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BepiColombo Venus flyby Science Operations Feasibility Analysis

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BepiColombo is an interdisciplinary ESA mission to explore the planet Mercury in cooperation with the Japan Aerospace Exploration Agency (JAXA). The mission consists of 2 spacecraft, ESA's Mercury Planetary Orbiter (MPO) and JAXA's Mercury Magnetospheric Orbiter (MMO) that carry in total 17 science payloads for the investigation of Mercury's structure, interior, composition, morphology, formation, evolution and environment. The Mercury Composite Spacecraft (MCS) made of MPO, MMO, a Mercury Transfer Module (MTM) and a sunshield (MOSIF) will be launched on an escape trajectory that will bring it into heliocentric orbit on its way to Mercury. During the cruise of 7.2 years toward the inner part of the Solar System, BepiColombo will make 1 flyby to the Earth, 2 to Venus, and 6 to Mercury. Only part of its payload will be obstructed by the sunshield and the cruise spacecraft configuration, so that the flybys will allow operations of many instruments, like: spectrometers at many wavelengths, accelerometer, radiometer, ion and electron detectors. A scientific working group (VFBWG, Venus Fly-by Working Group) has recently formed inside the BepiColombo community to identify potentially interesting scientific cases and to promote collaborations during the Venus flybys. At the same time, analyses of science operations requests has been carried out by the Science Ground Segment (SGS) at ESAC and the Operational Ground Segment (OGS) at ESOC to help scientists in the comprehension of feasibility of proposed investigations. The analysis of science observations includes special spacecraft pointing feasibility analysis taking into account the attitude constraints. During interplanetary cruise and outside electric propulsion, the default attitude of the MCS is +Y axis pointed to the Sun. The spacecraft attitude is then adjusted by ground around the sun line such that the angular momentum loading is minimized while ground contact is maximized during ground station passes. For the short duration of scientific interest around the Venus

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closest approaches however, the need for angular momentum load minimization can be relaxed and it is possible to offset the Sun direction in the spacecraft composite +YZ plane. The SGS at ESAC developed a tool that allows to check the possibility of observing Venus in different spacecraft configurations for different instruments, for example finding out when Venus is inside a given instrument FoV. With that tool and based on the scientific instruments pointing requests, candidate pointing timelines were extracted, indicating that it is possible to find a suitable spacecraft composite attitude to provide observing opportunities to most instruments requiring specific spacecraft pointing. In addition, the OGS at ESOC analysed the impact of the received scientific requests on power balance, thermal balance and data return and found well within the as-designed capability of the spacecraft. This paper includes a summary of the scientific requests, the analysis carried out by both SGS and OGS and the results of the analysis.

Nomenclature

AU	=	Astronomical unit
CA	=	Closest Approach
BELA	=	BepiColombo Laser Altimeter
ELENA	=	Emitted Low Energy Neutral Atoms
ENA	=	Energetic Neutral Atoms
ESA	=	European Space Agency
ESAC	=	European Space Astronomy Centre
ESOC	=	European Space Operations Centre
FOV	=	Field of View
HEP	=	High-Energy Ions
ISA	=	Italian Spring Accelerometer
ISAS	=	Institute of Space and Astronautical Science
JAXA	=	Japan Aerospace Exploration Agency
MAG	=	Magnetometer
MCS	=	Mercury Composite Spacecraft
MTM	=	Mercury Transfer Module
MEA	=	Mercury Electron Analyzer
MERTIS	=	Mercury Thermal Infrared Imaging Spectrometer
MGNS	=	Mercury Gamma-Ray and Neutron Spectrometer
MIA	=	Mercury Ion Analyzer
MIPA	=	Miniature Ion Precipitation Analyzer
MIXS	=	Mercury Imaging X-ray Spectrometer
MMO	=	Mercury Magnetospheric Orbiter
MORE	=	Mercury Orbiter Radio Science Experiment
MOSIF	=	MMO Sunshield and Interface Structure
MPO	=	Mercury Planetary Orbiter
MPPE	=	Mercury Plasma Particle Experiment
MSA	=	Ion Mass Spectrometer
N/A	=	Not Applicable
OGS	=	Operational Ground Segment
PHEBUS	=	Probing of Hermean Exosphere by Ultraviolet Spectroscopy
PICAM	=	Planetary Ion Camera
SERENA	=	Search for Exospheric Refilling and Emitted Natural Abundances
SGS	=	Science Ground Segment
SIMBIO-SYS	=	Spectrometers and Imagers for MPO BepiColombo Integrated Observatory System
SIXS	=	Solar Intensity X-ray and particle Spectrometer
SSOC	=	ISAS/JAXA Sagami-hara Space Operation Centre

I. Introduction

BepiColombo is an interdisciplinary ESA mission to explore the planet Mercury in cooperation with the Japan Aerospace Exploration Agency (JAXA).

The mission consists of 2 spacecraft, ESA's Mercury Planetary Orbiter (MPO) and JAXA's Mercury Magnetospheric Orbiter (MMO) that, between them, carry in total 17 science payloads for the investigation of Mercury's structure, interior, composition, morphology, formation, evolution and environment. The MPO will study the surface and internal composition of the planet, and the MMO will study Mercury's magnetosphere, that is, the region of space around the planet that is influenced by its magnetic field.

During the launch and the cruise to Mercury, the MPO and the MMO will be carried as part of the Mercury Composite Spacecraft (MCS). The MCS comprises, in addition to the two orbiters, the Mercury Transfer Module (MTM), which provides solar-electric propulsion and all services not required in Mercury orbit, and the MMO Sunshield and Interface Structure (MOSIF), which provides thermal protection and the mechanical and electrical interfaces for the MMO. ESA is building the MTM and the MOSIF. Shortly before Mercury orbit insertion, the MTM is jettisoned from the spacecraft stack. The MPO provides the MMO with the necessary resources and services until it is delivered into its mission orbit, when control is assumed by JAXA. After launch in October 2018 into Earth-escape orbit, the MCS will undergo a near-Earth commissioning phase. Leaving Earth on its way to Mercury, the spacecraft must decelerate against the Sun's gravitational attraction, which increases as it approaches the Sun. This is in contrast to accelerating away from the Sun, as is the case with journeys to the outer Solar System. In addition, the spacecraft orbital plane shall be changed to that of Mercury. BepiColombo will accomplish this deceleration and plane change by making clever use of the gravity of the Earth, Venus and Mercury itself, and by using solar-electric propulsion (SEP).

