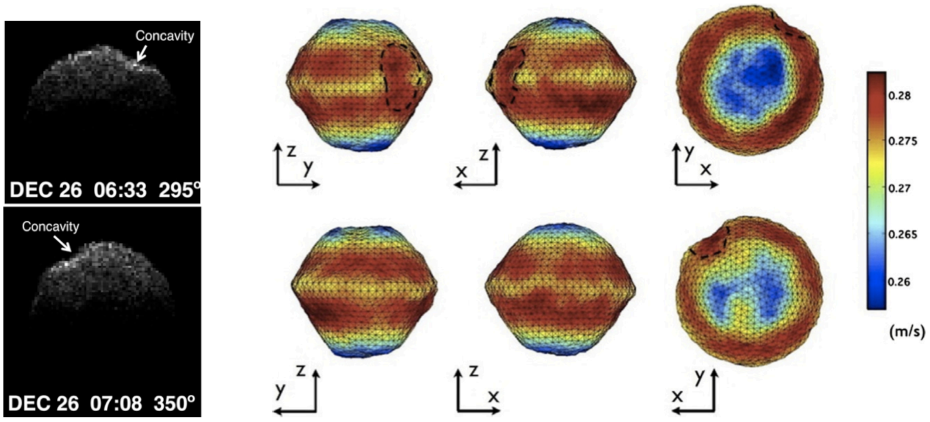


***Figure 2.9**: Left: Delay (range)/Doppler frequency (radial velocity) images of 2008 EV5 from Arecibo data. Right: Geopotential mapped as equivalent velocity over the surface of the radar shape model (assuming a bulk density of 3 g cm^{-3}). The equatorial ridge is at higher potential than the mid-latitudes. Note the gravitational minimum centered on the concavity (black dashed line). From Busch et al. (2011).*

2008 EV5 has a low inclination, near-circular orbit with semi-major axis of 0.96 AU, making it one of the most accessible primitive NEAs for sample return, with short mission durations possible in the early 2020s. In addition, its small range of heliocentric distance and relatively close proximity to the Earth throughout the mission provides optimum thermal environment and data communications. It will be accessible for ground-based observations during the planned mission, passing within 0.042 AU of the Earth in December 2023.

Table 2.1: *Physical properties of 2008 EV5* (Busch et al. 2011 and Ali-Lagoa et al. 2013).

Property	Value
Equivalent diameter	400 ± 50 m
Maximum dimensions along principal axes	(420 x 410 x 390) ± 50 m
Rotation period	3.725 ± 0.001 h
Pole direction	Ecliptic: (180°, -84°) ± 10°
Optical albedo	0.12 ± 0.04
Thermal inertia	450 ± 100 J $s^{-1/2}$ $K^{-1}m^{-2}$

2.1.5 MarcoPolo-R - a scientifically unique mission

MarcoPolo-R is proposed in a new era of high international interest in sample return missions to primitive asteroids. This is demonstrated by the recent selections of sample return missions by leading space agencies: OSIRIS-REx in the NASA New Frontiers program for launch in 2016 and Earth return in 2023; JAXA's Hayabusa2 for launch in December 2014-June 2015 and Earth return in 2020. Both missions will greatly improve our knowledge of the material composing primitive asteroids: OSIRIS-REx target is (101955) Bennu (formerly 1999 RQ36), a 500 metre-diameter B-type NEA; Hayabusa2 target is (162173) 1999 JU3, an 870 metre-diameter C-type. Their spectral characteristics and low albedos (<0.06, in contrast to the moderate albedo of 2008 EV5; Section 2.1.4) imply significantly different compositions from the MarcoPolo-R target. These clear compositional differences suggest that the parent body of 2008 EV5 may have formed in a different (possibly volatile-rich) region. The diversity of physical properties, composition and structure of NEAs means that different missions, with their own sampling mechanisms and strategies are likely to collect different types and amounts of material (e.g. Hayabusa2 to return less than 1 g). MarcoPolo-R will provide a unique opportunity to enhance our knowledge of the nature of a distinct population of primitive bodies, possibly composed of transitional objects between asteroids and comets.

The short mission duration offered by the MarcoPolo-R target will bring the time of the sample analysis relatively close to the expected return times of the JAXA and NASA sample return missions, allowing Europe to contribute in a timely and significant manner to the international sample return activities. MarcoPolo-R will ensure that European laboratories involved in sample analysis are positioned at the forefront of this new era of sample return and retain 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 (including cosmochemistry, astrophysics, astrobiology, and planetary science) and will generate tremendous public interest (see Section 8).

In addition to addressing the exciting science goals, the MarcoPolo-R mission also involves innovative technology development activities by ESA. They already achieved major breakthroughs, and can be used as pathfinders to future missions for science, human exploration and mitigation. The development of sample return technology represents a crucial element for Europe's science community and space industries. In particular, flight experience of autonomous navigation and control, and demonstration of the Earth re-entry capability are crucial components for the long-term goal of Mars sample return. The MarcoPolo-R samples will provide 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. Asteroids are also viewed as a major resource that can be exploited, by space agencies for future extended exploration missions but also by industry as a source of rare materials and elements. MarcoPolo-R will enhance our understanding of the diversity of the asteroid population, in particular their surface properties, required to achieve these objectives.

2.2 Measurements

2.2.1 Laboratory measurements

MarcoPolo-R will collect a sample of a primitive NEA, of a type resembling the most primitive class of meteorites, free from terrestrial contamination or alteration due to atmospheric entry. Measurements related to the key scientific questions and to the science objectives defined in the previous sections are summarised in Table 2.2.

Table 2.2*: Science goals, objectives, related measurements and the method to perform the measurements.*

Science Goals	Science Objectives	Measurements	Method
1. *What was the astrophysical setting of the birth of the Solar System?*	(A) To determine whether primitive NEAs contain pre-solar grains previously unknown in meteorites, and the stellar environments in which these grains formed (B) To investigate the interstellar processes that have affected the pre-solar grains (C) To understand the nucleosynthetic events that contributed to provide short-lived radionuclides to the Solar System	Chemistry Grain mineralogy and composition Isotopic composition of grains	Sample analysis
2. *What is the origin and evolution of material in the early Solar System and how did it evolve?*	(D) To characterise the chemical and physical environment in the early solar nebula. (E) To determine the timescales of solar nebula and accretional processes. (F) To determine the origin of large isotopic variations in early Solar System materials. (G) To characterise the large scale mixing processes in the protoplanetary disk. (H) To establish the abundance and signature of water and other volatiles – a possible source for the Earth's oceans and atmosphere.	Bulk chemistry Mineralogy, petrology Isotopic composition in inclusions (e.g. chondrules or CAIs), matrix; pre-solar grains and volatiles, water	Sample analysis
3. *What are the physical properties and evolution of the building blocks of terrestrial planets?*	(I) To determine the global physical properties of an NEA. (J) To determine the physical processes, and their chronology, that shaped the surface of the NEA. (K) To characterise the chemical processes that shaped the NEA composition. (L) To link the detailed orbital and laboratory characterisation to meteorites and interplanetary dust particles (IDPs) and provide ground truth for the astronomical database.	Volume, shape, mass Surface morphology and geology Mineralogy, petrology Isotope geochemistry & chronology Weathering effects Thermal properties	Imaging and radio science Visible and Near-IR Imaging-spectrometry Mid-IR spectrometry Sample analysis
4. *How do organics in primitive NEAs relate to the origin of life on Earth?*	(M) To determine the origin, diversity and complexity of organic species in a primitive asteroid. (N) To 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

Primitive meteorites can be considered as being composed of three principle components, formed at different temperatures and in different environmental settings (Figure 2.10). In meteorites these materials are intimately mixed on the scale of microns to mms, providing clear evidence of wide-scale mixing in the nascent Solar System. In order to extract the necessary information from complex samples, a vast array of analytical tools is required. This includes techniques such as microscopy, spectroscopy and spectrometry, shown in Table 2.3. An estimate of the required mass for a given measurement is also given. For each science area, the minimum mass of consumed material ('single analysis mass') is listed. The actual amount of material required for each analysis ('required mass' of material that could likely be allocated from a curation facility) is much larger. In many cases, this is because very specific phases of a sample, which may be present at very low abundances (as low as ppm levels), need to be analysed. Multiple analyses of different components are required to develop an understanding of a process, *e.g.* thermal history or space weathering. Some of the instruments demand very precise sample preparation – usually very flat surfaces (e.g. SIMS and EPMA) and this usually necessitates the preparation of mounts or slices, with the added benefit of providing contextual information for any given grain.

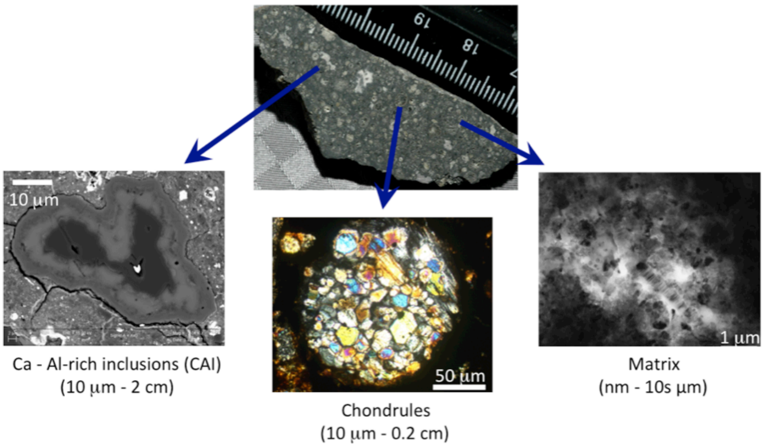
Table 2.3: *Scientific aspects and measurement requirements for returned samples.*

Component	**Scientific aspects**			**Measurement requirements**			
	Goal	**Objective**	**Theme**	**Measurement type**	**Techniques**	**Req-uired mass**	**Single analysis mass**
Chondrules, refractory inclusions, matrix	2	E	Age	Isotopic abundances	SIMS, LA-ICPMS, MC-ICPMS, TIMS	Gram	10s pg (SIMS) to 10s mgs (TIMS) per analyses
	2	G	Disk dynamics	Mineralogy & mineral chemistry	EPMA, SEM, TEM, XRS, FTIR, Raman, SIMS, LA-ICPMS	Gram	ng (EPMA) to µgs (LA-ICPMS) per analysis
	2, 3	D, H	Volatility fractionation	Elemental and isotopic abundances	SIMS, LA-ICPMS, GS-MS, NG-MS	100s mgs	10s pg (SIMS) to 100s µgs (NG-MS) per analyses
	2	G	Processing	Elemental and isotopic abundances	SIMS, LA-ICPMS, MC-ICPMS, GS-MS, NG-MS	Gram	10s pg (SIMS) to 10s mgs (MC-ICPMS) per analyses
	2	G, E	Thermal history	Mineralogy and mineral chemistry	EPMA, SEM, TEM, XRS, FTIR, Raman, SIMS, LA-ICPMS	Gram	ng (EPMA) to µgs (LA-ICPMS) per analysis
	2	D, G, E,	Accretion dynamics	Mineral chemistry	EPMA, SEM, TEM, XRS, FTIR, Raman, LA-ICPMS, SIMS	Gram	ng (EPMA) to µgs (LA-ICPMS) per analysis
	3, 4	N, H	Interstellar processes	Elemental and isotopic abundances	SIMS, CS-GS-MS, NMR, GC-MS, XANES, STXM, μL^2MS	Several grams	10s ag (GC-MS) to gram (NMR) per analyses
Organics	2, 3	D, F, G, H	Early solar-system processes	Chemical analyses, elemental and isotopic abundances	SIMS, GS-MS, NMR, Raman, XANES,	Several grams	10s ag (GC-MS) to gram (NMR) per analyses
	4	M	Asteroidal processes	Chemical analyses	NMR, Raman, XANES, HPLC, GCMS, μL^2MS	100s mgs	10s ag (GC-MS) to gram (NMR) per analyses
	3, 4	M, N, H	Origin of life	Chemical analyses	Laser GSMS, NMR, Raman, XANES, HPLC, GCMS, μL^2MS	Several grams	10s ag (GC-MS) to gram (NMR) per analyses
	3, 4	I, M	Collisional history	Mineral composition	EPMA, SEM, TEM, XRS, FTIR, Raman	100s mgs	10s pg (Raman) to ngs (EPMA) per analyses
Lithologies & breccias	3	K	Aqueous alteration	Mineralogy	EPMA, SEM, TEM, XRS, FTIR, Raman, GS-MS, SIMS	Several grams	10s ag (GC-MS) to 100s µgs (GS-MS) per analyses
	3	I	Shock processes	Mineralogy	EPMA, SEM, TEM, XRS, FTIR, Raman	Several grams	10s pg (Raman) to ngs (EPMA) per analyses
	3, 4	K, M	Thermal alteration	Mineralogy	EPMA, SEM, TEM, XRS, FTIR, Raman, SIMS, GS-MS	Several grams	10s ag (GC-MS) to 100s µgs (GS-MS) per analyses
	3, 4	J, K, L, M	Space weathering	Mineralogy	EPMA, SEM, TEM, XRS, FTIR, Raman, Opt. spectro., ESR, NG-MS, SIMS, GS-MS, susceptometer	Gram	10s pg (SIMS) to mgs (susceptometer) per analyses
	3	I	Physical properties	Strength, porosity, thermal diffusivity, magnetism	Helium pycnometer, differential scanning calorimeter, susceptometer	Gram	mgs (differential scanning calorimeter) to 100s mgs (Helium pycnometer)
	3, 4	I, J, N	Age	Mineralogy & isotopes	EPMA, SEM, TEM, XRS, FTIR, Raman, SIMS, NG-MS, ICPMS	Gram	10s pg (SIMS) to 10s mgs (ICPMS) per analyses
Pre-solar grains	1	C, A	Nucleosynthesis	Elemental and isotopic composition	SIMS, NG-MS, TEM, SEM	Several grams	10s pg (SIMS) to 100s µgs (NG-MS) per analyses
	1, 2	G, C, A	Circumstellar processes	Mineralogy and mineral chemistry	SEM, TEM, Raman, SIMS, Auger spectr.	Gram	10s pg (SIMS) to 100s mgs (NG-MS) per analyses
	1, 2, 3	C, B, F, H	Interstellar processes	Isotopes and mineralogy	SEM, TEM, Raman, SIMS, Auger spectr.	Gram	ags (Auger) to 10s pgs (SIMS)
	1, 2	E, A, B	Age	Isotopes	SIMS, NG-MS	Several grams	10s pg (SIMS) to µgs (NG-MS) per analyses

Other sample preparation techniques (particularly for organics) require extraction of specific components from a large sample, in either a partially destructive manner (e.g. solvent extraction for CS-GS-MS analyses) or in a highly destructive manner (*e.g.* demineralisation for NMR analyses). Finally, as the collected sample is expected to originate from the regolith of a rubble pile body with considerable heterogeneity, variability in the fragment composition is also expected, with variations in abundance, phases or elements of one to two orders of magnitude.

The required mass has been derived to guarantee the scientific success of the mission. A range of factors has been taken into account to determine the total required mass. Key aspects include the need for multiple measurements to provide statistical verification (e.g. at least three different measurements in three different laboratories have to reproduce the same results), and for nominally 30 % of the returned mass to be stored for an indefinite time in the curation facility for future analysis.

In the last few decades, revolutionary changes in instrumentation have increased the chances of obtaining advanced analytical information on the mineralogy, elemental and isotopic composition, organic chemistry, and surface and internal structures of solids at the micrometre and nanometre scales. However, no single measurement, or type of measurement, will provide the complete answer to any of these questions.



CAIs	Chondrules	matrix
Very high T phases	*High T phases*	*Low T formation*
Rich in Ca, Al, first solids to form	Silicate and metal spherules,	Volatiles incl. OH Noble gases, Organics pre-solar grains
• Stellar heritage • Very early chronology • condensation sequence • large-scale mixing	• Early chronology • first planetary processes • Gas-solid interactions	• interstellar heritage • Stellar heritage • Origin(s) of volatiles • Origin of life
• Electron and ion microscopes (incl. SIMS) • Stable and radiogenic isotope methods (TIMS, ICP-MS)	• Electron and ion microscopes (incl. SIMS) • Stable and radiogenic isotope methods (TIMS, ICP-MS) • Noble gas MS	• Fine mineralogy (X-ray XANES) • IOM analysis • SIMS, TIMS, ICP-MS • Noble gas MS

***Figure 2.10**: The main components found in meteorites formed pre-sumably at different tem-peratures. The matrix of meteorites, assembled at low temperatures, is a fine-grained mixture that contains clasts of other constituents but also hydrated phases, organics, oxidized com-pounds.*

Information regarding pre-solar heritage, origins of life and of volatile elements is found in such low temperature assemblages, but many of the phases present there are the most prone to degradation during the meteorite forming processes and interactions with the terrestrial environment (after Villeneuve 2011).

New knowledge will be derived by combining the results of several analyses of different components in the returned sample and by a multitude of techniques. The returned sample will contain heterogeneous fragments from different parts of the asteroid, each having experienced a unique geological history. It is only through careful characterisation of each component that the most primitive components can be identified, which is necessary for investigating Solar System formation and pre-solar processes. This characterisation is also necessary for a thorough assessment of the geological variability of the asteroid that is required to construct a model of the formation and history of the asteroid.

The sample of primitive material from an NEA returned by MarcoPolo-R will be heterogeneous at different scales, from centimetres to nanometres and, even at the molecular scale. Each component will be a remnant directly connected to specific astrophysical environments and processes, such that the chemical, isotopic, mineralogical and molecular information record the place where it formed, the processes it experienced, the timescales elapsed, and the environments crossed in space. Thus, any reliable laboratory analysis must be able to resolve these discrete components within the sample.

The analytical approach is now described for each of the areas of investigation associated with the four main science goals of MarcoPolo-R. Each section highlights the materials expected within the returned sample, the sample requirements, the principal techniques that will be employed for the analyses and the data generated.

2.2.1.1 What was the astrophysical setting of the birth of the Solar System?

Pre-solar grains formed in the envelopes of previous stars and survived the Solar System birth. They are predominantly micron-sized and concentrated in the fine-grained matrix of primitive meteorites. The study of potential new grain types found by MarcoPolo-R will provide new insight into stellar environments (e.g. Fig. 2.11). For example, some pre-solar silicon carbide grains carry isotopic signatures indicating that they formed during type II supernovae. But they require mixing from several non-adjacent zones within the precursor star, without significant incorporation of intervening oxygen-rich zones. By this means, C>O ratios are preserved in a suitable way for condensation of silicon carbide (Meyer & Zinner 2006). A major challenge will be to understand the residence times in the ISM of interstellar grains. Previous analyses of rare, large (50 micron) grains show residence times up to 10^9 years in the ISM (Heck et al. 2009). The challenge now is to extend this to more representative grains (micron-sized) and with different chronometers (e.g. heavy r-process elements). Primitive NEA material offers the best opportunity to accurately determine these unknown ages. The identification of interstellar grains in-situ, or concentrated via gentle separation techniques (e.g. freeze/thaw disaggregation) combined with density and settling techniques permits study of the mantles and reaction rims found on some grains (molecular species accreted from the interstellar environment) with techniques like NanoSIMS, TEM, XANES. These mantles offer a unique insight into the post-formation history of the grains, including processes in the ISM and solar nebula (see Figure 2.12). Such fragile mantles are readily modified during the extensive asteroidal processing required to generate meteorites. The more primitive material returned by MarcoPolo-R will offer an unprecedented opportunity to investigate the history of these grains in the ISM and the processes occurring there.

The analysis of presolar grains requires high spatial resolution techniques such as TEM and SIMS in which a primary beam of heavy ions extracts matter from the target at a scale resolution down to 10 nm. Such ion probes can readily provide isotope ratios for a range of different elements - e.g. those of H, C, N, O, Mg, Al, Si, S, etc. - on polished slices of whole rock or even fine powders of the most primitive materials present, to provide a detailed assessment of the pre-solar grain inventory. The mineralogy of micron-sized grains can be further investigated by sectioning with FIB-SEM for TEM analyses revealing seed grains, internal structures, *etc.,* in order to provide detailed understanding of the condensation sequences, formation intervals, pressures and temperatures in the circumstellar shells (Bernatowicz et al. 2006) and the nature of mantles deposited in the ISM.

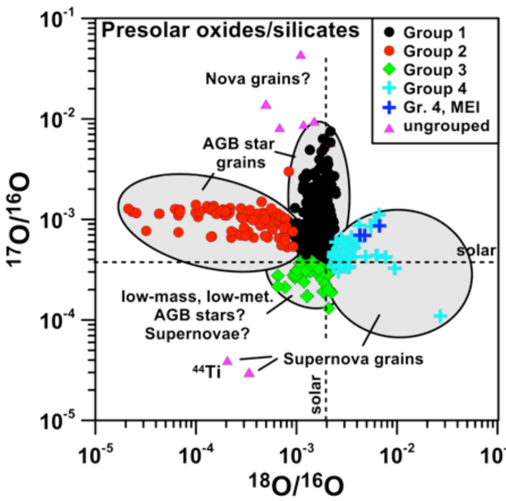


Figure 2.11*: O-isotopic systematics of presolar oxides and silicates from primitive Solar System materials (from Hoppe 2010).*

2.2.1.2 What is the origin and evolution of material in the early Solar System and how did it evolve?

Calcium-aluminium rich inclusions (CAIs) are the most refractory (formed at high temperature) and oldest known Solar System condensates. They are considered to be the first solids to form, with ages around 4.568 Gyr established by the U-Pb method that anchors the time-scale of the birth of the Solar System (see Figure 2.14). Furthermore, most CAIs contain remnants of the now extinct ^{26}Al that decayed to ^{26}Mg with a half-life of 0.7 Myr that provides time constraints for the first few million years of Solar System. ^{26}Al appears to have been sufficiently abundant to be a major source of heat for melting the first planetesimals. Of all early Solar System materials the CAIs most closely match the ^{16}O-rich composition of the protosolar nebula. Clues to the origin of the, as yet unexplained, effect that resulted in essentially all other solid material in the Solar System being much more depleted in ^{16}O may be recorded in some of later stages of CAI formation (see Figure 2.13).

However, the primary mineralogy of some of the meteoritic CAIs has been altered into secondary phases (e.g., nepheline, sodalite, grossulaire), where the conditions of formation are unclear (Krot et al. 2005). Metasomatism and metamorphism involved in the generation of secondary phases has been advocated to explain anomalous recent ages of some of the CAIs. The sampling and analysis of primitive material on an asteroid may permit to obtain new types of such phase assemblage and/or insight into processes of alteration. The analysis of CAIs in MarcoPolo-R samples will require a range of micro-analytical techniques such as SEM, EPMA, TEM and ion microprobe techniques to investigate the nature of the condensation, evaporation, melting and cooling history of these first solid phases. Ion probe, MC-ICPMS, and TIMS measurements can then be used to explore the large-scale isotopic evolution of the gas and dust in the protoplanetary disk and to establish a fine chronology of the early Solar System and of early processing and irradiation by the proto-Sun.

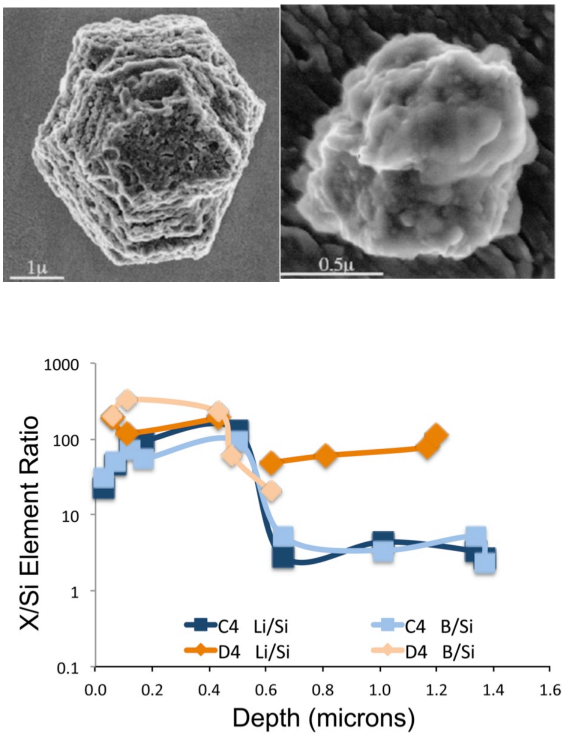


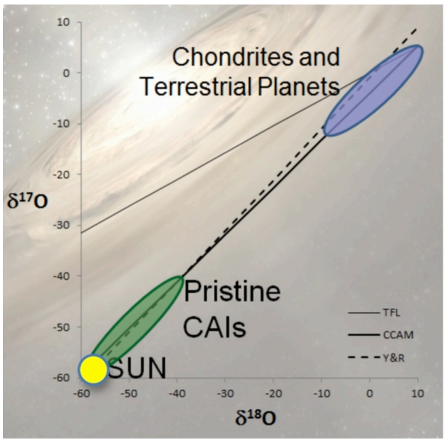
Figure 2.12: *Meteoritic presolar SiC grains obtained (top left) using harsh acid showing etched crystal phases and (top right) by gentle separation techniques showing amorphous, C-rich mantles formed in the ISM. Images from Bernatowicz et al. (2003). Bottom: trace element (Li, B) depth profiles in gently separated grains recording implantation by shock waves (1200-1800 km s^{-1}) in a homogenised molecular cloud prior to Solar System formation. Data from Lyon et al. (2007).*

Primitive material also contains chondrules, microns- to cm-sized silica-rich spherules that formed at slightly lower temperatures than CAIs and for a period of 2 to 3 million years after CAIs (see Figure 2.14). Their origin is unclear and debated, but requires high temperature processing of dust, possibly under irradiation (solar flares?), or associated with planetary formation, e.g. planetesimal bow shock heating of dust (Morris et al. 2012) or even impact ejecta from planetesimals in some cases (Krot et al. 2005). CAIs and chondrules, the two major components of chondritic meteorites, clearly formed almost contemporaneously under different gas compositions, with distinct chemical and isotopic signatures, were then subjected to differing post formation processes and accreted onto common asteroid parent bodies (see Figure 2.7), probably some distance away from their original formation. Fragments of CAIs and chondrules in the comet 81P/Wild2 samples, returned by the Stardust mission, provide further evidence for major transport mechanisms across the proto-stellar disk (Fig. 2.6). Therefore, this material provides a record of processes and environments spanning the first few million years following the birth of the Solar System across most of the solar accretion disk, from the conditions and processes of condensation through subsequent recycling, gas-solid exchange and the initial stages of accretion.

There are many aspects to the study of the early solar nebula that will be significantly advanced by the MarcoPolo-R samples – the following are examples of some of the more important areas:

Condensation and gas-dust reactions: After the formation of the refractory inclusions and chondrules, there is evidence from meteorites of complex reactions between gas and dust as the nebula continued to cool. Recycling of chondrules and CAIs through subsequent heating events will have aided exchange processes, involving evaporation and condensation. Such processes are recorded in the element diffusion profiles and isotopic heterogeneity imparted into these early Solar System components. Major and trace element distributions in CAIs and chondrules derived using techniques such as EPMA, LA-ICPMS and SIMS offer the possibility of determining the composition of the gaseous reservoir, the temperature and pressure of the environments where these processes occurred (e.g., Galy et al. 2000; Alexander et al. 2008). New methods for high precision isotope ratio measurements of moderately volatile elements such as Cu and Zn by MC-ICPMS have opened up new windows into the study of evaporation and condensation processes over a much wider temperature range. Such conditions are important in exploring the range of depletions observed in moderately volatile elements across inner Solar System bodies. Similar processes may also have played a critical role following the giant impact that led to the formation of the Moon as the super-heated disk of debris cooled. Unfortunately, redistribution of the elements and isotopes are also a consequence of later events on the parental asteroids of the meteorites, potentially more so for the more labile elements, which are also susceptible to terrestrial contamination.

The oxygen isotopic heterogeneity in the early solar nebula was clearly considerable – with CAIs and chondrules displaying variations of approximately 5% (e.g. Franchi 2008). The results from the Genesis mission show that the ^{16}O rich compositions equate to that of the solar composition (McKeegan et al. 2011) while all other Solar System materials measured to date are enriched roughly equally in ^{17}O and ^{18}O – indicating mixing with a mass-independently fractionated reservoir (Figure 2.13). Self-shielding of solar-composition CO gas is generally considered as the principle mechanism to generate the ^{16}O-poor reservoir. However, confirmation of this process, and where it may have occurred remain to be established. The exact signatures of the mass-independent fractionation, the end member compositions and slope of the mixing line are obscured or even obliterated by the effects of asteroidal alteration. A possible end member component extremely enriched in ^{17}O and ^{18}O has been identified in one meteorite but appears to be very susceptible to degradation during parent body processing (Sakamoto et al. 2007). Return of pristine samples of this material, even in small amounts, from a primitive NEA would provide the opportunity to determine a major constraint on the nature and location of the mass independent fractionation of oxygen isotopes that occurred in the proto-stellar disk – providing formation conditions from the mineralogy and definitive evidence of the magnitude and slope of the mass independent fractionation mechanism.



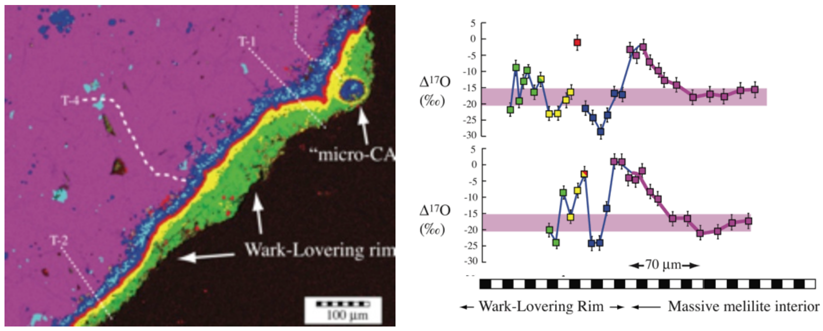
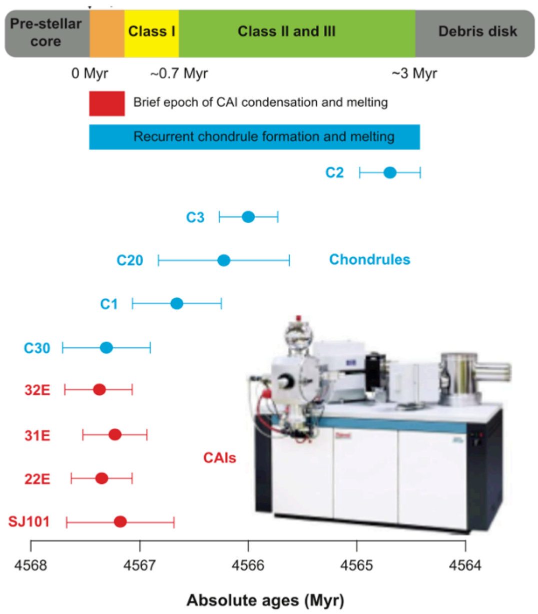
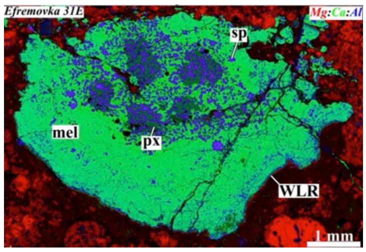


***Figure 2.13**: The CAIs display (left) the earliest stages of the evolution of the oxygen isotopic composition of the condensable phases in the early solar nebula from the ^{16}O-rich solar value to the ^{17}O,^{18}O-rich composition of all other planetary materials analysed to date. Recent work by Simon et al. (2011) indicated that (middle) the refractory rims of the CAIs recorded (right) a range of isotopic compositions as the inclusion rapidly migrated through different reservoirs as it formed. However, more recent work indicates that much of this variation may be related to parent body alteration processes (Bodenan et al. 2013), highlighting the need for pristine primitive material in order to understand the earliest stages of Solar System formation.*

Timescales and radionuclides: Recent advances in the dating of ancient materials found in meteorites indicate that the formation of CAIs and chondrules through to planetesimals took only a few to ten million years (Russell et al. 2006). Absolute ages via the Pb-Pb dating technique (from the decay of ^{235}U to ^{207}Pb and ^{238}U to ^{206}Pb) offer the possibility of determining crystallisation ages for individual components such as CAIs and chondrules with a temporal resolution of 0.1 Myr (Fig. 2.14). Further insight into the age of different components present in the early solar nebula will be obtained through the now extinct, short-lived radionuclides known to be present at the birth of the solar nebula. In addition to ^{26}Al advocated above, these include ^{41}Ca (half life ~ 0.1 Myr), ^{36}Cl (0.3 Myr), ^{26}Al (0.7 Myr), ^{10}Be (1.4 Myr), ^{60}Fe (~2 Myr) and ^{53}Mn (3.7 Myr) that offer a range of chronometers that can be analysed using SIMS, ICPMS and TIMS techniques to provide dates spanning a range of ages relevant to the formation of the Solar System. However, the origin of these short-lived radionuclides is poorly known, and therefore it is unclear when and how they were incorporated into the proto-stellar disk, and therefore if they were sufficiently homogeneously distributed at any point to act as a useful chronometer. Powerful X-ray flares observed in many pre-main sequence solar-like stars are likely accompanied by intense fluxes of accelerated particles (Feigelson & Montmerle 1999), yet our understanding of the irradiation history of early Solar System components remains poor. Such processes may play an important role in the production of short-lived radionuclides (such as ^{26}Al). There is evidence for spallogenic production of isotopes such as ^{10}Be and ^{6}Li in CAIs (e.g. McKeegan et al. 2000, Chaussidon et al. 2006) and some evidence for the presence of ^{7}Be (half life ≈53 days) in some CAIs. The occurrence of these isotopes probably reflects the intense activity of the young Sun. They are exceptional tracers for dating the first instants of the Solar System. This possibly happened close to the proto-Sun with subsequent ejection out towards the asteroid belt (or beyond) by strong X-winds (e.g. Shu et al. 1994). Such an environment may also generate significant amounts of other short-lived radionuclides such as ^{26}Al, ^{41}Ca and ^{53}Mn (e.g. Chaussidon & Gounelle 2006). Therefore it is essential to understand fully the origin of short-lived radionuclides in the early Solar System. Some of the elements of interest, such as Li, are particularly mobile and therefore materials from an NEA with little processing offer the best opportunity to unravel this important problem.

***The origin and accretion of volatile elements*:** The origin of the atmospheres of the terrestrial planets remains unknown. Accretion of the volatile elements at the heliocentric distances at which these planets formed is difficult to reconcile with our current understanding of the proto-stellar disk. Late accretion of icy comets or volatile-rich primitive asteroids is usually considered as a plausible alternative mechanism, but not without problems associated with the isotopic composition of hydrogen and volatile abundance, respectively. Fortunately powerful tools exist to address these problems. The abundances and isotopic compositions of the light elements (H, C, N, O, S) and of noble gases permit to investigate the origin and development of volatile reservoirs.





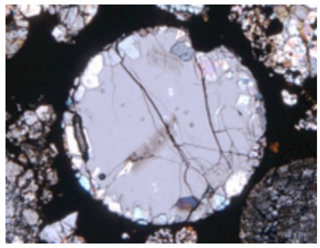


Figure 2.14: *Timescales of solid formation and disk evolution (left, Connelly et al. 2012). The brief formation interval of 160,000 years for the CAI-forming event is similar to the median lifetimes of class 0 proto- stars of ~0.1 to 0.2 Myr inferred from astronomical observation of star-forming regions. The absolute ages for the formation of these solar nebula components (CAIs (middle) and chondrules (right)) are determined by radiometric dating techniques. Specialised mass spectrometer systems such as TIMS (inset) or ICPMS are required to provide the high precision, sensitivity and mass resolution for the accurate isotope ratio measurements of trace elements such as Pb. CAI from Connelly et al. (2012); Chondrule courtesy of Kita, Univ. Wisconsin.*

Material present in chondritic meteorites displays a huge range in D/H ratios. The large enrichments in D are usually inferred to be the result of fractionation effects associated with the formation of organic matter at low temperatures in the ISM or outer portions of the proto-stellar disk. The lower D/H values are generally considered to reflect the D/H ratio of water ice with some increase (≈ x5) in D/H with heliocentric distance from the solar value (Robert 2003, Alexander et al. 2012). However, untangling the effects of mixing with the D-rich organics and comparison with remote observations of comets and gas giant moons show that there is considerable, non-progressive evolution of the D/H ratio of water in the Solar System (Alexander et al. 2011). Measurement of the H abundance and D/H ratio using SIMS, GS-MS and GC-IRMS of the numerous H carriers in primitive material from the MarcoPolo-R sample, together with those components that have interacted with the water ice will offer a unique opportunity to identify the H isotope reservoir end members in the vicinity of the primitive asteroid accretion zone. Such information will allow us to constrain models of the evolution of the D/H ratio across the proto-stellar disk, and ultimately to constrain the accretion zones of the volatile-rich bodies that may have subsequently migrated since their formation.

The nitrogen isotope ratio (^{15}N/^{14}N) presents heterogeneities among Solar System reservoirs that are comparable in scale to those of the D/H ratios. The protosolar gas, documented by the Genesis mission, was 40 % poorer in the heavy ^{15}N isotope than inner planets and meteorites (Marty et al. 2011), and organics and comets seem to be enriched by several tens, even hundreds of % in the heavy isotopes. Likewise, noble gases, which are chemically inert, are trapped in primitive meteorites in a poorly defined phase associated with organics (IOM). However, their elemental and isotopic abundances are distinctly different from those of the solar wind, our best proxy for the protosolar nebula composition. Although not proven, laboratory experiments suggest strongly that ionization by UV light is the only process able to significantly fractionate noble gas isotopes. Consequently, noble gases may keep a record of early irradiation episodes by the young Sun or by nearby stars. Furthermore, noble gases support an irradiation origin for their isotopic variations, and will provide a tracer for investigating the role of UV light on stable isotope fractionation.

Volatile elements are readily perturbed by asteroidal processes, and even more readily impacted by the effects of terrestrial contamination. This is particularly so for noble gases, where one of the major sites in meteorites is known to be organic matter. A sample collected by MarcoPolo-R containing materials with a range of alteration histories, or even unaltered disk material, will permit investigation of the isotopic signatures of the reservoirs in the gas phase of the proto-stellar disk and how this gas was accreted, and subsequently modified on the parent bodies.

