BepiColombo's Cruise Phase: Unique Opportunity for Synergistic Observations

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The investigation of multi-spacecraft coordinated observations during the cruise phase of BepiColombo (ESA/JAXA) are reported, with a particular emphasis on the recently launched missions, Solar Orbiter (ESA/NASA) and Parker Solar Probe (NASA). Despite some payload constraints, many instruments onboard BepiColombo are operating during its cruise phase simultaneously covering a wide range of heliocentric distances (0.28 AU–0.5 AU). Hence, the various spacecraft configurations and the combined *in-situ* and remote sensing measurements from the different spacecraft, offer unique opportunities for BepiColombo to be part of these unprecedented multipoint synergistic observations and for potential scientific studies in the inner heliosphere, even before its orbit insertion around Mercury in December 2025. The main goal of this report is to present the coordinated observation opportunities during the cruise phase of BepiColombo (excluding the planetary flybys). We summarize the identified science topics, the operational instruments, the method we have used to identify the windows of opportunity and discuss the planning of joint observations in the future.

Keywords: solar wind, multi-spacecraft measurements, inner heliosphere, spacecraft mission, coordinated measurements

1 INTRODUCTION

A new era of coordinated observations in the inner heliosphere has begun with the launch of NASA's Parker Solar Probe (PSP, Fox et al., 2016) in August 2018, followed by the ESA-JAXA BepiColombo spacecraft mission in October 2018 (Benkhoff et al., 2021), and by ESA-NASA's Solar Orbiter (Müller et al., 2020) in February 2020. Until the end of the cruise phase of BepiColombo (November 30, 2025), these three spacecraft will be traveling simultaneously in the inner heliosphere covering different heliocentric distances (Velli et al., 2020): BepiColombo's elliptical orbit will cover distances from about 1.2 Astronomical Unit (AU) to ∼ 0.31 AU, while Solar Orbiter from ∼ 1.02 to 0.28 AU, and Parker Solar Probe from about 0.7 to 0.04 AU. Together with these missions, previous (and future) spacecraft provide continuous *in situ* and remote sensing measurements in our Solar System (as shown in **Figure 1**): at Venus ∼ 0.7 AU (Akatsuki, also known as the Venus Climate Orbiter), around Earth, including the L1 Lagrange point ∼ 1 AU (e.g., SOHO, ACE, Wind, Cluster, THEMIS, and MMS), at Mars ∼ 1.5 AU (e.g., MAVEN, Mars Express, Mars Odyssey), and at Jupiter ∼ 5 AU (e.g., JUNO). In addition many Sun-observing including, SOHO, Hinode, Solar Dynamics Observatory, PROBA-2, and STEREO-A monitor the Sun with various instrumentations. The exceptional and complementary *in-situ* and remote sensing payloads on-board these different satellites, together with ground based measurements, will give the opportunity to perform unprecedented multi-point measurements of the solar wind plasma and the Sun. Hence allowing the community to address different fundamental physical processes in the solar wind, such as turbulence, the generation, acceleration, and transport of solar energetic particles (SEPs), and the characterization of large scale heliospheric structures such as Interplanetary Coronal Mass Ejections (ICMEs).