Only part of its payload will be obstructed by the sunshield and the cruise spacecraft configuration, so that the flybys will allow operations of many instruments, like: spectrometers at many wavelengths, accelerometer, radiometer, ion and electron detectors.

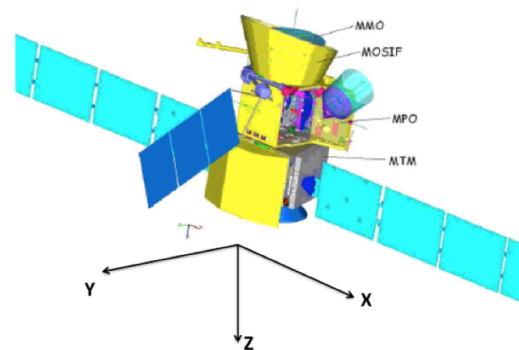


Figure 1. MCS Spacecraft Configuration. *The MCS is the composite spacecraft during cruise phase*

II. Bepicolombo Venus flybys geometry

BepiColombo will be launched as single payload on an Ariane 5 ECA rocket in October/November 2018. The first Earth flyby in April 2020 is used to deflect the spacecraft towards a Venus orbit. Two consecutive Venus flybys will reduce the perihelion to nearly Mercury distance. A sequence of 6 Mercury flybys together with thrust arcs will reduce the relative velocity such that the spacecraft will be weakly captured by Mercury on December 2025. In case of a launch delay, BepiColombo will be launched in April 2019 with no change in schedule or trajectory.

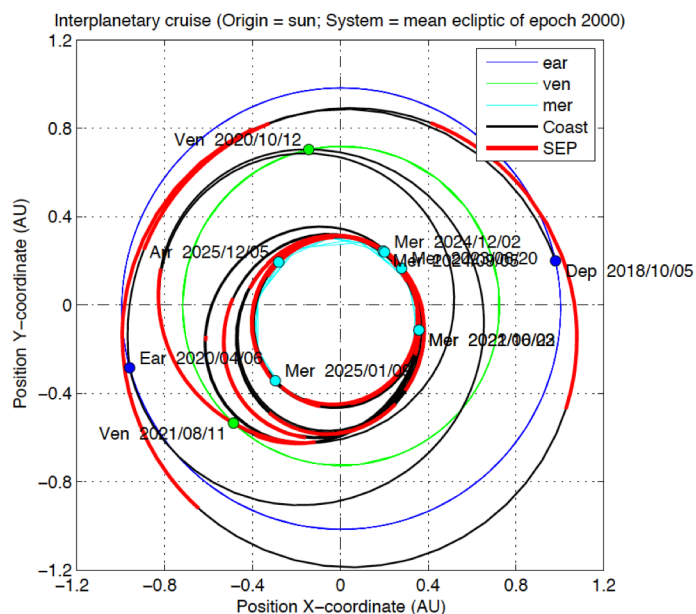


Figure 2. Interplanetary cruise. *The interplanetary cruise comprises 1 Earth, 2 Venus and 6 Mercury flybys*

The two Venus flybys will take place in 2020 and 2021 respectively (see main characteristics in Table 1).

	Venus flyby 1	Venus flyby 2
Date	12-Oct-2020	11-Aug-2021
Closest Approach (km)	11317	1000
Electric propulsion end before closest approach	N/A	CA-30d
Electric propulsion start after closest approach	N/A	CA+7d
Sun distance (AU)	0.72	0.72
Eclipse duration (mn)	0	0
Occultation duration (mn)	0	0
Sun-Earth-Probe angle (deg)	38	35
Earth distance (AU)	1.17	1.25
X-TM bit rate (kbps)	65.3	52.2

Table 1: Venus flybys characteristics

The first Venus flyby will take place in October 2020, with a closest approach altitude of 11317 km and a geometry depicted in Figure 3. The second Venus flyby will take place in August 2021 with a closest approach altitude of 1000 km imposed by thermal reasons, shown in Figure 4.

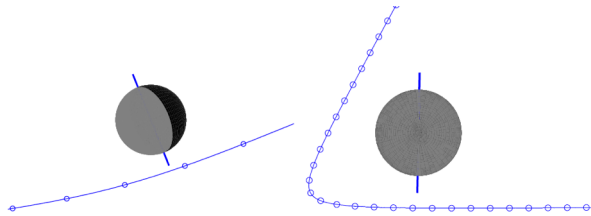


Figure 3. 1st Venus Flyby. *Venus 1 flyby as seen from Earth (left) and from the Sun (right). Tick marks are drawn every 20 minutes*

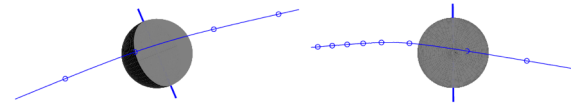


Figure 4. 2nd Venus Flyby. *Venus 2 flyby as seen from Earth (left) and from the Sun (right). Tick marks are drawn every 20 minutes*

During interplanetary cruise and outside electric propulsion, the default spacecraft composite attitude is +Y axis pointed to the Sun. Taking this into account further geometry information in terms of spacecraft altitude over Venus, Venus apparent angular diameter, and Venus angular distance to -Y axis can be derived as shown in Figure 5.