First steps of dust accretion: As dust formation progressed, leading to the formation of CAIs, chondrules and matrix, accretionary processes must have begun to dominate the disk, ultimately leading to the formation of the planets. Weak static and Van der Waals forces can lead to the formation of chondrule-sized aggregates or even clumps of chondrules. Building objects beyond this size remains very problematic as the very low gravity associated with such sized objects is insufficient to promote collisional accretion. Numerous possible mechanisms have been proposed to facilitate this next stage of accretion, such as particle concentrations into large-scale, high-pressure regions generated by turbulence (Johansen et al. 2011). Co-accretion of dust, ices, or organics may also act as binding or damping agents during the impact events (see Blum & Wurm 2008). The record of such growth would never survive atmospheric entry, and is not apparent following the meteorite forming processes on the asteroid parent bodies. However, the most primitive material present in the MarcoPolo-R sample, while likely partially disrupted in the regolith, may retain some record of such events. Detailed petrographic investigation (e.g. FIB-SEM, TEM) of the returned sample may therefore offer an exceptional opportunity to study the early stages of accretion.

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

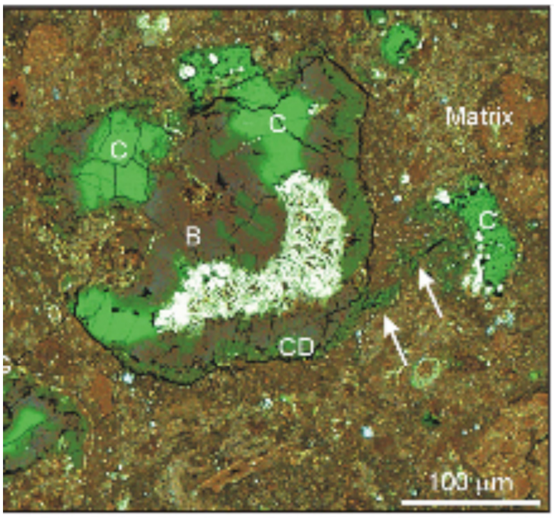
***Asteroid evolution*:** It is anticipated that the surface of 2008 EV5 will be a mixed regolith containing fragments from across the entire surface of the body. The asteroid itself is understood to be a rubble pile and therefore it is expected that there will be many different lithologies present in the regolith (see Figure 2.7). The thermal inertia of 2008 EV5 determined by Delbó et al. (2013) suggests that the particle size of the regolith should be in the range of mm to cm and therefore significant quantities of many of the lithologies will be present in the returned ≈100 g sample of regolith.

The visible-near IR spectrum of 2008 EV5 indicates that aqueous alteration has occurred in some places on the parent asteroid. However, while there is detailed information about the alteration history of individual meteorite specimens, there is little constraint or agreement as to how this alteration proceeds on a planetesimal scale. Oxygen isotopic composition helps constrain the water-rock ratio – but debate continues as to whether the alteration occurred under static conditions with little or no fluid flow, even over a few mms or cms (Bland et al. 2006), or whether alteration occurred under flowing fluid conditions (e.g. Young et al. 1999). Even giant convecting mud balls have been proposed (Bland et al. 2013). Indeed, it may be that we presently have little understanding of the nature of the bodies that accreted more than 4.5 Gyr ago that we now identify as primitive asteroids. The CI meteorites, which although now are extensively aqueously altered rocks, are in fact chemically unfractionated compared to the solar composition and have determined orbits, albeit rather poorly constrained, and contain amino acids, that are more typical of comets than asteroids or other chondritic meteorites. Did the CI meteorites originate from ex-comets? Or do they represent part of a continuum between comets and asteroids? As the visible-near IR spectrum of 2008 EV5 most closely matches that of CI chondrites, at least some components of the samples from this asteroid will be of critical importance in deciphering the nature of the most primitive asteroids.

Establishing the conditions and nature of any water-rock interaction will require a range of petrographic techniques to determine the phases present, their form and their inter-mineral relationships. The measurements will need to span a range of scales from the nm to mm and include optical microscopes, SEM and TEM, with a wide range of mineral characterisation techniques including X-ray diffraction and spectrometry (electron and synchrotron sources), electron diffraction, EELS, cathode luminescence, FTIR and Raman spectroscopy, XANES, a variety of SIMS techniques and LA-ICPMS. In part drawing upon knowledge gained from meteorites, such measurements will permit identification of those components that are of nebula origin, and the extent to which each lithology has suffered from asteroidal processing (impact events, thermal and aqueous metamorphism, space weathering). The timing of these events can then also be determined.

The oxygen and hydrogen isotopic composition of hydrated phases of the different components in the sample of regolith determined by SIMS and GS-MS will provide an understanding of the fluid involved in the aqueous alteration. A comprehensive understanding of the water and other volatile inventory in an NEA such as 2008 EV5 will provide a more accurate measure of the volatile flux to the early Earth from this type of source. In contrast, existing estimates are based upon data from meteorites, which by their very nature are a biased sample selected by survival through atmospheric entry, and likely not to be representative of the parental asteroid, particularly the more volatile-rich materials. Combined with measurement of other volatiles, particularly noble gases by NG-MS, this will provide a test of the viability of primitive asteroids from the main belt as a source of the Earth's oceans.

The chronology of the different asteroidal processes identified in the sample can be measured through high precision radio-isotope measurements. Carbonate minerals are a common product of aqueous activity, and information on the timescales of formation can be gathered from a number of approaches, such as Rb-Sr or Pb-Pb dating for younger ages (e.g. Borg et al. 1999) and Mn-Cr (from short-lived ^{53}Mn) for older ages (e.g. de Leuw et al. 2009). Shock age information can be readily gathered from Ar-Ar ages. Sample requirements are small – a few mg or even less if SIMS techniques can be employed. However such analyses can only be performed on mineral grains with known geological content and suitable compositions (e.g. Mn-Cr dating will require a number of grains with a range of Mn contents, including some high Mn content).



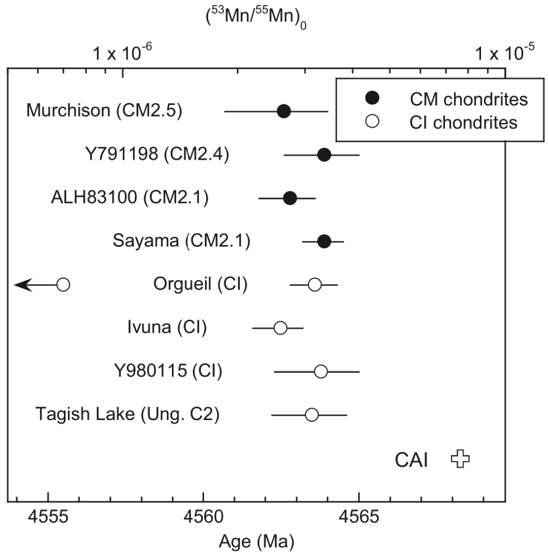


Figure 2.15: *Left: X-ray map showing that alteration on the carbonaceous chondrite parent asteroids was a complex process. Here Breunnerite (B) is replaced by Ca-poor dolomite (CD) that is replaced by calcite (C) (Lee et al. 2012). Top right: the age of the carbonates is ≈5 Myrs after CAIs, constraining accretion to <3 Myrs after CAIs (Fujiya et al. 2013). Samples of the earliest stages of alteration will provide more accurate timing of the onset of alteration (and therefore accretion) as well as understanding of the fluids involved; Bottom right: NanoSIMS ion probe used for this analysis.*

Understanding of the different geological events experienced by the different lithologies (Figure 2.15), coupled with spectral characterisation of these components can then be combined with the spacecraft observations at different scales to develop a detailed knowledge about the formation and history of the asteroid. Bulk density, grain density and porosity of the sample can be determined with a pycnometer and CT scans, providing further constraints for models of the bulk physical properties determined from spacecraft observations. Remnant magnetic fields are present in primitive materials, at levels that may indicate that some carbonaceous chondrites originated from partially differentiated parent asteroids (e.g. Carporzen et al. 2011) and therefore determining the palaeomagnetic properties of the returned samples will provide important constraints on the nature of the parent asteroid.

***Asteroidal surface components*:** Space weathering is the physical and chemical alteration of surfaces of airless bodies exposed to the space environment (Hapke 2001) such as the bombardment by ions from the solar wind, magnetosphere ions, energetic electrons, cosmic rays, ultraviolet photons, and fast interplanetary dust (micrometeorites), with the relative flux of each of those projectiles depending on the location of the surface in the Solar System.

The NEA region is irradiated by solar wind particles. Solar wind ions have energies of about 1 keV amu^{-1} with fluxes in the range of 10^8 (protons) to 10^2 (Ar ions) cm^{-2} sec^{-1} at 1 AU and decreasing as the square of the distance from the Sun. The 1 keV protons, although by far the most abundant, penetrate only the very thin skin of the asteroid and their effects are to sputter the surface material and to re-deposit it on a rough surface (Hapke 2001). This process alters the structure and composition of the surface material in such a way that it affects the optical properties in the UV–visible spectral region (Strazzulla et al. 2005; Loeffler et al. 2009). This process is so far more efficient than the effect due to micrometeoritic impacts (Yamada et al. 1999; Sasaki et al. 2001). A timescale for the weathering of NEA surfaces is on the order of 10^4–10^6 yrs for silicate asteroids (Brunetto & Strazzulla 2005), but is unknown for dark carbonaceous asteroids.

The effects of space weathering on the mineralogy can be identified by conventional electron microscopy (SEM/TEM). Development of nanophase iron, an important effect on the lunar surface, can be determined by techniques such as Mössbauer spectroscopy, electron spin resonance and magnetic susceptibility. The timescales of the gardening rate of the asteroidal regolith can be determined through measurement of short lived radionuclides – both by decay counting shortly after return and by accelerator mass spectrometry in order to establish cosmic ray exposure histories (saturation, multiple episodes, etc.).

The analysis of noble gases will permit to investigate the different components (e.g., solar, chondritic) present in the regolith, thanks to the diversity of their isotope compositions, as well as the residence time of the collected grains at the asteroid surface. Their extremely low detection limit (down to a few thousand atoms for some of their isotopes) allows one to analyse individual regolith grains of a few tens of microns. Some of their isotopes are produced by cosmic rays and therefore provide the most sensitive tracers of regolith processing and exposure. For instance, the noble gas analysis of Hayabusa grains have shown noble gas-based cosmic ray exposure ages of a few Myrs, showing the surprising dynamical activity of the asteroid surface (Nagao et al. *2011*). Combining the measurements of volume-correlated cosmogenic noble gas with surface-correlated solar wind implanted noble gas will permit detailed understanding of processes acting at the asteroid surface.

A sample returned from the surface of a primitive asteroid will also offer the opportunity to provide “ground truth” for remote observations (spacecraft and telescope) for the vast amount of information gathered on asteroids. Visible to near-IR and mid-IR spectroscopy of specific components within the sample, with well determined mineralogy, physical properties and known exposure history will provide unique information that will be invaluable for a greatly improved interpretation of the spectra that currently exist for minor bodies in the Solar System.

2.2.1.4 How do organics in primitive NEAs relate to the origin of life on Earth?

Many different theories about the origin of life are expressed in publications of the last 2 decades (Oparin 1957; Eigen et al. 1981; Cairns-Smith 1982; Gilbert 1986; Joyce 1989; Margulis and Sagan 1985; Martin et al. 2008). Among them, the extraterrestrial delivery of organic species identified in meteorites plays a major role (Figure 2.16). During the first 700 million years, cometary and asteroid impacts on Earth may have delivered large amounts of organic molecules (Chyba & Sagan 1992). It was established over a century ago that some meteorites contain organic material. The carbon content of collected meteorite samples consists of two distinct, but potentially intimately related fractions: soluble and insoluble carbonaceous components, which may be heterogeneously dispersed in the meteorite bulk material. The most abundant organic phase recovered in carbonaceous chondrites is a polyaromatic organic solid, insoluble in current solvents, which bears isotopic enrichments in accordance with a formation by cold chemistry, in the dense pre-solar core and/or the outer part of the solar nebula (Cody & Alexander 2005; Alexander et al. 2007).

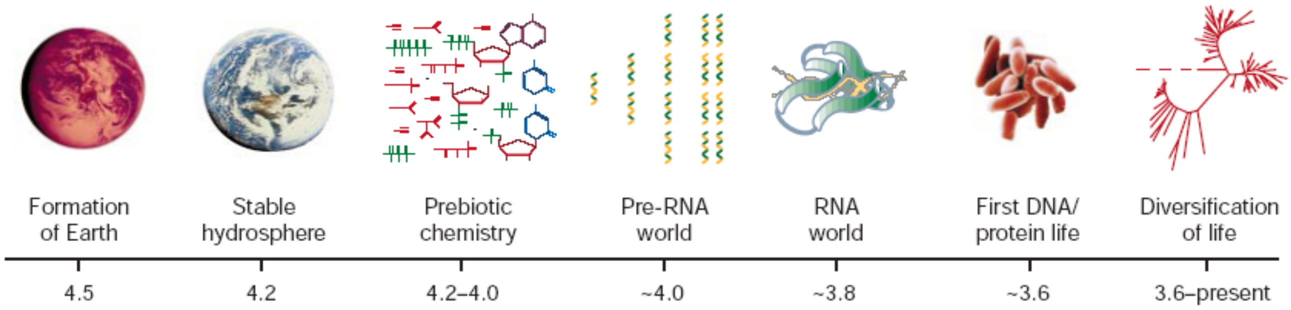


Figure 2.16: *Major steps in the origin of life. Current exobiological scenarios for the origin of life invoke that organic matter present on the primitive asteroids would have synthesized large and complex prebiotic molecules, resulting first in a self-replicating RNA that led to evolution in the first living organism (Joyce 2002).*

Organic volatile compounds of exobiological interest, which have been identified in carbonaceous chondrites, include amines and amides; alcohols, aldehydes, and ketones (Cronin & Chang 1993); aliphatic and aromatic hydrocarbons (Hahn et al. 1988; Kerridge et al. 1987; Gilmour & Pillinger 1994; Messenger et al. 1998; Alexander et al. 1998; Sephton et al. 1998; Stephan et al. 1998); sulfonic and phosphonic acids (Cooper et al. 1992); amino, hydroxycarboxylic, and carboxylic acids (see Sephton 2002 for a review); purines and pyrimidines (Martins et al. 2008; Callahan et al. 2013); and kerogen-type material (Becker et al. 1999).

The analysis of carbon compounds in fragments of asteroid 2008 TC3 revealed recently interesting insights into asteroid chemistry (Jenniskens et al. 2009; Glavin et al. 2010). The heterogeneous distribution of amino acids provides evidence of multiple sources and reaction pathways on a parent body (Figure 2.17); see Burton et al. (2011).

Recent meteoritic organic studies have also specifically addressed the relationship of meteoritic amino acids and the development of life (Pizzarello et al. 2013). Enantiomeric excess (the preference for left- or right-handed chirality, i.e. molecules that have a non-superimposable mirror image) has been measured in several meteoritic amino acids known to be of extraterrestrial origin (Glavin & Dworkin 2009). This suggests an extraterrestrial provenance for the homochirality, or at least primordial left- versus right-handed excess of amino acids that could subsequently be amplified by further reactions on Earth.

While some of the solvent-soluble organic compounds present in meteorites are important in terrestrial biochemistry (e.g. amino acids, nucleobases, etc.), it is necessary to assess their extra-terrestrial origin. There are several ways to determine whether an organic molecule present in carbonaceous chondrites is of terrestrial or extra-terrestrial origin: (1) detection of molecules that are unusual in the terrestrial environment; (2) comparison of the absolute abundances of the organic molecules in the meteorites to the levels found in the fall environment; (3) determination of enantiomeric ratios of chiral molecules; (4) measurement of the stable isotope values of hydrogen, carbon, and nitrogen in those compounds.

Investigation of the organic matter and its distribution within the principal lithologies requires a wide and complementary array of analytical techniques, tackling different, but related aspects of the organic inventory, its composition, structure, its distribution within the sample and how it is related to the silicate mineralogy. In order to provide quantitative measurements of these compounds it is usually necessary for them to be separated via various fractionation and chromatographic techniques. This often requires destructive analyses, and in some cases considerable amounts (grams) of bulk sample because many of the astrobiologically important molecules are present only at ppm level or less.

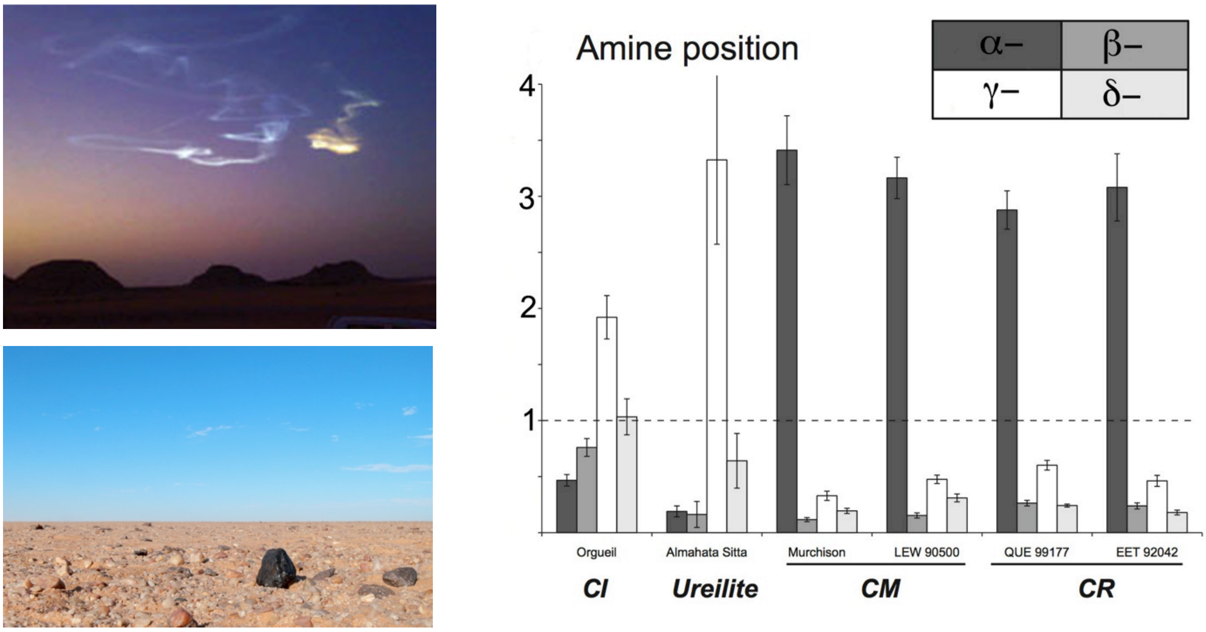


***Figure 2.17**: A small near-Earth asteroid entered Earth's atmosphere on 7 October 2008 and exploded over the Nubian Desert of northern Sudan. Scientists expected that the asteroid 2008 TC3 disintegrated into dust in the resulting high-altitude fireball. Top left: Image of the contrail left by 2008 TC3 during its descent (Image Credit: Shaddad). Bottom left: Almahata Sitta meteorite number 15 (a remnant of asteroid 2008 TC3) in situ on the desert floor during its find on 8 December 2008 (Image Credit: P. Jenniskens, SETI Institute). Right: The relative abundances of the five-carbon amino acids in the Almahata Sitta ureilite compared with several other carbonaceous meteorites as a function of amine position α–, β–, γ–, δ– (Glavin et al. 2010).*

***Soluble Fraction*:** Soluble organic molecules need to be efficiently extracted from the silicate and macromolecule matrix. A number of approaches are typically employed – such as ultra-sonication in a range of different solvents or super-critical fluid extraction. For example, non-polar solvents (e.g. toluene) can be used to primarily extract aliphatic and aromatic compounds while polar solvents can extract more polar molecules such as nucleobases and amino acids (e.g. Martins et al. 2007, Callahan et al. 2013 and references therein). Each extract contains a large number of different compounds that need to be separated prior to detection/analysis. There are mainly two important chromatographic methods in use for the analysis of the extracted organic compounds: Gas Chromatography (GC) and Liquid Chromatography (LC), respectively, equipped with a number of different detector types according to the nature of compound to be identified.

Combining different extraction, chromatography and detection methods is necessary for a complete analysis that identifies and quantifies the different molecules present. Molecular structure and relative abundance of organic compounds provide important insights into possible formation mechanisms (e.g., surface catalysed synthesis and gas phase addition reactions have very different outcomes in the generation of branched variants within some types of compounds; Pizzarello et al. 2006). The stable isotopic composition of H, C, N, O, and S of individual compounds can provide important information about the origin of identified species. Isotopic measurements of individual compounds across the different compound classes will provide confirmation of the extra-terrestrial nature of compounds, indicate the source region (e.g. high D/H ratios indicative of ISM or outer Solar System origin) and render information on formation processes. Isotopic measurements are the only means to provide direct evidence of commonality between different types of compounds, i.e. do left- and right-handed enantiomers have the same isotopic signatures (i.e. sources), and are there similarities between different compound types? They can also be used to determine the relationships with the non-organic components within the sample (e.g. oxygen isotope can be tracked across to silicates, D/H with the aqueous alteration components (i.e. role of fluids), carbon can be compared to carbonate signatures, etc.).

The MarcoPolo-R sample, collected under strict contamination control and handled appropriately, offers a unique opportunity to assess the indigenous levels of biomolecules in the asteroidal material.

Insoluble Fraction: More than 70 % of the organic matter in carbon-rich carbonaceous chondrites correspond to a complex macromolecular form of carbon that remains in the rock even after repeated solvent extractions. The insoluble organic fraction consists of molecules that cannot be readily separated and analysed individually, and therefore a range of techniques distinct from those applied to the soluble fraction is usually employed in the study of the macromolecule (Derenne & Robert 2010).

Solid state ^{1}H and ^{13}C NMR spectroscopy constitutes one of the most powerful spectroscopic approaches to the study of the organic macromolecule – establishing the types and distribution of the different functional groups in the amorphous macromolecular material. This can be used to provide a quantitative, albeit averaged, determination of the structural picture of the macromolecule and its elemental composition. A number of NMR methods applicable to small amounts (a few tens of mg) of a powdered sample at natural abundance have been used – although first the sample must be demineralised to remove the paramagnetic nuclei present in the silicate matrix, as they have a major impact on the quality of the NMR spectra in terms of both signal strength and sensitivity. Therefore gram amounts of whole-rock sample must be processed (Pizzarello et al. 2006).

A variety of pyrolysis-GC-MS techniques (flash heating, hydrous and hydro-pyrolysis) provides a complementary approach to the NMR studies, offering detailed characterisation of the molecular species or components within the macromolecule (Septhon et al. 2004). Such techniques convert a portion of the macromolecule to free compounds, providing a means to compare the nature of the soluble and insoluble fractions. Primitive material from an NEA returned by MarcoPolo-R will allow the investigation of the nature of the organics accreted on the asteroidal body and the role of asteroidal processes in the formation of carbonaceous material.

While the molecular abundance patterns obtained for the macromolecule pyrolysis experiments and that obtained from the soluble organic fraction can offer some hints on molecular relationships, isotopic measurements on the pyrolysis products (in the same way as described for the soluble fraction, i.e. with GC-isotope-ratio-MS attached to the pyrolysis sample introduction system) will give most conclusive answers. Such analyses are therefore key to developing an overall understanding of the nature and origin of the organic material present in the sample.

In terms of understanding the relationship between the silicate matrix and the organics - parameters of interest would include determining correlations with aqueous alteration and the distribution of presolar grains - all the conventional microscopy techniques (SEM and TEM) and the SIMS techniques for elemental and isotopic techniques provide complementary information to the organic analyses. Further techniques will provide detailed structural or molecular information on the distribution of organic compounds with high spatial resolution (e.g. μL^2MS, XANES, Raman and Infrared micro spectroscopy, etc.). Most of these techniques require small amounts of material, little or no sample preparation (microtome sections are needed for XANES), offer very high sensitivity (down to the level of attograms) and are non- or partially destructive.

The possibility to collect a heterogeneous set of samples with known context information under strict contamination control not altered by atmospheric re-entry processes offers a unique opportunity to assess the indigenous levels of biomolecules in the asteroidal material.

2.2.2 Remote sensing analysis

2.2.2.1 Sampling site selection

Remote sensing imaging and spectroscopic observations will provide critical information for close proximity operations and selection of a number of areas suitable for sample collection.

Global characterisation will be used to determine geometrically correct shape models and maps required for correct pointing of the remote sensing instruments and, in combination with radio science data (see Section 2.2.2.2), to safely manoeuvre the spacecraft towards its intended sampling site. A number of candidate sampling sites will be further examined in more detail from close proximity to determine the best sites for safe sample collection and to satisfy the mission science goals.

Imaging systems are required to produce global shape models and local topography of the potential sampling sites at the best possible resolution. They will be used to identify sites with minimal local slopes, and large boulders over an area comparable with the landing error as well as investigation of the regolith properties and geological history (Section 2.2.2.3). Multi-colour imaging as well as visible, near and mid-infrared spectrosocopy provides evidence for surface composition and freshly exposed, unweathered material (Section 2.2.2.4). Temperature maps from mid-infrared spectroscopy can be used to distinguish between areas with high and low thermal inertia, indicative of regolith particle size and depth, degree of compaction, and exposure of solid rocks and boulders within the top few centimetres of the subsurface (Section 2.2.2.2).

All investigations have to consider the context of the selected sampling sites, i.e. it must be possible to put the local characterisation, obtained for the sampling region, into the larger context of the surrounding surface and global scale properties.

2.2.2.2 Physical properties

In-situ observations of physical properties, such as size, shape, mass, spin properties and temperature are essential for successful mission operations and sample collection. In addition, the precision, spatial resolution and range of observation geometries, that are not possible from Earth-based observations, provide insights into the dynamical and physical evolution of the asteroid.

Size, shape, rotation: Size, shape, and rotation are basic physical parameters for any planetary body. In-situ imaging from MarcoPolo-R, combined with mass determination from radio science, is crucial to obtain the necessary precision for a safe navigation at close proximity and to collect the sample, as well as for the investigation of the physical and dynamical evolution of the asteroid.

Even simple shape models can reveal general characteristics of the asteroid, i.e., if the asteroid is a single monolithic rock, a contact binary, or a rubble pile. These shapes associated with rotational properties can be compared with equilibrium shapes of bodies with various kinds of internal structures with same rotational properties (Holsapple 2007). Shape models provide the framework for determination of local slopes, and surface illumination angles, required for studies of photometric and physical properties, such as roughness, porosity, and particle size, as well as for thermal models and internal heat transport.

The combination of imaging and ranging data will allow us to determine parameters of the body rotation model with great accuracy. Observations of changes in the spin rate (and obliquity) will provide ground-truth for models of the YORP effect (see below) of fundamental importance for the dynamical and physical evolution of small asteroids. Direct measurement of the moments of inertia should be obtained from the measurements of any spin axis wobble. In the event that no wobble is observed, the moments of inertia must be derived from the shape model, assuming constant density. Precise identification of excitation modes of the body rotation would indicate the action of external torques, for instance resulting from a very recent impact event (perhaps still evident in the image data), tidal interaction during recent planet encounters, or the long-term action of the YORP effect. Other rotation states (e.g. tumbling) would then provide indications on the internal energy dissipation within the body and on the precise way YORP modifies the spin rates of small bodies (Vokrouhlicky et al. 2007).

Mass, density and gravity field: The mass of the asteroid can be determined from radio science measurements of the Doppler shift resulting from the spacecraft's motion in orbit or on unpowered flyby (Andert et al. 2010; Pätzold et al. 2011). The bulk density, derived using the volume of the shape model, can then be used to determine the mean porosity from comparison with densities of meteorite analogues or of the solid material constituting the body. Such analyses have been performed for the two NEAs visited by rendezvous missions. In the case of (25143) Itokawa, whose size is in the same range as 2008 EV5, and therefore provides a consistent comparison, the mass was determined with an uncertainty of 5 % by the Hayabusa spacecraft (Abe et al. 2006). The analysis suggests for Itokawa a mean density of 1.9 ± 0.15 g cm^{-3} and a bulk porosity of 40% (assuming chondritic meteorite composition). Bulk density and porosity are precious information for defining scenarios of the body's history. Indeed, the collisional lifetime and history of a small body depend on its response to impacts, which, in turn, depends on the kind and degree of porosity that constitutes its interior.

Returned samples offer the unique possibility of direct measurement of the solid density of real surface materials. Low density and high porosity are expected for primitive, widely unaltered asteroids, such as C-class objects (Britt et al. 2002; see Figure 2.18), that have not been affected by internal condensation processes during their evolution, such as differentiation.

Comparing measured and modeled values of the low order gravity coefficients C_{20} and C_{22} may also allow us to infer information about mass concentrations or layering (Andert et al. 2011), which cannot be done on the sole basis of a bulk density estimate. The simulated values are based on a combination of a shape model and a model for the mass distribution inside the body. 2008 EV5 shows an oblate spheroidal shape with dimensions along principal axis of (415 x 410 x 385) ± 50 m (Busch et al. 2011), which results in C_{20} = -0.027 and C_{22} = 0.0013 assuming constant bulk density distribution. Deviations from the constant density based values can be used for the interpretation of the internal mass distribution of the asteroid. Determining whether the mass is distributed more or less homogeneously can also tell us whether the porosity inferred from both the bulk density and that of the sample is dominated by the presence of large voids or due to microporosity inherent to the material itself. Note that 2008 EV5 is, due to its small size and its associated limited collisional lifetime, expected to originate from a larger body disrupted by a collision and formed by gravitational reaccumulation of small fragments (e.g. Michel et al. 2001). However, the way the reaccumulation process works is still not well understood and determining the distribution of mass in the asteroid would shed some light on how small fragments come back together to form a body like the MarcoPolo-R target.

If the Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect (see below) is detected then it is possible to infer density inhomogeneities in the asteroid by comparison with YORP predictions based on shape models and thermophysical measurements, as has been achieved for Itokawa (Lowry et al. 2013).

Knowledge of the internal structure also has great implication on the origin of the oblate shape of the asteroid and the potential origin of the equatorial ridge suggested by radar observations. There are two main hypotheses for the formation of an oblate shape asteroid and an equatorial ridge (Walsh et al. 2008; Jacobson & Scheeres 2010). Both scenarios rely on the YORP spin-up but have very different implications on the internal structure of the asteroid and consequently on the formation of the asteroid itself. Therefore, detailed in situ observations by MarcoPolo-R may be able to determine which scenario is correct, e.g. by the characterisation of the internal structure inhomogeneity from detailed gravity measurements. Moreover, the ridge existence as suggested by radar observations as well as its actual properties may also depend on the behaviour of the regolith at the equator. Observations by MarcoPolo-R of this region will allow understanding in a unique way the equator properties and whether radar inversion gives a correct interpretation of those properties for such an asteroid with an oblate shape.

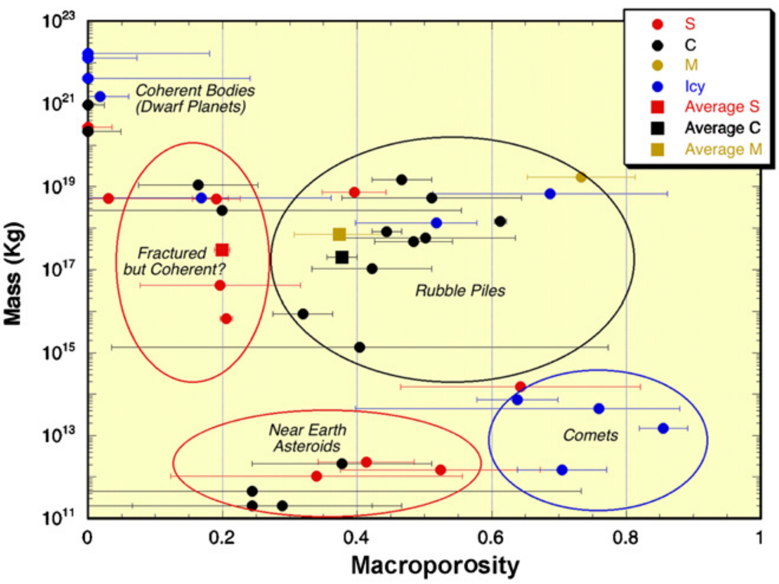


***Figure 2.18**: Estimated macro-porosity for a range of main belt asteroids, NEAs, and comets. Macro-porosity is estimated by subtracting the average porosity of an asteroid meteorite analogue from its bulk porosity. This is considered an estimate of the large-scale fractures and voids that determine the asteroid internal structure. Only the largest objects with masses of over 10^{20} kg appear to be coherent and have low macro-porosity, whereas small bodies have substantial macro-porosity (adapted from Britt et al. 2002 and Consolmagno et al. 2008).*

Shape and gravity models in combination with rotation can also help to determine local gravity that affects local geological features such as crater morphologies and regolith escape. Surface slopes will reveal the magnitude and orientation of local gravity vectors to study redistribution of surface masses, such as regolith and boulders ("mass wasting", and possible landslides).

MarcoPolo-R will thus allow us to estimate the potential history and lifetime of a body from which a sample will be analysed in the laboratory. Moreover, knowledge of the porosity of a PHA is crucial for optimization of mitigation strategies against such an object (Jutzi & Michel 2013).

Thermal properties: Mid-infrared photometric and/or spectroscopic observations of the thermally emitted radiation from an asteroid surface, coupled with thermal models, are used to determine the surface temperature and thermal properties.

Thermophysical models (e.g., Spencer 1990; Lagerros 1998; Delbó et al. 2007; Müller 2007; Rozitis & Green 2011) are used to calculate the temperature distribution of each planar facet of an asteroid shape model by numerical solution of the heat diffusion equation with boundary conditions defined by the energy balance between insolation and emission/conduction at the surface. Thermal inertia, a measure of the resistance of a material to temperature change, is the key parameter affecting the diurnal variation of temperature. It is defined as $\Gamma = (\rho \kappa c)^{1/2}$, where κ is the thermal conductivity, ρ the density and c the specific heat capacity.

Thermal inertia is strongly affected by the average grain size of the regolith. Fine-grained and loosely packed material typically exhibits a low value (Γ~50 J m^{-2} K^{-1} $S^{-1/2}$ for large main-belt asteroids and for the Moon, Müller & Lagerros 1998), while higher values (Γ~2000) are common for rocks and exposed bedrocks. NEAs show a trend of higher globally averaged values (Γ= 100 – 1000; e.g. Delbó et al. 2007; Campins et al. 2009) with decreasing size, indicative of increasing dominant particle size in the regolith.

Surface roughness (i.e. on scales smaller than the shape model facets) also influences the thermal emission characteristics. The various treatments of macroscopic surface roughness (on scales larger than the thermal skin depth ~cm) in different models all show that the emitted flux is dependent on the mean surface slope (Emery et al. 1998). Rozitis & Green (2011) showed that reproduction of the directional dependence of emission (thermal infrared beaming) requires explicit modelling of macroscopic roughness, whereas microscopic roughness does not influence the thermal emission (Jakosky et al. 1990).

While we can constrain globally averaged thermophysical properties from ground-based observations (see Section 2.1.4 for derived properties of 2008 EV5), spatially resolved data obtained from MarcoPolo-R at a range of rotational phases and local solar phase angles will allow study of the influence of local topography (shadowing and beaming) and regolith properties (composition, size distribution), providing more powerful constraints on the surface conditions and improved regolith particle size determination for sampling site selection. The identification of cold or hot spots can be used as a proxy to track a difference in insolation conditions, composition, albedo or thermal properties (e.g. Groussin et al. 2013).

Yarkovsky and YORP effects: The asymmetric reflection and thermal re-radiation of sunlight from an asteroid surface imposes a net force and torque. The net force (Yarkovsky effect; see e.g. Farinella & Vokrouhlicky 1999) causes changes in the asteroid semi-major axis and is believed to be the dominant mechanism for injecting small asteroids into gravitational resonances that cause their escape from the main belt to replenish the NEA population. The effect has been measured for a number of NEAs since the first detection in 2004 (Chesley et al. 2003). Improved understanding of the Yarkovsky force will enhance our ability to predict high precision orbits of small NEAs, thereby improving our determination of the asteroid impact hazard to Earth, particularly from passage through “keyholes” during close NEA encounters. The net torque (YORP effect; Rubincam 2000) can change the spin period and obliquity of small asteroids on relatively short timescales and was first measured for the NEA (54509) YORP (Lowry et al. 2007; Taylor et al. 2007).

2008 EV5 has, in common with a number of small asteroids, a shape consistent with past YORP spin-up (Figure 2.9). The combination of precise, high resolution shape models and thermophysical properties determined from a mid-IR imager/spectrometer will place strict constraints on models used for predictions of the Yarkovsky and YORP effects (see Rozitis & Green 2012 for a comprehensive list). In particular, the high sensitivity of the YORP effect to unresolved shape features (Statler 2009) and to the shape model resolution (Breiter et al. 2009) can be investigated. The inclusion of global self-heating (Rozitis & Green 2013) has implications for reducing the sensitivity of the YORP effect predictions to detailed variations in an asteroid shape model, but definitive data to confirm these conclusions are currently lacking.

2.2.2.3 Morphology and geology

Imaging maps of the whole body from close proximity (~ a few hundred m to two km) will provide the database for detailed and synoptic geological analysis and interpretation of the surface. Such information is important in order to place the returned sample into its geological environment and to relate it to the surface history as well as make inferences on internal structure (as done for Itokawa; Barnouin-Jha et al. 2008).

Colour maps allow study of the regional distribution of the surface material, through continuum bands and/or specific absorption dips. The higher spatial resolution and more rapid global coverage, compared with spectroscopy, enhance the value of these maps in defining the extent of geological units and correlating them with surface morphology. For instance the global analysis of Eros colour units illustrates complex regolith processes and grain sorting that may hold clues to understanding space weathering processes and the link between asteroids and meteorites (Riner et al. 2008). Crater statistics (cumulative number vs. size) provide the 'age' of the surface which at most goes back to the creation of the NEA itself either as a planetesimal during its formation or as a product of a major impact on the parent body (see e.g. Michel et al. 2009). Crater statistics may also reveal global or local resurfacing events covering or completely erasing earlier stratigraphic layers. Other geological surface features like flat and hilly terrains, reefs, edges, or scarps, etc. (Figure 2.19) are to be interpreted in the framework of restructuring processes in the body's interior (for instance, rearrangement of 'rubble in the pile') or during creation of the body.