During the cruise phase, the BepiColombo spacecraft is in a so-called "stacked" configuration: the Mercury Magnetospheric Orbiter (MMO/Mio) is inside the Sunshield and Interface Structure (MOSIF) which is attached to the Mercury Planetary Orbiter (MPO). MPO, MOSIF, and Mio are all connected to the Mercury Transfer Module (MTM) (Mangano et al., 2021). Therefore, unlike some MPO instruments that are fully operational during cruise, all the instruments onboard Mio are shielded by MOSIF and not all of them can be scientifically operational (i.e., limited field of view, undeployed instruments). It is only after entering Mercury's orbit in December 2025, that all the instruments will be fully deployed and operational at full capacity. Nevertheless, despite some operational and instrumental constraints, science operations could be performed during cruise in coordination with other spacecraft missions. Moreover, since long term planning is required for at least BepiColombo and Solar Orbiter (9 months and 6 months in advance respectively), a close coordination between BepiColombo, Solar Orbiter, and PSP teams was necessary (Velli et al., 2020). In this context, the BepiColombo Coordinated Observations Working Group (BC-CoObs WG) was initiated in November 2019. The BC-CoObs WG consisted of the project scientist and deputy project scientist of BepiColombo, along with instruments Principal Investigators (PIs) and members from BepiColombo, Solar Orbiter and PSP teams and researchers from the planetary and heliophysics community. The main goal of the BC-CoObs WG was to identify the science opportunities during the cruise phase of BepiColombo from September 1, 2020 till November 30, 2025, excluding the planetary flybys. In order to achieve this goal, we have defined three main tasks: 1) to specify the different science
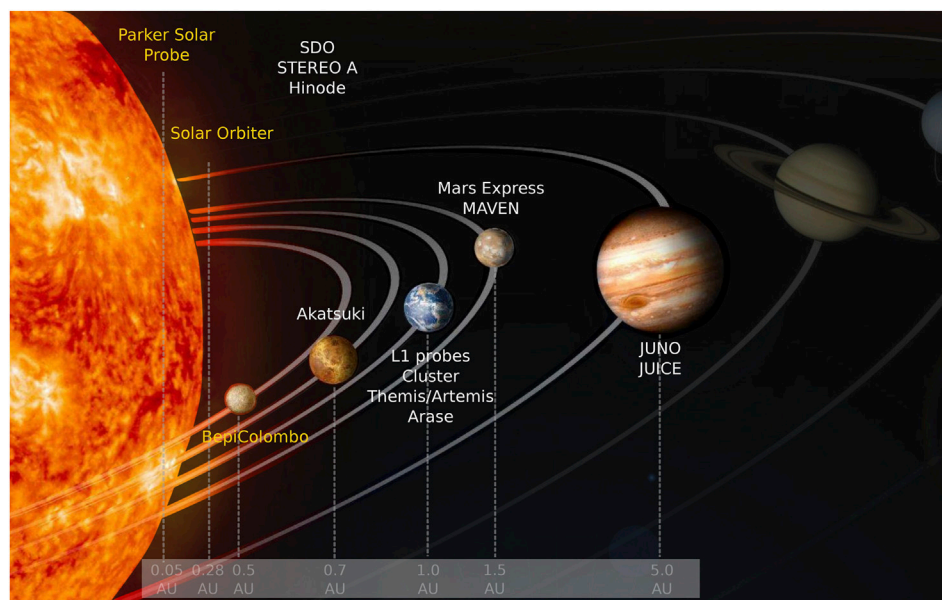
FIGURE 1 | Examples of operational missions covering different heliocentric distances in our Solar System.

TABLE 1 | Operational instruments during the cruise phase (excluding the periods of the planetary flybys).

Consortium and reference	Instrument and information	Target	Sensitivity
MMO/Mio			
MPPE (Mercury Plasma Particles Experiment). Saito et al. (2021)	MEA1 and MEA2 (Mercury Electron Analyzer), reduced FOV	Low energy electrons	3 eV–26 keV
	HEP-e (High Energetic Particles–electrons), reduced FOV	High energy electrons	30–700 keV
Kobayashi et al. (2020)	MDM (Mercury Dust Monitor), reduced FOV	Impact momentum and dust particles direction	—
MPO			
SERENA (Search for Exospheric Refilling and Emitted Natural Abundances). Orsini et al. (2021)	MIPA (Miniature Ion Precipitation Analyser), reduced FOV	Low energy ions	15 eV–15 keV
	PICAM (Planetary Ion CAMera), reduced FOV	Low energy ions	10 eV–3 keV
SIXS (Solar Intensity X-ray and particles Spectrometer). Huovelin et al. (2020)	SIXS-X, partially in the MOSIF shadow. It could face the Sun on request during specific periods	Solar X-ray	1–20 keV
	SIXS-P, hot distributions can be detected	High energy protons	0.33–30 MeV
		High energy electrons	50 keV–3 MeV
	MPO-MAG, fully operational	B-field (nominal mode)	~ DC–16 Hz
		B-field (reduced mode)	~ DC–1 Hz
Quémerais et al. (2020)	PHEBUS (Probing of Hermean Exosphere by Ultraviolet Spectroscopy): can be operated	Far-Extreme UV	55–330 nm
Hiesinger et al. (2020)	MERTIS (MErcury Radiometer and Thermal Infrared Spectrometer), fully operational	Infrared radiation	7–14 μm
	BERM, fully operational	High energy protons	1–200 MeV
		High energy electrons	0.3–10 MeV
	MORE, fully operational	Radio emissions	X-band and Ka-band
	MGNS, fully operational	Gamma-rays	300 keV–10 MeV
		Neutron flux	1 eV–10 MeV
	ISA, fully operational	Non-gravitational acceleration vector	$3.10^{-5} - 10^{-1}$Hz