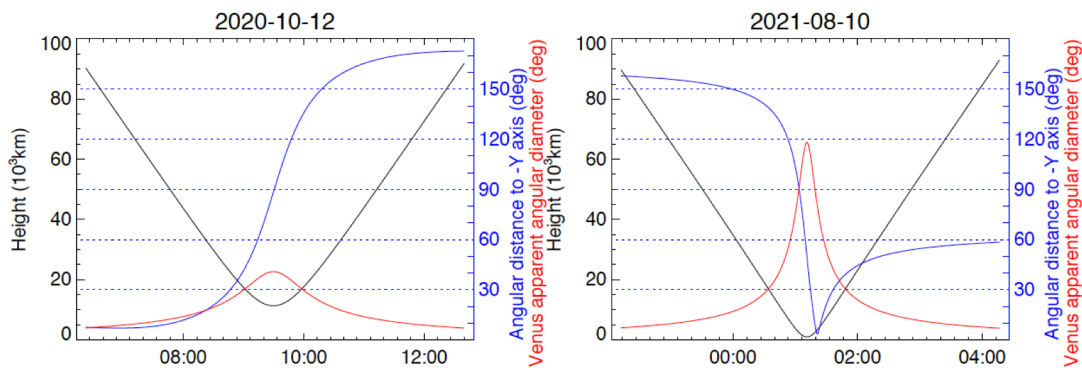


Figure 5. Venus Flyby angular info. *Spacecraft altitude over Venus, Venus apparent angular diameter and Venus angular distance to -Y axis*

The most interesting geometrical aspect is that for Venus swingby 2, the composite spacecraft flies over the sunlit part of Venus, thereby providing Venus visibility to instruments with a field of view on $-Y$.

III. Spacecraft Attitude constraints

During interplanetary cruise and outside electric propulsion, the default spacecraft composite attitude is $+Y$ axis pointed to the Sun. The spacecraft attitude is then adjusted by ground around the sun line such that the angular momentum loading is minimized while ground contact is maximized during ground station passes. For the short duration of scientific interest around the Venus closest approaches however, the need for angular momentum load minimization can be relaxed. What remains are the general attitude constraints. According to these constraints, at a Sun distance of 0.7 AU, it is possible to offset the Sun direction in the spacecraft composite $+YZ$ plan, in the range of $+27$ to -14 degrees. A roll phase around the Sun direction is also possible (360 degrees rotation).

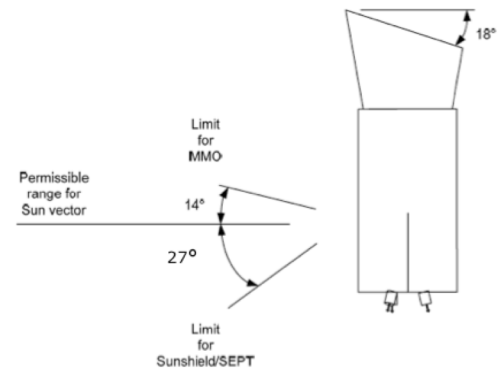


Figure 6. Attitude Constraints. Sun vector range in YZ plane

IV. Scientific instruments

A. MPO scientific instruments

The MPO has 11 instruments or instruments suites summarized in Table 2. Only the instruments whose baffle is not obstructed by the MTM could observe at the Venus flybys.

Instrument	Long Name	Scientific Objective	Observing at Venus
BELA	BepiColombo Laser Altimeter	Mercury surface topographic mapping	NO
ISA	Italian Spring Accelerometer	Non-gravitational acceleration measurements of the spacecraft	YES
MPO-MAG	Mercury Magnetometer	Measurement of Mercury magnetic field, its source and interaction with solar wind	YES
MERTIS	Mercury Thermal & Infra-red spectrometer	Global mineralogical mapping, surface temperature and thermal inertia	YES (only the space view)
MGNS	Mercury Gamma-ray & Neutron Spectrometer	Elemental surface and sub-surface composition, volatile deposits on polar areas	YES
MIXS	Mercury Imaging X-ray Spectrometer	Elemental surface composition, global mapping and composition of surface areas	NO
MORE	Mercury Orbiter Radio-science Experiment	Core and mantle structure, Mercury orbit, fundamental science, gravity field	YES
PHEBUS	Probing of Hermean Exosphere by Ultraviolet Spectroscopy	UV spectral mapping of the exosphere	YES
SERENA	Search for Exospheric Refilling and Emitted Natural Abundances	In-Situ study of composition, vertical structure and source and sink process of the exosphere	YES (only MIPA and PICAM units)
SIMBIO-SYS	Spectrometer & Imagers for MPO BepiColombo - System	Optical high-resolution and stereo imaging. Near-IR imaging spectroscopy for global mineralogical mapping	NO
SIXS	SIXS Solar Intensity X-ray and Particle Spectrometer	Monitor for solar X-ray intensity and solar particles in support of MIXS	YES

Table 2: MPO scientific instruments

B. MMO scientific instruments

The MPO has 5 instruments suites, of which 3 of them could observe during the Venus flybys even if partially obstructed by the MOSIF shield.

Instrument	Long Name	Scientific Objective	Observing at Venus
MPPE	<i>Mercury Electron Analyzer (MEA)</i>	<i>Low-energy electrons</i>	<i>YES</i>
	<i>Mercury Ion Analyzer (MIA)</i>	<i>Low-energy ions</i>	<i>YES</i>
	<i>Ion Mass Spectrometer (MSA)</i>	<i>Ion mass spectroscopy</i>	<i>YES</i>
	<i>High-Energy Ions (HEP-ion)</i>	<i>High-Energy Ions</i>	<i>YES</i>
	<i>High-Energy Electrons (HEP-ele)</i>	<i>High-Energy Electrons</i>	<i>YES</i>
	<i>Energetic Neutral Atoms (ENA)</i>	<i>Plasma imaging</i>	<i>YES</i>
MGF	<i>Magnetometer</i>	<i>Magnetic field</i>	<i>YES</i>
PWI	<i>Plasma Wave Investigation</i>	<i>Electric field, Plasma wave, Radio wave</i>	<i>YES</i>
MSASI	<i>Mercury Sodium Atmosphere Spectral Imager</i>	<i>Na-atmosphere image</i>	<i>NO</i>
MDM	<i>Mercury Dust Monitor</i>	<i>Interplanetary dust</i>	<i>NO</i>

Table 3: MMO scientific instruments

V. Science operations request

Teams of the MPO and MMO scientific instruments that could observe during the cruise phase of Bepicolombo have provided science operations request for the Venus flybys, relative to the Venus closest approach. They have been analysed by the Science Ground Segment at ESAC and the Operational Ground Segment at ESOC.