Regolith, with particles ranging from sub-micron powders to metre-sized boulders, is present, to some extent, on all asteroids, natural satellites, and terrestrial planets. The key physical parameters are porosity, surface roughness, the different kinds of friction (sliding, rolling, static, dynamic), as well as size, shape, and orientation distributions of the grains. Each asteroid surface and associated regolith is unique and contains information about the origin of the body itself and its geological evolution. Little is known of the detailed physical conditions of the surface material of NEAs and in particular of the vertical extent of the regolith.

The NEAR mission provided the first evidence of regolith mobility on asteroids: downslope regolith movement was observed on Eros with 'debris aprons' and 'talus cones', which both refer to accumulations of material that have been gravitationally transported away from topographic highs (Robinson et al. 2002; Thomas et al. 2002; Veverka et al. 2001). It has been suggested that impact-induced seismic shaking, which can lead to regolith motion, may erase small crater features on bodies as small as Eros or Itokawa, and thus explain the paucity of small craters compared to predictions by dynamical models (e.g. Michel et al. 2009; Richardson et al. 2004). Dust levitation has also been invoked on Eros to explain the small crater paucity. Knowledge of the surfaces of C-class asteroids remains very poor as no C-class asteroid has yet been the subject of a rendezvous mission. Compaction processes and consequent strong shock wave attenuation during impacts have been invoked for C-type bodies under the assumption that they contain some crushable micropores (Housen et al. 1999). C-type bodies may thus have different morphologies and regolith distributions from S-types due to the different mechanical properties (and associated impact response) of their material. Local gravity was first understood to be of importance to asteroid surface processes (Robinson et al. 2002) from the NEAR observations of Eros. This was further emphasized by the entirely different structural and surface properties of the much smaller, but also S-class, Itokawa. If gravity is the discriminator, then Itokawa is expected to be as different from Eros, geologically, as Eros is from the Moon (Asphaug 2009). Images and modelling of Itokawa suggest that it is composed of rubble held together by gravity instead of being a monolithic body (Fujiwara et al. 2006; Michel & Richardson 2013). Locations and morphologic characteristics of the gravel indicate that it experienced considerable vibrations, which may not only have erased small craters but also triggered global-scale granular processes like granular convection, landslide-like granular migrations, and particle sorting, resulting in the observed segregation of the fine gravels into areas of potential lows. Close-up images show remarkably that the asteroid surface is covered with unconsolidated gravels and boulder fields, which are typically piled on each other without being buried by fines (very small particles), and ponds of well-sorted pebbles in smooth terrain (Figure 2.19). The images obtained by Hayabusa provide evidence that granular processes can be major resurfacing processes for small size regolith-bearing bodies, whereas images of (21) Lutetia from the ESA Rosetta spacecraft also show evidence for landslides on a 100 km-sized asteroid (Figure 2.19; although the resolution limitations from a distant, fast flyby precluded direct observation of the regolith properties).

Imaging at high (mm) resolution gives direct access to the texture and morphology of components in the rock, contributes to the determination of the particle size distribution and can resolve the geometric shape of the larger particles. Extending this analysis into the sub-millimetre range, for instance by surface imaging from very close distance while sampling, is extremely beneficial for understanding the regolith processing either during its formation or while embedded in the body. Light-scattering parameters (e.g. single-scattering albedo, scattering phase function, etc.) are further important physical parameters for the characterisation of the regolith ensemble on the surface, also partially constraining the composition of the regolith material. In addition, bi-static radar investigations will provide constraints on the surface properties.

The sampling process will likely alter the structural properties of the surface. Images of the sampling site taken during and after the sample collection can show how the constitution of the surface will be affected, in particular the grain size distribution, aggregation state, and arrangement of larger and smaller particles. The probable post-sampling generated dust cloud, and charged particles/dust levitation can also be monitored.

MarcoPolo-R will provide a unique opportunity to observe in detail the outcome of an interaction with an asteroid surface by a tool, in a gravitational environment that cannot be achieved in terrestrial laboratories or perfectly in parabolic flights. MarcoPolo-R will thus provide information that will greatly contribute to a better understanding of granular material behaviour in a low gravity environment, which is crucial to prepare future robotic or human missions aimed at interacting with asteroid surfaces.

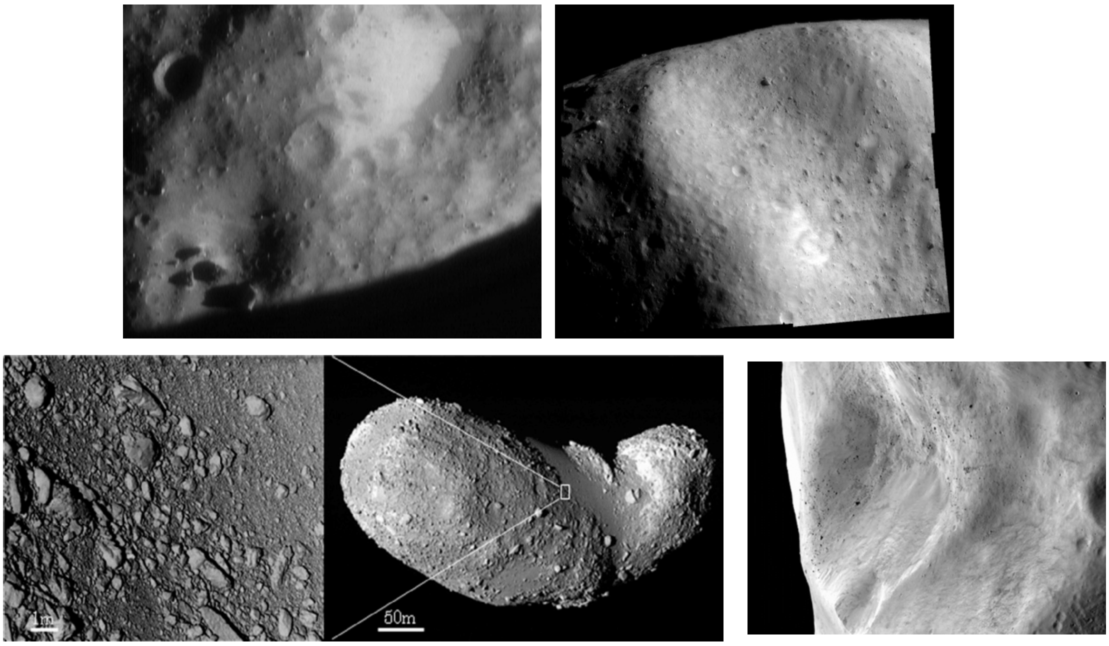


Figure 2.19*: Evidence for regolith sorting and mobility on asteroids: Top Left: Picture (from an altitude of 46 kilometers) of Eros showing several telltale features of the layer of fragmental debris, or "regolith." The four large boulders in the lower left are among the largest rocks in the regolith (the largest one here is about 90 metres across). In the smooth patch at upper right, the regolith appears to have filled in a depression. The tongue-shaped bulges along the margin of the bright area to the left of the patch suggest flow of regolith toward the smooth patch. Top Right: A region on Eros having few superposed craters and, unlike other parts, few geologic structures like curvilinear ridges or troughs. Instead, this region is covered with the densest concentrations of boulders, suggesting that the craters that must once have populated the area have either been buried or eroded by regolith movement (NEAR/JHUAPL). Bottom Left: Itokawa, showing a close up of a region on the boundary between the boulder-rich rough terrain and the smoother pebble-covered Muses Sea, which has characteristics similar to a terrestrial landslide deposit (JAXA). Bottom Right: Close-up of a ~20 km-diameter crater on Lutetia showing boulders and landslides (MPS/ESA).*

2.2.2.4 Composition

The determination of the composition of the MarcoPolo-R target over its whole surface is important both for characterisation of potential sample sites, and for the scientific study of the nature of the object. In particular, it is crucial to determine the nature and degree of heterogeneity of the surface, the cause of any differences and the implications of these differences for the primitive nature of the asteroid surface and collected sample.

The search for the 3µm absorption band is one of the major objectives of remote sensing spectroscopic observations. The band is typically caused by a combination of a very strong OH-radical absorption feature and the very strong first overtone of the 6 µm H_2O fundamental. Adsorbed water has a symmetric stretch mode (see Figure 2.20), giving rise to an absorption feature at 3.1 µm and an anti-symmetric stretch feature at 2.9 µm. Structural hydroxyl (OH) that has been incorporated into mineral lattices produces a stretch absorption at 2.7 µm. In fact on primitive asteroids, the observed presence of a 3 µm absorption feature tells us that hydrated minerals can persist on the surface of these airless bodies formed on parent bodies in the presence of liquid water, presumably since early in Solar System history. The band may constrain the maximum heating a body has experienced in the past.

Spectral characterisation in the visible-near IR (400 nm – 4000 nm) will allow us to: i) identify the presence of undissociated water in minerals and OH groups like hydroxyls; ii) explore the presence of primary silicates such as olivine and pyroxene and their chemistry (abundance of Fe in olivine and of Ca in pyroxene); iii) understand the relation between clinopyroxene (high Ca) and orthopyroxene (low Ca); iv) analyse the mineralogy of clays and other phyllosilicates, which can imply aqueous alteration processes; v) identify the presence of carbonates; vi) identify the presence of organic compounds, which are very important for the emerging field of astrobiology.

Evidence of surface movements on the asteroid through spatial variations of spectral features can also be detected. MarcoPolo-R will provide the spectral characterisation of the whole surface of 2008 EV5. It will allow the identification of minerals and organic compounds (Table 2.4) and their spatial distribution. In the case of 2008 EV5 a feature at 0.48 μm that is attributed to the presence of magnetite, associated with aqueous alteration, has already been detected by ground observations.

Table 2.4*: Possible signatures of organics in near-infrared spectra of NEAs.*

Wavelength (μm)	Assignment
1.21	2nd overtone of CH_3 asymmetric stretch
1.39-1.41	1st overtone of OH stretch
1.69-1.76	1st overtones and comb. of CH_2 and CH_3 stretching modes
2.15-2.17	combination of aromatic C-H stretch and C=C stretch
2.27	combinations of CH_2 asymmetric stretch and symmetric bend
2.31, 2.35	combinations of CH_3 asymmetric stretch and symmetric bend
2.46	CH_2
2.94-3.12	N-H and NH_2 group (stretch)
3.27-3.29	aromatic CH stretch or Fermi resonance
3.38-3.39	aliphatic CH_3 asymmetric stretch
3.41-3.42	aliphatic CH_2 asymmetric stretch
3.48-3.50	aliphatic CH_3 symmetric stretch
3.50	aliphatic CH_2 symmetric stretch
3.66-3.67	aldehyde groups

Many of the major rock-forming elements and their complexes have fundamental vibration frequencies in the mid-IR wavelength range. The 8-16 μm range covered by MarcoPolo-R is well suited for studying the composition of silicates, since this range contains the Si-O stretch and bend molecular vibration modes. Those mid-IR measurements will allow detection and characterisation of the presence of silicates (olivine and pyroxene, in both amorphous and crystalline state) and phyllosilicates (e.g. serpentine).

Interplay between surface and volume scattering around these bands creates complex patterns of emissivity highs and lows which are very sensitive to, and therefore diagnostic of, mineralogy as well as grain size and texture. The three main types of feature observed in mid-IR spectra are: i) Christiansen feature, which is directly related to the mineralogy and the grain size; ii) Reststrahlen features, which are due to the vibrational modes of molecular complexes and strongly dependent on grain sizes; iii) Transparency features. In the spectral region where the absorption coefficient decreases, grains become more transparent. If the grain size is small, volume scattering occurs and transparency features are observable due to a loss of photons crossing many grains.

Asteroid spectra are affected not only by the chemical composition of the surface, but also by several physical parameters, such as particle size and porosity. Mid-infrared spectroscopic analysis will thus provide some constraints on these quantities (Section 2.2.2.2). Finally, this spectral region also allows determination of whether the silicates are mainly crystalline and/or amorphous, which is of primary importance for constraining the thermal evolution of the asteroid.

Extended investigation in the near-IR (2.5-4 μm) and mid-IR (8-16 μm) could deeply constrain the physical and chemical properties of the MarcoPolo-R target. Space weathering could be used as a remote tool to study surface age and evolution. It is very important during the global mapping to define the areas affected by space weathering, in particular for the selection of the best site for the sample collection.

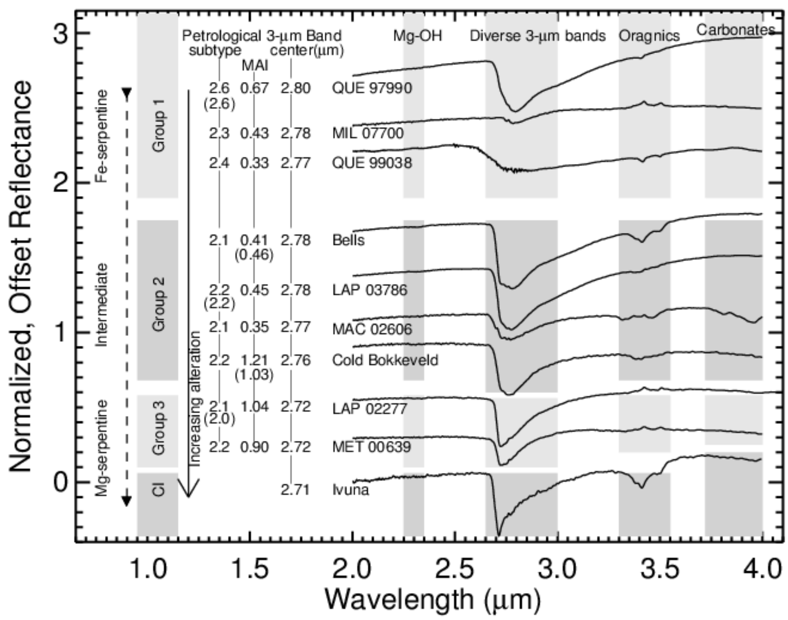


Figure 2.20: *IR reflectance spectra of some CM and CI chondrites measured under dry and vacuum conditions: Group 1 (QUE 97990, QUE 99038, and MIL 07700), Group 2 (Bells, LAP 03786, MAC 02606, and Cold Bokkeveld), and Group 3 (LAP 02277 and MET 00639). The 3-µm band centre decreases with increasing alteration (Takir et al. 2013).*

Space Weathering modifies the structure and optical/chemical/ mineralogical properties of the asteroid upper layers. Its effects are different, depending on the heliocentric distance and surface composition of a body. Previous results on space weathering are very intriguing and generate many questions that can only be answered by returning a sample. Laboratory experiments have been focused on space weathering simulation by irradiation of meteorite samples, essentially on analogues of S-type asteroids (Moroz et al. 1996; Brunetto et al. 2005; Ishiguro et al. 2007) because of their high albedo and strong bands. Only a few works have been dedicated to dark carbonaceous chondrites (Lazzarin et al. 2006; Lantz et al. 2013; Vernazza et al. 2013) and to complex organic materials (Moroz et al. 2004). The effect of space weathering on large absorption bands can produce a depth variation of 20-30 % or as little as a few % on small absorption features of a dark primitive surface. It should act also on albedo and spectral slope. The reflectance slope can vary up to 10-15 % for minerals.

2.2.2.5 Ground truth

MarcoPolo-R allows complete characterisation of the structure and composition of a primitive object, at both microscales (from sample analysis) and macroscales (from in situ observations). This will allow us to identify links between each of these observation regimes that can be applied to the wider asteroid population (that will not be explored by spacecraft) and meteorite collections:

- The degree of alteration and contamination of meteorite samples from atmospheric entry and exposure can be assessed by comparison with an unaffected sample;
- Laboratory reflectance spectra of individual components from a returned sample of a primitive NEA can be compared with telescopic spectra;
- The level of space weathering that 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;
- Physical measurements (e.g. size, shape, spin properties, thermal inertia) from spatially resolved in-situ observations can be compared with those inferred from unresolved Earth-based observations;
- A link between the detailed orbital and laboratory characterisation to meteorites and interplanetary dust particles (IDPs) can be established that provides ground truth for the astronomical database.

MarcoPolo-R offers an exceptional opportunity to obtain critical ground-truth information for a primitive asteroid population for which there is currently little or no information. The accessibility of 2008 EV5 provides a unique and cost-effective way within the time window of M3-class missions to achieve an unpreceded leap in our understanding of the origin of matter in the Solar System and early processes that led to the formation of planetary bodies.

3 Scientific requirements

3.1 Introduction

This section is intended to go through the detailed scientific requirements as documented in the Science Requirements Document (Sci-RD; MarcoPolo-R SST 2013). For each of the sections in the Sci-RD, this document gives a corresponding section where more information on the text is given and the requirements are justified.

3.2 Structuring the mission

In the Sci-RD, some structure in the operational timeline of the mission was assumed:

- After approaching the asteroid, a so-called global characterisation will take place. In the current mission scenario this phase is split in a Far Global Characterisation phase and a Global Characterisation phase. The requirements given below under global characterisation address both of these phases. The complete asteroid - or at least a large part of it - will be characterised on a global scale. The resolution requirements for this phase are in the order of decimetres for imaging in the visible wavelength range, in the order of metres for the VIS/IR spectrometer, and in the order of 10 m for the mid-IR instrument.

- After the global characterisation, up to five potential sampling sites will be selected. This selection will be based both on engineering grounds (can we land safely?) and on scientific grounds (is the site interesting?). These potential sampling sites will undergo more detailed local characterisation with more detailed resolution requirements: in the order of millimetres for the visible, decimetres for the spectrometers.

- One of these sites will be selected for taking the sample. When the actual sample is taken, a so-called 'Context Investigation' will be performed to get high-resolution context information on the site.

3.3 Target selection

To address the science questions of MarcoPolo-R the selected target should be as representative as possible of the time of the Solar System formation. This is expected from primitive asteroids. Whether an asteroid can be seen as primitive has to be decided on a case-by-case basis, using the spectral class, albedo, and possibly spectral features as criteria. The current baseline asteroid as given in R-TS-010 is considered such a target.

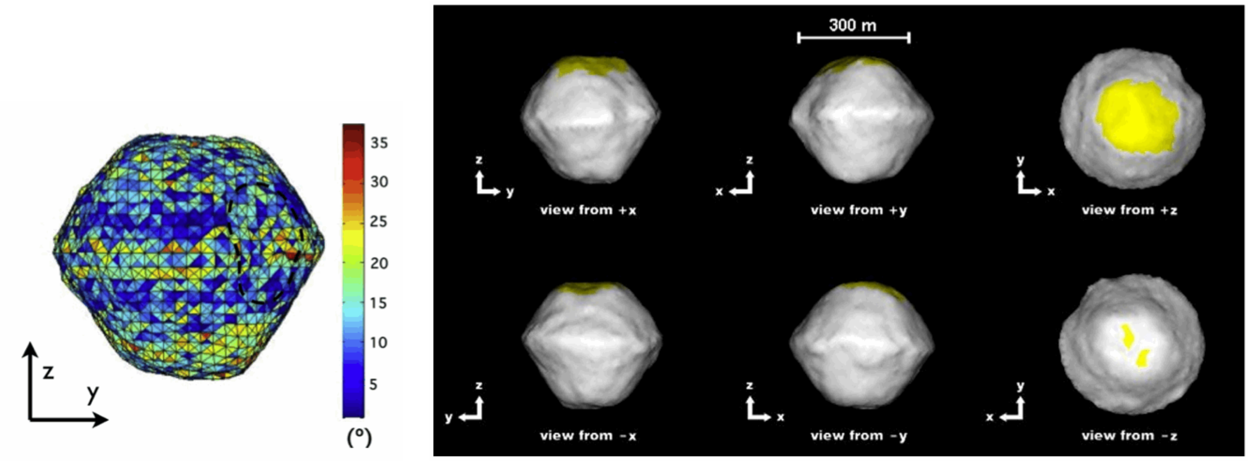


Figure 3.1: *Left: Shape model of asteroid 2008 EV5 showing the gravitational slopes (angle between the local acceleration and inward normal vector). Right: Principal axis views of our 2008 EV5 shape model. The model is viewed from six orthogonal directions, along its principal axes. Rotation is around the z-axis, with +z in the direction of the angular momentum vector. Yellow-shaded regions were seen only at incidence angles >45° or not seen at all. (Busch et al. 2011).*

R-TS-020 and -030 as stated, are indirect science requirements. If the object were too small for its fundamental properties to be estimated, it would be difficult to design a mission for it.

R-TS-010: Target class: The target shall be a primitive NEA. 2008 EV5 is the baseline target.

R-TS-020: Target size: There is no strong scientific requirement for a minimum target size. However, the target should be of a size such that:

i) It has sufficient gravity to allow the determination of the gravity field to an accuracy good enough to provide some constraint on the internal structure (*e.g.* determine the J2 coefficient to 10 %).

ii) It is bright enough for fundamental properties (size, shape, albedo, rotation) to be estimated from ground-based observations.

R-TS-030: As no precise numbers can currently be given for the above points, a constraint for the absolute visual magnitude of $H \leq 21$ mag shall be assumed, corresponding to a diameter $D \geq 340$ m for a representative primitive body assuming a visual geometric albedo of 0.06.

3.4 Sample-related requirements

The Sci-RD gives the following sample-related requirements:

R-SA-010: It shall be possible to characterise up to 5 potential sampling sites before the actual sampling. “Characterise” means:

(a) Determine the particle size distribution of the regolith down to scales of the order of millimetres;

(b) Determine the rough mineralogical composition down to scales of the order of decimetres;

(c) Determine the thermal skin depth indicative of regolith properties.

R-SA-020: It shall be possible to perform multiple sampling attempts (up to 3).

R-SA-030: The sampling device shall have the capability to acquire a minimum mass of the order of a hundred grams and shall return it to Earth.

R-SA-040: n/a

R-SA-050: The sampling device shall have the capability to acquire a selection of cm-sized fragments, plus a large number (minimum several grams) of small (hundreds of µm-sized to mm-sized) particles.

R-SA-060: Highest priority for sampling shall be given to a target area which, from the global and local characterisation of the NEA, appears to contain the most primitive material. This may be anywhere on the asteroid.

Returning a sample is the key element of this mission. The sample must be representative of the asteroid. Therefore it is important to have the possibility to select a sampling site - some areas may be not representative from a scientific point of view. R-SA-010 describes what is needed to make this assessment. Of course also spacecraft safety is addressed here, as well as in R-SA-020. If the first sampling attempt fails for whatever reason, repeating it must be possible.

R-SA-030 specifies the mass of the sample that the spacecraft should be designed for. Table 2.3 outlines in detail how much mass is required for which measurement. Adding up all the mass for destructive measurements and taking into account that some material should be maintained for future studies, a total mass in the order of 100 g should be returned.

The asteroid surface is expected to be covered with regolith, i.e. loose material of different sizes. To get a representative sample, the sampling device should return both small and large regolith particles. Particles larger than about 2.5 cm are especially important, as they are large enough to shield the inside from modifications due to cosmic radiation. R-SA-050 specifies this.

R-SA-060 emphasises again that MarcoPolo-R aims at returning primitive material. If for example a fresh impact crater is found on the asteroid surface, it may be good to take a sample from the recently exposed interior to get material from lower surface layers.

A second part of requirements describes the required cleanliness of the sample after its acquisition. The requirements R-SA-070 to R-SA-100 were derived from the currently available measurement capabilities of ground-based instrumentation. The concept is that the contamination of sample should be below what can be measured, else the measurement will give misleading results.

In the case that contamination cannot be avoided, at least one should know what the contaminant was and in which quantity it appeared. This is addressed by R-SA-110 requiring tracking of contamination by witness plates, and by the requirement R-SA-140. If a suspicious measurement is made, it must be possible to take samples of spacecraft fabrication material and make comparative measurements.

G-SA-010 is a goal requirement for keeping the temperature of the sample low. It is expected that already a few centimetres below the surface of the asteroid, the temperature of the regolith is quite stable. Material is expected to be recovered from a few cm depth, thus it should not have been exposed to high temperatures.

There is the possibility that the sample contains a remnant magnetic field, which could originate from the time of the formation of the Solar System. Fulfilling goal G-SA-020 would allow to measure this field.

R-SA-070: During collection and storage (departure from NEA, cruise, Earth re-entry, ground retrieval and transfer to curation facility) the sample shall be maintained free of organic and particulate contamination. The number of contaminating molecules deposited on the asteroid surface by the propulsion system shall be lower than 10^{+14} / cm^2 (goal 10^{+13} / cm^2).

R-SA-080: The spacecraft materials affecting the sample collection and storage shall be free of organic compounds or compounds that may react to materials, which can possibly contaminate the sample to a limit to be specified.

R-SA-090: After being placed in the sample container, the sample shall not be contaminated by dust or liquid particles larger than 1 µm.

R-SA-100: Until the sample arrives in the curation facility, it shall be kept free of moisture from the atmosphere (goal: avoid all terrestrial gases) such that less than 0.1 ppm terrestrial water is present in the sample.

R-SA-110: The possible contaminants (*e.g.* propellant, S/C outgassing, etc.) shall be tracked in-situ (*e.g.* by using witness plates).

R-SA-120: During the complete manufacturing process of the spacecraft, procedures shall be in place to keep all parts of the spacecraft clean to a level to be specified.

R-SA-130: The sampling mechanism and container shall be kept clean to a level to be specified and the cleanliness shall be monitored from the very beginning of the manufacturing.

R-SA-140: The materials used in the spacecraft fabrication and handling shall be archived.

3.5 Global characterisation requirements

The following requirements are given for the Global Characterisation phase:

R-GR-010: The complete surface of the NEA shall be imaged in at least 3 different colours, in the visible range with a spatial resolution (= twice the pixel scale) of the order of decimetres, and with local solar elevation angle between 30 and 60° (Note: it is acknowledged that depending on the rotation axis of the asteroid there may be areas which cannot be imaged due to illumination constraints).

R-GR-020: The complete surface of the NEA shall be imaged in the visible and near-IR wavelength range from 0.4 to 3.3 µm and with a mean spectral resolution of $\lambda/\Delta\lambda$ of the order of 200 and a spatial resolution (= twice the pixel scale) of the order of metres to characterise the mineral properties of the surface (Note: it is acknowledged that depending on the rotation axis of the asteroid there may be areas which cannot be imaged during the global characterisation phase due to illumination constraints).

R-GR-030: A shape model of the NEA shall be obtained with an accuracy of typically 1 m in height and spatial resolution with respect to the centre of mass.

R-GR-040: n/a

R-GR-050: The mass of the NEA shall be determined with an accuracy of about 1 %.

R-GR-060: The surface temperature of the complete NEA shall be derived to an accuracy of at least 5 K (goal 1 K) above 200 K (tbd). The spatial resolution shall be of the order of 10 m at a number of rotational phases from which the thermal inertia can be determined to a precision of better than 10 %.

R-GR-070: The complete surface of the NEA shall be imaged in the mid-IR with a spatial resolution of the order of 10 m or better and with a spectral resolution of $\lambda/\Delta\lambda$ of the order of at least 200 to determine the wavelength dependent emissivity, and hence identify mineral features in the range 8 – 16 μm (goal 5 – 25 μm).

G-GR-010: The flux, speed, direction and mass of atomic/molecular particles escaping from the surface should be measured to detect products of solar wind sputtering or other active release processes. Then, the energy range from 0.01 to 1 keV shall be covered with an energy resolution of about 25 % and an angular resolution of 5° x 5°; the particles with energies <0.01 keV shall be measured with $m/\Delta m$ of about 50.

G-GR-020: The spatial resolution (= twice the pixel scale) of the relative 3-D topography (*i.e.* in relative coordinates) should be determined to an accuracy of the order of decimetres.

The main aim of the global characterisation is to get an overview of the complete asteroid. What was its collision history, what are its overall shape, surface structure, composition. This is important to place the returned sample in context. From counting craters and the overall shape of the object, its collision history can be constrained, which directly addresses the second MarcoPolo-R question "What are the physical properties and evolution of the building blocks of terrestrial planets".

The first requirement, R-GR-010, describes requirements for the surface imaging in the visible wavelength range. To allow judging whether a certain area is suited for taking a sample, the resolution must be good enough to see whether the area is sufficiently flat, has a typical boulder size distribution, and is free of large obstacles. For that, a resolution of tens of centimetres is required.

The solar elevation angle constraint comes from the fact that for high angles, details of the topography will be lost as shadows are too short. For small angles the shadows get so large that they would dominate the scene. The requirement of 'at least three filters' comes from the fact that colour information will allow giving a first hint at the mineralogy and how representative a certain area is.

R-GR-020 expands the previous requirement to the spectroscopic instruments. As variations in the mineralogy (which would affect the spectral response) are expected on a larger scale, the resolution requirement is not as stringent as for the visual wavelength range.

R-GR-030 places a requirement on the shape model accuracy. The Radio Science Experiment will allow the determination of the mass of the object, with an accuracy as required in R-GR-040. With the shape model, the density of the asteroid can be computed. This value will give information on the interior of the asteroid - e.g. does it have cavities. The accuracy with which the shape model is obtained will therefore limit the accuracy of the density estimate. The values given here are an estimate of what is needed - together with the determination of the higher-order terms of the gravity field - to produce reasonable constraints for the interior of the asteroid.

R-GR-060 defines the surface temperature measurements. The surface temperature can be modelled by assuming certain thermal properties of the regolith. These are related to the size distribution, the packing density, and to the material itself. The required measurements will allow determining the thermal inertia to better than 10 %.

R-GR-070 is an extension of R-GR-010 and -020 to the thermal infrared. Again the resolution requirement has been relaxed because changes are expected on a larger scale only. The required spectral resolution is what is needed to distinguish the expected absorption features.

The goal requirement G-GR-010 addresses atomic and molecular particles measured on board the spacecraft. These are particles that are sputtered off the asteroid surface. They would allow constraining the composition of the surface material. In the current spacecraft design this goal cannot be fulfilled, as it would have required a Neutral Particle Analyser that is not part of the proposed payload.

G-GR-020 is another goal which, when fulfilled, would allow a good 3-D reconstruction on a relative scale. This would allow understanding the local gravity field and allow the interpretation of the movement of boulders.

3.6 Local characterisation requirements

The Sci-RD gives the following requirements for the local characterisation phase.

R-LR-010: A representative area within the expected landing[1] area ellipse (typically 50 % around the centre of the landing ellipse; goal: entire ellipse) shall be imaged in the visible in at least three colour filters, with a spatial resolution (= twice the pixel scale) of the order of millimetres.

R-LR-020: A representative area within the expected landing area ellipse (typically 50 % around the centre of the landing ellipse; goal: entire ellipse) shall be imaged in the visible and near-IR wavelength range to characterise the mineral properties of the surface with a mean spectral resolution of $\lambda/\Delta\lambda$ of the order of 200 and a spatial resolution (= twice the pixel scale) of the order of decimetres to characterise the mineral properties of the surface.

R-LR-030: A representative area within the expected landing area ellipse (typically 50 % around the centre of the landing ellipse; goal: entire ellipse) shall be imaged in the mid-IR with a spatial resolution (= twice the pixel scale) of decimetres and a spectral resolution of at least $\lambda/\Delta\lambda$ of the order of 200 or better to determine the wavelength dependent emissivity, and hence identify mineral features in the range 8 – 16 μm (goal 5 – 25 μm).

G-LR-010: (As G-GR-010) The flux, speed, direction and mass of atomic/molecular particles escaping from the surface should be measured. Then, the energy range from 0.01 to 1 keV shall be covered with an energy resolution of about 25 % and spatial resolution at surface of about 10 m; the particles at energy <0.01 keV shall be measured with $m/\Delta m$ of about 50.

The underlying goal is similar to that of the global characterisation. After having defined potential sampling sites from the global characterisation, the spacecraft now takes 'a closer look'. The data will again be used both by scientists to judge the scientific quality of a sampling site, and by the engineers to assess spacecraft safety. In addition, the data will provide the required context for the returned sample. Was the surrounding area homogeneous, were there any special features observed which would be important to interpret the results of the sample analysis later?

The required resolution in the visible is in the order of millimetres (R-LR-010). This is needed to assess the size distribution of the regolith. It is not expected that the returned sample retains the size distribution, as particles may be crushed during sampling. As a goal the complete potential landing area should be characterised. Acknowledging possible constraints in terms of data downlink, the requirement states 'a representative area'.

R-LR-010, -020, and -030 follow the same logic as in the global characterisation, putting requirements on the different wavelength regimes with less and less stringent resolution requirements; the goal G-LR-010 corresponds to G-GR-010.

3.7 Sample context requirements

The following related requirements are given in the Sci-RD:

R-SC-010: The regolith in the vicinity of the actual sampling site shall be imaged before and after sampling to sizes as small as 1.0 mm spatial resolution (= twice the pixel scale) in an area of about 1 m x 1 m on the surface. This should include the actual sampling site.

R-SC-020: An additional "local characterisation" shall be performed after the sample collection (*i.e.* fulfil R-LR-010 to R-LR-030 again), for the site where the sample was collected.

G-SC-010: The images taken by the navigation camera (if any) during the descent should be made available

[1]In the Science Requirements Document, the term 'landing area' or 'landing site' refers to the sampling site.

to scientists upon request.

The current sampling happens in a 'touch-and-go' scenario, which means that there is not a lot of time to perform measurements from close-up. However, to put the sample in its local context, at least imaging is required. The regolith size distribution has to be determined, as argued in the previous section, but to a better resolution.

Depending on the location and pointing of the navigation camera, this camera may take images of the surface that cannot be taken with the science camera at that location or at that time. Therefore as a goal it is requested that at least a part of these images can be downlinked to Earth and made available to the scientists.

3.8 Other requirements

This section in the Sci-RD addresses points that did not fit in any of the previous sections:

R-OR-010: The sample shall not be exposed to a shock load higher than 800 g (possibly up to 2000 g pending future sample testing).

G-OR-010: It shall be possible to calibrate the colour response of the instruments, by providing a calibration target (if mission analysis foresees a lunar flyby, allow imaging of Apollo 16 landing site).

G-OR-020: After sample collection, a device or method shall allow verification that a suitable sample has been collected, giving a rough estimate of the volume or mass of the sample.

G-OR-030: n/a

G-OR-040: If the mission scenario foresees any planetary flyby, it shall be possible to switch on all payload elements for testing.

The shock load in particular when the sample hits the ground upon Earth return could change the structure of the material, in particular since primitive material is expected to be very fragile. A simple analysis of the expected loads was used to derive the limits given in R-OR-010. Azougagh-McBride et al. (2008) have performed drop tests with an experimental version of a proposed robotic sample collector and find no change in the sample (sand, rock, glass, and chalk) for shocks up to 2800 g. This indicates that it should be possible to relax the requirement.

G-OR-020 is a requirement that increases the chance of mission success, together with R-SA-020 that requires multiple sampling attempts to be possible. If it cannot be verified that a sample is taken, another attempt will be performed.

G-OR-040 is important for the remote sensing instrumentation. While all instrument teams will perform a thorough calibration of the instrument, it has to be ensured that the instruments are functioning properly in flight. While this will normally be done in instrument checkout phases, a flyby gives the unique chance of imaging known extended targets. This will allow ensuring the proper calibration of the instruments.

3.9 Additional NEA science requirements

This section provides a number of additional goals, which can be addressed e.g. with extended radio science phases (G-AS-020). G-AS-010 and -030 would require a surface element and are not achievable with the current mission design. G-AS-040 would allow data that will be obtained anyway to be used for scientific purposes. Images from a possible navigation camera may be taken at different times, thus different illumination conditions or different resolution compared to the imaging with the science camera.

G-AS-010: The inner structure of the NEA should be constrained, with the goal of doing this to a depth of about 100 m and a spatial resolution of about 10 m.

G-AS-020: The second-degree gravity field coefficients should be determined with an accuracy high enough to provide constraints on the internal density distribution with an uncertainty not exceeding 10 %.

G-AS-030: It should be possible to do near-surface investigations of several areas on the NEA.

G-AS-040: Complete images obtained with the Star Trackers and navigation camera (if any) should be made available to scientists upon request.

3.10 Requirements on the curation facility

While for schedule reasons the bulk of the Sci-RD focuses on requirements for the space segment of the mission, the main goal of the mission is to return a sample. To be able to handle the sample distribution properly, a curation facility is needed. The following requirements are already given:

R-CU-010: The curation facility shall maintain the sample free of organic and particulate contamination. In particular, the number of contaminating molecules and particulates deposited on the sample surface during an expected stay time of 2 years shall be lower than 10^{13} cm^{-2} (goal 10^{12} cm^{-2}) and lower than 1 particle of size 1 µm on 1 cm^2, respectively.

R-CU-020: After arrival in the curation facility and extraction from the sample container, the sample shall be kept and processed in an environment equivalent to ISO class 4 (ISO 14644-1).

R-CU-030: After arrival in the curation facility, the sample shall be kept free of moisture from the atmosphere such that less than 0.01 ppm terrestrial water is present in the sample after an assumed stay time of 2 years.

R-CU-040: It should be possible to manipulate sample volumes from 5×10^{-7} to 4 cm^3.

R-CU-050: The sample shall be classified through preliminary characterisation according to its size and morphology (accuracy at least 0.5 µm), weight (accuracy 1% in the microgram to gram range), and mineralogical phase (accuracy at least 1 % vol)(*tbc*).

R-CU-060: The possible contaminants shall be tracked and monitored in-situ (*e.g.* using witness plates).

R-CU-070: Parts of the sample shall be stored for 50 years in clean conditions (goal: in vacuum).

***Figure 3.2**: Processing facility in the lunar sample building at Johnson Space Center (credit: NASA).*

R-CU-010 to -030 constrain the cleanliness of the sample. To perform the needed measurements as described in Section 2.2.1 in Table 2.3 the number of contaminating molecules and particles after return to the Earth have to stay below the given levels. Similar to what is requested on spacecraft level (R-SA-110), R-CU-060 requires that possible contaminants must be tracked. If contamination is present, at least one must know what it is and in which quantity it accumulated.

R-CU-040 is linked to R-SA-050, requiring the sampling device to be capable of sampling cm-sized fragments. The curation facility must of course be capable of handling such fragments.

Since the capability of ground-based instrumentation is continuously increasing, R-CU-070 requires parts of the sample to be stored for a long period of time. This will allow future generations of scientists to use new techniques on the existing sample, achieving new scientific results.

4 Payload

This section will give a short overview of all selected payload elements for MarcoPolo-R. Table 4.1 summarises the science goals and objectives, which are addressed by the payload. Note that most of the science will be addressed by the returned sample; however the payload is of utmost importance to put the sample into its geological context.