topics that are related to the multi-spacecraft observations, 2) to report the potential operational instruments on-board BepiColombo, and 3) to identify the potential windows of opportunities of BepiColombo in coordination with all the operational spacecraft, by selecting the most interesting spacecraft configurations.

In the following sections, we summarize the operational instruments on board BepiColombo, the science topics that can be addressed during cruise, and some operation constraints. Then, we describe the method and the tool that we used to identify the different windows of opportunity. Finally, we discuss the planning of the joint observations and present some specific examples.

2 OPERATIONAL INSTRUMENTS, SCIENCE TOPICS, AND CONSTRAINTS

The only official instrument onboard BepiColombo that was originally planned to be operating during cruise was the Mercury Orbiter Radio science Experiment (MORE, Iess et al.,

2021) during superior solar conjunctions. Nevertheless, the beginning of the cruise phase has revealed that other instruments on board Mio and MPO could be operating as well and exploited for scientific studies. In fact, some of the instruments on-board MPO will be continuously operating during cruise, except for the Electric Propulsion (EP) periods, such as the BepiColombo Radiation Monitor (BERM), the Magnetometer (MPO-MAG, Glassmeier et al., 2010; Heyner et al., 2021), the Mercury Gamma-ray and Neutron Spectrometer (MGNS, Mitrofanov et al., 2010), the Italian Spring Accelerometer (ISA, Iafolla et al., 2021) and MORE. In **table 1**, we summarize all the operational instruments during the cruise phase, excluding the planetary flybys periods [more details regarding the planetary flybys periods and the pointing of the different instruments can be found in Mangano et al. (2021)]. A detailed description about the combined *in situ* and remote sensing instruments on-board Solar Orbiter and Parker Solar Probe can be found in Velli et al. (2020) and Müller et al. (2020).

Despite the limited science operations, interesting science studies can be performed. During the cruise phase of BepiColombo, at least from September 2020 until December 2025, the Sun will be