C. ISA

The ISA acceleration measurements during the flyby will allow the analysis of gravity gradients induced by Venus gravitational field. For that the instrument requires to be switched on between 2-3 days before and after Venus closest approach. No special MCS attitude is required.

D. MPO-MAG

The MPO-MAG magnetometer will measure in nominal mode 24 hours before and after the closest flyby. The data analysis will concentrate on the identification of flux robes. No special MCS attitude is required.

E. MERTIS

The MERTIS space baffle is located in the radiator and points towards the -Y axis. The field-of-view is 4 degrees in the XY plane 1 degree in the YZ plane. Through this baffle, the MERTIS spectrometer measurements in the 7-14 μm spectral range will allow to study cloud parameters from 55 to 100 km through the sounding of CO_2 , SO_2 , H_2SO_4 and aerosol properties. These measurements will be the first spectrally resolved observations since the Venera 15 mission in 1983. For that the instrument requires Venus to pass through the field of view of the radiator baffle, when the distance to Venus is less than 1700000 km. Special MCS attitude is required to fulfil that request.

MERTIS space baffle is located in the radiator pointing towards -Y axis, which field of view has a 4 degrees opening angle in the XY plane and 1 degree in YZ plane. In addition, MERTIS will acquire data of "Venus as an Exoplanet", observing the planet from the distance with sub-pixel resolution. MERTIS will obtain time series of spectra that will be analyzed to test retrieval algorithms commonly used for determining the (cloud) rotation period as well as information about the cloud structure.

F. MGNS

The MGNS instrument will operate its neutrom and γ -ray detectors to identify lines originating from the Venus surface and fluxes of Na, Fe, Ti, Al, Mg, Si, Ca, O + radioisotopes K, U, Th plus detection of volatile deposits and H. MGNS does not require a specific spacecraft attitude for its observations, but due to the spacecraft composite configuration, the quality of the MGNS observation would be improved, if Venus would be in the spacecraft -X direction.

G. MORE

The MORE radio science experiment will operate the X-band and Ka-band in tracking mode (TBC). The measurements will allow to improve of planetary ephemerides. Tracking info (1 pass per day) during 3 days before and after closest approach will be needed. No special MCS attitude is required.

H. PHEBUS

PHEBUS spectrometer would like to perform an UV star occultation in the night side of Venus in order to measure the UV intensity from a given level (from the selected star) to "0" when occulted. The star occultation should be performed perpendicular to the limb. Inertial MCS attitude and PHEBUS baffle position will be required to fulfil this request, that should be kept fixed too. PHEBUS instrument is sitting behind the radiator with a rotating baffle extending through the radiator. The baffle allows 360° rotation and as it is angled at 10° from the radiator. The instrument Field of View is defined by the spectrometer slit size (5.6 x 0.28 mm). With a focal length of 170 mm, it corresponds to $\sim 2^\circ \times 0.1^\circ$ projected on the horizon. A baffle parking bracket obscures the field of view a 35 degrees angle interval.

I. SERENA

SERENA instrument consist of 4 units: ELENA, STROFIO, PICAM and MIPA. Only PICAM and MIPA are not obstructed by the MTM, and would be able to do science during the Venus swing by.

MIPA is an ion analyser with a field of view of half hemisphere designed to measure positively charged particles of hot plasma with energies ranging from 10 eV/q to 15 keV/q. Data will allow the analysis of the solar wind, boundary crossings, pick-up ions from bow shock, ion escape flux and Venus ionosphere composition.

MIPA unit is located behind the radiator in the -X panel, below PICAM unit, pointing along the -X-axis. No special MCS attitude is required.

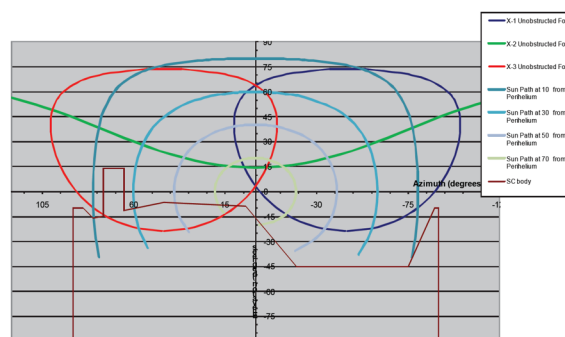


Figure 18 SIXS-X detectors' fields of view

Figure 7. SIXS FoV. *SIXS-X detectors field of view (FoV) without MOSIF obstruction*

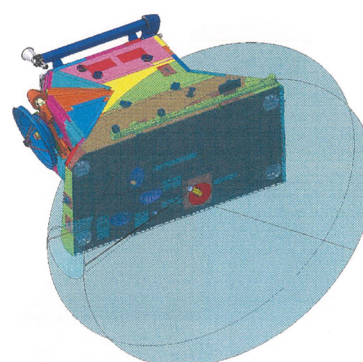


Figure 8. PHEBUS FoV. *PHEBUS 360 degrees rotation coverage*

PICAM is an ion mass spectrometer able to derive velocity distributions and mass spectrum for ions over a half hemisphere. The detector is sensitive to ion of up to 3 keV and a mass range up to 132 amu. The obtained data can be used to analyse solar wind pick-up ions and the ion population in the terminator/wake region as well as in the plasma boundaries. PICAM unit is located behind the radiator in the -X panel, pointing along the -X-axis. No special MCS attitude is required. PICAM would operate one hour before and after the closest approach.