Table 4.1*: Science goals and objectives addressed by the payload. For a similar table for the sample analysis, see Table 2.2. Open circle: instrument partially contributing; closed circle: instrument fully contributing.*

Science Goals	Science Objectives	Measurements per instrument						
		MaNAC	CUC	MaRIS	THERMAP	RSE	VISTA2	Laboratory analysis
1. What was the astrophysical setting of the birth of the Solar System?	(A) To determine whether primitive NEAs contain pre-solar grains previously unknown in meteorites, and the stellar environments in which these grains formed.							●
	(B) To investigate the interstellar processes that have affected the pre-solar grains.							●
	(C) To understand the nucleosynthetic events that contributed to provide short-lived radionuclides to the Solar System.							●
2. What is the origin and evolution of material in the early Solar System and how did it evolve?	(D) To characterise the chemical and physical environment in the early solar nebula.							●
	(E) To determine the timescales of solar nebula and accretional processes.							●
	(F) To determine the origin of large isotopic variations in early Solar System materials.							●
	(G) To characterise the large scale mixing processes in the protoplanetary disk.							●
	(H) To establish the abundance and signature of water and other volatiles – a possible source for the Earth's oceans and atmosphere.			○				●
3. What are the physical properties and evolution of the building blocks of terrestrial planets?	(I) To determine the global physical properties of an NEA.	●	○	○	●	●		
	(J) To determine the physical processes, and their chronology, that shaped the surface of the NEA.	●	●	○	○		●	○
	(K) To characterise the chemical processes that shaped the NEA composition.	○	○	●	○			●
	(L) To link the detailed orbital and laboratory characterisation to meteorites and interplanetary dust particles (IDPs) and provide ground truth for the astronomical database.	○	○	●	○			●
4. How do organics in primitive NEAs relate to the origin of life on Earth?	(M) To determine the origin, diversity and complexity of organic species in a primitive asteroid.			○				●
	(N) To provide insight into the role of organics in life formation.							●

4.1 MaNAC: MarcoPolo-R Narrow Angle Camera

The MarcoPolo-R NAC shall perform global and local characterisation of the Near-Earth Asteroid to retrieve sample context information at the spatial resolution of the order of dm and mm, respectively.

4.1.1 Instrument Description

A single band pass axial asymmetric and fully catoptric Three Mirrors Anastigmatic imaging system is able to match with the imposed instrument mission task and it is based on the heritage of the OSIRIS cameras on board the Rosetta mission. The instrument configuration allows surface imaging in both panchromatic and filter bands down to 7.5 m pix^{-1} during Asteroid Rendezvous phase to go down to 7.5 x 10^{-2} m pix^{-1} during Global Characterisation phase. During the Local Characterisation phase, the IFOV goes down to 3.7 x 10^{-3} m pix^{-1}.

The MaNAC design meets all scientific and performance requirements of both visible cameras (NAC and WAC) foreseen to be on-board MarcoPolo-R. For instance the MaNAC can obtain an image of the entire asteroid at 100 km on the half frame covered by the panchromatic filter with a spatial resolution of 1.5 m pix^{-1}. The camera may have 5 filter elements: 1 panchromatic filter (700/200 nm) filling half the field of view and another 4 filters filling the other half of the field of view with different bandwidths and central wavelengths according to the required scientific return.

The NAC will consist of two units with physical interface with MarcoPolo-R: a) the optical head including the telescope mounting structure and the focal plane with its proximity electronics on the mounting structure (see Figure 4.1); b) the main electronics including camera control, data handling, compression and power supply. The following architectural design was developed: a catoptric telescope with excellent optical quality is coupled with a framing detector, avoiding any scanning mechanism and, above all, any operational requirement on the S/C.

According to preliminary calculations the minimum RMS spot radius centroid condition and the MTF higher than 60 % over the entire FoV at the Nyquist frequency of the system (i.e. 50 mm^{-1}) condition can be imposed. Moreover, the entrance pupil can be fixed to be 82.5 mm wide and the MTF can be imposed to optimize the NAC effective focal length up to 660 mm.

A crucial aspect in the design is the requirement of a focus depth that will allow the NAC to operate both at 5 km and 250 m altitude. We will study different approaches to this problem taking into account not only a specific mechanism, but also slightly modifying the opto-mechanical design.

The detector is a 2k x 2k hybrid based on CMOS technology with 10-micron pixels that is already mounted on the SIMBIOSYS cameras.

The NAC design was tuned to have the highest probability to guarantee scientific success to the mission by the best usage of the resources allocated to imaging on MarcoPolo-R. This has been achieved through the implementation of a single NAC channel, with WAC capabilities, with high reliability due to the redundancy philosophy.

4.1.2 Interfaces and resource requirements

Table 4.2: *Instrument characteristics of MaNAC.*

Characteristic	Value
Overall dimensions	
Optical Head including focal plane assy	52 x 37.7 x 19.7 cm^3
Main Electronics	29 x 22 x 10 cm^3
Mass	
Total	10.57 kg
Power	
Science	21.44 W
Standby	16.0 W
Data volume	
Observations	46.1 Gbit
Calibrations	1 Gbit
Total	47.1 Gbit
Temperature range	
Non operating	-40 °C to +50 °C
Operating	-20 °C to +20 °C

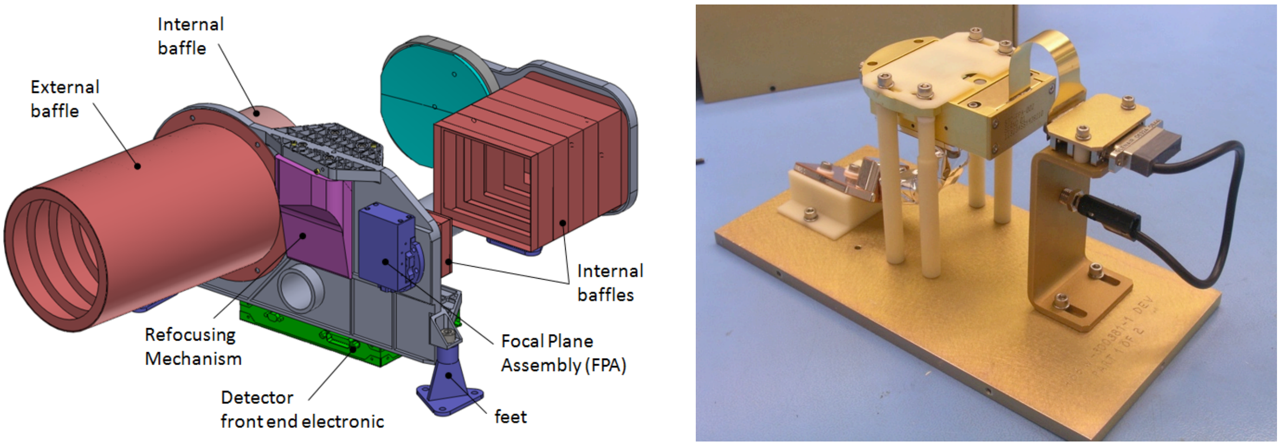


Figure 4.1: *CAD view of the proposed MaNAC design (left). Test setup of the detector used for SimbioSys on BepiColombo, which is the current baseline detector for MaNAC.*

4.1.3 Operation requirements

MaNAC optomechanics including the detector is fixed nadir pointing. The Proximity Electronics is to be placed close to the detector system. Maintenance of the operating temperature range of the detector system and optomechanics is critical for camera operations and performance quality. Active control may be required (including Main Electronics).

MaNAC will be used for:

- Nadir pointing during global mapping of the target
- Nadir and off-nadir pointing for the Digital Terrain Model application of the target
- Any pointing direction for in-flight calibrations and special applications at the target

MaNAC operations are done in quasi-continuous mode and snapshot mode at the target (see Section 5.1.2).

4.1.4 Heritage

All units and subsystems are based on heritage from previous space missions, such as HRSC on Mars Express, Osiris and Rolis on Rosetta, FC on Dawn, VMC on Venus Express, BELA and SIMBIOSYS on BepiColombo.

4.2 CUC: Close-Up Camera

The Close-Up Camera (CUC) is designed to characterise, at high resolution and in colour, the sampling area and provide the geological context of the sample prior to the sampling operations, which is crucial for the subsequent analysis of the sample back to Earth. The aim is to determine physical key properties of the asteroid surface, such as grain size distribution, textural, mineralogical, structural, and morphological details in geologic materials, influence of space weathering processes.

Thanks to its varying focal length, CUC images will also be acquired before and after the sampling operation: during the descent, to provide information on the unperturbed regolith surface state of a larger area around the sampling site, and during the ascent, to study how the sampling process will have altered the structural properties of the surface.

With its ~14° field of view (diagonal), the CUC will contribute to the local and global characterisation phases as well, in synergy with the other instruments.

Using CUC images of the same surface acquired under different geometries (be it from 10 km, 5 km, 250 m, or close to the surface) it is possible to generate 3D maps at different levels of detail, and thus further extend the knowledge of the asteroid surface.

4.2.1 Instrument Description

The CUC instrument is a powerful miniaturised, low-power, efficient and highly adaptive imaging system. It is composed of optics with focus mechanism, a direct high-resolution colour image sensor and controlling/processing electronics (see Figure 4.2).

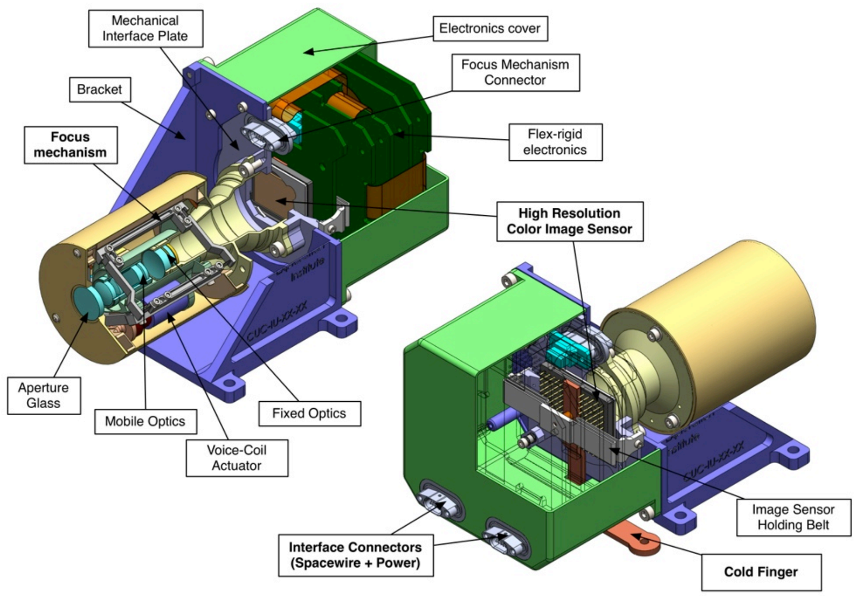


***Figure 4.2**: Close-Up Camera CUC.*

The focus mechanism uses a voice coil actuator to smoothly and precisely control the focus of the optics as well as to provide dust and radiation protection for the internal optical elements.

The direct high-resolution colour image sensor allows for full RGB colour images without any loss in spatial resolution.

Both the image sensor and the focus mechanism are controlled by the electronics, which also handles memory storage, image processing and communication to the spacecraft. After a start-of-sequence command has been received, this allows for a completely autonomous instrument. It will self-adjust to the environment via automatic focus and exposure algorithms, take the given series of images, perform all needed image processing and store the final compressed image data, ready to be uploaded to the spacecraft Data Handling System.

Table 4.3 describes the characteristics of the CUC instrument. The current baseline for the CUC field of view provides a surface resolution that is compliant with respect to the scientific requirements of the MarcoPolo-R mission for the CUC.

4.2.2 Interfaces and resource requirements

The CUC is to be accommodated inside the spacecraft for thermal reasons.

The prime objective of the CUC is to image the sampling site and sampling process. Therefore the main accommodation requirement is that the CUC shall have the sampling tool tip in its FOV when deployed, as well as having the sampling target in its field of view during the whole descent. This may imply a slight tilt of the instrument with respect to nadir viewing.

Optical reflectance of surfaces included in the FOV of the CUC may impact the CUC performance, so no part of the spacecraft shall be in the FOV of the CUC except for the sampling boom/arm during the Descent/Ascent Phases. The sampling boom/arm surfaces shall be treated to avoid undesired reflections.

Without compromising the sampling observation, co-alignment with MaNAC would greatly optimize the CUC extended activities (i.e. when the CUC is operated during the Far Global, Global, and Local Characterisation phases).

Table 4.3: CUC Instrument characteristics

Characteristic	Values
Physical characteristics	
Dimensions	225 x 100 x 120 mm^3
Mass	820 g
Optical characteristics	
Detector type	Full color APS (Active Pixel Sensor)
Image dimension	2652 x 1768 x 3 pixels in colour
Pixel size	7.8 µm x 7.8 µm
Field of view (FOV)	14° ± 2° diagonal (11.9° x 8.0°)
Image resolution, viewed area	7 µm/pixel at 10 cm distance, viewed area 1.9 cm x 1.3 cm 39 µm/pixel at 50 cm distance, viewed area 10 cm x 7 cm 79 µm/pixel at 100 cm distance, viewed area 21 cm x 14 cm
Working distance	10 cm to infinity with variable focus
Focal length	Varying to take sharp images from 10 cm to infinity
Spectral range	400-700 nm
Exposure time	Up to 1024 seconds
Electonics	
Quantization	12-14 bits
Dynamic range	62 dB (sensor) quantified on up to 16384 levels (14 bits)
Electrical interface	SpaceWire on LVDS
Electronic features	Sequencer, Converter, Internal buffer Internal clock of 40 MHz (TBC) SpaceWire Data Coding
Data processing	Automatic Exposure Time Autofocusing Binning 2x2 and 4x4 Z-stacking (between 2 and 16 images) Windowing
Data storage	4 Gb
Power	
Max. mean power consumption	< 15 W incl. 20 % margin
Power lines	+ 28 V
Temperature range	
Operating temperatures	-20 °C to +50 °C
Storage Temperatures	-30 °C to +60 °C

4.2.3 Operation requirements

Descent and Context Measurements: The current baseline for the CUC image acquisition operational sequence for context measurements begins when the spacecraft reaches the 100 m hold point, and then 2 images are taken at each hold point (hold points are still TBC). Once the spacecraft begins the final descent (10 m above the surface) the CUC enters an operational mode where it takes 1 image every 5 seconds. This continues until the sampling mechanism contacts the surface at which point the CUC enters a second operational mode where it takes 4 images s^{-1} for a 5 s duration (this can be adjusted to the actual sampling process time). Assuming that the sampling process will take about 3 s, the high rate of image acquisition for the remaining 2 s is needed to obtain information on the fall and deposition of the regolith particles following the sampling operation and the ascent of the spacecraft.

Ascent Observations: After sampling and completion of the second operational mode the CUC then automatically switches to a third operating mode of taking 1 image every 5 seconds for 100 seconds. The images acquired during the ascent phase will allow a further characterisation of the sampling site following the sampling operations, providing additional scientific information on the physical surface properties of the asteroid regolith, in particular: dust cloud, ordering of the particles and falling materials due to the sampling process, tracks left by the sampling process, effects of the thrusters.

Local and Global Characterisations: Thanks to its ability to focus on any target located between 10 cm and infinity, the CUC can acquire images from the 250 m orbit for the Local Characterisation and post-sampling Local Characterisation phases with a resolution of 2 cm pix^{-1}.

The CUC can also acquire images during the Far Global (10 km orbit) and Global (5 km orbit) Characterisation phases with resolutions of 79 cm pix^{-1} and 39 cm pix^{-1} respectively, making the CUC highly complementary with MaNAC (see Figure 4.4).

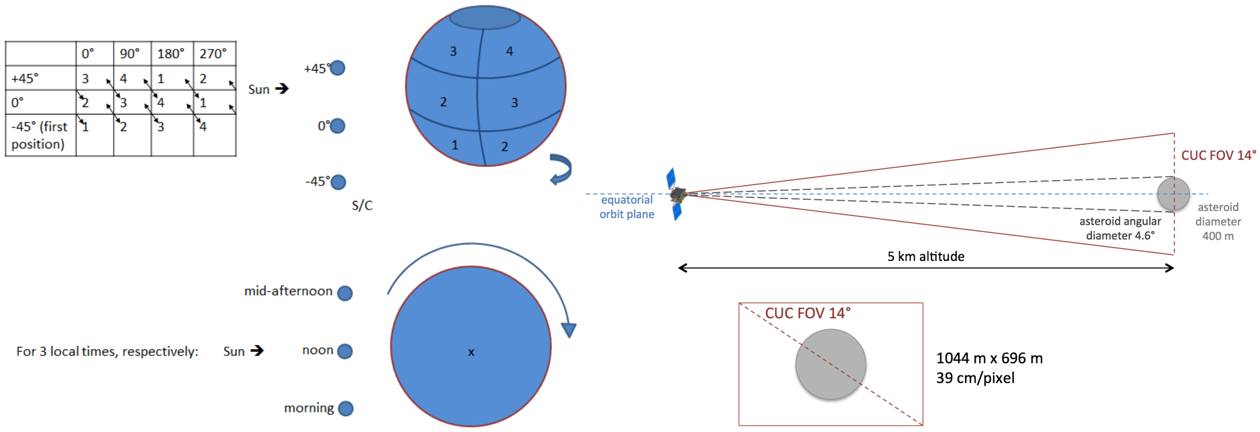


Figure 4.4: *Viewing geometry of the CUC when used as wide-angle camera.*

4.2.4 Heritage

The CUC instrument concept is mainly based on the development of the CLUPI (Close-Up Imager) instrument for ESA's ExoMars 2018 Rover Mission. It has been adapted to suit the MarcoPolo-R mission design and environment in terms of temperature range, radiation shielding, electronics (added functionalities). The AMIE/SMART-1 Camera heritage will also be used in particular for the remote sensing 3D mapping purposes.

4.3 MaRIS: MarcoPolo-R imaging spectrometer, Visible and Near-Infrared

The visible and near-infrared imaging spectrometer MaRIS will investigate the composition of the selected NEA. It will provide remote sensing information of different geological units as well as the overall surface mineralogy with a spatial resolution of the order of meters (globally) down to decimeters (for selected sites).

MaRIS will provide essential contributions to the following scientific objectives:

- Determine the global physical properties of the target
- Characterise the mineralogy to understand the chemical processes (e.g. role of volatiles, water)
- Investigate the surface distribution and diversity of organic species on a primitive asteroid
- Link the detailed orbital and laboratory characterisation to meteorites and interplanetary dust particles (IDPs) and provide ground truth for the astronomical database
- Provide detailed characterisation of the sampling site and sample in its native environment

4.3.1 Instrument Description

MaRIS (MarcoPolo-R Imaging Spectrometer) is used to spectrally map the complete surface of the target in the visible and near-infrared wavelength range from 0.4 µm to 4.0 µm with mean spectral resolution $\lambda/\Delta\lambda$ of the order of 200. The instrument (Figure 4.5) is designed to operate both on the dayside and the night side.

A 4-lens telescope images the asteroid on a field stop. A modified Offner relay uses 2 pure conic off-axis mirrors and an on-axis mirror to re-image the entrance slit on the detector. Two sapphire prisms placed within the Offner relay assure the dispersion. A shutter is placed in front of the entrance slit to subtract background images. The spectral image is formed on a 320x480 MCT detector (CHROMA-320 from Teledyn) with a pixel pitch of 30 µm. The spectral image covers 320x128 pixels. On a two-dimensional detector, this kind of imaging spectrometer records a 1-D image and a full spectrum for each point of the 1-D image. An internal spectral calibration system using Fabry-Perot, allows checking of the spectral registration before each session. The scanning system is used to point the calibration device. Detector control, digitization and data transmission are managed by dedicated proximity electronics. The main electronics, interfaced with the spacecraft, control the optical head of MaRIS and handle all the data associated with MaRIS experiment.

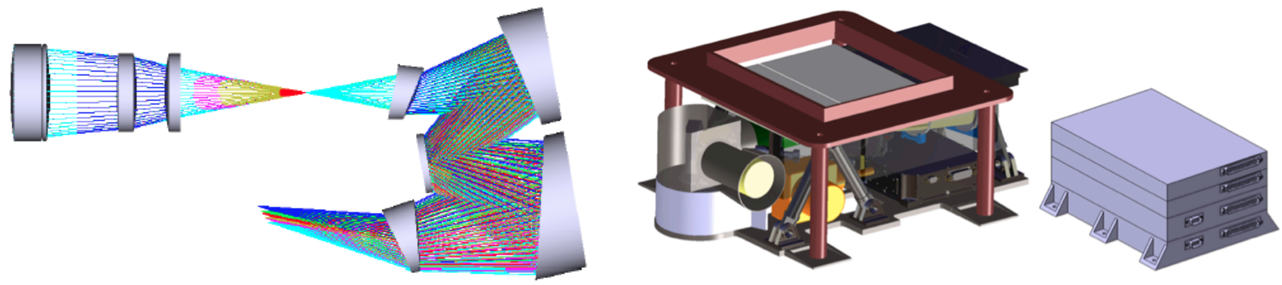


Figure 4.5: *Optical head (left) and mechanical design (right) of MaRIS.*

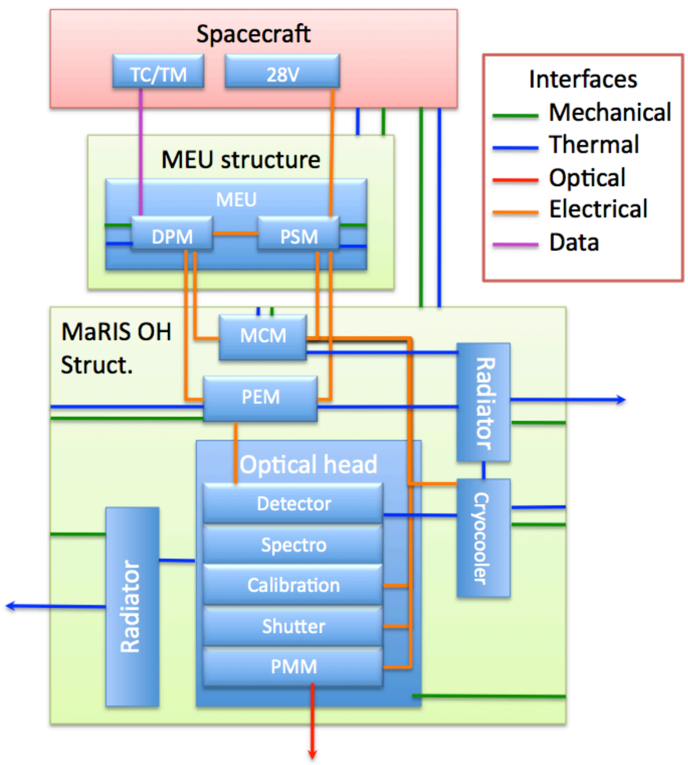


Figure 4.6: *MaRIS functional diagram.*

To limit the thermal emission of the instrument, the spectrometer is passively cooled to 190 K and the detector to 130 K using a cryocooler. The two radiators (one dedicated to the spectrometer and the other one to the heat loads) are mounted on the optical head structure.

The radiometric study shows that a SNR of the order of 200 (on the day side) is obtained with 26 ms integration time. On night side, the integration time reaches 336 ms to obtain a SNR of 10 at 3.5 µm and 40 at 4.0 µm.

MaRIS is separated into two structures (Figure 4.6):

- The Electronics Structure, thermally coupled to the spacecraft, that includes the Main Electronics (DPU and DC/DC converter).
- The Optical Head Structure is an insulated unit that contains the spectrometer, the cryocooler, the radiators and the Proximity Electronics.

4.3.2 Interfaces and resource requirements

Table 4.4: *Instrument properties of MaRIS.*

Characteristics	Values
Overall dimensions	
Optical head structure	300 x 399 x 151 mm^3
Electronics structure	263 x 210 x 120 mm^3
Mass	
Nominal	8.23 kg
Power	
Observations	19.3 W
Peak	21.7 W
Data handling	
Data rate [Mb/s]	day side: 21.7 / night side: 2.1
Data volume [Gb]	Far global: 0.52 / Global: 6.8 / Local: 21.9
Compression factor	Lossless / Wavelets
Operating temperature range	
Optical head structure	-93 °C to -73 °C
Electronics structure	-20 °C to +50 °C
Non-operating temperature range	
Optical head structure	-173 °C to +50 °C
Electronics structure	-50 °C to +60 °C

4.3.3 Operation requirements

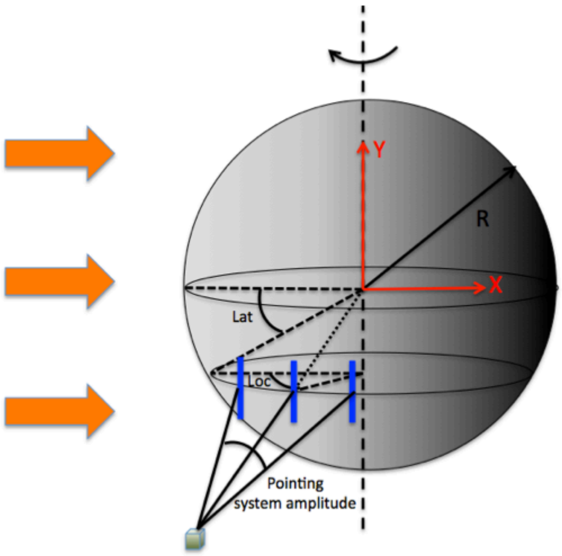


Figure 4.7: *MaRIS pointing concept.*

The MaRIS architecture is based on the use of a pointing system mechanism positioned in front of the entrance telescope. The hovering position allows nadir observations at local times of 0°, 45° and -45°. The pointing system is used to reach any local time (slit projection in blue on Figure 4.7). The pointing system mechanism is also used during the internal calibration process by folding the optical path from the calibration to the entrance telescope.

The overall mapping of the asteroid is ensured by the rotation of the asteroid and the nadir pointing at different latitudes. The use of a standalone pointing system mechanism increases the science feedback by the measurement of the asteroid albedo at any phase angle.

MaRIS depth of focus is sufficient to allow observations during all operational phases with a spatial resolution of the order of metres at a distance of ~5 km.

4.3.4 Heritage

MaRIS is a low risk implementation of a flight-proven instrument. The TRL of each subsystem ranges between 5 and 9. The heritage in the field of spectrometers comes from: VIRTIS-Rosetta, VIRTIS-VenusExpress, OMEGA-MarsExpress, SIR SMART-1, SIR-2 Chandrayaan-1, NEAR Infrared Spectrometer, the CRISM spectrometer on MRO, BepiColombo MMO, Proba-V DHU, Sentinel-2 MMFU.

4.4 THERMAP: the mid-infrared spectro-imager for the MarcoPolo-R mission

THERMAP is the ideal instrument to characterise the surface thermal environment of a NEA, to map its surface composition and to help to select the sampling site and to put the sample in its context.

4.4.1 Instrument Description

THERMAP is a mid-infrared spectro-imager with two channels, one for imaging (8-18 µm) and one for spectroscopy (8-16 µm). The THERMAP imaging channel is a tri-mirror anastigmat telescope (TMA), with a field of view of 9.0° x 9.0°, a focal length of 50 mm and an F-number of 2. It is based on a 640x480 uncooled micro-bolometer array, with a pixel size of 25 µm and an IFoV of 500 µrad. The THERMAP spectroscopic channel is a slit spectrometer. It follows the imaging channel in the optical path, and is composed of a slit and an Offner relay. As the imaging channel, it uses a 640x480 uncooled micro-bolometer array with a pixel size of 25 µm and an IFOV of 500 µrad. The spectral resolution is 0.3 µm over the 8-16 µm wavelength range ($\lambda/\Delta\lambda = 25 - 55$). A flip mirror allows switching between the imaging and spectroscopic channels. A rotating mirror at the entrance of the instrument allows pointing alternatively at the asteroid and three calibration targets (deep space and two internal black bodies).

The THERMAP imaging channel is a camera, with full 2-D imaging capabilities, which can easily map the entire surface of the NEA and the sampling site in one or a few frames to derive the surface temperature distribution with an accuracy better than 5 K above 250 K. The THERMAP spectroscopic channel can acquire spectra of the surface with a spectral resolution of 0.3 µm over the 8-16 µm wavelength range, with a signal-to-noise ratio exceeding 20 for surface temperatures around 400 K. Spectra will be used to study the surface composition and mineralogy. The THERMAP instrument will acquire images and spectra of the target during the different phases of the mission, with a spatial resolution of 10 m (2 pixels) for the far global characterisation, 5 m for the global characterisation and 0.25 m for the local characterisation of the sampling site.

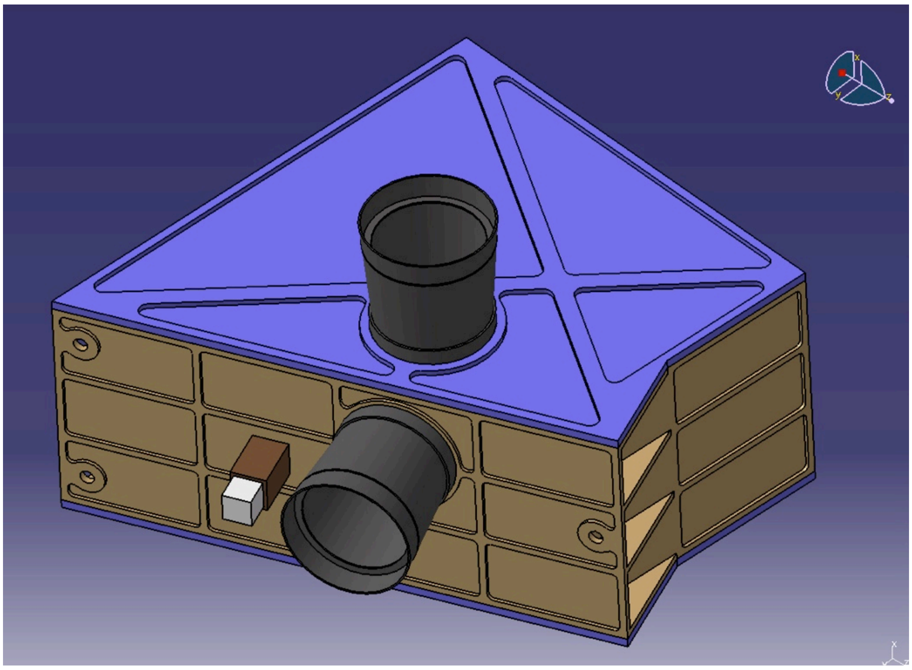


Figure 4.8: *External view of the THERMAP instrument, showing the main box and the two external baffles toward the asteroid and deep space (for calibration purposes).*

4.4.2 Interfaces and resource requirements

***Table 4.5**: Resources of the THERMAP instrument, including margins.*

Characteristic	Value
Overall dimensions	
Baffles, MLI and connectors excluded	28.7 x 25.5 x 14 cm^3
Mass	
Total	7.5 kg
Power	
Observations	20.4 W
Peak	30.5 W
Standby	4.2 W
Data volume	
Observations	6.4 Gbit
Calibrations	2.7 Gbit
Total	9.1 Gbit
Temperature range	
Non operating	-40 °C to +40 °C
Operating	+5 °C to +15 °C

4.4.3 Operation requirements

THERMAP will observe the asteroid on its illuminated side, where the surface temperature is above 250 K for imaging and above 350 K for spectroscopy. We aim for spectroscopic observations around local noon to maximize the signal-to-noise ratio. The THERMAP spectroscopic channel is a slit spectrometer with no scanning possibilities, so that spatial information in the dimension perpendicular to the slit is acquired as the asteroid rotates and passes in front of the slit. To do so, THERMAP requires having its slit orientated parallel to the polar axis, along a meridian. In addition, THERMAP requires regular calibration cycles, typically every 30 min, by pointing alternatively at three calibration targets (deep space and two internal black bodies).

4.4.4 Heritage

The THERMAP design follows the same philosophy as MERTIS, the Mercury Radiometer and Thermal Infrared Spectrometer for the ESA BepiColombo mission. It uses the same detector technology, the same optical design, and the same principle for calibration. To maximize the heritage of MERTIS, the THERMAP consortium includes the DLR institute in Berlin, responsible for the technical development of the MERTIS hardware. In addition concerning the heritage, the 640x480 uncooled micro-bolometer detector of the THERMAP instrument is identical to that used for the Infrared Camera (IRCAM) of the Japanese Experiment Module (JEM) Extreme Universe Space Observatory (EUSO). The IAC, which is part of the THERMAP consortium, is responsible for the detector, control electronics, tests and characterisation of the IRCAM.

4.5 RSE: Radio Science Experiment

One of the main science objectives of the MarcoPolo-R mission is the determination of the global physical properties of an NEA. One of the key parameters in this context is the gravity field, especially GM (gravitational constant times the mass) and the low order gravity coefficients C_{20} and C_{22}. The precise determination of the mass of the target asteroid also has a high priority for allowing navigation in close proximity to the body.

From the gravity field important physical properties of the NEA like mass, density, porosity and the internal structure can be derived (Andert et al. 2010; Andert et al. 2011). Consequently, the determination of the gravity field is considered as a high priority scientific objective.

Secondary scientific objectives of the RSE experiment comprise the determination of the surface roughness of the asteroid and its dielectric constant by Bi-Static Radar (BSR) experiments (Simpson 1993).

4.5.1 Instrument Description

The experiment team provides no extra hardware; the observations are done by using the on-board radio subsystem, which consists of

- two redundant transponders providing a coherent two-way X-band uplink/X-band downlink (X/X) radio link,
- two redundant Traveling Wave-Tube Amplifiers which amplify the X-band downlink radio signal generated by the transponder,
- one High-Gain Antenna (HGA) which receives and transmits the radio signals.

These components are connected with each other via waveguides and switches, which are usually incorporated in a Radio Frequency Distribution Unit. Only one single string of waveguides connecting any antenna with any transponder is active.

A hydrogen maser in the ground station is used as the frequency standard for generation/reception of the uplink/downlink signal. A transponder system working in the X/X band would also be used for spacecraft operations and communications.

4.5.2 Interfaces and resource requirements

The experiment team provides no additional hardware. The on-board radio subsystem as described above shall be used for the operations. The current scenario for the radio science phase is ~ 25 days, with 20 days dedicated to a gravity campaign and 5 days for Bistatic Radar investigations. The gravity campaign shall be performed as close as possible to the asteroid. The current scenario foresees a distance of 1 km. Radio science analysis showed that the level of uncertainty that can be reached after 20 days for the mass is ~1 %. The near-spherical shape and size of the target NEA 2008 EV5 reduces the magnitude of the second order gravity coefficients C_{20} and C_{22} and consequently their gravitational attraction. However, any deviation from the values of C_{20} and C_{22} assuming constant density provides information about the internal structure, i.e. it enables distinction between a layered structure and an inhomogeneous density distribution.

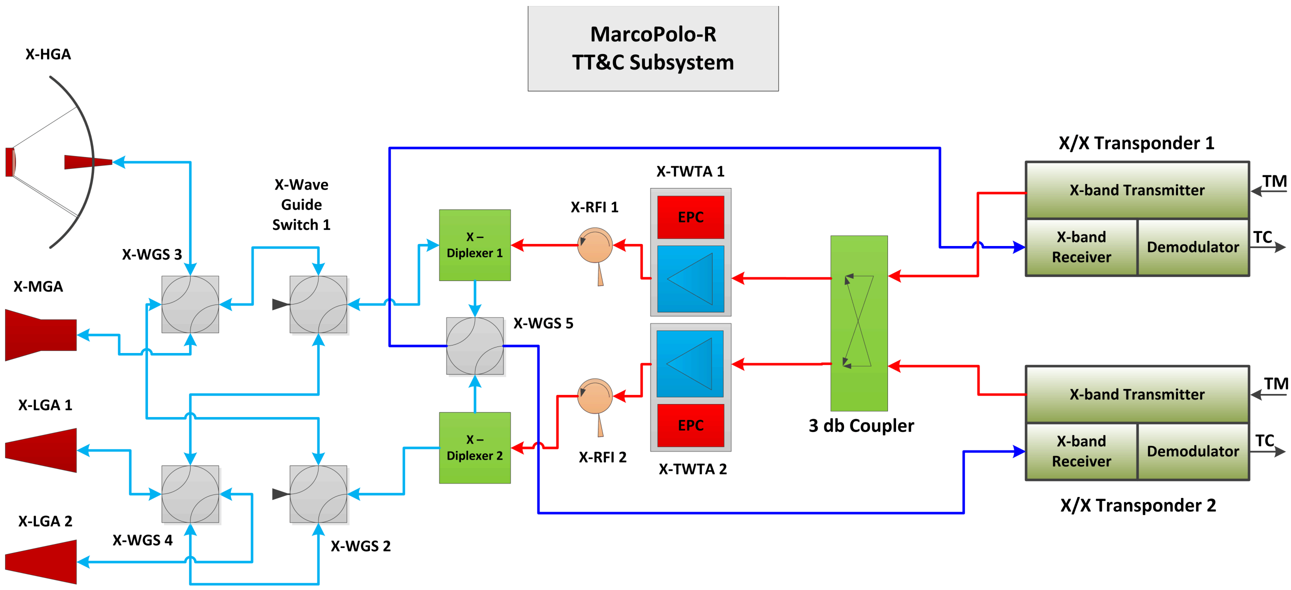


***Figure 4.9**: Design of the TT&C subsystem (X/X band link) onboard MarcoPolo-R which can be used for RSE in its basic configuration.*

4.5.3 Operation requirements

The Radio Science technique enables the estimation of the gravity field of a planet, a moon or a small body like a comet or an asteroid by measuring the gravity induced Doppler shift of the radio carrier frequency (Andert et al. 2010; Pätzold et al. 2011). From Doppler shifts, it is even possible to detect variations in mass distribution within the body. During gravity measurements the RF carrier frequency shifts due to relative motion between spacecraft and ground station on Earth (Doppler), the relative velocity of spacecraft, and the propagation time of coded (Ranging) signal are recorded. In order to perform measurements with the necessary accuracy the following operational requirements apply:

- The HGA shall be pointed towards the Earth during RSE gravity operations.
- The Orbiter shall not perform AOCS operations during at least four consecutive RSE operation windows. This can be realized by stable orbits (Pätzold 2006; Hussmann 2012).
- Radio Science gravity measurement shall be supported by Delta Differential One-Way Ranging (ΔDOR) measurements (James et al. 2009).
- RSE gravity observations shall not be performed at or near superior solar conjunction (defined by radio science as within an elongation angle of +/-10°). The observations shall be done provided the Sun-Earth-spacecraft angle is larger than 30°.