approaching Solar maximum (predicted in July 2025). The joint measurements with BepiColombo, Solar Orbiter, and Parker Solar Probe including other operational spacecraft in the interplanetary space, will allow a better understanding of the evolution of the solar wind plasma and its large scale three-dimensional distribution under different conditions of the solar activity using both remote sening and *in-situ* meaurements. An extensive discussion on the science investigations during the cruise phase of BepiColombo can be found in Mangano et al. (2021). Briefly, the main science topics can be grouped into seven cases: 1) Solar wind turbulence properties (e.g., Tu and Marsch, 1995; Bruno and Carbone, 2013; Sahraoui et al., 2020). They include studies of the scaling properties (e.g., Alberti et al., 2020), characterization of the wave modes propagation (e.g., Howes et al., 2012), high order statistics, and intermittency (e.g., Bruno et al., 2001), and their evolution with heliocentric distances. 2) Solar wind structures. These include the study of the properties and radial evolution of small scale structures, such as discontinuities, including reconnection exhausts (e.g., Gosling et al., 2005), magnetic holes (e.g., Turner et al., 1977; Volwerk et al., 2020; Karlsson et al., 2021), interplanetary shocks and of large scale heliospheric structures, such as transient events [e.g., ICMEs, flux ropes (Kilpua et al., 2017)], and the Co-rotating Interaction Regions (CIRs, Richardson, 2018) which are compressive regions formed in the background magnetic field where high-speed wind runs into the slower wind ahead (e.g. Pizzo, 1980; Gosling and Pizzo, 1999). Moreover, the large scale properties of the solar wind (electron number density and velocity) could be done by combining ground-based interplanetary scintillation observations (IPS) observations (e.g., Iwai et al., 2019), heliospheric imaging (e.g., Harrison et al., 2018) and global magnetohydrodynamic (MHD) simulations and models such as SUSANOO (e.g., Shiota et al., 2014), IPS-ENLIL (e.g., Odstrcil, 2003; Jackson et al., 2015), or EUHFORIA (e.g., Pomoell and Poedts, 2018). The solar wind plasma parameters measured onboard one of the spacecraft can also be propagated with the help of a simple 1D MHD model such as Heliopropa (http://heliopropa.irap.omp.eu) to another planet, comet, or spacecraft in order to provide a virtual solar wind monitor and predict the properties of the solar wind in another heliospheric location. 3) Solar Energetic Particles (SEPs). The study of their generation, acceleration and transport processes and their flux-time profiles at different locations in the solar wind (e.g., Miroshnichenko, 2018). Moreover, combining *in situ* SEP data with type-II radio burst data, and global MHD simulations may provide information regarding the structure of the background interplanetary magnetic fields and the propagation of ICMEs. 4) Dust and Comets. The characterization of the dust distribution in the inner Solar System (e.g., Grün et al., 1980) and the analysis of the cometary composition such as the hydrogen coma at Lyman-α in Extreme Ultraviolet Violet (EUV) (e.g., Bertaux et al., 1995). Even though this depends on the passage of the comets in the field of view of BepiColombo's EUV spectrometer (PHEBUS), at least one observation of comet 2P/Encke would be possible by the end of November 2023 as it arrives at a distance of ~ 0.6 AU from BepiColombo. 5) Solar Corona. Measurements of the density fluctuations of the solar corona down to a few solar radii (e.g., Miyamoto et al., 2014) will be possible using radio measurements from the Mercury Orbiter Radio-science Experiment (MORE). 6) High frequency electromagnetic radiation. These include the
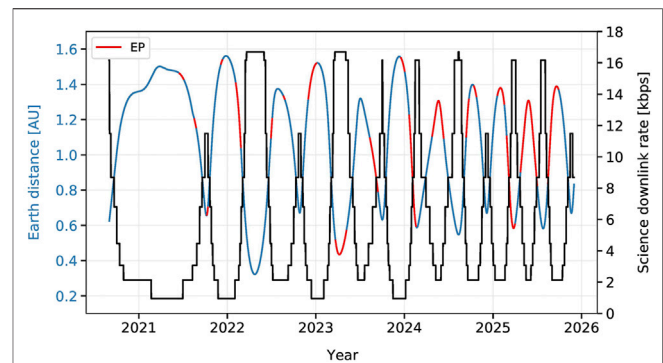
FIGURE 2 | Distance of BepiColombo from Earth in AU (left axis, in blue) and the science downlink rate (right axis, in black) as a function of time during cruise. The Electric Propulsion (EP) periods are highlighted in red lines.

detection of Gamma-Ray Bursts (GRBs) and their localization, in particular the gamma-rays that originate from solar flares, and monitoring the local radiation background of the spacecraft due to bombardment by energetic particles of Galactic Cosmic Rays. Last but not least, 7) General relativity test could be performed during superior solar conjunctions (e.g., Bertotti et al., 1993; Iess et al., 2021).

Two major constraints had to be taken into account for the planning of the joint observations with BepiColombo. The first one is related to the Electric Propulsion periods during which no instruments operations can be performed, and the second one is related to the science downlink rate, as BepiColombo moves away from Earth. As one can see from **Figure 2**, in periods with a distance between BepiColombo and Earth larger than 1.2 AU the data downlink rate gets very low (< 0.3 kbps), not even allowing the instruments' background operations. Therefore, we assume that all *in-situ* instruments can operate in background mode when the distance Bepi-Earth is less than 0.7 AU (data downlink rate > 6 kbps).

3 METHODS

In order to identify the potential windows of opportunities, we have focused our investigation on five different spacecraft geometries and used the Centre de Données de la Physique des Plasmas (CDPP) tools, in particular the Automated Multi-Dataset Analysis (AMDA) tool. In the following subsections, we give a short overview of AMDA and describe the different spacecraft configurations.