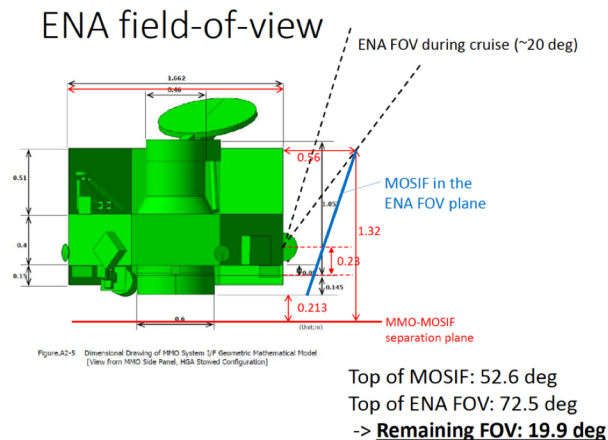


Figure 9. MME-ENA FoV. ENA field of view during cruise phase

K. MPPE-ENA

The Mercury Particle and Plasma Experiment (MPPE-ENA) measures energetic neutral atoms in the energy range 10 eV to 3.3 keV. The obtained data will allow to analyze the energetic neutral atoms of the Venus environment: detection of H, He, O, Na/Mg-group, K/Ca-group, Fe. ENA would like to have Venus in its field of view, which is partially obstructed by the MOSIF, see Figure 9. The remaining field of view is 19.9 degrees.

L. MPPE-HEP-ele

The MPPE-HEP-ele detector, a high-energy particle detector for electrons, measures electrons in the energy range from 30 to 700 keV, and would like to detect electron populations at selected ranges in the Venus environment. The HEP-ele detector would benefit having Venus in its field-of-view, which is partially obstructed by the MOSIF. The remaining field-of-view is 14 degrees.

M. MPPE-LEP

MPPE-LEP detector MPPE-LEP would like to have Venus in its field of view (FoV), which is a circular FoV of 5 degrees from MMO +Z direction (-Z-axis of the MCS).

N. PWI

The Plasma Wave Instrument (PWI) would like to measure the plasma wave at Venus and does not have specific pointing requirements for their observation.

O. MGF

J. SIXS

SIXS instrument consist of two detectors: a X-ray spectrometer (SIXS-X) in the range of 1-20 keV, and a particle detector (SIXS-P) in the energy range 0.33-30 MeV for protons and 50keV-3Mev for electrons. Both detectors are mounted on the spacecraft -Z axis with a supporting bracket, which holds the instrument on top of the Magnetometer Boom. The particle detector dome is located on the top of the unit and three X-ray detectors are located on three side panels of the instrument main body. The three X-ray detectors each covering a solid angle larger than $\pi/2$ (sterad). Altogether, the X-ray detection field of view of at least π (sterad) is able to cover a continuous quarter of the sky. In the MCS configuration the MOSIF partially obstructs the SIXS-X detectors field of view (two of them are totally obstructed and one of them, the one "looking" in the -Z axis direction is partially obstructed. No special MCS attitude is required.

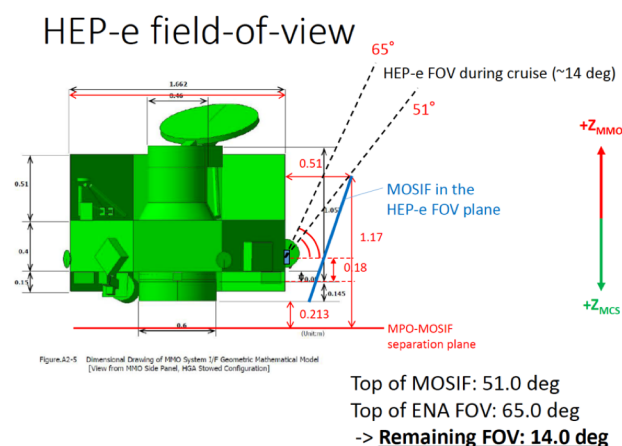


Figure 10. HEP-ele FoV. ENA field of view during cruise phase

MGF would like to make magnetometer measurements at Venus and does not have specific pointing requirements for their observation.

P. Summary of science operations requests

A summary of the science operations request for all the scientific instruments wrt the Venus Closest approach (CA) is provided in Table 4.

<i>Instrument</i>	<i>Start</i>	<i>End</i>	<i>Pointing</i>	<i>Remarks</i>
<i>ISA</i>	<i>CA – 2/3d</i>	<i>CA + 2/3d</i>	<i>No</i>	
<i>MERMAG</i>	<i>CA – 1d</i>	<i>CA + 1d</i>	<i>No</i>	
<i>MERTIS</i>	<i>As per visibility – max. few hours around CA</i>	<i>As per visibility – max. few hours around CA</i>	<i>Yes</i>	
<i>MGNS</i>	<i>CA – 6h</i>	<i>CA + 6h</i>	<i>Yes</i>	<i>Pointing is to optimize observation conditions.</i>
<i>MORE</i>	<i>CA – 3d</i>	<i>CA + 3d</i>	<i>N/A</i>	<i>MORE is piggy back. Tracking over closest approach is desirable. One pass per day is sufficient.</i>
<i>PHEBUS</i>	<i>As per visibility – CA-1d (earliest start)</i>	<i>As per visibility – CA+1d (latest end)</i>	<i>Yes</i>	
<i>SERENA MIPA</i>	<i>VSB1: CA -4h VSB2: CA-72h (TBD)</i>	<i>VSB1: CA+72h (TBD) VSB2: CA+4h</i>	<i>No</i>	<i>Provided timeline depends on the details of the trajectory.</i>
<i>SERENA PICAM</i>	<i>CA – 1h</i>	<i>CA + 1h</i>	<i>No</i>	
<i>SIXS</i>	<i>CA-1d</i>	<i>CA+6h</i>	<i>No</i>	
<i>MMO</i>	<i>CA – 12h</i>	<i>CA + 1h</i>		
<i>MPPE ENA</i>			<i>Yes</i>	
<i>MPPE HEP-ele</i>			<i>Yes</i>	
<i>MPPE LEP</i>			<i>Yes</i>	
<i>PWI/SC</i>			<i>No</i>	
<i>MGF</i>			<i>No</i>	

Table 4: Summary of science operations requests

VI. Operational Analysis

Science operations requests for the Venus flybys have to be analysed from pointing feasibility, power availability, thermal balance and data return capability pointing of view. The analysis have been carried out by the Science Ground segment (SGS) at ESAC and the Operational Ground Segment (OGS) at ESOC and have been focused in the first Venus flyby. Operational request for the second flyby are still under collection and will be analysed later, closer to the 2nd flyby occurrence, although the methodology and the constraints are of the same applicability.