The scientific objectives of Bistatic Radar investigation are the determination of the dielectric constant and roughness of the asteroid surface from scattering and polarisation studies of Bistatic Radar echoes reflected off the asteroid and received on Earth. These measurements provide valuable clues about the composition and physical structure of the asteroid.

The circular polarised one-way downlink carrier signal from the spacecraft, impinging on the asteroid at the angle of incidence γ, is transformed into a linearly polarised signal when specularly reflected from the asteroid surface at the Brewster angle $\gamma = \gamma_B$ (Simpson 1993). The total power contained in the Bistatic Radar echoes will be recorded for an estimate of the radio reflectivity of the asteroid surface, a quantity directly related to the roughness of the surface on scales of the radio wavelength. The dielectric constant ε of the asteroid surface can be inferred from determinations of the Brewster angle. Operational requirements for BSR measurements are:

- The HGA shall be pointed towards the asteroid during RSE bistatic radar operations.
- A 70 m ground station capable of reception of right circular polarised and left circular polarised radio signals is necessary for bistatic Radar measurements in the open-loop receiver mode.

4.5.4 Heritage

The RSE instrument serves as basic TT&C subsystem on board Mars Express, Rosetta and Venus Express and can be considered as an extremely reliable instrument with a very high TRL.

4.6 VISTA2

The VISTA2 sensor was proposed among a suite of environmental sensors of the VESPA package for *in situ* measurements in response to the ESA AO for scientific payloads for M3 mission candidates. The VISTA2 device was selected as part of the payload of the MarcoPolo-R by the ESA-Science Programme Committee.

Its scientific goals are the following:

- *Measure the volatile content (water and organics) in the asteroid regolith*
- *Support the sampling procedure by measuring the regolith dust raised at touchdown*

VISTA2 is the only instrument of the MarcoPolo-R payload that performs in-situ measurements, allowing a pre-characterisation of the sample.

4.6.1 Instrument Description

VISTA2 is a new concept device that allows for collecting regolith and measuring its volatile content by heating. VISTA2 has two sensor heads, each consisting of a heated $GaPO_4$ crystal microbalance and proximity electronics (PE). The crystal includes a built-in heater and a built-in temperature sensor (Figure 4.10) placed on opposite faces of the microbalance. Each sensor head has its own proximity electronics (PE) that is connected with a nine-wire shielded cable to the Main Electronic Unit (MEU) shared with the MaNAC instrument.

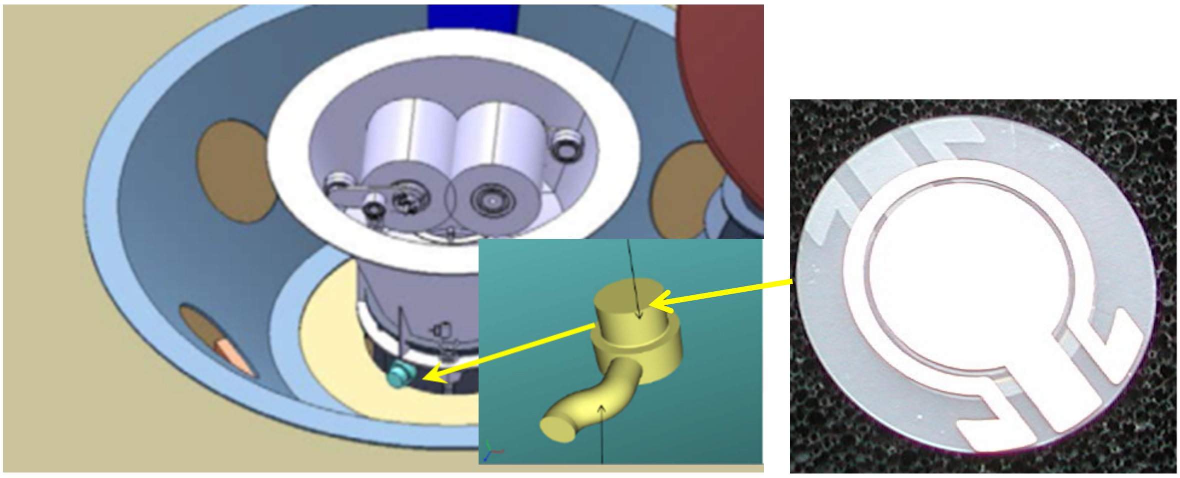


Figure 4.10: *Left: Location of the VISTA2 sensor mounting (insert) on the brush-wheel sampling tool viewed from below. Right: Photo of the $GaPO_4$ crystal located on top of the sensor mounting (IMM-CNR).*

The $GaPO_4$ crystal has a 14 mm diameter, a 2 mm thickness and a resonance frequency of 5.8 MHz. The measurable mass range goes from 1.6 ng to 10 μg, whereas the accuracy for volatile content measurement is 100 ppm. The instrument FOV is 70°.

Each VISTA2 measurement consists of a frequency and temperature acquisition. The deposited mass is linearly linked to the frequency (Sauerbrey 1959).

VISTA2 will be able to detect the regolith dust raised by the sampling procedure. Once the dust particles have been collected, high-temperature thermogravimetric measurements will be performed. In particular, it should reach temperatures of 320-420 K to allow the physically adsorbed water to desorb, whereas at 470-570 K decomposition of organics should occur and at higher temperatures desorption of surface-bound water and decomposition of carbonates are expected (Grady et al. 2002; Sephton 2002; Halbout et al. 1986, Bruckenthal & Singer 1987).

4.6.2 Interfaces and resource requirements

Table 4.6: *VISTA2 resources*

Characteristic	Value
Overall dimensions	**7 cm^3**
Mass	
Sensor head	40 g
Total (sensor head +2 harnesses +1MEU)	900 g
Power	
Accumulation/Calibration mode	120 mW
Heating mode average	470 mW
Heating mode peak	920 mW
Data volume	
Data rate	30 bit/s
Total data volume	200 kbit
Temperature range	
Non operating	-190 °C to +100 °C
Operating	-190 °C to +100 °C

In order to reach the scientific goals described above, the two sensor heads should be placed near the sampling device, possibly with the FOV of each sensor oriented differently.

4.6.3 Operation requirements

VISTA2 can work in the following operational modes:

Calibration mode. Sensor frequency and temperature are measured during the flight to test the microbalance's stability.

Accumulation mode. This consists of passive collection of dust on the microbalance. It will operate during and after the sampling to retrieve the amount of dust raised.

Heating mode. Microbalance warming, up to the water and organics desorption temperature. This operational mode will follow the accumulation mode.

During the accumulation mode, the microbalance FOV should include the sampling area. No specific pointing direction for calibration and heating modes is requested.

4.6.4 Heritage

VISTA2 is based on the heritage of GIADA-Rosetta. Other space experiments were based on microbalances such as IECM-STS2, PIC-PRCS, MBA-SMART1, SAMMES, MSX. In addition, the VISTA2 sensor has been studied for the Cosmic Vision mission studies Marco Polo and the Penetrator Consortium for EJSM (Gowen et al. 2010). The sensor was proposed for the instrument DREAMS-ExoMars 2016 (Palomba et al. 2011).

5 Mission design

This chapter describes the overall MarcoPolo-R mission profile and the design of the space segment, resulting from the system phase A and the dedicated technology development activities. Two design options, Astrium Ltd. (design A) and Thales Alenia Space Italy (design B), are presented. Cost-optimization has been a key design driver throughout the phase A. The design builds on a comprehensive set of engineering and programmatic requirements, described in the Mission and System Requirements Document (ESA MP-R Study Team 2013) deriving from the primary mission objectives. The mission design presented in this chapter is entirely relying on European capabilities, which have reached the necessary level of maturity over recent years.

5.1 Baseline Mission Architecture

5.1.1 Overview

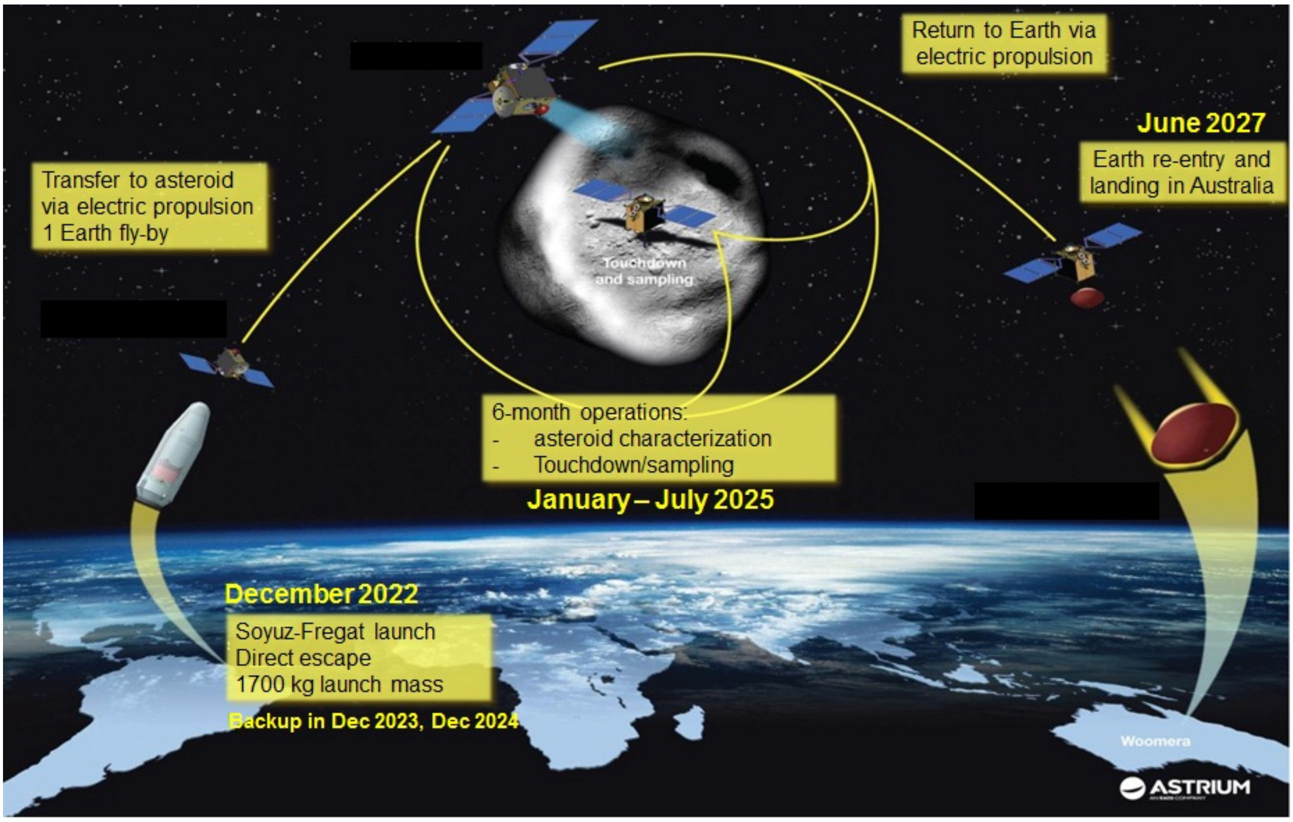


Figure 5.1: *Overall mission scenario (modified from original image by Astrium Ltd.).*

The baseline mission is launched by Soyuz-Fregat 2-1b from Kourou on a direct escape outbound trajectory to 2008 EV5 in December 2022 with backup launch dates in December 2023 and December 2024 (Figure 5.1). The spacecraft then uses a space-proven electric propulsion system for transfer and rendezvous with the NEA in January 2025, after an Earth swing-by one year earlier. The spacecraft remains within proximity of the asteroid for 180 days. During these proximity operations, the NEA is fully characterised thanks to the suite of instruments and navigation sensors on-board the spacecraft, which allows selection of safe and scientifically valuable sampling site candidates. Then, a number of sampling rehearsals are performed, down to about 250 m altitude, in order to try out the procedures, key spacecraft systems and software during descent to the asteroid surface, and verify the system performances and robustness. These rehearsals also allow full preparation of the ground operational teams. Finally, the spacecraft carries out a so-called “touch and go” sampling operation on the asteroid surface. Three sampling attempts are foreseen in total to mitigate the risk of encountering a very harsh, and unexpected, surface. After verification that a sample has been collected, the spacecraft departs from the asteroid and returns to Earth in June 2027. It releases the re-entry capsule which enters the atmosphere at a speed of ~12 $km \cdot s^{-1}$ and lands at the Woomera test range (Australia) which is well prepared for such operations, as already demonstrated by Hayabusa. Table 5.1 summarises the main mission analysis features for all 3 main launch opportunities. No special measures need to be taken from a Planetary Protection point of view for the return leg, as the mission falls within the COSPAR Planetary Protection Category "V - unrestricted sample return".

Table 5.1: *Main mission analysis key parameters.*

Mission	Baseline	Back-Up	
	2022	**2023**	**2024**
Launch date	12 Dec 22	14 Dec 23	19 Dec 24
Asteroid arrival	28 Jan 25	20 Nov 25	11 Oct 27
Stay duration [days]	180	180	180
Earth return	24 Jun 27	24 Jun 28	25 Jun 31
Total mission duration [years]	4.5	4.5	6.5
Launch parameters			
Escape velocity [km s^{-1}]	2.369	2.643	2.778
Escape declination [°]	0	0	0
Launch mass capacity [kg]	1761	1681	1646
Earth return			
Arrival velocity [km s^{-1}] [prograde]	11.8	11.8	12.1
Delta V			
"Electric" Delta-v [km s^{-1}]	3.67	3.85	3.95
Thrust-on time [hours]	19170	19195	18875
Distances [AU]			
Min. to Sun	0.88	0.85	0.85
Max. to Sun	1.12	1.16	1.2
Max. to Earth	0.73	1.1	1.66

The selection of the propulsion system for an interplanetary mission fundamentally drives the mission design and is non-dissociable from the mission analysis aspects. Following an extensive and iterative trade-off involving both industrial consortia and ESOC, electric propulsion has been selected over chemical propulsion for this mission because it leads to a very efficient mission scenario. The whole transfer propulsion system is based on the use of the flight-proven SNECMA plasma thruster PPS1350G (Figures 5.2 – 5.3) which has been retained as baseline for both design options and is an ideal thruster for small interplanetary missions. Three engine heads are implemented to cover the mission requirements and cope with the thruster qualification limits. In design option B, four units are foreseen due to an alternative redundancy concept. In its current configuration, this thruster propelled the ESA spacecraft Smart-1 to the Moon in 2003 and is being used again on-board the ESA AlphaBus telecommunication satellite launched in summer 2013, performing nominally. The resulting 15 m^2 of solar arrays do not put any particular constraints on the asteroid sampling operations as demonstrated by analysis and discussed in Section 5.1.3.

Figure 5.2: *PPS1350G*

Table 5.2: *PPS1350G Main Characteristics at 1 AU*

Parameter	Value	Unit
Power required	1500	W
Thrust	90	mN
Specific impulse	1660	s
Total impulse delivered	3.4×10^6	N s
Maximum firing time	10530	h

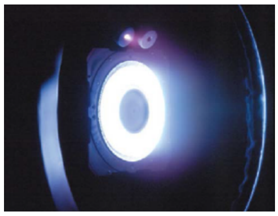


Figure 5.3: *PPS 1350G tests*

Due to the various manoeuvre requirements around the asteroid (see Section 5.1.2 and 5.1.3), a separate chemical propulsion system is necessary, but due to the very low delta-V and the simplicity of the required operations, a simple and cost-efficient mono-propellant system is baselined, which also limits contamination on the asteroid surface during sampling. The scientific instruments, featuring a total mass of 33 kg including margins, are particularly simple for this mission and are described in Section 4.

5.1.2 Proximity operations

The NEA observation and surface sampling phases, together referred to as the "Asteroid proximity operation phase" lasts 180 days. During this period, starting roughly at about 500 km from the asteroid, various key sub-phases have been defined. They are based on the NEA characteristics, orbital analysis and required instrument and spacecraft characteristics and operations. 2008 EV5 is a small asteroid, of about 400 m diameter, and it is a single body, which poses no particular thermal or power constraints onto the spacecraft thanks to its almost constant distance to the Sun of 1 AU. This allows simple proximity operations. The characterisation phases can be achieved in a very quick manner and the resulting data volume of around 120 GB is quite low for a planetary mission, allowing use of a low-cost, fixed, HGA.

Table 5.3*: MarcoPolo-R proximity key operation phases definitions.*

Sub-Phase name	Orbit/Location	Main Event
Far Global Characterisation (FGCP)	Far "formation-flying" (10 km distance to the asteroid surface)	▪ Initial mapping and determination of physical properties ▪ 5 days
Global characterisation (GCP)	5km	▪ Global mapping of the asteroid at medium spatial resolution ▪ Communication to Earth via fixed HGA ~ 8 hours/day ▪ 25 days
Radio Science (RSP)	1 to 2 km	▪ Gravity field campaign on a radio science, manoeuvre-free orbit ▪ 25 days
Local characterisation (LCP)	250 m	▪ Local mapping of 5 selected sampling sites at high spatial resolution ▪ 15 days, ~ 3 days/site
Sampling/descent rehearsals	Descent phase down to 250 m	▪ Sampling attempt down to at least 250 m ▪ Up to validation of critical events/GNC software, except sampling ▪ 10 days
Descent and sampling, SAM	Descent and surface	▪ Autonomous descent, touchdown and sampling (+ re-ascent) ▪ 21 days, ~ 3 attempts, 7 days allocation/attempt
Post-sampling LCP	250 m distance to the asteroid surface	▪ Local mapping of the site which has been sampled ▪ 3 days
Margins	Same as GCP	▪ Transfer of the collected sample to ERC + extended GCP ▪ Preparation for return phase ▪ 24 days

The Far Global Characterisation Phase (FGCP) basically consists of keeping the spacecraft at a fixed position between the asteroid and the Sun at 10 km from the surface. Meanwhile, 2008 EV5 rotates beneath in 3.5 hours, allowing the instruments, sized accordingly, to map the entire surface in a very short time. The same principle is used for the Global Characterisation Phase (GCP) but at 5 km from the asteroid due to the higher resolution mapping requirements. Also, this is done at 3 defined latitudes and longitudes so as to guarantee full asteroid coverage and get images in different illumination conditions. In order to map the gravity field of the body very accurately, the radio science experiment is performed from a manoeuvre-free terminator orbit at 1 to 2 km distance from the asteroid surface. During Local Characterisation Phase (LCP), the spacecraft hovers at a safe 250 m altitude above the candidate sampling site and slowly slews for a few minutes to scan across the 50 m x 50 m area. The various phases are illustrated in Figure 5.4. The sampling operations are described in the next section.

Altogether, the key sub-phases including descent, touchdown and sampling strategy phase defined in Table 5.3, last 103 days, with 24 days of margin. The remaining 77 days account for transfers between the various sub-phases, as for example the arrival from around 500 km up to the FGCP at 10 km distance. In case of major issue, preventing departure from the asteroid on the foreseen date, it has been assessed that the spacecraft could stay at least 120 days more at the cost of a one-year longer return transfer.

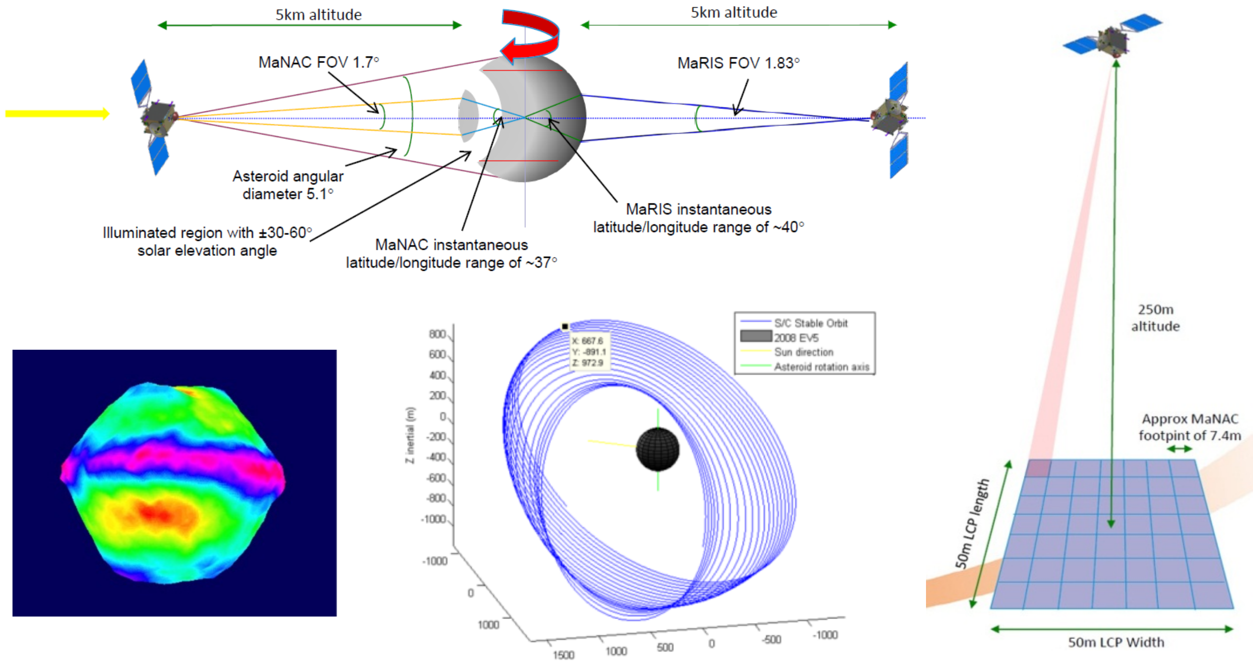


Figure 5.4: *Observation strategy during the GCP (top-left), LCP (right), RSP (bottom-centre). Simulation of 2008 EV5 as seen by MaNAC during GCP (bottom-left).*

5.1.3 Descent, touchdown and sampling strategy

The asteroid descent and sampling operation is of course the operational centrepiece of MarcoPolo-R and it has to be designed carefully to ensure the mission success. The following parameters are some of the key drivers for designing this phase:

- Soil properties,
- Touchdown accuracy (in position and vertical/horisontal speed),
- Illumination constraints of the sampling site (e.g. for enabling optical navigation techniques),
- Level of spacecraft autonomy,
- Communication constraints with Earth (e.g. turn-around times, downlink capacity, Earth visibility).

Some of these parameters are based on scientific best knowledge, such as the soil properties. Other parameters result from a global system-level trade-off such as the level of autonomy or the touchdown accuracy, taking into account the asteroid environment, mission cost, risk, technological progress achieved and lessons learnt from previous missions such as Hayabusa or from the previous Marco Polo study. In the latter, the approach consisted of a full landing. This led to strong constraints on the Guidance, Navigation and Control (GNC) system and sampling operations, requiring a fully autonomous spacecraft and advanced on-board image processing.

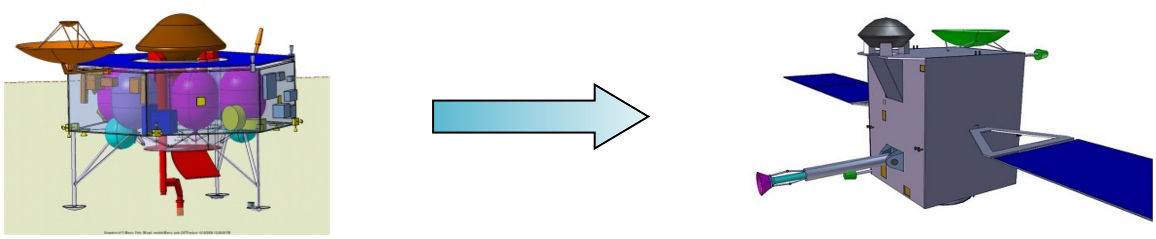


Figure 5.5: *From Marco Polo to MarcoPolo-R, a cost-optimization case (CDF study designs)*

A simpler and more cost-efficient approach has been selected for MarcoPolo-R (see Figure 5.5), based on a short touch and go operation of maximum 5 seconds. This allows removal of the landing system and enables a major relaxation of the required touchdown accuracy as the main spacecraft body stays away from the surface. The result is also a large simplification of the GNC system, involving much less image processing. The key navigation strategy is now essentially based on a hybrid ground-based and autonomous optical terrain-relative navigation, which is a mature technology in Europe. The latter is based on the comparison of two images taken by a simple but robust on-board navigation camera to derive the spacecraft terrain-relative velocities. In fact, only a few surface features are extracted from each image and compared, leading to very simple image algorithms. The altitude is directly provided by an on-board altimeter. Overall, this yields a substantial mission cost reduction. The overall descent and sampling strategy is shown in Figure 5.6.

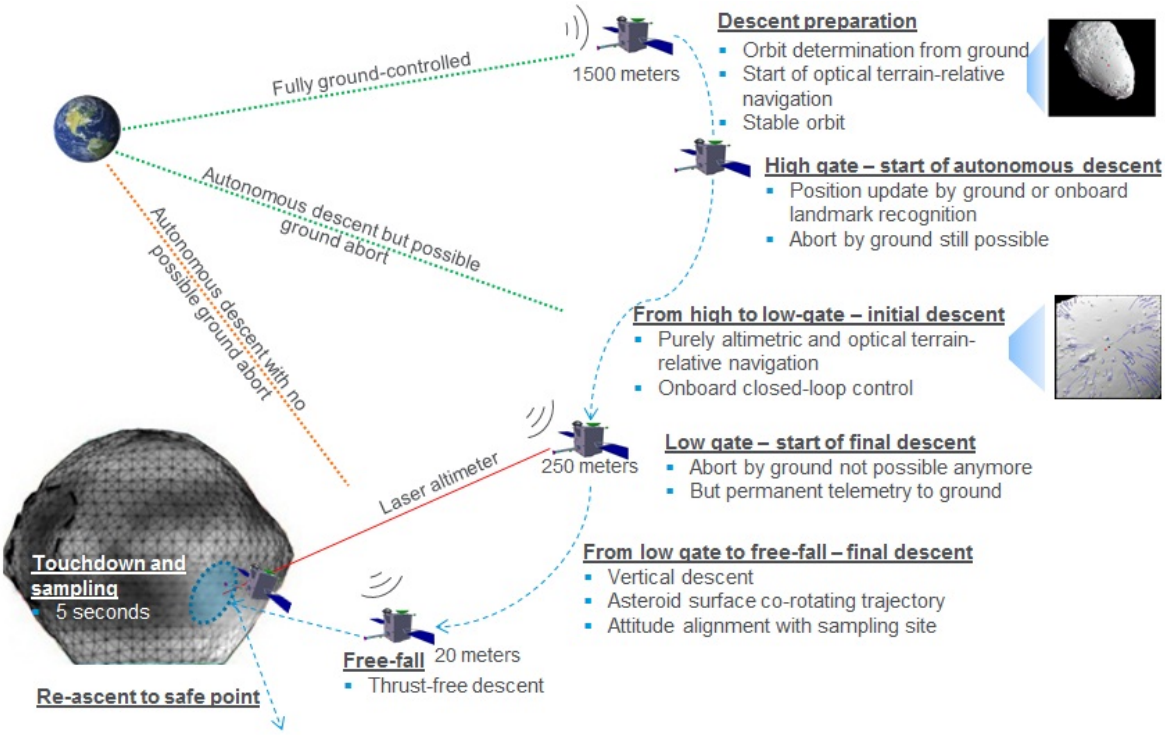


Figure 5.6: *MarcoPolo-R asteroid descent and sampling sequence (altitudes and exact procedures vary depending on the design option)*

The above approach delivers the spacecraft to the surface of the asteroid within 25 m of its target position at about 10 cm s^{-1} vertical velocity with the goal of cancelling any residual horisontal velocity and with an attitude of maximum 10 degrees with respect to the local terrain. This performance was verified via dedicated GNC analyses and is under test on a dedicated hardware and processor-in-the-loop test bench. A particularly robust collision avoidance strategy is put in place defining a safe “velocity and altitude corridor” during descent. The last 15 to 20 m of the descent are thrust-free in order to limit contamination of the surface by propellant and thus the spacecraft is in free-fall. The dynamics of the touchdown manoeuvre is quite similar to a rendezvous and docking but much less complex from a system viewpoint. These conditions enable design of a simple touch and go mechanism.

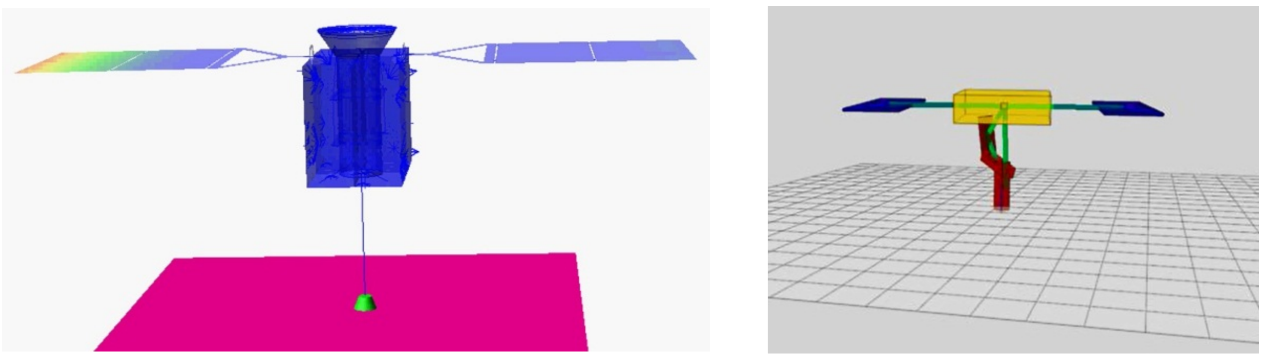


Figure 5.7: *Touchdown simulations, option A (left) and B (right)*

As can be seen in Figure 5.7, the touch and go operation has been simulated by both industrial primes for their respective designs. Performances were validated via preliminary Monte Carlo simulations. They show that the spacecraft is very safe at touchdown and its solar panels remain far away from the surface at all times. The loads applied to the spacecraft, in particular onto the solar array mechanisms, are benign.

The sampling tool subsequently collects a sample within 5 seconds in a very robust manner, after which the thrusters are automatically switched on in order to re-ascend on a non-colliding trajectory and up to a safe and stable point.

The two sampling tool options, a brush-wheel mechanism on one hand, a grab-bucket mechanism on the other hand, were selected following an extensive early test campaign of various prototypes as well as numerical modelling of zero-gravity sampling. Their design is described in the relevant chapters below. The sample is collected directly into the sample container. The container is in turn efficiently transferred to the re-entry capsule through the touch and go mechanism thus also incorporating the sample transfer function. A simple sealing, based on a Viton ring for instance, is then applied to the sample container inside the re-entry capsule either by the transfer arm or by a dedicated system. A special device will verify whether a sample has been acquired.

5.1.4 Earth re-entry and capsule recovery

A direct Earth prograde re-entry with a landing in the Woomera Test Range (Australia) at dawn at around 7 am on 24 June 2027 is baselined. The Earth Re-entry Capsule (ERC) is fully passive. It will decelerate from 12 km s^{-1} (typical re-entry speed for a sample return mission) down to 45 m s^{-1} in 500 s. It is solely decelerated by the heat shield and an impact absorbing material limiting shocks on the sample container. Properties of existing absorbing materials integrated into capsule impact numerical analysis demonstrate the feasibility of this approach as it results in a maximum mechanical load on the sample of 800 g and temperature of 40 ^{o}C, therefore entirely preserving its science value. The stability of the capsule is ensured by adequate design and balancing, and has been verified by tests (Figure 5.8). It ensures an oscillation throughout transonic and subsonic flight below 20^{o}. Its shape is similar to that of the Hayabusa capsule, with a 45^{o} half-cone angle. The heat shield material required for this mission has undergone extensive testing and is now available in Europe.

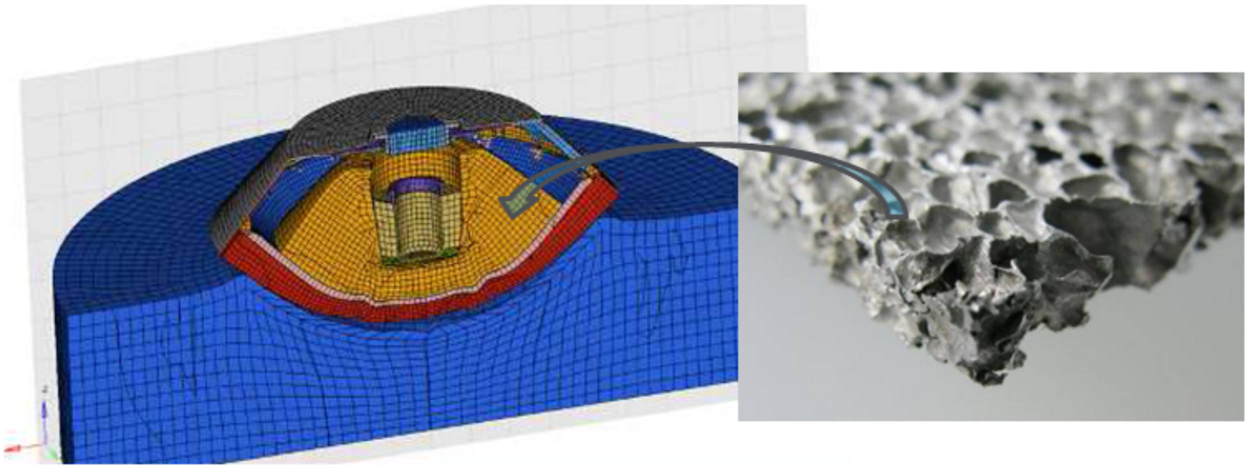


Figure 5.8: *Re-entry capsule numerical impact analysis (left), sample of impact absorbing material (right).*

The capsule design leads to a substantial cost reduction as the capsule basically consists of the heat shield, the main structure, the impact absorbing material and the sample container with no mechanisms or active devices. In the absence of an on-board tracking beacon, the emphasis must be put on the ground recovery system described in Figure 5.9 in order to pinpoint very precisely (a few km) the ERC impact location. It relies on the ground radars existing at the Woomera test range, standard pre-entry navigation campaign and airborne optical and IR observations, as already done for the Hayabusa (and the ESA-ATV) re-entry campaign. Seismic measurements can also be used. This will allow recovering the capsule within 2 hours after touchdown to enable its transfer to the curation facility back in Europe. Since the re-entry takes place at dawn the re-entry blast and thus the capsule trajectory will be very visible from aircraft.

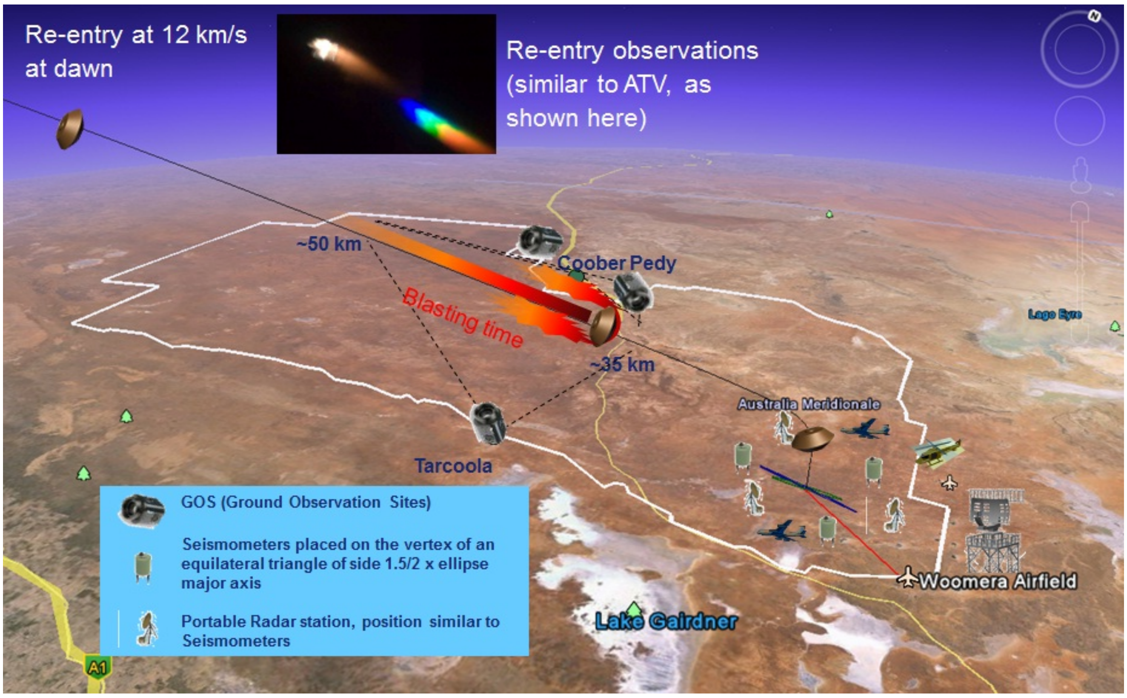


Figure 5.9: *ERC re-entry and recovery strategy.*

5.2 Baseline Mission Options

5.2.1 Astrium Ltd. mission design - Option A

5.2.1.1 Spacecraft overview

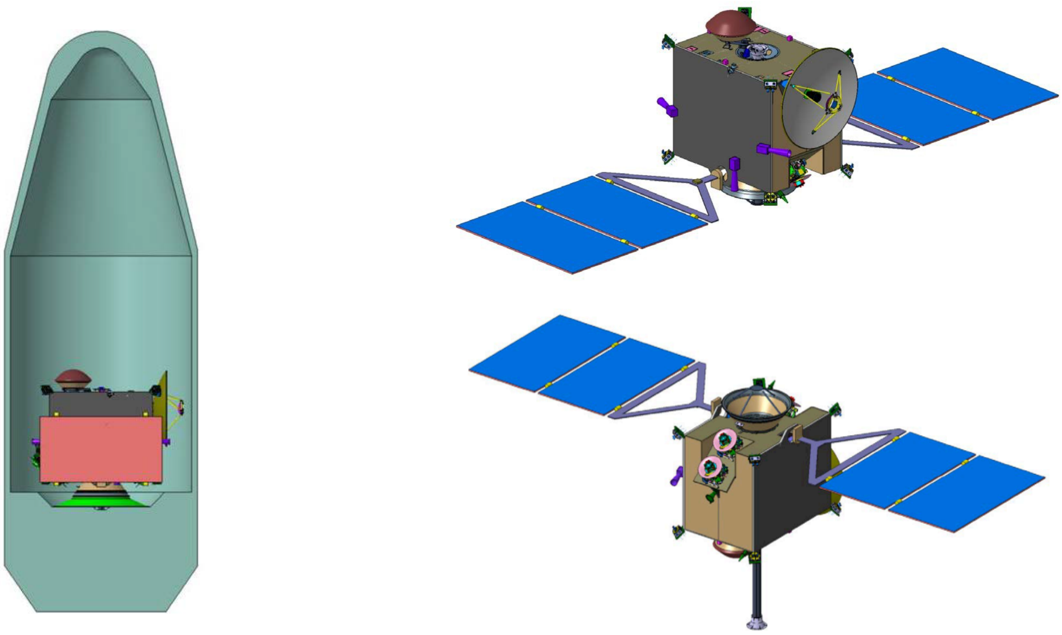


Figure 5.10: *Option A – Spacecraft in launcher fairing (left), during cruise (top-right), in touchdown configuration (bottom-right)*

The option A configuration, as shown on Figure 5.10, is based on the reuse of the platform of Solar Orbiter. Of rectangular shape and of 2.2 m maximum length, it is composed of a central cylinder and shear panels (composing the primary structure) in addition to the (non-load bearing) external panels. All hardware is mounted directly on the lateral and top panels with the exception of the propellant tanks that are directly mounted to the central cylinder. It is to be noted that the 3 electric thrusters and each of their pointing mechanisms are mounted on 2 tilted additional panels on the bottom side of the structure (note that this represents the single largest difference with respect to the original Solar Orbiter structure). The Aeolus platform was looked at, but barely compliant in terms of accommodation. The touch and go and sampling systems are mounted within the central cylinder for easy transfer to the re-entry capsule fixed on the top panel. The spacecraft has a 9-thruster mono-propellant redundant configuration to support all proximity phases, including re-ascent after touchdown. Figure 5.11 highlights some of the spacecraft's main components, including instrument units, and their location, all comfortably accommodated. Thanks to this and the re-use of the Solar Orbiter structure there is very little risk of mass increase.