3.1 AMDA Tool

AMDA is an online database and analysis tool (http://amda.cdpp.eu/) developed for 15 years by the CDPP (http://www.cdpp.eu/). It gathers a large variety of plasma data from space missions and ground instruments together with simulations and models. It also offers a dedicated work space to all registered users where plot layouts, data mining conditions, and event lists can be stored and reused. Hundreds of user accounts have been provided over the years from space physics students to senior researchers. Several papers describe the basics of AMDA and its various applications in heliophysics and planetary sciences (Génot et al., 2021, and references herein). Registration is done by sending an mail to
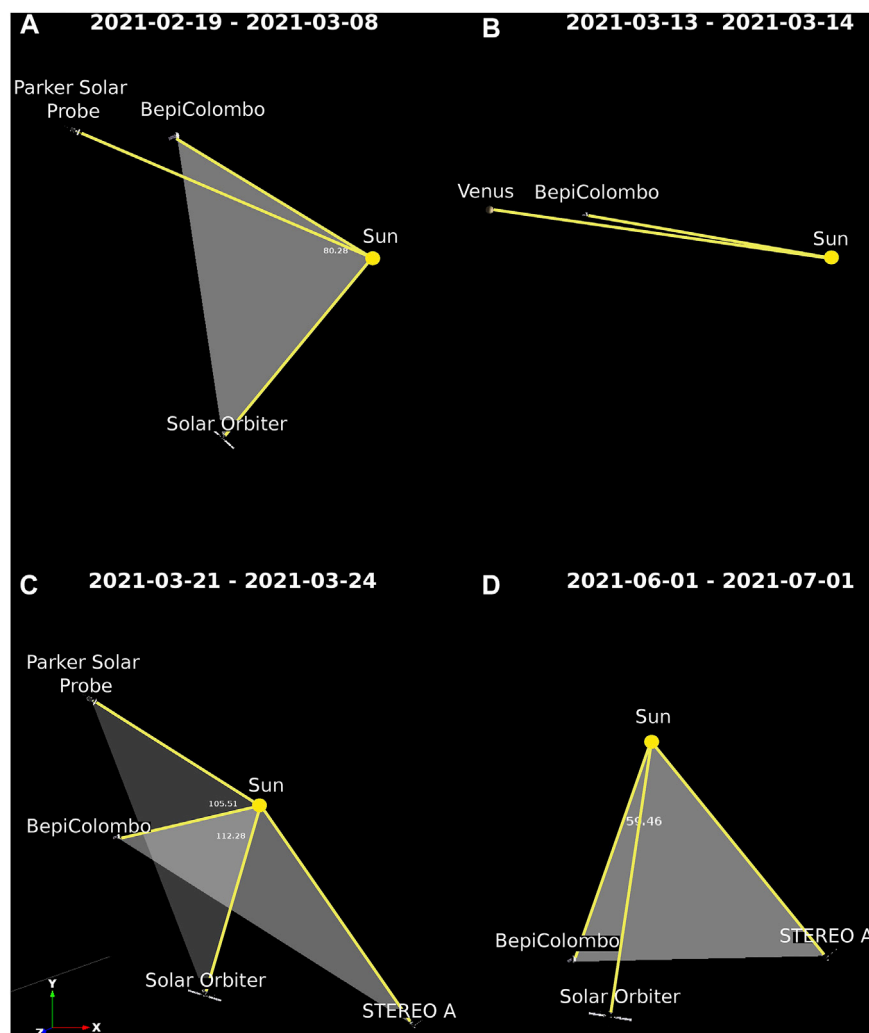
FIGURE 3 | 3DView illustration of the downselected configurations for the first half of 2021, in the HEE coordinate system: **(A)** 2021-02-19–2021-03-08: Parker Solar Probe and BepiColombo are in a cone geometry and in Quadrature geometry with Solar Orbiter. **(B)** 2021-03-13–2021-03-14: BepiColombo and Venus are in a cone geometry. **(C)** 2021-03-21–2021-03-24: Parker Solar Probe is in quadrature geometry with Solar Orbiter and BepiColombo is in quadrature geometry with STEREO A. **(D)** 2021-06-01–2021-07-01: BepiColombo and Solar Orbiter are in cone geometry and in quadrature geometry with STEREO A.

amda@irap.omp.eu, and a public access (with no workspace) is also available. For the planning activities of the BC-CoObs Working Group, the choice of using AMDA arose for several reasons. First, the tool gives access to the ephemeris of all considered objects (spacecraft and planets) in several common coordinate systems and measurements at several cadences. Second, it enables to create new parameters from existing data, to perform conditional search on a large volume of data-set, and finally, to manage resulting event lists, and so, to produce catalogues which are relevant to this study.