A. Pointing timeline analysis tool

The BepiColombo Science Ground Segment developed a tool, to allow the analysis of the instrument operations that require special pointing (shown in Figure 10). The tool includes a Venus skymap that shows Venus trajectory and planet appearance from spacecraft reference point of view considering different orientations or phases around the Sun line. The tool allows to check the possibility of observing Venus in different spacecraft configurations for different instruments, for example when Venus is inside a given instrument field of view. The tool also includes information on HGA coverage with the Earth at a given attitude.

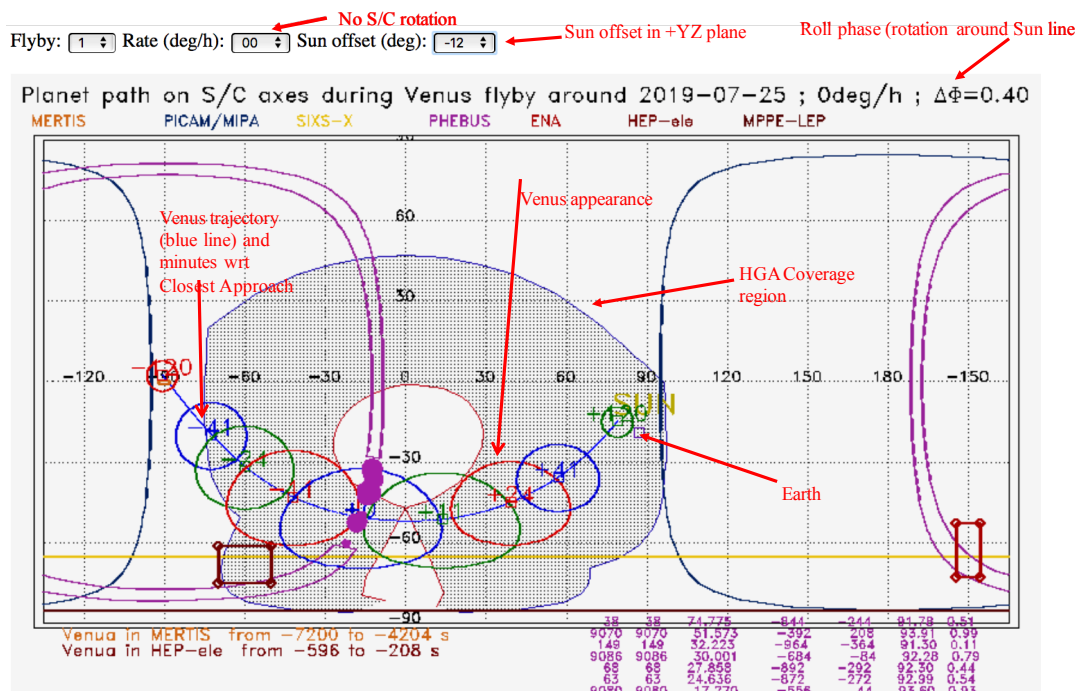


Figure 10. Venus Skymap. *SGS Venus Skymap tool for pointing analysis*

The MCS spacecraft attitude is defined by the Sun offset (Sun line) and a roll phase (from 0.0 to 1.0, being 0.1 equal to 36 degrees) with respect to a reference attitude defined as follows:

- Time reference is the time of the Closest Approach.
- the +Y axis is pointing to the Sun.
- the +X axis is the cross product of the +Y and the direction of the centre of Venus.

For each attitude the Venus skymap gives in the bottom part, in addition to the Venus trajectory and planet appearance, the opportunity windows (in seconds) for:

- Venus inside the following instruments field of views:
 - o MPO: MERTIS
 - o MMO: HEP-ele, ENA and MPPE-LEP
- Star occultation by Venus in the night side for PHEBUS. This includes:
 - o Star ID in PHEBUS star catalogue
 - o Star ID in Harvard Revised o Bright Star Catalogue, Hoffeit 1991
 - o UV intensity (F165 factor)
 - o Start time of the occultation in seconds
 - o End time of the occultation in seconds
 - o “Tangentiality” parameter, used to distinguish if the star occultation is perpendicular or not to the limb. If the tangentiality parameter is close to 0, the occultation is perpendicular to the limb as required by PHEBUS instrument.

B. MERTIS pointing analysis

MERTIS instrument requires Venus to pass through the field of view of the radiator opening, when distance to the Venus is less than 1700000 km. MCS attitudes compatible with MERTIS request have been derived from the Venus skymap tool, see Table 5.

Payload	Sun-offset (deg)	Roll phase	Tstart (min wrt CA)	Tend (min wrt CA)	Total Obs time (min)
MERTIS	-12	0.30	-120,0	-79,9	40,1
		0.40	-120,0	-56,1	63,9
		0.5	-100,4	-55,2	45,2
	10	0.0	-107,5	-61,3	43,5
		0.8	-120,0	-79,3	19,1
		0.9	-120,0	-61,2	43,5
	-10	0.3	-120,0	-79,3	19,1
		0.4	-120,0	-61,2	43,5
		0.5	-107,5	-61,3	43,5
	20	0.0	-77,6	-38,1	39,5
		0.9	-86,67	-43,4	43,3

Table 5: MCS attitudes compatible with MERTIS

C. PHEBUS pointing analysis

PHEBUS instrument would like to perform an Star occultation during the 1st Venus swing by that can be achieved by placing the MCS spacecraft body and PHEBUS instrument mechanism pointed such that a bright UV star of interest passes through the PHEBUS field of view and is occulted by Venus. Occultation should be perpendicular to the limb and on the night side of Venus. Attitude and baffle shall be kept fixed. MCS attitudes compatible with PHEBUS request and stars suitable for star occultation have been derived from the Venus skymap tool. An example of compatible attitude is given in Table 6.