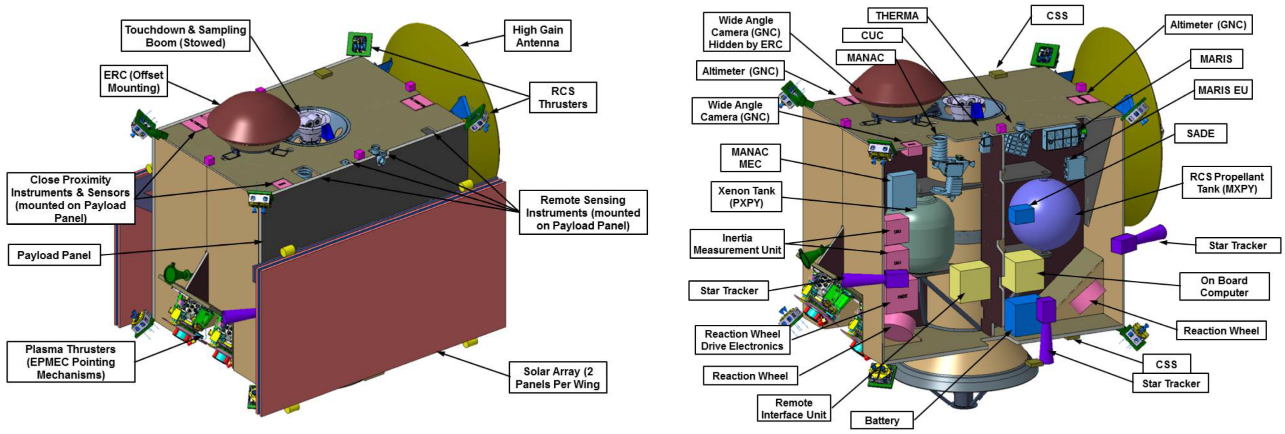


Figure 5.11: *MP-R Option A - Overview*

The power system is based on a dual power bus architecture employing an unregulated 50 V power bus to support the power demand of the electrical propulsion sub-system and a second, fully regulated 28 V bus to support the remaining platform equipment and payloads. The regulated power bus is supported by a lithium-ion battery module especially used towards the end of the descent to the asteroid. The solar array assembly is derived from Sentinel 2, with two 7.8 m^2 wings in two panels each to provide the required worst-case power of 3 kW at 1 AU. The thermal control concept is standard and radiators can easily be accommodated. Heat loop pipes are required due to the high dissipation of the Power Processing Unit (PPU) of the electric propulsion system. The data handling system comprises an on-board computer and a Remote Interface Unit (RIU). The on-board computer is based on Solar Orbiter re-use, and has two redundant LEON2 processers running the central software in hot redundant reconfiguration modules while the RIU derives from Sentinel 5. A mass memory unit of 80 Gbit is incorporated into the on-board computer, which is compatible with the mission needs. 1553 buses are used for all data links, except for the payload that uses Spacewire.

Due to the low data volume and distances to Earth, the communication system makes use of low-cost recurrent equipment, comprising the following antenna:

- 1.6 m High-Gain Antenna (HGA), re-use of Mars Express, for nominal downlink (150 kbps) and RSE.
- Medium-Gain Antenna (MGA), re-use of LISA Pathfinder, for safe mode recovery.
- 2 Low-Gain Antennas (LGA), re-use of Sentinel 5P, for communications during descent.

All antennas are fixed for cost-saving purposes, meaning the spacecraft must point towards the Earth to use the HGA and MGA. The LGA gives full coverage but much reduced data rates. A flexible communication strategy is proposed for MarcoPolo-R, particularly during the cruise period, with antenna selection dependent on the Earth range and the electric propulsion operation. During proximity operations, the communication system will utilise daily 8 hour downlink windows to downlink all the science and telemetry data acquired through the remainder of the day. During descent and touchdown, permanent telemetry link will be ensured via the LGA using an MFSK (Multiple Frequency-Shift Keying) modulation system. The descent requires the navigation camera to be pointed at the asteroid, so that the HGA cannot be pointed to Earth at the same time. MFSK tones, used on Mars missions for entry, descent, and landing, allow basic key information or events (e.g. altitude, touchdown) to be communicated back to Earth without any complicated re-pointing during the critical descent. It is a simple and robust strategy that fulfils the Beagle 2 recommendations concerning communications during critical events.

5.2.1.2 Sample return key capability: Descent & Proximity AOCS/GNC

In this design option, the sampling operation starts from a stable orbit at around 2 km altitude. The spacecraft performs a direct fully autonomous descent of about 40 minutes down to the surface, with no intermediate hovering (Fig. 5.12). The absolute position with respect to the asteroid surface is provided by the ground before descent, but to limit the drift induced by the communication times it is assisted by the on-board optical terrain-relative navigation. During descent, only the latter is used in closed-loop while permanent link to ground is provided via MFSK, yielding a low risk, low cost solution. After extensive analyses, the touchdown accuracy has been estimated to be better than 15 m.

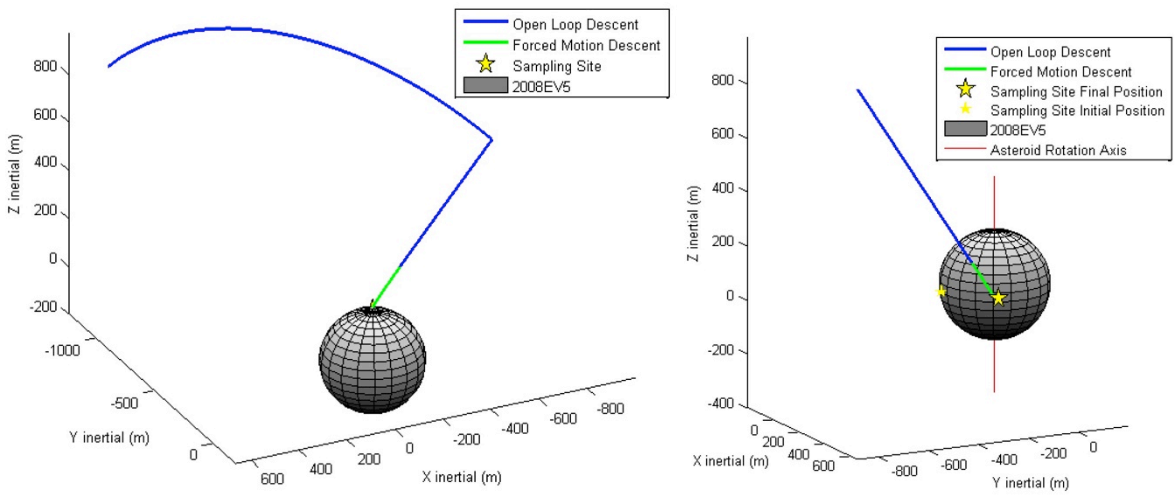


Figure 5.12: *Option A GNC approach Examples (left: polar sampling, right: equatorial sampling)*

A low-cost AOCS hardware is sufficient to fulfil the mission needs, e.g. reaction wheels, sun sensors, inertial measurement units, 9 redundant 20 N mono-propellant thrusters, star trackers. The optical terrain-relative navigation sensor is a simple camera (APS sensor, 30^{o} field of view). The core of the GNC system is the image processing algorithm and Astrium's navigation filter (UFS3), already developed and integrated in the simulations. A redundant altimeter, providing simple altitude information, is baselined. It can be either a laser or radar, but the laser option leads to better touchdown performance.

5.2.1.3 Sample return key capability: Sample Acquisition, Transfer and Containment System (SATCS)

The "brush-wheel" sampling mechanism selected in this design is shown on Figure 5.13. It uses 2 counter-rotating brushes that collect and sweep the sample material inside the container. If one brush fails, the other one was proven by tests to still be able to collect large amounts of material. It is mounted at the end of the touch and go and transfer arm. This boom has a single translation degree of freedom and is deployed into its touchdown configuration before descent. It is equipped with well-proven Eddy current damping motors for limiting the loads on the spacecraft during touchdown. It can be moved up and down as required for deploying the sampling tool and transferring the sample into the re-entry capsule.

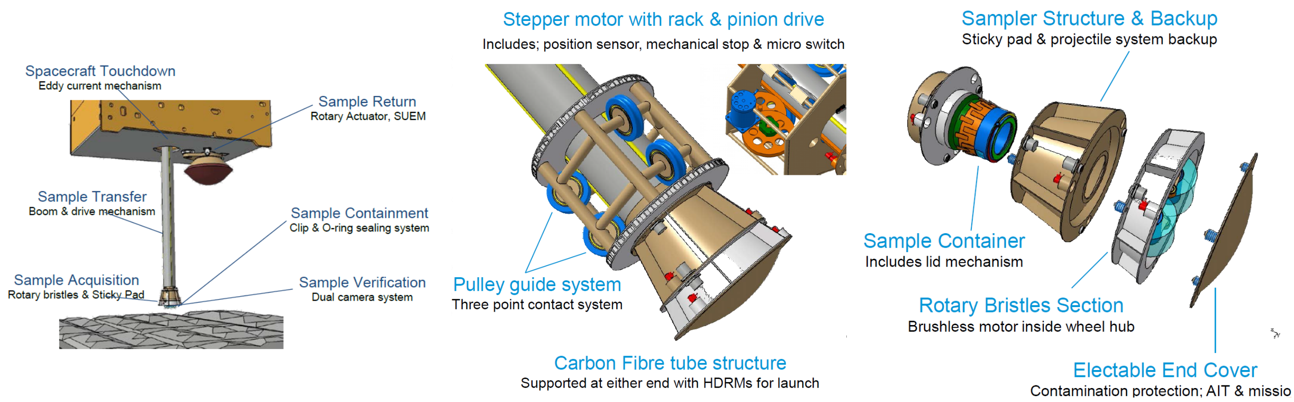


Figure 5.13: *Option A - SATCS*

In order to verify that samples have been captured during the attempt, the design incorporates a micro-camera and associated LED lighting observing directly inside the sample container. Obviously, all mechanisms are sized so as to be reversible to enable 3 sampling attempts. Eventually the capsule rotates sideways on the top panel in order to receive the sample container from the boom. Should the sampling system fail, the design accounts for a backup system based on a sticky pad that would allow capture of dust and debris. This system is part of the sample container and is revealed by simply ejecting the sampling tool and contacting the tip of the container with the surface.

5.2.1.4 Sample return key capability: Earth Re-entry Capsule (ERC)

The design of the ERC in option A is presented in Figure 5.14. As indicated earlier, it is fully passive, so very robust. With a mass of 45 kg, it has a diameter of 880 mm and a half cone angle of 45°. Its stability is ensured by design and shape of the front and backshell and appropriate balancing. The front heat shield is made of ASTERM, the European ablative material developed for sample return mission. The back shield uses conventional Norcoat Liege. As for the energy absorption during impact, it is based on the use of two materials: Al foam in the front section and PU Foam in the back (note that this has been sized for the worst-case surface impact angle of 20°). A decoupling of the sample container from the back shell by using mechanical fuses has been implemented in order to insure the free path of the sample container into the crushable material as soon as the impact deceleration exceeds 100 g.

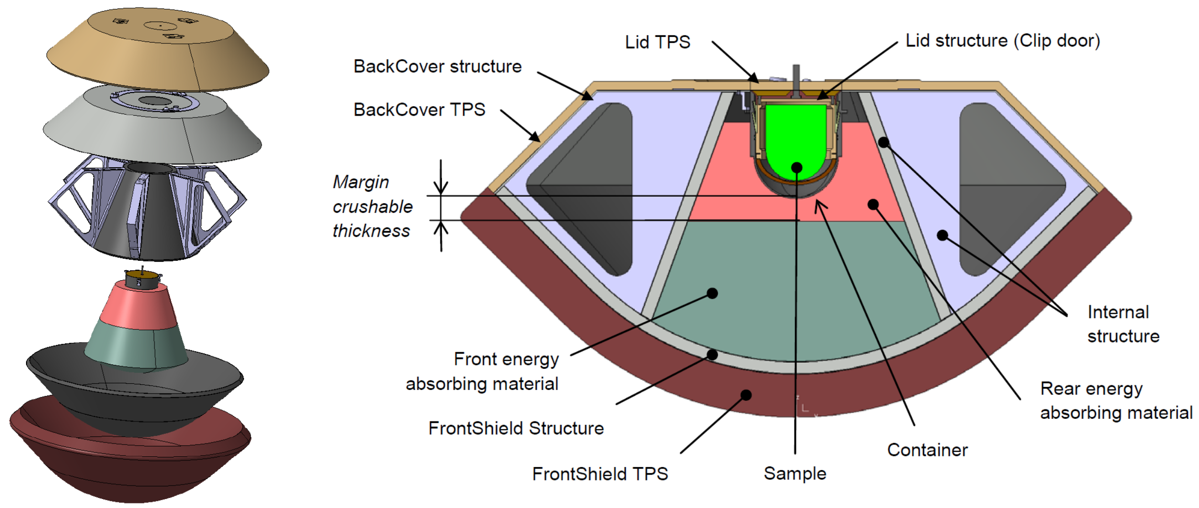


Figure 5.14: *Option A - design of the ERC.*

5.2.2 Thales Alenia Space mission design - Option B

5.2.2.1 Spacecraft overview

Based on the reuse of the structure of the service module of the ESA Herschel/Plank/Euclid octagonal structure, but scaled down to 3 m diameter, the configuration of option B (Figure 5.15) is arranged around a central cone with shear walls structure (primary structure). The Proteus platform was looked at, but barely compliant in terms of accommodation. The propulsion tanks are mounted directly around the central structure and all remaining hardware are attached to the 8 lateral and top panels (secondary structure).

For the simplification of the integration and test, this option allocates specific and dedicated panels to the spacecraft subsystems (telecommunications, GNC, Power, Electrical Propulsion and Payload). The only shared panel is common to the SATCS, one of the payload (CUC) and the data handling system. Both HGA and MGA are accommodated on the top panel together with the Star trackers. As for the ERC, it is directly attached to the upper section of the central structure making its back shell accessible through the central cone for sample container insertion via the transfer boom, also used as touch and go system. The spacecraft has an 8-thruster mono-propellant redundant configuration. Figure 5.16 highlights some of the spacecraft's main components, including instrument units, and their location.

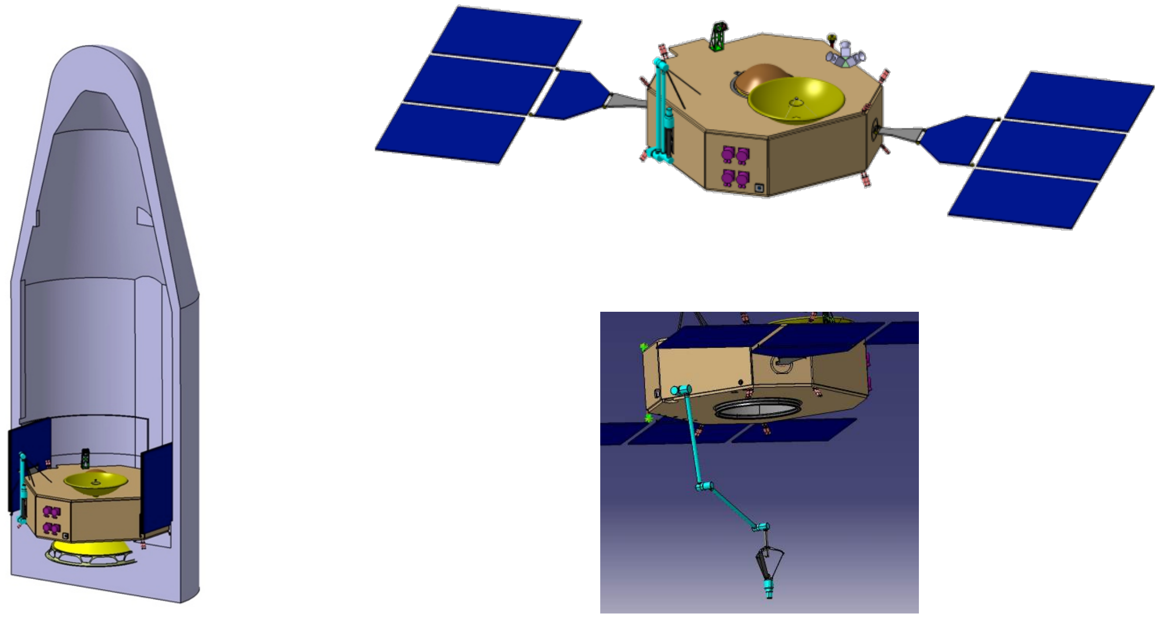


Figure 5.15: *Option B - Spacecraft in launcher fairing (left), during cruise (top right), in touchdown configuration (bottom right).*

The spacecraft is equiped with two 7.5 m^2 solar array wings. It also involves a dual power bus at 50 and 28 V for the same reasons as in option A. 4 x PPS 1350 thrusters are mounted on 2 orientation mechanisms. The thermal system is also very standard and no heat loop pipes are needed for highly dissipative units (e.g. PPU), instead Aluminium doublers are used. The data handling system has a similar architecture and cross-interfaces as in option A, but is based on a LEON 3 processor. Option B's telecommunication system is mostly similar to option A, but it has a 1.3 m diameter HGA based on VEX and a pointing mechanism for the MGA in order to use it during descent and sampling. This is due to the higher ground involvement during the descent phase for this design option (see next Section). Using the MGA during descent means that the data rate is relatively high during that phase and voluminous data such as navigation images can be sent to ground for ground-based navigation.

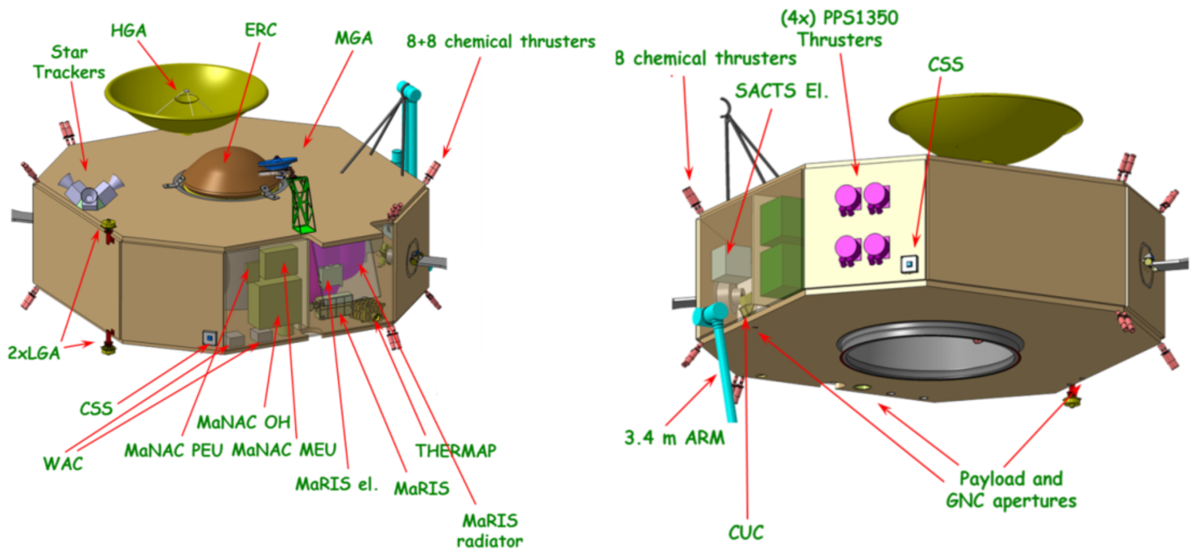


Figure 5.16: *MP-R Option B - Overview.*

5.2.2.2 Sample return capability: Descent & Proximity GNC

In this design option, the sampling operation starts from a stable position at 5 km altitude. The spacecraft performs a very long descent of about 38 hours. The spacecraft position is tracked by the ground via radio tracking and Doppler and navigation images are sent to ESOC every 3.5 hours. ESOC computes the actual navigation position and updates the guidance profile of the spacecraft for the next phase around 3 times during the descent. The total time between guidance updates is around 8 hours, re-using the procedures of Rosetta and saves cost, accounting for communications and ground-processing times. The main difference with option A is that on-board optical terrain-relative navigation is not used during this phase because the choice was to have more involvement from the ground. At some point however, for instance at 250 m altitude low-gate, it is no longer possible to control the spacecraft from the ground from a safety viewpoint and on-board navigation and guidance are engaged, which feed the closed-loop control. The same hardware as in option A is used, but not the same navigation filter, which is here a simply extended Kalman filter. Overall this descent option turns out to provide degraded performances, especially in the early phase when the ground is in the loop. The touchdown accuracy of 25 m is only met at 1-sigma or at 3-sigma with a prohibitively narrow angle (2^o) navigation camera. From a system viewpoint it is desirable to have a larger field of view and therefore it will be necessary to optimize the navigation filter and start autonomous descent earlier in this strategy in order to meet the touchdown accuracy.

5.2.2.3 Sample return capability: Sample Acquisition, Transfer and Containment System (SATCS)

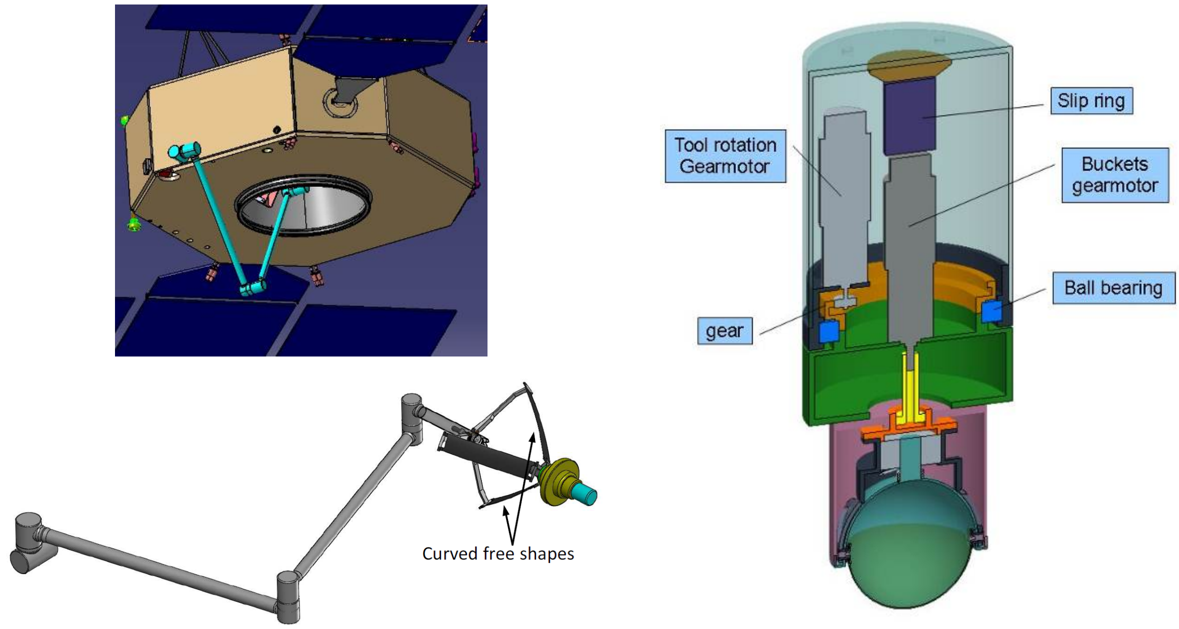


Figure 5.17: *Option B – SATCS: transfer of the sample container (upper left), touch and go arm (bottom-left), sampling tool (right)*

The "grab bucket" sampling mechanism selected in this design is shown in Figure 5.17. It uses a rotating bucket, directly used as the sample container, which closes two claws very fast at the end of the 5 s, thus collecting the sample. It is mounted at the tip of a robotic arm. Should the sampling mechanism fail to capture a sample, it can be reset into the open position for the following attempts. Note that in case of failure of the primary sampling tool, the design incorporates either micro roughness or adhesive layers on the lateral cylindrical surface of the tool in order to make sure that sample debris and/or powder, already generated during sampling attempts, are captured and brought back to Earth. As for the robotic arm, the current design is composed of 3 segments as well as a compliance device where the sampling tool is attached. This compliance device is a 3-blade mechanism that once activated serves as a shock absorber by dissipating most of the loads produced at the time of the contact of the sampling tool with the surface during the touch and go manoeuver. Once it has been verified that a suitable sample has been acquired, the compliance device relocks so the robotic arm can proceed with the accurate transfer of the sample container into the ERC through the central cylinder. A separate mechanism closes the ERC lid and seals it.

5.2.2.4 Sample return capability: Earth Re-entry Capsule

The ERC in option B has a quite similar design to that in option A. The main differences are a slightly different internal structure configuration, a slightly lower mass of 43 kg, a diameter of 81 cm and a different heat shield material (Figure 5.18). The capsule front and back shields are made of the TAS ATLAS ablative material. The impact absorbing material filling in most of the capsule volume to limit the deceleration loads to 800 g is a Duocel carbon foam.

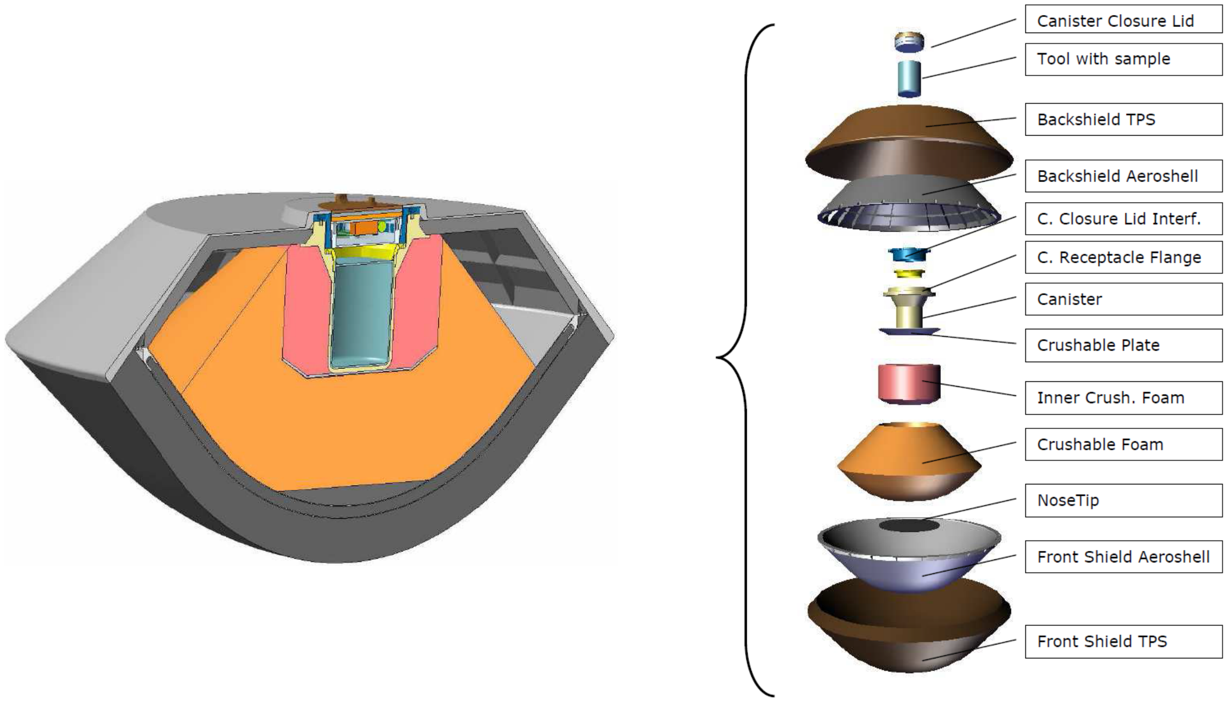


Figure 5.18: *Option B - ERC Design (left) and sample container accommodation (right).*

5.3 Summary of the design options

The mission designs presented above have completed the Preliminary Requirements Review, marking the end of Phase A. They are well prepared to enter phase B1 as the various sub-systems and system requirements are adequately defined. Moreover, the technical risk is low, thanks to maximum re-use of space-qualified hardware and major simplification of the key sample return technologies with respect to the previous Marco Polo. In particular, the mission, based on a small spacecraft platform, features high volume and launch mass margins (Table 5.4). The payload consists of simple and light instruments building on a large heritage. The overall complexity of this mission has been drastically decreased compared to the previous concept and can be undertaken within the M3 mission slot.

Sample return missions have been of interest and studied in Europe for many years. The concept is well-known, the risks are well-identified and the appropriate technology development has been implemented to ensure MarcoPolo-R readiness for implementation. The next Section gives an overview of the major achievements made on these key sample return capabilities under ESA funding.

Table 5.4: *MP-R System Mass Budgets (2022 mission opportunity)*

	Option A	Option B
Earth Re-entry Capsule (incl. maturity + 20% system margin)	45	43
Main spacecraft dry (incl. maturity + 20% system margin)	1053	1005
Spacecraft Total Dry	1098	1048
Xenon Mass	325	328
Hydrazine Mass	131	133
Spacecraft Wet Mass (w/o adaptor)	1554	1509
Launch Mass Margin	+11%	+13.5%

5.4 Enabling Technology Development

5.4.1 Descent & Touchdown GNC

Several streams of activities are currently on-going as far as the maturation of the GNC during the descent and touchdown phase is concerned. It already started 10 years ago with the breadboarding of the Astrium's Navigation and Planetary Approach and Landing NPAL camera (Figure 5.20). A GMV-led activity has matured throughout the last few years all the GNC and image processing concepts and software required for the terrain-relative navigation, specifically for an asteroid (Figure 5.21). The whole GNC chain and strategy has been simulated and shown to work according to requirements. The current focus, which will be completed early in 2014, is the real-time system validation of the descent GNC. This includes the FDIR, on a dynamic test bench in GMV in Spain (Figure 5.19), integrating the flight processor, navigation camera, and laser altimeter hardware in the loop.

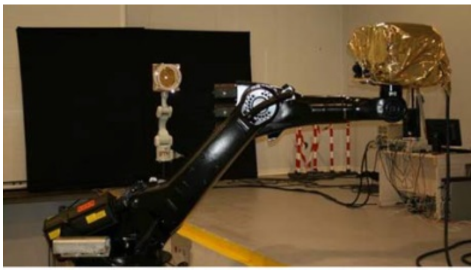


Figure 5.19: *GNC Test Bench by GMV.*

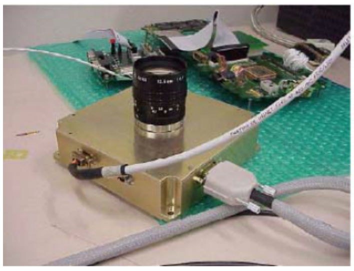


Figure 5.20: *NPAL camera by Astrium.*

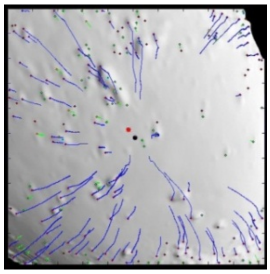


Figure 5.21: *Asteroid landmark tracking.*

In addition, the GNC approach has been defined in very close cooperation with the ESOC Rosetta mission flight dynamics teams to ensure that the operational concepts are mature and that the GNC-operations interfaces are valid. Finally, the operational teams will soon gather very good knowledge and experience for operating a spacecraft around a small body and release of a lander, thanks to the arrival of Rosetta around the comet in 2014.

5.4.2 SATCS

The sampling tools shown in Figure 5.23 and fully compliant with the system designs presented above are the object of two dedicated technology activities under the lead of AVS in Spain and Selex Galileo in Italy. The tool design is the result of a very large prototyping campaign where many different concepts were looked at and tested, and of modelling of sampling in microgravity.

Figure 5.23: *SATCS Sampling Tools by AVS (left), Selex Galileo (middle) and AVS sampling test (right).*

These tools are currently under breadboarding and testing, and demonstrate outstanding performances. These breadboards were designed for and will be tested in micro-gravity in 2014 on-board parabolic flights. A dedicated technology activity to breadboard and test the touch and go and sample transfer system is about to start. It will be tested in the relevant environment as was done for the Philae Rosetta lander for instance (Figure 5.24). The proposed concepts are simple, robust and made use of space-qualified components. They are planned to be tested early in 2015, so these systems should also be at TRL5 well before the mission adoption.

The following activities, which are either on-going or planned, are not critical according to the requirements, but are paving the way to ensuring that the contamination on the returned sample will be minimal:

- Sample container, containment (Viton) and witness plates breadboard and ground impact
- Thruster contamination characterisation (firing tests in vacuum chamber on analogue asteroid material)
- Definition of appropriate AIT/AIV procedures (cleaning solvent selection, contamination tracking, etc.)

Figure 5.24: *Touch and go landing test facility in DLR.*

5.4.3 ERC

The development by Astrium of the “ASTERM” Thermal Protection System material shown in Figure 5.25 has been very successful. This material is a lightweight ablative Carbon Phenolic, similar to the US PICA material (Stardust, MSL, Dragon) and has already reached TRL 5 with successful plasma tests in relevant sample return re-entry conditions, with heat fluxes up to 14-16 MW m^{-2} at relevant pressure. It is also to be noted that in order to demonstrate the manufacturability of an ASTERM-based mono-block heat shield, an approximately 7:10 scale front heat shield has been successfully built.

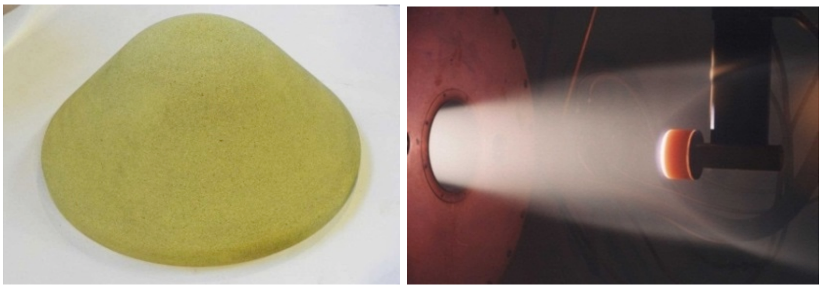


Figure 5.25: *Heat shield material prototype (left) and sample plasma tests in DLR (right)*

In addition, ballistic flights are validating the shape of the capsule and verifying its stability to confirm that the design is appropriate (Figure 5.26). The Hayabusa shape as shown on Fig. 5.26 demonstrates a very good compromise between stability in subsonic flight, large internal volume (for sample container and crushable material) and low heat flux. The crushable materials are available and are being characterised so as to clearly understand their behaviour in the conditions induced by the capsule impact.

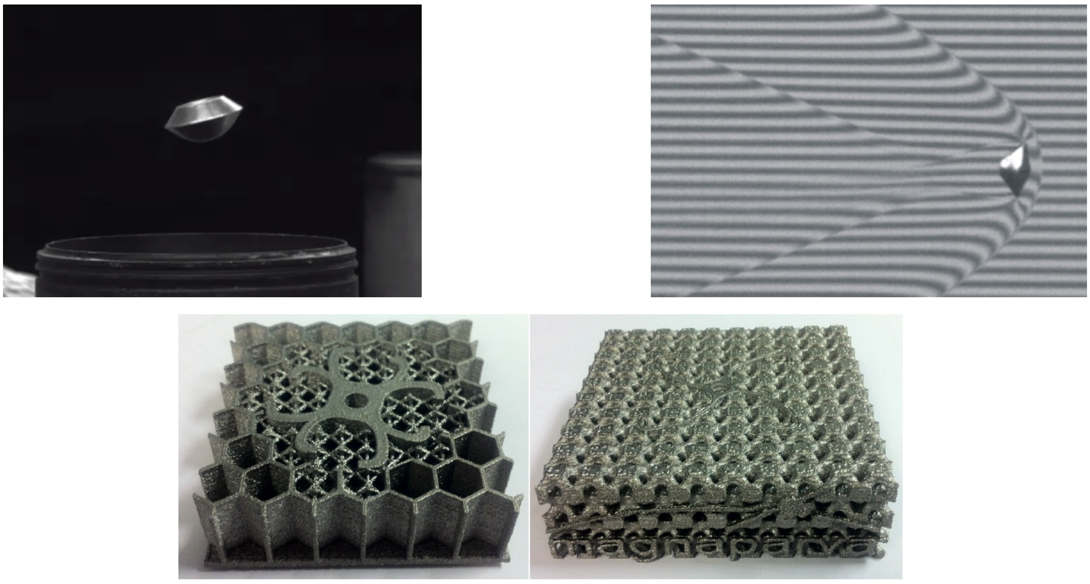


Figure 5.26: *ERC stability tests in the subsonic regime at DLR (top-left) and the super/transonic regime at ISL (top-right); Titanium foam crushable material by Magna Parva (bottom left and right).*

6 Ground Segment

6.1 Overview

The MarcoPolo-R Space Segment to be operated by ESOC comprises the MP-R spacecraft with its payload. The Operation Ground Segment (OGS) and the Science Ground Segment (SGS) will form the Ground Segment (Figure 6.1). The MP-R Ground Segment design and development will be based on maximum reuse of concepts and systems developed and utilised for previous ESA Solar System missions, to ensure inheritance of proven design and performance and to maximise cost-efficiency.