3.2 Spacecraft Configurations

The investigation of the different windows of opportunity was done based on five different geometries, "Cone," "Opposition," "Parker," "Cone-Parker," and "Quadrature" and by considering the following spacecraft/bodies: BepiColombo, PSP, Solar

Orbiter, STEREO-A, Venus, Earth, Mars, and Jupiter. Each of these configurations are defined below in the Heliocentric Earth Ecliptic (HEE) system, where the *X* axis points towards the Earth and the *Z* axis is perpendicular to the plane of the Earth's orbit around the Sun (positive North). This system is fixed with respect to the Earth-Sun line.

- Cone: radial alignments between two or more spacecraft/bodies, i.e., when they are within a small longitude cone from the Sun. For the radial alignment we require here the maximum cone width of 10 ± 3 in longitude without putting any constraints on the latitude assuming that it's sufficient to identify all the events that are radially aligned within a cone (**Figure 3B**). The "Cone" geometry allows mainly to study the *in situ* evolution of the same plasma parcel and the underlying processes as a function of the distance from the

Sun, such as the properties of the solar wind plasma, and turbulence as it has been already done using Helios 1 and 2 probes (Schwartz and Marsch, 1983), Ulysses and ACE (D'Amicis et al., 2010) and more recently using PSP and Solar Orbiter (Telloni et al., 2021), as well as the evolution of large-scale heliospheric structures (e.g., Gosling and Pizzo, 1999).

- Opposition: two or more spacecraft/bodies are oppositely aligned forming a cone with respect to the Sun. The difference in longitude (in absolute values) between the spacecraft is defined as 180 ± 10. This geometry is particularly interesting for periods of superior solar conjunctions, during which simultaneous radio occultation observations can be performed to observe remotely the solar corona using both remote sensing measurements and ground based observations.
- Parker: magnetic alignment between two or more bodies, i.e., when the footpoints of Parker field lines passing through the bodies are in a small latitude/longitude region at the so-called "source surface" (R_s), which is an imaginary spherical surface above the corona. The alignment along the same spiral field line would allow to study the evolution of the solar wind plasma that originate from the same source at different locations on the field line (with a time difference that corresponds to the travel time of the plasma that would change over this time). Moreover, it would allow to analyze unpredictable bursty events (e.g., SEPs) that originate from the same "active" region on the solar surface.

For this configuration, the longitude of the Parker field line at the source surface (ϕ_s) has first to be computed for a given Solar Wind velocity u_{SW}; the formula is given below by:

$$\phi_s = \phi(r) + \Omega(r - R_s)/u_{SW} \qquad (1)$$

where $\phi(r)$ is the spacecraft heliocentric longitude at distance r, $\Omega = 2\pi/25.38$ days, and $R_s = 2.5R_{Sun}$. Several values of u_{SW} were used in the range 200–800 km/s, to take into account the slow (200–400 km/s), intermediate (400–500 km/s) and fast solar wind (600–800 km/s). At the source surface a small region of 3×3 in longitude/latitude is considered for the footpoints to be said co-located. Varying the size of this region impacts the duration of the magnetic conjunction. The footprint of a given spacecraft at a given time is defined by its longitude (ϕ_s) and by its latitude (equal to the one of the spacecraft as a Parker field line is inscribed on a cone of constant latitude). Below the source surface, the Parker approximation to model the magnetic field generally fails as the coronal magnetic field becomes more complex; refined models that take into account observed/modeled magnetograms (e.g., Potential-Field Source-Surface model Wang et al., 1992) can then be used. This is what is done, for instance, in the "Magnetic Connectivity" tool developed at IRAP[1] to estimate the solar source location of the solar wind and energetic particles measured by different spacecraft. Nevertheless the first order

approach explained above and used in AMDA by the working group is a quick way to derive times of interest for the coordinated analysis.