Payload	Sun-offset (deg)	Roll phase	Tstart (min wrt CA)	Tend (min wrt CA)	Total Obs time (min)	Star ID	F165	Tangentiality
PHEBUS	-12	0.0	-27,7	-17,7	10,0	490	60.877	0.05
			-30,5	-20,5	10,0	438	51.344	0.06
			-26,9	-16,9	10,0	446	51.305	0.06
		0.1	-24,1	-14,1	10,0	348	78.186	0.12
			-26,0	-16,0	10,0	422	10.794	0.23
			-23,2	-13,2	10,0	324	3.900	0.43
		0.2	-21,5	-11,5	10,0	226	446.001	0.32
			-19,5	-9,5	10,0	193	256.208	0.69
			-19,6	-94,6	10,0	189	143.940	0.67
		0.30	-17,6	-7,6	10,0	78	95.802	0.09
			-17,6	-7,6	10,0	38	74.775	0.25
			-18,1	-8,1	10,0	68	27.858	0.19
		0.4	-13,5	-3,5	10,0	8965	225.246	0.62
			-12,3	-2,3	10,0	8913	19.342	0.65
			-12,2	-2,2	10,0	8902	13.236	0.58

Payload	Sun-offset (deg)	Roll phase	Tstart (min wrt CA)	Tend (min wrt CA)	Total Obs time (min)	Star ID	F165	Tangentiality
		0.5	-9,5	0,5	10,0	8806	1.253	0.79
			-10,1	-0,1	10,0	8825	0.425	0.74
		0.6	-14,4	-4,4	10,0			
			-9,5	0,5	10,0	49	11.361	0.47
			-11,4	-1,4	10,0	8806	1.253	0.79
			-13,5	-3,5	10,0	8864	0.796	0.63
		0.7	-13,5	-3,5	10,0	8976	243.760	0.66
			-17,6	-7,6	10,0	8965	225.246	0.62
			-22,4	-12,4	10,0	78	95.802	0.09
		0.8	-17,9	-7,9	10,0	291	57.466	0.16
			-18,8	-8,8	10,0	70	50.635	0.52
			-19,5	-9,5	0,0	104	31.278	0.53
		0.9	-19,6	-9,6	10,0	193	256.208	0.69
			-24,1	-14,1	10,0	189	143.940	0.67

Table 6: MCS attitudes compatible with PHEBUS

D. MGNS pointing analysis

Although MGNS does not require any special spacecraft pointing for its observations, due to the MCS configuration, the quality of the MGNS observation would be improved if Venus would be in the spacecraft $-X$ direction. MCS attitudes compatible with MGNS request have been derived from the Venus skymap tool, see Table 7.

Payload	Sun-offset (deg)	Roll phase	Tstart (min wrt CA)	Tend (min wrt CA)	Total Obs time (min)
MGNS	-12	0.7-0.8	-11,0	11,0	22,0
	-10	0.7-0.8	-11,0	11,0	22,0
	10	0.7-0.8	-11,0	11,0	22,0
	0	0.7-0.8	-11,0	11,0	22,0
	20	0.7-0.8	-11,0	11,0	22,0

Table 7: MCS attitudes compatible with MGNS

E. MMO instruments pointing analysis

MMO instruments that require special pointing (Venus in their field of view) are MPPE-ENA, HEP-ele and MPPE-LEP. MOSIF effect has been considered in the analysis since it is obstructing the instruments field of views. MCS attitudes compatible with PHEBUS request and stars suitable for star occultation have been derived from the Venus skymap tool, see Table 8.

Payload	Sun-offset (deg)	Roll phase	Tstart (min wrt CA)	Tend (min wrt CA)	Total Obs time (min)
ENA	-12	0.5	-5,4	6,9	12,3
		0.6	-13,8	9,0	22,8
	0	0.5	-12,1	2,1	12,4
		0.6	-19,7	3,5	24,8
	-10	0.5	-6,5	6,1	12,7
		0.6	-14,7	8,0	23,8

Payload	Sun-offset (deg)	Roll phase	Tstart (min wrt CA)	Tend (min wrt CA)	Total Obs time (min)
	10	0.5	-17,9	-2,1	14,4
		0.6	-25,3	-0,6	26,4
	20	0.5	-24,3	-6,9	17,3
		0.6	-31,7	-4,9	26,8
HEP-ele	-12	0.4	-10,6	-0,3	10,3
		0.5	-15,4	11,1	28,7
	0	0.4	-18,9	-4,1	13,3
		0.5	-21,5	4,8	27,8
	-10	0.4	-11,9	-0,9	7,7
		0.5	-16,3	10,0	28,1
	10	0.4	-26,6	-7,5	40,4
		0.5	-26,8	-0,5	27,7
	20	0.4	-39,0	-11,5	27,5
		0.5	-31,8	-6,3	25,5
MPPE-LEP	0	0.5	-11,9	13,6	25,5
	-12	0.5	-5,9	20,2	26,1
	-10	0.5	-6,9	19,1	25,9
	10	0.5	-17,3	8,5	25,8
	20	0.5	-23,3	3,6	26,9

Table 8: MCS attitudes compatible with MMO instruments

F. Pointing timeline candidates

MMO Based on the instruments pointing requests, candidate pointing timelines have been concluded that fulfils all instrument needs except for MGNS, since its request would require a large slew to accommodate an MCS attitude for a very short MGNS observation of better quality with respect to other configurations. Reduction of observation time windows has been applied when needed to accommodate all the request. Candidate timelines have been selected from other possible timelines since they do not require any intermediate slew. An example of candidate pointing timeline is given in Table 9.