The main elements of the MarcoPolo-R Ground Segment are:

- The ESTRACK Ground Stations, belonging to the ESA network
- A Mission Operations Centre (MOC)
- A Science Operations Centre (SOC), part of the Science Ground Segment or SGS
- Principal Investigator (PI) Teams, part of the SGS
- A Sample Curation Facility, part of the SGS

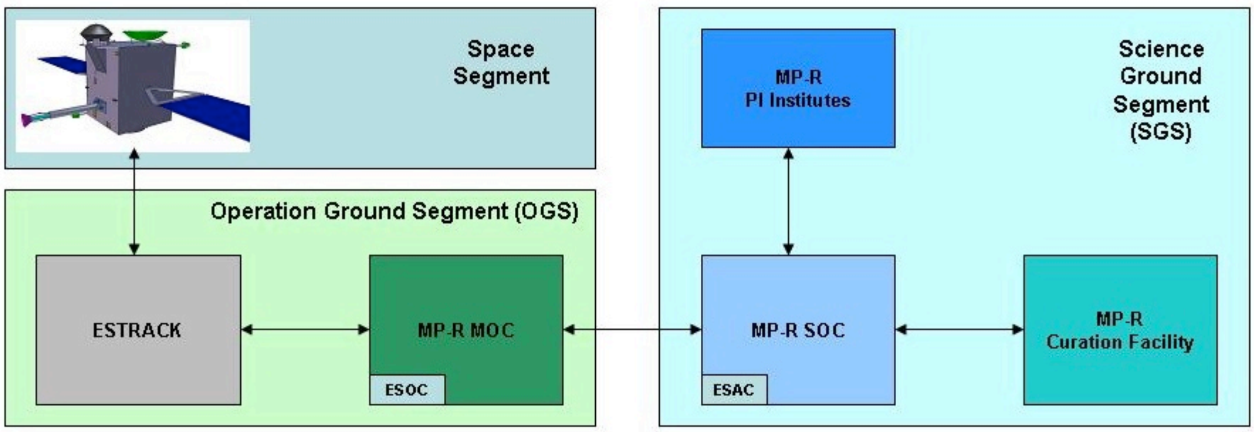


Figure 6.1: *MP-R ground segment architecture, showing the SOC interface with the MOC for uplink and downlink support to the MP-R spacecraft, and the SOC interface with the PI Institutes and Curation Facility.*

The OGS is under the responsibility of ESOC, both for the network of Ground Stations and the development and operation of the MOC. The SOC will be developed, implemented and run at ESAC (i.e., activities linked to science planning and commanding, as well as the archiving process). It is foreseen that the Sample Curation Facility will be in close contact with ESA and considered part of the SGS.

6.2 Mission operations

6.2.1 Operations schedule

The schedule of the spacecraft operations, starting in December 2022, is depicted in Table 6.1. Science operations at the asteroid are summarised in Section 6.3. The development of the operations and the ground segment implementation phase, including testing and validation, starts ~5 years before launch. Detailed mission and science operations are described in the Mission Assumptions Document, the Consolidated Report on Mission Analysis and the Science Operations Assumptions Document (SOAD).

Table 6.1: Spacecraft operations schedule and activities.

Mission Phase	Duration	Operations Support
LEOP	**3 days**	Real-time support. 2 ground stations. Solar panel deployments. Orbit tracking and trajectory correction manoeuvres.
Outbound Cruise	**~ 23 m**	See sub-phases below
Commissioning and Verification	3 m	Real-time support. S/C and instruments commissioning including HGA deployment/calibration. S/C system tests.
Initial Cruise	~ 9 m	Daily passes. Intense operations during early cruise and then off-line operations support. System and element health checks. Includes passive payload checkouts (4 x 1 week)
Earth Flyby	1 m	Daily passes. Flyby navigation. Trajectory correction manoeuvres, Instrument calibration/check-out.
Cruise to asteroid	~ 10 m	Weekly passes. Off-line operations support (S/C, flight dynamics, ground segment maintenance).
Asteroid Preparation Phase	Overlaps w. cruise	Asteroid operations procedures updated, tested and validated. Simulation campaigns. Team build-up for asteroid phase. Mission planning for asteroid phase. Throughout the whole transfer phase.
Asteroid Approach	**~ 6 w**	Optical navigation throughout the phase, manoeuvres throughout the phase, ephemeris Refinement, ΔDOR, See also specific sub-phases below
Asteroid Detection	5 w	ΔDOR. Increased pass frequency. Real-time support (S/C, flight dynamics, etc.) during manoeuvres. Intense system checks and detailed planning activities
Insertion to close distance from NEA	1 w	Real-time shift support for manoeuvres otherwise routine daytime support (spacecraft ops., flight dynamics, ground segment maintenance and support)
Asteroid Proximity operations phase	**180 d**	Daily communication passes with one station, except SAM. Mission planning/re-planning, intense flight dynamics activities. See sub-phases below.
Close approach and FCP	22 d	Payload commissioning, operations coordinated by Science Ground Segment.
GCP and LCP	56 d	Downlink of global and local characterization data + selection of 5 most suitable sampling sites, selection of the primary candidate. Construction of digital elevation model and asteroid landmark database used by navigation teams
RSP	25 d	Daily off-line control, instrument operations as commensurable with RSE.
SAM	44 d	Descent and sampling/descent rehearsals. Two ground stations. Real-time operations. Analysis of descent/sampling flight data. Updates of onboard navigation software/on board parameters if required after sampling rehearsals.
Preparation for return cruise and escape, margins	33 d	Real-time support
Inbound Cruise	**~ 23 m**	Similar to outbound cruise albeit no flyby, no payload checkouts. Weekly passes.
Near Earth Phase	**Some weeks**	▪ Manoeuvres for entry optimization ▪ Final approach: navigation, ERC [Earth Re-entry Capsule] separation and Earth avoidance manoeuvres, navigation/tracking, intense preparation, real-time operations in critical phases ▪ Re-entry and capsule recovery: ERC tracking (UHF beacons, possibly airborne optical trajectory determination), calculation of landing site by flight dynamics, recovery by helicopter within 2 h, transport of sealed capsule to curation facility

6.2.2 Operations concept

The MarcoPolo-R mission operations will consist of:

- Mission Planning: 24 hours to 1 week timeframe.
- Spacecraft control, following the flight operations plan and the short-term plan (including in particular deep space and asteroid orbit manoeuvres, sampling operations and ERC separation).
- Spacecraft status monitoring and off-line performance analysis.
- Instrument status monitoring, control, implementation of the observation schedules and collection and data control of the instrument housekeeping telemetry following requests coming from the SGS.
- Orbit determination and control using tracking data and implementing orbit manoeuvres.

- Off-line attitude determination and control based on the processed attitude sensors data in the spacecraft telemetry and by commanded updates of control parameters in the on-board attitude control system.
- On-board software maintenance.
- Capsule tracking and recovery operations (Woomera test range - Australia) and transport to curation facilities.

The operational concept will call for maximum sharing and re-use of manpower, facilities and tools already used by the Solar and Planetary Science family of missions (e.g. Mars Express, BepiColombo).

The spacecraft will spend most of its time at distances from the Earth where the two-way light-time delay in communications is of the order of 10 minutes. This requires the operational mission to be considered as "off-line" for which the on-board systems must be robust and have an advanced level of autonomy, in particular in case of on-board anomalies where the spacecraft should autonomously perform corrective actions. Only one ground station will be allocated for communications and precision orbit determination with the spacecraft during most of the commissioning, cruise and asteroid phases, except for critical events. Dual ground station coverage will be used when required for navigation during cruise and during the critical asteroid descent and sampling phase. During cruise the nominal coverage will be limited to a single pass per week while daily passes will be used during asteroid proximity operations.

6.2.2.1 Mission Planning, Spacecraft Monitoring and Control

All operations will be conducted by ESOC according to procedures contained in the flight operations plan. Nominal spacecraft control during the routine mission phase will be 'off-line'. All operations will be conducted by up-linking of a master schedule of commands for later execution on the spacecraft. Nominal science operations are coordinated by the SGS and command files for the instrument operations will be delivered to the OGS in regular intervals. Specifically, descent and sampling operations require presence of a team with expertise on the drill and sample transfer mechanisms as well as vision-based GNC. The minimum required ground reaction time is in line with the spacecraft autonomy periods as shown in Table 6.2.

***Table 6.2**: Ground reaction times for the space segment to operate nominally.*

Phase	Autonomy for mission safety
Launch and Early Orbit Phase (LEOP)	12 h
Cruise	2 weeks
Asteroid Proximity Phase (high orbits)	48 h
Low Asteroid Orbits and manoeuvres	48 h
Descent and sampling	1-3 h
Special manoeuvres (low-thrust cruise navigation manoeuvres, flyby, asteroid insertion/escape, separation and Earth avoidance)	Coverage plan developed on a case by case basis taking into account navigation and telemetry/telecommand.

6.2.2.2 Orbit and Attitude Control

The trajectory, attitude and coverage analyses required for mission preparation are carried out by mission analysis. The flight dynamics team will support tasks such as:

- Orbit determination using two-way Ranging and two-way coherent Doppler data,
- Preparation of flybys and asteroid orbit insertion (Doppler, ranging and ΔDOR measurements),
- Trajectory/Manoeuvre optimisation, command generation, execution and monitoring, including those needed for the sampling,
- Attitude Control System Monitoring,
- Antenna steering, commanding the navigation camera (used for spacecraft asteroid relative navigation),
- Capsule separation, capsule re-entry trajectory location analysis (based on re-entry observations).

6.2.3 Operations Ground Segment infrastructure

The ESA/ESOC OGS will consist of:

- The ground stations and the communication network
- The MOC (infrastructure and computer hardware)
- The flight control software system (data processing and Flight Dynamics Software)
- Computer infrastructure (Mission Control System, simulator, etc.).

6.2.3.1 Ground Stations and communications network

All communications with MarcoPolo-R are done via X-Band and will use the 35 m ESTRACK antennas (e.g. New Norcia; Fig. 6.2) as a baseline. During periods of conflict with other missions New Norcia could be switched to the Cebreros or Malargue stations which can also be used when a second ground station is required. This network almost provides ≥ 16 hours coverage of the spacecraft during critical periods. For LEOP activities, it will be supported by the 15 m antenna in Maspalomas. The use of the ground stations will be optimized to share coverage time with other missions. On the spacecraft, communications will be mostly made through the HGA. For LEOP, LGA will be used and an MGA is planned for safe mode and during asteroid descent to guarantee a minimum health status of the spacecraft during this critical phase (i.e. ~ 100 bps data rate). The Ground Facilities Control Centre monitors and remotely controls all ground stations and is responsible for the TM/TC links to and from the ground stations.

6.2.3.2 The MOC

The flight control team, integrated into the Solar and Planetary Division at ESOC, will operate the mission from ESOC. The mission will be controlled from the mission operations centre, which consists of the main control room (Figure 6.2) augmented by the flight dynamics room and dedicated control/support rooms. The main control room will be used for mission control during LEOP (and possibly during sampling operations at the asteroid). During cruise and the other asteroid operations the mission control will be conducted from a dedicated control room shared with other solar and planetary science missions. The control centre is equipped with workstations for different tasks of operational data processing and staffed by experts.

The flight control team, expert in spacecraft control dedicated to the MarcoPolo-R mission, defines the mission operations. The spacecraft operations manager leads the team. At least one operations engineer is dedicated to instrument operations that are provided via the SGS.

Figure 6.2: *Left: ESA New Norcia (Australia) 35 m deep-space antenna. Right: ESOC Main Control Room.*

6.2.3.3 The Flight Control Software System and computer infrastructure

The flight control system will be based on an evolution of existing infrastructure development (SCOS 2000), using a distributed architecture for all spacecraft monitoring and control activities. It includes various facilities: telemetry reception and analysis, telecommand processing, uplink and verification capabilities, monitoring of instrument housekeeping telemetry, etc. The computer configuration will be derived from existing structures, for example: a multi-mission server to edit the flight operations plan, a mission dedicated computer system for mission planning (commands/instructions schedules for spacecraft and ground systems), the simulation computer, providing an image of the spacecraft system during ground segment verification, etc.

6.2.3.4 Capsule recovery infrastructures and operations

For MarcoPolo-R, the capsule landing is assumed to take place in Woomera, South Australia in mid-2027 (longitude: 136.5 ºE, latitude: 31 ºS). The capsule retrieval operations, described in Section 5.1.4 will be quite similar to those of Stardust and Hayabusa (Figure 6.3). Europe already has some experience in this field with Mirka (DLR) and the ARD (ESA).

After recovery, the capsule is then transported to a working area where it is cleaned before being further transferred to the curation facility where it is unsealed and the sample can be recovered.

The Woomera Test Range (WTR) hosts a wide spectrum of ground, air and space activities. The favourable desert climate, benign electromagnetic environment and flat, easily accessible terrain for test object recovery are additional major assets of the WTR. Infrastructure or logistics such as radar tracking services, helicopters, *etc*. are readily available or can easily be rented so no new investment is required.

The following services for management and the actual capsule recovery are assumed to be provided by ESA:

- Technical interface to the project and working level interface to Woomera facility.
- Coordination with scientists for sealed container processing.
- Detailed planning of recovery operations, including manpower and transportation.
- Landing rehearsals in Europe and Woomera and actual landing in 2027.
- Flight dynamics services for re-entry site prediction.


Figure 6.3: *Spectacular re-entry observations of Hayabusa (left, Credit: Hayabusa Re-entry Observation Team, National Astronomical Observatory of Japan); Hayabusa capsule recovery operations (right)*

6.3 Science operations and data handling/archiving

The Science Operations Centre (SOC) is the ESA-provided part of the Science Ground Segment (SGS). The SGS is the overarching entity that encompasses the SOC and elements external to ESA like the science operations personnel and infrastructures of the PI teams and of the Sample Curation Facility (Figure 6.4).

The MP-R SOC represents an essential functionality of the Science Ground Segment in terms of overall coordination of planning, commanding and archiving activities. It is the main point of contact of the scientific user community for the mission. Detailed assumptions on the required functionalities of the Science Ground Segment are given in the 'Science Operations Assumptions Document' [SOAD], which also outlines the baseline mission scenario of MarcoPolo-R (see timeline in Figure 6.5).

The ESAC-based SOC will collect science observation requests from the PI teams and produce a consolidated science operations plan. With the PI teams, it will then generate conflict-free operational timeline files, which will be sent to the MOC and merged with spacecraft commanding for uplink. The returned instrument telemetry will be partially processed by the SOC and made available to the PI teams.

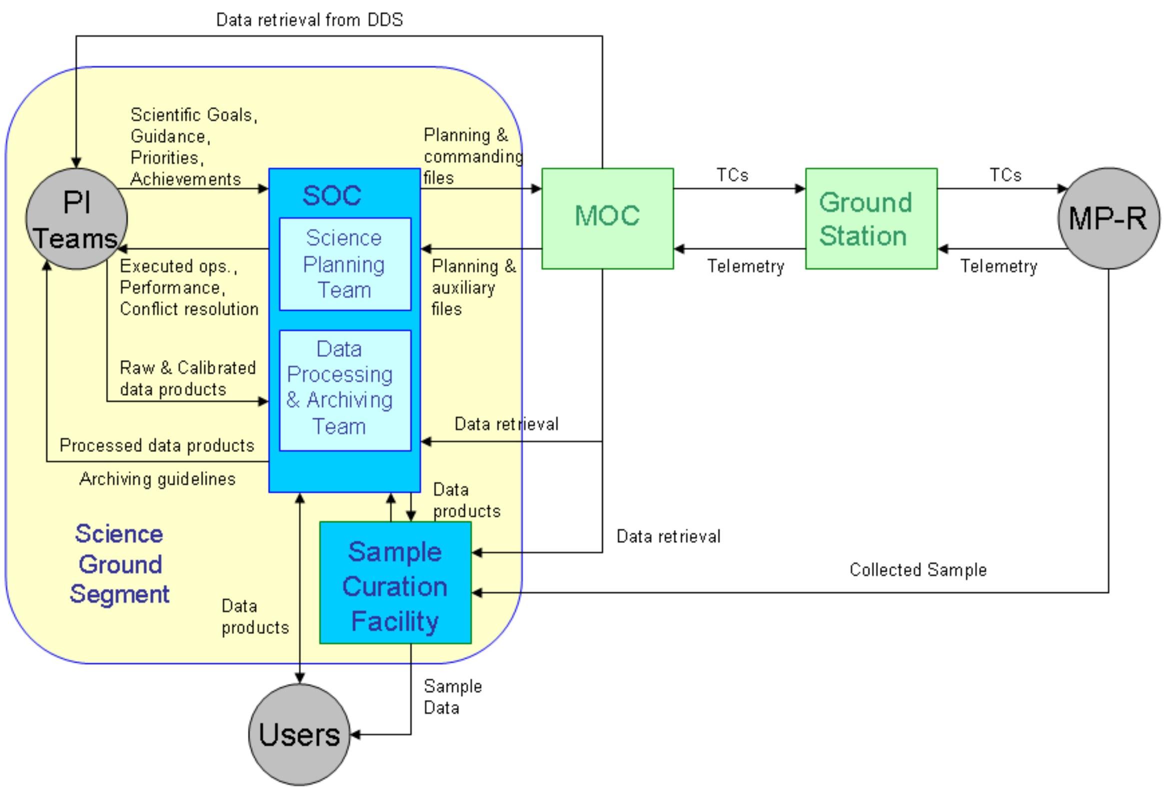


Figure 6.4: *Data flow to and from the MP-R Science Ground Segment (SGS). Science Operations are developed and implemented within the SGS that encompasses ESA functionalities (SOC, for both uplink and downlink including Science Planning and Data Handling and Archiving Teams) and non-ESA science operations activities (PI teams and Sample Curation Facility Team).*

The following science operations functionalities will be provided by the SOC:

- Build a top-level mission Science Activity Plan, coordinated by the Project Scientist (PS)
- Produce and validate consolidated planning timelines of operations for all MP-R instruments and prepare the detailed instrument commanding to be sent to the MOC
- Transfer conflict-free, verified timelines to MOC for execution
- Retrieve MP-R raw data from the MOC, via the Data Disposition System and provide the infrastructure for and partially process the MP-R science data products via a dedicated processing pipeline. A quick-look system dedicated to instrument science data quality analysis and mission planning feedback is also foreseen to be run by the SOC.
- Develop, operate and maintain the MarcoPolo-R Science Archive
- Ensure that the Curation Facility obtains the data products required for sample/context data analysis

The PI teams are expected to provide the SOC with science planning and commanding requests as well as inputs for the data processing pipelines, and in particular perform the data calibration, where the expertise is within the PI teams. The PI teams will also prepare the final, long-term data archive products which will be made available to the scientific community.

Users (the scientific community) will have access to the science data through the legacy archive of the mission located at ESAC, following the rules laid down in the Science Management Plan. The data are assumed to be made available via the Planetary Science Archive (PSA).

ID	Task Name	Distance	Duration
1	Close approach trajectory	500-100 km	17 days
2	FCP=Far Global Characterization	10 km	5 days
3	GCP=Global Characterization Phase	5 km	25 days
4	RSP=Radio science phase	2-1 km	25 days
5	LCP 1 to LCP 5 (Local Characterisation Phase)	250 m	28 days
6	Sampling rehearsal (s)	1.5 km to 100 m	18 days
7	SAM = Descent/sampling phase	1.5 km to surface	26 days
8	Post-sampling LCP	250 m	3 days
9	Margin		30 days
10	Departure from asteroid		1 day

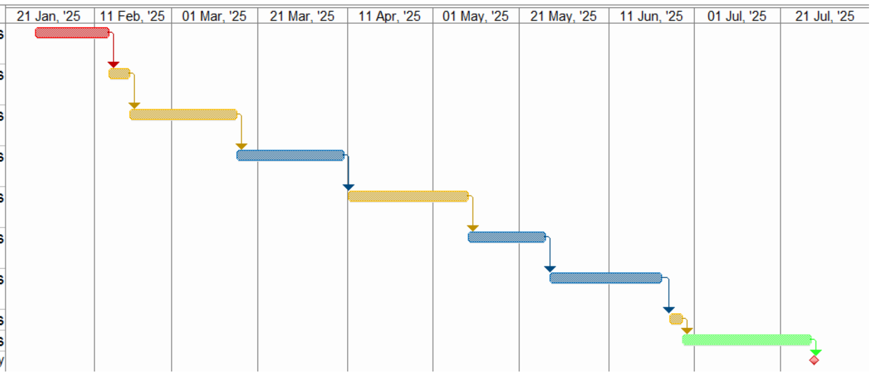


Figure 6.5: *Baseline science operations during the asteroid proximity operations phase.*

6.4 Curation facility

A sample return receiving and curation facility is an essential requirement for the preservation and distribution of the collected extra-terrestrial sample for analysis and the long-term archiving of such a valuable resource. It is foreseen to be requested and selected via an AO process as a nationally-funded contribution. A terrestrial facility capable of receiving the sample returned from the MarcoPolo-R mission must be designed to guarantee that the most thorough analyses with the highest scientific return are possible.

The facility has to provide secure and appropriate long-term storage, receive the ERC and recover the sample from the sample container, undertake some preliminary characterisation of the sample, and have the ability to prepare appropriate sub-samples for allocation in order to achieve the required effectiveness and collaborative outcomes for the whole international scientific community. Above all, the facility must guarantee to preserve the sample in its pristine condition, avoiding chemical and physical alteration of materials by the Earth environment in order to avoid misleading results. The facility shall also be able to store the samples for future generations, in conditions able to preserve the sample integrity.

It needs to provide a comprehensive and useful catalogue of the collection that enables individual researchers to identify the specimens to request for detailed laboratory investigation and to accurately record all activities on the sample, both within the facility and in the scientific community. Comparable curation and handling of all likely contaminants and witness plates from the spacecraft, its manufacture, and all stages of sample curation and handling will also be required to aid in the interpretation of analyses of the samples.

The design and construction of the facility and its operating systems and personnel will benefit from the experience from NASA and/or JAXA for handling and curating extra-terrestrial material returned by space missions.

The facility also has a unique opportunity to act as a focal point for outreach activity associated with extra-terrestrial materials.

6.4.1 Security

Experience from the Apollo lunar programme and meteorites indicates that extra-terrestrial materials, particularly pristine returned samples, attract great interest from the general public. Such material represents great commercial value (*e.g.* Lunar meteorites are worth many thousands of Euros per gram), and therefore, given the need for access to the facility by scientists, the facility will require carefully considered security aspects. In addition, protection of the sample from extreme natural events is also required. However, no bio-containment of the sample is required as MarcoPolo-R will only be a COSPAR designated "unrestricted" sample return mission.

6.4.2 Contamination control

Contamination is defined as molecular (chemical substances) and particulate (solid tiny particles of micrometre size), which has the potential to react with or become intimately mixed with the sample – with the potential for generating misleading analytical results. Thus, any transfer of chemicals, liquids or particulates of terrestrial origin (environmental, human, processing, facility, equipment and working activity) to the samples has to be minimized. The levels of contamination that the sample will be exposed to must be controlled during all operational tasks involving the samples inside the curation facility:

- ERC handling;
- ERC storage;
- Sample handling;
- Sample storage;
- Sample characterisation;
- Sample preparation and delivery for external studies and returns;
- Maintenance of the curation facility.

Witness plates will be used to monitor contamination during each task of the curation activity. These will be able to record particulates and volatile organics present during all stages of sample activity and storage. Concerning unknown contaminants, tests and analyses have to be performed periodically (e.g. outgassing rates as a function of time, chemical composition of outgassing products, condensation rates or degradation from radiation). The results of these tests and analyses will be used to calculate expected contamination levels and their subsequent effects on returned sample status if other relevant parameters are known.

High temperature can change sample properties and induce desorption. The best solution for this problem is to keep the samples at the same temperature they have experienced at their collection site, or to define acceptable temperature ranges.

Illumination could alter chemical characteristics of returned samples through photochemical processes. It is mandatory to avoid any use of camera flashlight inside the curation facility or addressed directly to the samples. Only professional UV-free camera light will be accepted to take pictures. Indoor illumination must also guarantee to be UV-free.

The confining atmosphere of the sample will be designed to be as harmless as possible for the sample integrity. The composition and pressure of this atmosphere will be specific to the planned analysis of the sample.

Materials and Environmental Properties: Considering the contamination issues and according to technical characteristics, the materials present in the sample handling areas must be strictly controlled. Materials should be clean room compatible (*i.e.* low particle shed) and in the case of the need to preserve the organic inventory of the sample, have low volatile organic content.

Materials in direct contact with the sample (handling, storage) should be restricted to the absolute minimum; at least until a sample aliquot has been designated for a specific analysis programme. Potential materials for storage and handling should be restricted to stainless steel and quartz (or glass). All the materials with which the sample comes into contact have to be sterilised, cleaned and packaged according to approved procedures, and introduced to the storage area only through sterilised transfer locks.

The environmental requirements for the working area inside the curation facility are strictly related to its design. The anticipated facility can be summarised as (Class defined per ISO 14644-1):

- **Control room**, for control of environmental parameters, verification of procedures, control of operations and general viewing.
- **Entrance room** (ISO Class 7 clean room) - access of personnel and materials to the working area.
- **Exchange room** (ISO Class 6 clean room) - transit room for personnel and materials.
- **ERC handling room** (ISO class 6 clean room) – for partial disassembly of ERC to recover witness plates and sample container(s) and subsequent storage of ERC.
- **Laboratory room** (ISO Class 5), is the area where complex sample preparation is performed.
- **Sample handling** (ISO Class 4 – purged with inert gas (see below)) – initial sample selection and sub-sampling and preliminary characterisation.
- **Storage** (ISO Class 4 – purged with inert gas (see below)), is the core area where the parts of the sample are stored in their boxes and cabinets.
- **Archive** (ISO Class 4) – houses vacuum storage system for long-term archive preservation of a portion of the sample.
- **Contamination archive room** (ISO Class 6) – purged with inert gas (see below)), stores (sealed) samples of materials from spacecraft likely to contaminate the sample –components that the samples may contact and volatile containing materials (e.g. plastics, lubricants, fuel, etc) that may degas when the spacecraft is in space.

6.4.3 Sample storage

It is anticipated that the long-term storage of the sample will be strictly in environments with controlled atmosphere composed of inert gas (argon or nitrogen). A portion of the sample (nominally 30 %) will be maintained under conditions mimicking the conditions on the asteroid surface from which the sample was collected (i.e. temperature, vacuum). This will provide the best sample for future generations and assist in the study of space weathering effects during the initial study phase.

Initial sample handling should also be performed under the same conditions as storage, as there could be multiple handling of the same fragment. Dry, filter gas purged storage areas linked to sample handling glove boxes (most probably by robotic mechanisms) are therefore required as the innermost part of the curation facility. Sample storage will be in numbered holders (for materials – see above), easily accessible by a remotely controlled robotic arm inside a storage cabinet, where many sample holders are packed. The robotic arm transfers the sample holder to the glove box for initial processing. This makes it possible to keep the sample always in a controlled and inert atmosphere in order to minimise contamination at least until its delivery to external laboratories.

The storage cabinets should be fabricated in stainless steel in order to allow clean surfaces compatible with the requirements for an ISO class 4 environment and to avoid any contamination from molecular outgassing. To this purpose, lateral apertures should allow better gas flow inside the entire cabinet volume. The storage cabinet should also allow an efficient packing of sample holders that allows robotic and remote operations for storing and retrieving parts of the sample.

Figure 6.6: *The JAXA curation facility for Hayabusa.*

6.4.4 Sample characterisation

It is anticipated that a detailed study of the sample will be performed by the scientific community (building on successful programs following Apollo, Stardust and Genesis sample returns). However, a preliminary characterisation of all principal components (down to 1 mm particle size - TBD) will need to be performed to provide sufficient information to understand the variation of material types present and allocate appropriate sub-samples to the scientific community (*e.g.,* in the first instance organic-rich material may be prioritised for organic studies, low aqueous alteration for interstellar grain and early Solar System studies, *etc*.).

To provide this information a number of non-destructive and non-contaminating analytical tools will be required within the clean area of the sample curation facility:

- Optical microscopes - for recording colours, grain sizes, *etc*. of particles.
- High precision balances – for measuring the sample masses.
- FTIR microscope – for providing mineralogy and nature/abundance of organics on exposed surfaces.
- Laser Raman microscope – for providing more specific mineralogical and chemical information.
- High resolution X-ray CT scanner – for providing 3-D information on structure and mineralogy of individual fragments.

- A mass spectrometer, e.g., quadrupole type, should be connected to the sample canister housing during its opening. Monitoring of the confining atmosphere should also be run continuously to check the integrity of the confining atmosphere and, possibly, sample degassing.

Additional analytical facilities will be required within the curation facility to support various aspects of the sample preparation and operation of the facility:

- Analytical Electron Microscopy and Focused Ion Beam systems – for recording morphology, size, mineralogy and composition of a sub-set of particles; for screening/quality control of prepared sub-samples, and assessment of particulate contamination on witness plates; for the preparation of location-specific electron-transparent wafers.
- Organic analysis tools including HPLC, LC-MS and GC-MS systems - for assessing organic contamination levels on witness plates and ERC.
- XPS – for assessing contamination levels on surfaces and cleaning procedures.

6.4.5 Sample preparation

Many of the analytical techniques employed by the scientific community demand special preparation of the sub-samples – *e.g.* polished sections, homogenised powders, electron transparent sections. In order to ensure optimum use of materials in the preparation of these sub-samples and minimizing contamination of the parent fragments, preparation of these specialised sub-samples must be performed within the curation facility. This will require clean room compatible splitting, cutting, polishing and microtoming equipment as well as the electron microscope capability already listed above.

6.4.6 Sample 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. The sample catalogue will be accessible through a web interface.

6.4.7 Other activities

In addition to the returned sample, the curation facility should also be responsible for documentation, curation and distribution of witness plates from the spacecraft and the sample curation facility itself as well as representative materials collected during the construction phase of the spacecraft and key systems (*e.g.* lubricants, fuels, materials in close proximity to the sample, *etc*.). Because of the potentially contaminating nature of these materials they will need to be stored and handled in an entirely separate, albeit lower specified, adjoining facility.

7 Management

This section summarises the envisaged management approach for MarcoPolo-R. It also serves as a starting point for writing the MarcoPolo-R Science Management Plan (SMP). In this document the following topics are covered and described:

- The overall mission management within ESA
- The various steps from the end of the assessment study to the launch
- The overall procurement and model philosophy
- The major actors and teams involved in the MarcoPolo-R project
- The payload-related aspects, in particular the set-up of the consortia, the various actors, the selection process and the data rights
- The overall project schedule

The procurement schedule and model philosophy described herein are provided for illustrative purposes only, as a result of the assessment study. The procurement approach is based on a fixed price contract instead of a cost reimbursement type of contract.

7.1 Project management

The science and project management will follow the current practises of ESA science missions, also taking into account that this mission will require expertise related to sample collection, laboratory analysis, and contamination knowledge. The Preliminary Requirements Review is being completed at the time of writing. The mission baseline is well-established and documented. Following the approval of the MarcoPolo-R mission in February 2014 ESA will release an Invitation to Tender (ITT) for the selection of two competitive industrial contractors for the competitive Definition Phase (Phase B1) for a typical duration of 20 months. The payload, described in Section 4, has already been selected via an Announcement of Opportunity in February 2013. The phase B1, starting in July 2014, will be led by a Study Manager (responsible for all technical and management aspects under ESA responsibility), a Study Scientist (responsible for all science aspects), a Payload Study Manager (responsible for all payload interfaces), and a Science Operations Study Manager, as during the phase A.

To support the ESA Study and later Project team in this and other tasks, a MarcoPolo-R Science Working Team (SWT) will be formed, made up of PIs and the Study/Project Scientist along with support from components of the Operational and Science Ground Segments. So-called Interdisciplinary Scientists (IDS) will have to be brought in very early. The IDSs should include representatives of the curation and sample characterisation and analysis community. This SWT will form the primary scientific voice of MarcoPolo-R, chaired by the Project Scientist.

The phase B1 will be completed with the Systems Requirements Review (SRR), which will close this phase. Most of the technology development activities will be completed by mid-2014 and feed the phase B1 system activities. Should they not be completed they will run in parallel to the definition phase and their intermediate results will be fed to the system study as necessary. Critical activities will be completed well before the mission final adoption in order to confirm planning and cost.

At the end of the definition phase a scientific evaluation by ESA’s scientific advisory bodies in early 2016 will provide a recommendation for the final adoption of the mission to go into Implementation Phase. This recommendation will be provided to the Science Programme Commee (SPC) for approval and MarcoPolo-R will move into the Implementation Phase (Phase B2/C/D/E1) and a Prime industry contract will be selected via a further ITT. The final industrial organization will be completed in phase B2, mostly through a process of competitive selection, by taking into account geographical distribution requirements. It may, for instance, follow a thin-prime approach, where most sub-systems are sub-contracted, as it is currently the case for Solar Orbiter or Euclid. This is the approach which is retained at the moment for costing as it leads to a conservative, but robust, cost estimate.

At the start of this phase a project team will be formed in the Project Department (SRE-P) at ESTEC in the Netherlands. This team is led by a Project Manager, who has the overall technical and management responsibility for implementing the mission. He/she will be supported by the Project Scientist who keeps the responsibility for all science-related aspects. The ESA Project team will conduct a preliminary design review, a critical design review and a flight acceptance review..

After successful commissioning of the instruments shortly after the launch, the responsibility of the Project Manager will be handed over to the Mission Manager who is located in the Science Operations Department (SRE-O) at ESAC in Spain. The Project Scientist will continue his/her task.

7.1.1 Management of operations

ESA will be responsible for the launch, checkout, and operations of the spacecraft. ESA will establish an Operation Ground Segment (OGS) and a Science Ground Segment (SGS). The MOC, part of the OGS, will be located at ESOC, the SOC, part of the SGS, will be located at ESAC.

ESOC will support the definition of the OGS from the beginning of the project, nominating a Ground Segment Manager who will report to the Project Manager (later to the Mission Manager). The definition of the Science Ground Segment will be done under the lead of an SGS Development Manager in the Science Operations Development Division at ESAC in Spain. This will be done in close interaction with the Project Scientist but formally reporting to the Project Manager. After handover of the responsibility from Project Manager to Mission Manager in the operations phase, the SGS will move from the Science Operations Development Division to the Science Operations Division.

7.2 Procurement philosophy

The proposed procurement scheme for MarcoPolo-R is based on the concept that the payload (instruments and associated processing, data handling and control components) will be provided by PIs funded by national funding agencies of ESA member states. Also, the curation facility will be provided via nationally funded activities.

ESA would have overall responsibility for:

- The overall spacecraft mission and design (via industrial contract)
- Provision of spacecraft equipment and integration of the spacecraft bus and payload module (via industrial contract)
- Equipment, sub-system and system testing (via industrial contract)
- Spacecraft launch and operations (Arianespace, ESOC and ESAC)
- Acquisition and distribution of data to the OGS and SGS.

7.3 Schedule

With a launch in December 2022 for the baseline scenario, the total time for development, manufacturing, assembly, integration, verification/testing and launch campaign from beginning of Phase B2 to launch is 6 and a half years. The phase B1 before that will be 20 months and most technologies are already at TRL 5. Those not yet at such a level of maturity (touch and go mechanism) will reach this level with a high confidence by mid-2015 well before mission adoption. Figure 7.1 shows the master project development schedule.

ID	Task Name	Duration	Start
1	SPC Mission Selection	1 day	Tue 25/02/14
2	**Phase B1**	625 days	Wed 26/02/14
3	*SRR*	58 days	Mon 05/10/15
4	SPC Mission Adoption	7 days	Mon 01/02/16
5	**Implementation phase**	**2293 days?**	**Thu 15/09/16**
6	Phase B2	351 days	Thu 15/09/16
7	PDR	78 days	Thu 15/06/17
8	Phase C	821 days	Fri 01/09/17
9	CDR	79 days?	Sun 01/09/19
10	Phase D	774 days	Tue 19/11/19
11	Phase E1/Launch preparation	130 days	Sat 01/01/22
12	FAR	28 days	Wed 01/06/22
13	Contingency	180 days	Wed 29/06/22
14	Launch	1 day?	Mon 26/12/22
15	Phase E2 / Operations	3000 days	Tue 27/12/22

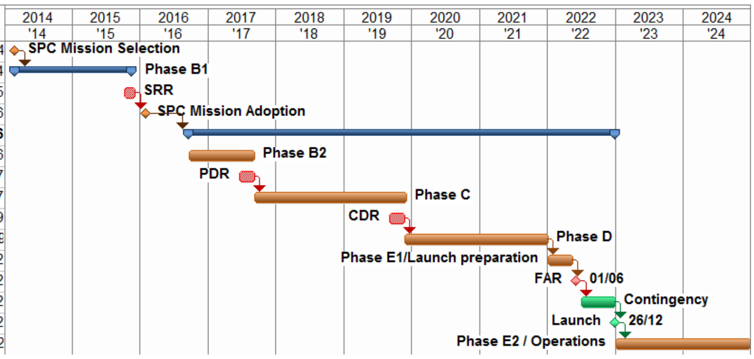


***Figure 7.1**: MarcoPolo-R development schedule.*

7.4 Science Management

The following text adds some details on the roles of the scientific players in the mission. It serves as a starting point for the Science Management Plan (SMP), which will be the top-level management document of MarcoPolo-R to be agreed by the Science Programme Committee (SPC).

7.4.1 The Project Scientist

Once the mission enters the implementation phase, ESA will nominate a Project Scientist (PS) for MarcoPolo-R. The PS will be located at ESTEC in the Scientific Support Office (SRE-S). He/she will be the Agency's interface with the PIs for scientific matters. The PS will chair the Science Working Team and coordinate its activities.