- Cone-Parker: the combination of the Cone and Parker geometries. This configuration is mainly interesting to study and analyze ICMEs, SEPs, or any other bursty event that propagates and expands at different longitude and radial distances.
- Quadrature: Spacecraft with remote sensing instruments (e.g., imagers, coronographs) forming an angle of 90 ± 10 with the Sun and other spacecraft/planet. For this particular geometry we only considered BepiColombo, Earth (L1 probes, e.g., Wind, SOHO) and the solar missions: PSP, Solar Orbiter, and STEREO-A. This configuration is optimal for observing remotely the structure of the Solar corona (Lamy et al., 2020) or any transient events that emanate from the Sun, and linking them to the heliosphere observed *in-situ* 90° from the Sun-spacecraft line. An example would be when Parker Solar Probe is in quadrature with Solar Orbiter. Close to the Sun, the remote sensing instruments onboard Solar Orbiter (such as the Solar Orbiter Heliospheric Imager using Thomson scattering) would be providing imagery of the plasma lifting up from the limb and so the solar wind plasma parcel that is, expected to be encountered by Parker Solar Probe further away from the Sun at 90° from the Sun-Solar Orbiter line (Howard et al., 2020). The quadrature geometry and the combination of the *in situ* and remote sensing measurement would allow to observe the global structure of the eruptive events as they evolve in the interplanetary space and contribute to the understanding of their initiation at the Sun.

In a recent study, Davies et al. (2021) could investigate *in situ* the propagation of an ICME through the interplanetary medium as Solar Orbiter, BepiColombo, and Wind spacecraft were radially aligned, and could observe its global shape and expansion using the remote observations from STEREO-A as it was in a quadrature geometry with respect to the Sun-Earth line.

A detailed description of AMDA's data mining conditions can be found in the Bepi-CoObs WG AMDA manual (see data availability statement). It is worth noting that the travel time of the plasma from one spacecraft to another was not taken into account when selecting the different events and this should be taken into account when considering the radial alignment case studies.

4 WINDOWS OF OPPORTUNITY AND FUTURE PLANNINGS

Using the AMDA tool and applying the method described in **section 3**, the investigation of the joint observations with BepiColombo by the CoObs WG, has led to 921 windows of opportunity between September 1st, 2020 and November 30th,

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[1]http://connect-tool.irap.omp.eu/

2025. We note that this large number of events is mainly due to the "Parker" geometry condition, that was applied assuming different ranges of the solar wind speed. The full list of events is publicly available on AMDA, and will be shared on BepiColombo's Cruise Science study group ESA's website (see data availability statement). The timetable includes an identifier (ID) for each case study, the starting and ending time of the observation window, the geometry, the name of the spacecraft or objects, whether the event coincides with any particular flyby of BepiColombo, Solar Orbiter or PSP, or to an EP period. Furthermore, for each of the considered objects (BepiColombo, PSP, Solar Orbiter, STEREO-A, Venus, Earth, Mars, and Jupiter) we added the minimum, maximum and average values of the latitude, longitude, and radial distance from the Sun. We note that movies of Solar Orbiter, BepiColombo, PSP and STEREO-A trajectories, and the planning of Solar Orbiter's joint observations for July-December 2021 (and future plans) are available at Solar Orbiter's Science Operation Center website (see data availability statement).

After identifying all the potential opportunities with the different conjunctions, a down-selection of the most feasible and realistic cases was necessary in order to plan and coordinate well in advance the joint observations, in particular between the two ESA missions, BepiColombo and Solar Orbiter teams. The down-selection is based on the following selection approach: 1) we assume that the BERM instrument is always operational in the background and not further analyzed, as its downlink rate is relatively low (38 bps); 2) the EP and instruments checkout periods are immediately excluded from any analysis; 3) all the *in situ* instruments are assumed to be operating in background mode when the distance BepiColombo-Earth is less than 0.7 AU. The only question to the teams during these periods would be related to the spacecraft pointing requirements; and 4) no events near the flyby's periods (closest approach ± 1 week) are down-selected, as the flyby operations are discussed withing the flyby working group.