From (min wrt CA)	To (min wrt CA)	Sun offset (deg)	Roll phase	Instrument Observation	Slew rotation (deg)	Rotation axis	Observation duration (min)
-100,4	-55,2	-12	0.5	MERTIS	0,0	Sun direction	45,2
-9,5	0,5	-12	0.5	PHEBUS star ID 8806			10,0
-15,4	19,1	-12	0.5	MMO instruments	0,0	Sun direction	
-15,4	11,1			HEP-ele			26,5
-5,4	6,9			ENA			12,3
-5,9	19,1			MPPE-LEP			25,0

Table 9: Candidate Pointing timeline compatible with science operations requests

G. Power availability

While the spacecraft cruise composite power system can provide more than 10kW in electric propulsion phase, the operational concept for the coast arcs including the planet swingbys is to offset the MTM solar arrays from the Sun as far as possible while guaranteeing a certain power demand, selected such that it envelops the entire interplanetary cruise from launch to MTM separation. This power demand value is expected to be of the order of 4000W. There is no eclipse of the spacecraft at the Venus flybys. This means that the entire composite power demand can be served by the MTM solar arrays without involvement of the spacecraft batteries. For engineering analysis, power demand cases have been defined. One of them is the cruise solar conjunction case. The MPO power demand recorded for this case is 869.9W – including 15% margin (113.5W) and not taking into account unit duty cycle. This case assumes the radio-science contributing elements to be active, i.e. MORE, ISA and the Deep Space Transponder Ka-band transmitting chain. The corresponding spacecraft cruise composite demand includes 300W for MMO operations, which is enveloping the worst case MMO power demand when active. The additional demand on top of the case is 79.09W – this is about 2% of power level typically required for cruise (4000W). This is much less than the margins currently considered for performance analysis. The additional power demand necessary to serve the Venus flybys science requests has been therefore considered to be well within the capability of the cruise spacecraft configuration.

Instrument	Power in W (from ORCD)
MERMAG	5.75
MERTIS	15.1
MGNS	6.44
PHEBUS	22.5
SERENA SCU	4.6
SERENA MIPA	3.5
SERENA PICAM	8
SIXS DPU	10
SIXS sensors	3.2
Total non RSE	79.09

Figure 11. Power consumption. MPO
Payload Power Demand

H. Thermal Balance

In the case of the first Venus flyby, the flyby altitude is very high, and there is no eclipse. This case does not constitute a driver for the spacecraft design and is well within the interplanetary cruise worst cases. For the second Venus flyby where the composite spacecraft flies over the sunlit part of Venus, the altitude of 1000km was selected after coordination with the BepiColombo Project to remain within the heat rejection capability of the MPO radiator. With this altitude, the flyby is not deemed critical either. As a result, both flybys are considered safe from thermal/temperature point of view.

I. Data Return

In this case, what has been analysed is the data return capability versus the science data generated by the instruments during the flyby. Table 10 provides the expected science data volume generation during the Venus flybys.

	Expected science data volume (MB)	Assumption
ISA	95.32	Assumed 1542.4bps for 6 days
MERMAG	489.38	Assumed 23.2kbps for 2 days
MERTIS	21.70	MERTIS provided figure for VSB1
MGNS	365.90	Provided by MGNS team: (PID90 - 34.85 Mbytes/day) (PID91 - <696.92 Mbytes/day) for 12 hrs =PID90: 17.4MB, PID91<348.5MB
PHEBUS	7.03	16.3kbps, assumed one 1hr ops elapsed time
SERENA	86.23	Assumed: - MIPA 590Mb (PI provided figure for VSB1) - PICAM 14.2kbps for 2 hours
SIXS	7.00	Assumed for 30 hrs: SIXS-X: 289.1bps, SIXS-P: 254.25bps
MMO	45.70	Assumed 8kbps for 13 hours
Total	1118.25	

Table 10: Payload science data generation

The data return capability is derived assuming daily 8 hours passes on one ESTRACK 35m ground station. The downlink is assumed to be on X-band only. The capability is provided in Table 11.

Data Volume to be returned (MB)	1118.25	
	VSB1	VSB2
Earth distance (AU)	1.17	1.25
X-TM BR (kbps)	65.3	52.2
non-science rate platform + PL (kbps)	2.50	2.50
Data volume for science return per 8hr daily pass (MB)	194.41	148.36
Number of 8 hrs daily passes needed for VSB return	5.75	7.54

Table 11: Data return capability

Table 11 shows very clearly that data return is not an issue for the first Venus flyby. For the second one, the return capability is in the expected order of magnitude, the only concern is that electric propulsion is baselined to restart 7 days after closest approach and it is very desirable from the operational point of view to complete the downlink of the Venus flyby science data before. This will require some fine-tuning closer to the event, but is expected to be possible after consolidation of the science data volume estimates and of the actual ground station schedule for the flybys phase.

VII. Conclusions

The scientific observation requests as part of the two Venus swingbys of a typical BepiColombo mission have been collected by the Science Ground Segment at ESAC and the Operational Ground Segment at ESOC for feasibility analysis. The operational feasibility of the requests has been analysed in more details for the first Venus flyby. The analysis indicates that it is possible to find a suitable spacecraft composite attitude to provide observing opportunities to most instruments requiring specific spacecraft pointing. The only exception in this analysis is MGNS, however this will not prevent the instrument to operate as the pointing request in this case is to optimise observation conditions in the cruise composite configuration. For the second flyby, whose altitude is much lower (1000 Km), pointing analysis will be done closer to the event following the same approach as for the first flyby. On the other hand the impact of the received requests on power balance, thermal balance and data return have been analysed and found well within the as-designed capability of the spacecraft for both Venus flybys.

References

¹Benkhoff J., Fujimoto M., BepiColombo—Comprehensive exploration of Mercury: Mission overview and science goals Planetary and Space Science, Vol.58, Issues 1-2, January 2010