During all phases of the mission the PS will be responsible for all scientific issues within the project. The PS will monitor the state of implementation and readiness of instrument operations and data processing infrastructure. The Science Operations Department (SRE-O) will develop and run the science operations and archiving activities.

7.4.2 Science Working Team

The MarcoPolo-R Science Working Team (SWT) will consist of all Principal Investigators and Interdisciplinary Scientists (IDSs). The PS will chair the SWT. The SWT will monitor and advise ESA (and any potential collaborating agencies) on all aspects of the MarcoPolo-R mission that will affect its scientific performance. It will assist the PS in maximizing the overall scientific return within the established boundary conditions, advise on aspects of science coordination of all partners, and act as a focus for the interests of the scientific community of MarcoPolo-R.

7.4.3 Modes of participation

The possible modes of participation to the MarcoPolo-R programme are:

(1) Principal Investigator (PI), heading an instrument consortium providing an instrument (= payload).
(2) Co-Investigator (Co-I), a member of an instrument consortium providing an instrument.
(3) Interdisciplinary Scientist (IDS), an expert in specific science themes connected to asteroids and/or the relevant sample analysis.

The detailed tasks of these participants will be described in the Science Management Plan.

7.4.4 Data rights

7.4.4.1 Payload data

The data from the MarcoPolo-R payload will be made available in compliance with the established ESA rules concerning information and data rights and release policy. The PI teams will have a proprietary period where they can use the data within their team only, for scientific publications. After the proprietary period, the data has to be made available to the wider scientific community. The detailed data delivery schedule will be defined in the Archive Plan, which will have to be agreed and signed by all PIs. Currently, a proprietary period of 6 months from receipt of the original science telemetry is envisaged.

The PIs will also be required to share data with the IDSs so as to enhance the scientific return from the mission, in accordance with procedures to be agreed and formalised within the SWT.

The PI teams will provide raw data and all relevant information on calibration and instrument properties to the MarcoPolo-R science data archive. The data format will be such that the data can be ingested into the Planetary Science Archive (PSA).

The Science Operations Centre (SOC) of ESA will be working together closely with the PI teams to produce data processing pipelines ensuring that the received data can be ingested quickly into the PSA. It will not perform any scientific analysis of the data. The PI teams will support the preparation of data processing pipelines installed at the SOC.

Scientific results from the mission have to be published by the PI teams in a timely manner, in appropriate scientific and technical journals. Proper acknowledgement of the services supplied by ESA will be made.

A Memorandum of Understanding between the involved agencies will be required to set:

- The data policy rules, the selected format and the length of the period after which the data have to become available to any user of the PSA;
- The criteria that will be adopted for the selection of the proposals of the study of the NEA sample resulting from a call to the worldwide scientific community on a competitive basis.

The PI teams will provide the agency(ies) with processed and useable data for Public Outreach purposes as soon as possible after their reception. The PI teams will also engage in supporting a Science Communication Plan.

7.4.4.2 Sample analysis

The main scientific legacy of MarcoPolo-R will be the returned sample and the data derived from its measurements. A detailed data policy will have to be agreed later in the mission. Currently, it is envisaged that the data evaluation will follow closely the already established ways of previous sample return missions such as Stardust or Hayabusa.

Preliminary Examination Teams (PET) will be established before the return of the sample to Earth. It will comprise leading experts in the appropriate fields. Shortly after the arrival of the sample on the Earth, the PET will characterise the sample mineralogy, chemistry, isotopic composition, and organic inventory within a defined interval of time (nominally 1 year). It will report their findings to the international community.

After the initial analyses performed by the PET, it will be possible for any scientist to request samples for their own scientific analysis. A sample distribution team will decide on a regular basis on the distribution of samples. All scientists who will be granted samples should publish their results within a certain time to ensure that the complete international community can benefit from the sample.

8 Communications and Outreach

The public outreach possibilities of a mission like MarcoPolo-R are considerable because asteroids fascinate the public, both as examples of targets of space exploration that provide exciting new images and accessible science and because of their potential threat to our planet.

Planetary science and space exploration are at the forefront of worldwide public interest – the Solar System is the only part of the Universe beyond the Earth that is currently within reach of direct exploration rather than remote observation. The challenges of each new step of planetary exploration, from the first close-up views of each of the planets as well as comets and asteroids, followed by the landing of terrestrial robots on alien worlds (from the Luna, Ranger and Surveyor landers on the Moon followed by human exploration with Apollo; to Veneras on Venus, to Viking, Pathfinder, Spirit, Opportunity, Phoenix and MSL on Mars, to NEAR and Hayabusa on asteroids and Huygens at Titan) have all taken place within a single human life-span. Sample return missions (so far from the Moon, the solar wind, a comet and an evolved asteroid) offer the opportunity of bringing back a piece of another world to the Earth. Although there is no direct public access to these samples, people's excitement when they can hold a meteorite coming from space, demonstrates the interest they generate.

As every planetary scientist discovers when giving a public talk on the subject, the impact hazard is a real concern for the public and enhances the curiosity for these small, potentially threatening worlds. Media and popular interest reached a peak when a small rock exploded in the atmosphere over the area of Chelyabinsk (Russia) in February 2013, within 24 hours of a predicted, but unrelated, close approach of a much larger asteroid within the geostationary satellite ring. This subject has inspired the scenario of several Hollywood movies dedicated to the mitigation of an NEA impact (most notably *Deep Impact* and *Armageddon*). The role of NEAs, either directly or indirectly, in the extinction of the dinosaurs is well established in the public psyche, even if the scientific evidence is still not universally regarded as conclusive. What is less commonly appreciated is that impacts have had beneficial as well as destructive effects on Earth over geologic time: impacts may have brought the water and organics that formed the precursors of life but are also implicated in a number of mass extinctions, some of which were even more widespread than the end of the dinosaur era. The baseline target of MarcoPolo-R is a potentially hazardous asteroid, i.e. one whose orbit closely approaches that of the Earth and is large enough to cause widespread damage if it collides with the planet in the future. Although there is no danger in the foreseeable future from this asteroid, MarcoPolo-R provides us with a tool to characterise an asteroid that might be a future threat to our planet, while still addressing the demands of fundamental planetary science.

MarcoPolo-R therefore provides the vehicle for a wide range of outreach opportunities to foster planetary science, space exploration and the role of ESA and European scientists through:

- easily understandable scientific objectives. Asteroids as time capsules record:
  - the properties of the building blocks of the terrestrial planets,
  - the conditions at the beginning of the Solar System,
  - material that pre-dates the Solar System, revealing the properties of stars and interstellar clouds,
  - the link with life and death on the Earth (through the influx of organic material, the terrestrial impact hazard and mass extinctions);
- the excitement of exploration of a primitive Solar System body in our neighbourhood;
- the prospect of having extra-terrestrial samples "in our hands";
- interest maintained by key mission events: launch, Earth fly-by, first detection of the target asteroid, rendezvous, close approaches, very high-resolution characterisation, sample collection, Earth return, capsule landing;
- continued post mission activities leading to the most important science results.

Public awareness of missions is often initiated by particular events reported through the media. Newspapers, magazines and scientific publications are extraordinarily powerful tools for spreading news, which have already been exploited frequently during the assessment study phase of MarcoPolo-R. The world wide web gives everyone the possibility of accessing an immense range of information regarding discoveries as well as new and old projects. Public events associated with scientific conferences are also effective in approaching the general public and increasing their involvement in the mission.

The existing MarcoPolo-R mission web page (http://www.oca.eu/MarcoPolo-R/) will be maintained for both internal communication among the various scientific/technical teams participating in the mission and outreach to the general public. The web page content will be regularly updated, particularly during key mission events and will include the following:

- mission description and mission status;
- upcoming meetings and workshops;
- links to other relevant conferences, workshops and societies;
- an image gallery, multimedia tools, kits for teachers and other public outreach materials and information for the general public.

The project already has a facebook page and the use of other multimedia tools will be investigated to publicise the mission.

We have already set up an Outreach and Public Affairs (OPA) Team composed of some representatives from the scientific and technical teams involved in the mission study, to support the public with outreach material and activities. The OPA team has organized all the MarcoPolo-R workshops carried out during the study phase and will continue after the selection to organize at least one meeting per year designed to provide opportunities for MarcoPolo-R team members to discuss and propose new tools and initiatives in the mission outreach activities.

The excitement of exploration encourages a new generation of scientists through all stages of school to postgraduate researchers.

OPA has produced a series of cartoons presenting MarcoPolo-R (personified as a cute young robot – Fig. 8.1) and describing the on-going activities within the mission study. The full collection of these cartoons is available on the MarcoPolo-R website (https://www.oca.eu/MarcoPolo-R/Cartoon/MarcoPolo-R_Cartoon.html) translated in many languages.

We will develop an educational game and application for mobile devices (smartphones and tablets) and laptops, to “drive” and “command” the MarcoPolo-R spacecraft during the mission. This video game, for 6- to 15-year olds, aims to improve awareness of mathematics, space missions and Solar System bodies.

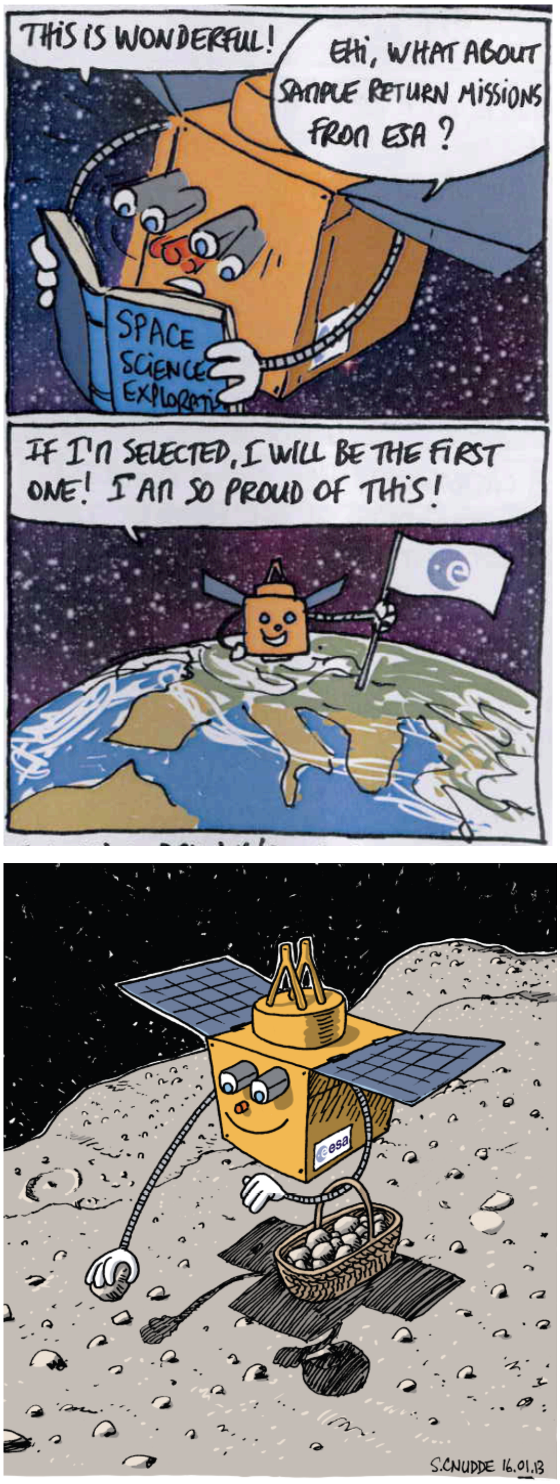


***Figure 8.1**: Example frames from the MarcoPolo-R cartoon series.*

As soon as the mission is selected a call for students in European schools will be organized in collaboration with ESA to name the asteroid 2008 EV5.

Successful outreach campaigns for past missions have fostered a perception of inclusiveness – the spacecraft is seen to belong to all of us and its success will be a shared success. This perception may be of belonging to Europe (e.g. headlines of “First European spacecraft to touch down on an asteroid") but can equally well be seen as a truly international achievement (“We are bringing back pieces of the building blocks of planets"). We will investigate ways to directly associate people with the mission hardware (for example with microchips containing names of mission supporters as included on past missions).

9 References

Abe et al. (2006) *Science* 312, 1344.
Alexander et al. (1998) *Meteorit. Planet. Sci.* 33, 603.
Alexander C.M.O'D. et al. (2007) *Geochim. Cosmochim. Acta* 71, 4380.
Alexander C.M.O'D. et al. (2008) *Science* 320, 1617.
Alexander C.M.O'D., et al. (2011) *Meteorit. Planet. Sci. Suppl.* 74, 5459.
Alexander C.M.O'D. et al. (2012) *Science* 337, 721.
Ali-Lagoa V. et al. (2013) *Astron. Astrophys.* arXiv:1310.6715v1.
Anders E. (1978) In *Asteroids: An Exploration Assessment,* NASA, Chicago, 57.
Andert T.P. et al. (2010) *Geophys. Res. Lett.* 37, 9202.
Andert T.P. et al. (2011) *EPSC-DPS Joint Meeting,* 210.
Asphaug E. (2009) *Ann. Rev. Earth Planet. Sci.* 37, 413.
Azouggagh-McBride S. et. al. (2008), *Adv. Space Res.* 42, 29.
Barnouin-Jha O. et al. (2008) *Icarus* 198, 108.
Barucci M.A. et al. (1987) *Icarus* 72, 304.
Barucci M.A. et al. (1998) *Icarus* 132, 388.
Barucci M.A. et al. (2011) *Astron. Astrophys. Rev***.** 19, 48.
Barucci M.A. et al. (2012) *Planet. Space. Sci.* 66, 23.
Baker J. et al. (2005) *Nature* 436, 1127.
Becker et al. (1999) *Earth Planet. Sci. Lett.* 167, 71.
Bernatowicz T.J. et al. (2003) *Geochim. Cosmochim. Acta* 67, 4679.
Bernatowicz T.J. et al. (2006) In *Meteorites and the Early Solar System II*, Univ. Arizona Press, 109.
Bizzarro M. et al. (2007) *Science* 316, 1178.
Bland P.A. et al. (2006) *Meteorit. Planet. Sci.* 41, 5227.
Bland P.A. et al. (2013) *LPSC* 44, 1447.
Blum J. & Wurm G. (2008) *Ann. Rev. Astron. Astrophys.* 46, 21.
Bodenan J.-D. et al. (2013) *Meteorit. Planet. Space Sci.* 76, #5187.
Borg L.E. et al. (1999) *Science* 286, 90.
Bottke W.F. et al. (2002) *Icarus* 156, 399.
Breiter S. et al. (2009) *Astron. Astrophys.* 507, 1073.
Brearley A.J. (2006) In *Meteoritics and Early Solar System II,* 584.
Britt D.T. et al. (2002) In: *Asteroids III*, Univ. Arizona Press, 485.
Brown P.G. et al. (2013) *Nature,* doi:10.1038/nature12741.
Brownlee D. et al. (2006) *Science* 314, 1711.
Bruckenthal E.A. & Singer R.B. (1987) *LPSC abstracts* 18, 13.
Brunetto R. et al. (2005) *Icarus* 191, 381.
Brunetto R. & Strazzulla G. (2005) *Icarus* 179, 265.
Busch M.W. et al. (2011) *Icarus* 212, 649.
Cairns-Smith A.G. (1985) *Seven Clues to the Origin of Life.* Cambridge University Press.
Callahan M.P. et al. (2011) *PNAS* 108,13995.
Callahan M.P. et al. (2013) *Meteorit. Planet. Sci.* 48, 786.
Cameron A.G.W. & Pine M.R. (1973) *Icarus* 18, 377.
Cami J. et al. (2010) *Science* 329, 1180.
Campins H. et al. (2009) *Astron. Astrophys.* 503, L17.
Campins H. et al. (2013) *Astron. J.* 146, 6.
Cano J. et al. (2013) SSA-SN-VII-DMS-TEC-TNO06, Roadmap for the Advance in NEO Mitigation Measures
Carporzen L. et al. (2011) *PNAS* 108, 6386.
Cataldo F. et al. (2004) In *Astrobiology: Future Perspectives*, Kluwer 305, 97.
Chaussidon M. et al. (2006) *Geochim. Cosmochim. Acta* 70, 224
Chaussidon M. & Gounelle M. (2006) In *Meteorites and the Early Solar System II*, Univ. of Arizona, 323.
Chesley S. et al. (2003) *Science* 302, 1739.
Chyba C. & Sagan C. (1992) *Nature* 355, 125.
Clayton R.N. (1978) *Ann. Rev. Nucl. Part. Sci.* 28, 501.
Clayton R.N. (2002) *Nature* 415, 860.
Cloutis E.A. et al. (2011) *Icarus* 212, 180.
Cody G.D. & Alexander C.M.O'D. (2005) *Geochim. Cosmochim. Acta* 69, 1085.
Connelly J.N. et al. (2008) *Astrophys. J. Lett.* 675, L121.
Connelly J.N. et al. (2012) *Science* 338, 651.
Consolmagno G.J. et al. (2008) *Chemie der Erde – Geochemistry* 68, 1.
Cooper G. et al. (1992) *Geochim. Cosmochim. Acta* 56, 4109.

Coradini et al. (2011) *Science* 334, 492.
Crawford I. (2012) *Astronomy & Geophysics* 53, 2.22
Cronin J.R. & Chang S. (1993) In *The Chemistry of Life's Origin*. Kluwer Academic Publishers, 209.
Dauphas N. & Chaussidon M. (2011) *Ann. Rev. Earth Planet. Sci.* 39, 351.
Delbó M. et al. (2007) *Icarus* 190, 236.
de Leuw S. et al. (2009) *LPSC* 40, 1794.
Derenne S. & Robert F. (2010) *Meteorit. Planet. Sci.* 45, 1461.
Ebihara M. et al. (2011) *Science* 333, 1119.
Ehrenfreund P. & Charnley S.B. (2000) *Ann. Rev. Astron. Astrophys.* 38, 427.
Ehrenfreund P. et al. (2002) *Reports on Progress in Physics* 65, 1427.
Ehrenfreund P. et al. (2006) *Astrobiology* 6/3, 490.
Eigen M. et al. (1981) *Sci. Am.* 244, 88.
Emery J.P. et al. (2008) *Icarus* 136, 104.
Engrand C. & Maurette M. (1998) *Meteorit. Planet. Sci.* 33, 565.
ESA MP-R Study Team (2013) Mission and System Requirements Document, Iss.3.4
Farinella P. & Vokrouhlicky D. (1999) *Science* 283, 1507.
Feigelson E.D. & Montmerlem T. (1999) *Ann. Rev. Astron. Astrophys.* 37, 363.
Franchi I.A. (2008) *Rev. Min. Geochem.* 68, 345.
Fujiwara A. et al. (2006) *Science* 312, 1330.
Gaffey M.J. (1976) *J. Geophys. Res*. 81, 905.
Gaffey M.J. et al. (1993) *Meteoritics* 28, 161.
Galad A. et al. (2009) *Minor Planet Bull.* 36, 116.
Galy A. et al. (2000) *Science* 290, 1751.
Gilbert W. (1986) *Nature* 319, 618.
Gilmour I. & Pillinger C.T. (1994) *Mon. Not. Roy. Astr. Soc.* 269, 235.
Glavin, D. et al. (2010) *Meteorit. Planet. Sci.* 45, 1695.
Glavin, D. & Dworkin, J. (2009) *PNAS* 106, 5487.
Gomes R. et al. (2005) *Nature* 435, 466.
Gounelle M. & Zolensky M.E. (2001) *Meteorit. Planet. Sci.* 36, 1321.
Gounelle M. & Meynet G. (2012) *Astron. Astrophys.* 545, 4.
Gowen R.A. et al. (2010) *Adv. Space Res.* 48, 725.
Gradie J.C. et al. (1989) In *Asteroids II,* Univ. of Arizona Press, 316.
Grady M.M. et al. (2002) *Meteorit. Planet. Sci.* 37, 713.
Groussin et al. (2013) *Icarus* 222, 580.
Gundlach B. & Blum J. (2013) *Icarus* 223, 479.
Hahn J.H.et al. (1988) *Science* 239, 1523
Halbout J. et al. (1986) *Earth Planet. Sci. Lett. 8*0, 1-1.
Hapke B. (2001) *J. Geophys. Res.* E5, 10039.
Harris A.W. et al. (2009) *Icarus* 199, 310.
Hartmann W.K. et al. (2011) *Lunar Planet. Sci.* 42, #1360.
Hartogh P. et al. (2011) *Nature* 478, 218.
Heck P.R. et al. (2009) *Astrophys. J.* 698, 1155.
Henning T. & Salama F. (1998) *Science* 282, 2204.
Herbst E. & van Dishoeck E. (2009) *Ann. Rev. Astron. Astrophys.* 47, 427.
Herrin J.S. et al. (2010) *Meteorit. Planet. Sci.* 45, 1789.
Hester J.J. et al. (2004) *Science* 304, 1116.
Hiroi T. et al. (2001) *Science* 293, 2234.
Holsapple K.A. (2007) *Icarus* 187, 500.
Holsapple K.A. (2010) *Icarus* 205, 430.
Hoppe P. (2010) *Proceedings of Science* (NIC XI) 021.
Hoppe P. et al. (2007) *Meteorit. Planet. Sci.* 42, 1309.
Housen K.R. et al. (1999) *Nature* 402, 155.
Hussmann H. et al. (2012) *Planet. Space Sci.* 70, 102.
Ishiguro M. et al. (2007) *Meteorit. and Plan. Sci.* 42, 1741.
Jacobson S.A. & Scheeres D.J. (2010) *LPSC* 41, 2098.
Jakosky B.M. et al. (1990) *Geophys. Res. Lett.* 17, 985.
James N. (2009) *Acta Astronautica* 64, 1041.
Jenniskens P. et al. (2009) *Nature* 458, 485.
Jenniskens P. et al. (2010) *Meteorit. Planet. Sci.* 45, 1590.
Jewitt D. (2012) *Astron. J.* 143, 66.
Johansen A. et al. (2011) *Astron. Astrophys.* 529, A62.
Joyce G.F. (1989) *Nature* 338, 217.

Joyce G.F. (2002) *Nature* 418, 214.
Jutzi M. & Michel P. (2013) *Icarus*, accepted.
Kanno A. et al. (2003) *Geophys. Res. Lett.* 30, PLA 2-1.
Keays R.R. et al. (1970) *Science* 167, 490.
Keller H.U. et al. 2010. *Science* 327, 190.
Kerridge J.F. et al. (1987) *Geochim. Cosmochim. Acta* 51, 2527.
Krot A.N. et al. (2005) *Nature* 436, 989.
Lagerros J.S.V. (1998) *Astron. Astrophys.* 332, 1123.
Lantz C. et al. (2013) *Astron. Astrophys.* 554, 138.
Larson S.M. et al. (2006) *Bull. Am. Astron. Soc.* 38, 592.
Lazzarin M. et al. (2006) *Astrophys. J.* 647, L179.
Loeffler M.J. et al. (2009) *J. Geophys. Res.* E 114, E03003.
Lewis J.S. (1974) *Science* 186, 440.
Lowry S.C. et al. (2007) *Science* 316, 272.
Lowry S.C. et al. (2013) *Astron. Astrophys.* in press.
Lyon I.C. et al. (2007) *Meteorit. Planet. Sci.* 42, 373.
MarcoPolo-R SST, 2013. MarcoPolo-R Science Requirements Document, MPR-RSSD-RS-001/1.6
Margulis L. & Sagan D. (1995) *What is Life?* New York: Simon and Schuster.
Martin W. et al. (2008) *Nature Reviews Microbiology* 6, 805.
Martins Z. (2012) ln *Life on Earth and other Planetary Bodies*, Springer, 271.
Martins Z. et al. (2007) *Meteorit. Planet. Sci.* 42, 2125.
Martins Z. et al. (2008) *Earth Planet. Sci. Lett.* 270, 130.
Marty B. (2012) *Earth and Plan. Sci. Lett.* 313, 56.
Marty B. et al. (2011) *Science* 332, 1533.
Mayor M. & Queloz D. (1995) *Nature* 378, 355.
McKeegan K.D et al. (2000) *Science* 289, 1334.
McKeegan K.D. et al. (2011) *Science* 332, 1528.
Messenger S. et al. (1998) *Astrophys. J.* 502, 284.
Meyer B.S. & Zinner E. (2006) In *Meteorites and the Early Solar System II,* Univ Arizona Press, 69.
Michel P. (2013) *Acta Astronautica* 90, 6.
Michel P. & Richardson D.C. (2013) *Astron. Astrophys.* 554, L1.
Michel P. & Yoshikawa M. (2006) *Astron. Astrophys.* 449, 817.
Michel P. et al. (2000) *Icarus* 145, 332.
Michel P. et al. (2001) *Science* 294, 1696.
Michel P. et al. (2009) *Icarus* 200, 503.
Montmerle T. et al. (2006) *Earth Moon & Planets* 98, 39.
Morbidelli A. et al. (2006) *Meteorit. Planet. Sci.* 41, 875.
Moroz L. et al. (1996) *Icarus* 122, 366.
Moroz L. et al. (2004) *Icarus* 170, 214.
Morris M.A. et al. (2012) *Astrophys. J.* 752, 27.
Müller M. (2007) *PhD thesis*, Freie Univ. Berlin.
Müller T.G. & Lagerros J.S.V. (1998) *Astron. Astrophys.* 338, 340.
Nagao K. et al. (2011) *Science* 333, 1128.
Nakagawa Y. et al. (1981) *Icarus* 45, 517.
Nakamura T. et al. (2011) *Science* 333, 1113.
Nesvorny D. et al. (2005) *Icarus* 173, 132.
Nguyen A.N. et al. (2007) *Astrophys. J.* 656, 1223.
Noguchi T. et al. (2011) *Science* 333, 1121.
Oparin A.I. (1957) *The Origin of Life on the Earth,* 3rd ed., trans. Ann Synge. Edinburgh: Oliver and Boyd
Ostro S.J. et al. (2006) *Science* 314, 1276.
Palomba E. et al. (2011) *EPSC-DPS* 87.
Pätzold M. et al. (2006) Don Quijote RSE, ESA
Pätzold M. et al. (2011) *Science* 334, 491.
Perozzi E. et al. (2001) *Planet. Space Sci.* 49, 3.
Pizzarello S. et al. (2006) In *Meteorites and the Early Solar System*, Univ. of Arizona Press, 625.
Pizzarello S. et al. (2013) *Proc. Natl Acad. Sci. USA,* http://dx.doi. org/10.1073/pnas.1309113110
Reddy V. et al. (2012) *Icarus* 221, 678.
Richardson D.C. et al. (2002) In *Asteroids III*, Univ. of Arizona Press, 401.
Richardson J.E. et al. (2004) *Science* 306, 1526.
Riner M.A. et al. (2008) *Icarus* 198, 67.
Robert F. (2003) *Space Sci. Rev.* 106, 87.
Robinson M.S. et al. (2002) *Meteorit. Planet. Sci.* 37, 1651.

Rozitis B. & Green S.F. (2011) *Mon. Not. Roy. Astr. Soc.* 415, 2042.
Rozitis B. & Green S.F. (2012) *Mon. Not. Roy. Astr. Soc.* 423, 367.
Rozitis B. & Green S.F. (2013) *Mon. Not. Roy. Astr. Soc.* 433, 603.
Rubincam D.P. (2000) *Icarus* 148, 2.
Rumble D. et al. (2011) *Elements* 7, 23.
Russell S.S. et al. (2006) In *Meteorites and the Early Solar System II*, Univ. Arizona Press, 233.
Safronov V.S. & Ruskol E.L. (1994) *Astrophys. Space Sci.* 212, 13.
Sakamoto N. et al. (2007) *Science* 317, 231.
Sauerbrey G.Z. (1959) *Zeitschrift für Physik* 155, 206
Sasaki S. et al. (2001) *Nature* 410, 555.
Sears D.W.G. & Dodd R.T. (1988) In *Meteorites and the Early Solar System,* Univ. of Arizona Press, 3.
Sephton M.A. et al. (1998) *Geochim. et Cosmochimi. Acta* 62, 1821.
Sephton M.A. (2002) *Natural Product Reports* 19, 292.
Sephton M.A. (2004*) Geochim. Cosmochim. Acta* 68, 1385.
Shaddad M.H. et al. (2010) *Meteorit. Planet. Sci.* 45, 1618.
Shearer C.K. et al. (2011) *Meteorit. & Planet. Sci.* 46, 1345.
Shu F.H. et al. (1994) *Astrophys. J.* 429, 797.
Shu F.H. et al. (1997) *Science* 277, 1475.
Simon J.I. et al. (2011) *Science* 331, 1175.
Simpson, R.A. (1993) *IEEE Transact. Geosci. Remote Sens.* 31, 465.
Spencer J.R. (1990) *Icarus* 83, 27.
Statler T.S. (2009) *Icarus* 202, 502.
Stephan T.R. et al. (1998) *Meteorit. Planet. Sci.* 32, A149.
Stokes G.H. & Yeomans D. (2003) *AGU* abstract #P51E-02.
Strazzulla G. et al. (2005) *Icarus* 174, 31.
Takir D. et al. (2013) *Meteorit. Planet. Sci.* 48, 1618.
Taylor P.A. et al. (2007) *Science* 316, 274.
Thomas P.C. et al. (2002) *Icarus* 155, 18.
Tsuchiyama A. et al. (2008) *IPEWG* Abstract Book.
Tsuchiyama A. et al. (2011) *Science* 333, 1125.
Vernazza P. et al. (2013) *Icarus* 225, 517.
Veverka J. et al. (2001) *Science* 292, 484.
Villeneuve J. (2011) *Ph.D. thesis, Nancy.*
Vokrouhlicky D. et al. (2007) *Icarus* 191, 636.
Walsh K. et al. (2008) *Nature* 454, 188.
Walsh K. et al. (2011) *Nature* 475, 206.
Wasson J.T. (1974) *Meteorites: Classification and Properties,* Springer Verlag New York, 327.
Weiler R. et al. (2006) In *Meteorites and the Early Solar System II*, Univ. of Arizona Press, 499.
Wetherill G.W. (1975) *Ann. Rev. Nuc. Particle Sci.* 25, 283.
Yamada M. et al. (1999) *LPSC 30,* 1566.
Young E.D. (2007) *Earth Planet. Sci. Lett.* 262, 468.
Young E.D. et al. (1999) *Science* 286, 1331.
Yurimoto H. & Kuramoto K. (2004) *Science* 305, 1763.
Zinner E.K. (2005) In *Meteorites, Comets and Planets*, Elsevier 17.
Zolensky M.E. et al. (2006) *Science* 314, 1735.

10 Appendix A: List of scientific working groups with their chairs

Working Group	Subgroup	Chair, Co-Chair
Global and Local Characterisation	Spectral and optical properties	J. Licandro, A. Fitzsimmons
	Mechanical properties	A. Campo Bagatin
	Surfaces	K. Muinonen
	Thermal properties	M. Delbó
	Morphology	S. Marchi
	Mass, gravity field	T. Andert
Sampling site selection		J. Oberst
Sampling mechanism/strategy	Design & approach	A. Cheng
	Regolith development	A.C. Levasseur-Regourd
Remote-sensing payloads		S. Fornasier
Lander		S. Ulamec
Laboratory analysis	Chemical composition	F. Brenker
	Mineralogy	G. Baratta
	Elemental/isotopic composition	L. Remusat
	Space weathering	J. M. Trigo-Rodríguez
Curation facility		J. Aléon
Astrobiology		H. Cottin & Z. Martins
Public outreach		M. Fulchignoni
Astrometry		M. Birlan
Backup target identification		M. Mueller

The complete list of working group members can be found here: http://www.oca.eu/MarcoPolo-R/WorkingGroups/WorkingGroupsMarcoPolo-R.html.

11 Appendix B: List of Acronyms

AIT	Assembly, Integration, and Test
AIV	Assembly, Integration, and Verification
AO	Announcement of Opportunity
AOCS	Attitude Orbit Control System
APL	Applied Physics Laboratory
ARD	Atmospheric Re-entry Demonstrator
ASI	Italian Space Agency
ATLAS	Advanced Technology for Lightweight Ablative System
BSR	Bi-Static Radar
CAI	Calcium-Aluminium Inclusion
CMOS	Complementary Metal-Oxid Semiconductor
CODMAC	Committee on Data Management, Archiving, and Computation
CNES	Centre Nationale d'Etudes Spaciale
CS-IR-MS	Compund Specific Isotope Ratio Mass Spectrometry
CT	Computed Tomography
CLUPI	Close-Up Imager (for ExoMars)
CUC	Close-Up Camera
DC	Direct Current
DLR	Deutsche Agentur für Luft- und Raumfahrt
DNA	Deoxyribonucleic Acid
DPU	Data Processing Unit
DSM	Deep Space Manoeuvre
EDX	Energy Dispersive X-ray Spectroscopy
EJSM	Europa Jupiter System Mission
EPMA	Electron Micro-Probe Analyser
ERC	Earth Return Capsule
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
ESTEC	European Space Technology Centre
ESTRACK	European Space Tracking network
EVA	Extra-Vehicular Activity
FCP	Flight Control Plan
FDIR	Failure Detection, Isolation, and Recovery
FESEM	Field Emission Scanning Electron Microscopy
FIB	Focused Ion Beam
FTIR	Fourier transform infrared spectroscopy
FoV	Field of View
GC-MS	Gas Chromatography - Mass Spectroscopy
GCP	Global Characterisation Phase
GNC	Guidance, Navigation, and Control
GS-MS	Gas Source Mass Spectrometry
HGA	High-Gain Antenna
HPLC	High-performance liquid chromatography
IAC	Instituto de Astrofisica de Canarias
ICPMS	Inductively Coupled Plasma Mass Spectrometry
IDP	Interplanetary Dust Particle
IDS	Inter-Disciplinary Scientist
IECM	Induced Environment Contamination Monitor
IFOV	Intrinsic Field of View (of one pixel)
INAF	National Institute for Astrophysics
IOM	Insoluble Organic Matter
IRCAM	Infrared Camera on board the Extreme Universe Space Exploratory
ISL	Institut Saint Louis
ISM	Interstellar Medium
ISO	International Standardisation Organisation
ITT	Invitation to Tender
IMM	Institute for Microelectronics
JAXA	Japan Aerospace Exploration Agency
LA-ICPMS	Laser Ablation ICPMS
LC-MS	Liquid chromatography – mass spectrometry
LCP	Local Characterisation Phase
LEOP	Low-Earth Operations Phase
LGA	Low-Gain Antenna
LIDAR	Light Detection and Ranging
LISA	Laser Interferometric Space Antenna
LVDS	Low Voltage Differential Signaling
MAG	Mission Analysis Guidelines
MaRIS	MarcoPolo-R Imaging Spectrometer
MBA	Micro-Balance Assembly (on Smart-1)
MC-ICPMS	Multi-Collection ICPMS
MCT	Mercury Cadmium Telluride

MEC	Ministry of Economy and Competivity (Spain)
MGA	Medium-Gain Antenna
MOC	Mission Operations Centre
MP-R	MarcoPolo-R
MPRISM	MarcoPolo-R Integrated Sampling Mechanism
MSL	Mars Surface Laboratory
MSX	Midcourse Space Experiment
MTF	Modulation Transfer Function
NAC	Narrow Angle Camera
NAIF	Navigation and Ancillary Information Facility (of JPL, USA)
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
NG-MS	Noble Gas Mass Spectrmetry
NMR	Nuclear Magnetic Resonance
OGS	Operational Ground Segment
PET	Preliminary Examination Team
PHA	Potentially Hazardous Asteroid
PI	Principle Investigator
PICA	Phenolic Impregnated Carbon Ablator
PRR	Preliminary Requirements Review
PS	Project Scientist
PSA	Planetary Science Archive
RMS	Root Mean Square
RNA	Ribonucleic Acid
RSE	Radio Science Experiment
RSP	Radio Science Phase
S/C	Spacecraft
SAM	Sample Acquisition Mechanism
SAMMES	Space Active Modular Materials Experiment
SATCS	Sampling Acquisition and Transfer System
Sci-RD	Science Requirements Document
SCOS	Spacecraft Control and Operation System
SEM	Scanning Electron Microscope
SGS	Science Ground Segment
SIMBIOSYS	Spectrometers and Imagers for MPO BepiColombo Integrated Observatory SYStem
SIMS	Secondary Ionisation Mass Spectrometry
SMP	Science Management Plan
SNR	Signal to Noise Ratio
SOAD	Science Operations Assumptions Document
SOC	Science Operations Centre
SPC	Science Programme Committee
SPICE	Spacecraft ephemerides, Planet, Instrument, Pointing, Events - s/w library from NAIF
SRE	Science and Robotic Exploration Directorate
SRE-O	Operations Department of SRE
SRR	System Requirements Review
SST	Science Study Team
STFC	Science and Technology Facilities Council
STR	Star Tracker
SWT	Science Working Team
TAGSAM	Touch-And-Go Sample Acquisition Mechanism
TBC	to be confirmed
TBD	to be determined
TC	Telecommand
TEM	Transmitting Electron Microscope
TIMS	Thermal Ionisation Mass Spectrometry
THERMAP	Thermal Mapper (for MarcoPolo-R)
TMA	Three-Mirror Anastigmat
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking and Command
UHF	Ultra-High Frequency
UHV	Ultra-High Vacuum
UKSA	United Kingdom Space Agency
UV	Ultraviolet
VHF	Very-High Frequency
VISTA2	Volatile In-Situ Thermogravimetry Analyser
WAC	Wide Angle Camera
XANES	X-ray Absorption Near-Edge Structure
XPS	X-ray photoelectron spectroscopy
XRS	X-ray Spectroscopy
ΔDOR	delta-DOR = delta Differential One-way Ranging
μL^2-MS	Micro Two-Step Laser Mass Spectrometry

12 Appendix C: Credits

In addition to the core SST and the PIs, we acknowledge the contribution to this report of H. Böhnhardt (MPS) and international partners: M. Yoshikawa (JAXA), as well as A. Cheng (APL) and C. Reed (APL) representing the NASA contribution study (see http://us-marcopolor.jhuapl.edu). Scientific working groups provided input that was taken into account in the writing of this report; the chair persons of these working groups are given in Appendix A. We acknowledge the support of national funding agencies: ASI Italy, Canton Neuchatel and SERI/SSO Switzerland, CNES France, DLR Germany, MEC Spain, STFC/UKSA United Kingdom.