The down-selection step is implemented by a small group including the Project Scientists of the missions, who discusses 9 months in advance, a 6 months planning period for the coordinated observations between BepiColombo and Solar Orbiter - and any other non-ESA missions, taking into account the constraints as discussed above in the selection approach (**Figure 2**). The down-selected opportunities are then sent by the project scientists to the different instruments PIs of both missions, who analyze the different periods and specify for each of them a set of information (a priority level, a description of the observation, operational mode, pointing requests, and the expected science downlink rate and volume) that are then studied and validated by the ESA Mission Operation Center (MOC). Due to the spacecraft and payload constraints, only few windows of opportunities could be down-selected. In fact, for the planning of the year 2021 and the first half of 2022 (January 1st, 2022–June 30, 2022), only 17 events out of 349 could be requested to MOC. Examples of these joint observations, plotted using 3DView tool (Génot et al., 2018), are shown in **Figure 3** and listed below:

- 2021-02-19–2021-03-08: BepiColombo is in a cone geometry with PSP and in quadrature geometry with Solar Orbiter.
- 2021-03-13–2021-03-14: BepiColombo and Akatsuki in solar conjunction.
- 2021-03-21–2021-03-24: PSP, BepiColombo, Solar Orbiter, and STEREO-A are longitudinally distributed around the Sun. PSP-Solar Orbiter and BepiColombo-STEREO-A are more or less in quadrature geometry.
- 2021-06-01–2021-06-12: BepiColombo is in a cone geometry with Solar Orbiter and in quadrature geometry with STEREO-A.
- 2021-07-01–2021-08-02: BepiColombo, Solar Orbiter and Mars are in Cone-Parker geometry. On 2021-07-15 BepiColombo is radially aligned with Solar Orbiter, and STEREO-A is in quadrature geometry.
- 2021-08-14–2021-08-26: BepiColombo and Solar Orbiter are magnetically aligned, and STEREO-A in quadrature geometry.
- 2021-09-05–2021-09-25: PSP, Solar Orbiter, and STEREO-A are in a Cone geometry and BepiColombo is nearby.
- 2021-10-07–2021-10-08: BepiColombo, Solar Orbiter, and STEREO-A are magnetically connected on the same parker spiral.
- 2021-10-14–2021-10-15: BepiColombo, Solar Orbiter, and STEREO-A are magnetically connected on the same parker spiral.
- 2021-10-23–2021-10-28: BepiColombo is radially aligned with Earth and Solar Orbiter is in a quadrature geometry.
- 2022-03-11–2022-03-31: BepiColombo is radially aligned with STEREO-A and Solar Orbiter is in a quadrature geometry.
- 2022-04-06–2022-04-18: BepiColombo is radially aligned with Earth.
- 2022-06-09–2022-06-10: BepiColombo is close to Mercury and radially aligned with PSP, and STEREO-A is in a quadrature geometry.

CONCLUSION

In this short report we attempt to summarize the extensive investigation that we have done within the BepiColombo CoObs WG to identify the potential scientific coordinated observations related to BepiColombo, Solar Orbiter and any other operational spacecraft mission. Despite some spacecraft and payload constraints, this work has revealed many interesting science opportunities for *in-situ* and remote sensing synergistic observations in the inner heliosphere even before the orbit insertion of BepiColombo around Mercury in December 2025. The joint *in situ* and remote sensing observations of BepiColombo, Solar Orbiter, Parker Solar Probe including other space, and ground based observatories, would allow detailed mapping of the inner heliosphere and to better understand the solar wind properties, structures and magnetic field expansion at different heliocentric distances. Recent studies of coordinated observations between BepiColombo, Solar Orbiter and Wind (Davies et al., 2021), and Parker Solar Probe and Solar

Orbiter (Telloni et al., 2021) and additional on-going studies, highlight the need for careful advance planning to optimize the scientific return from this unprecedented opportunity of synergistic observations. At the time of writing this report, regular meetings for the planing of the future years are being held and the approved selected events will be made public to the community and will available on BepiColombo's Cruise Science Study Group ESA cosmos website (see Data Availability Statement).

DATA AVAILABILITY STATEMENT

The SPICE kernels are used for the different missions with the official data sources as given below. The kernels are regularly updated at the official sources and in orbitography services (including AMDA), for instance when reconstructed kernels are replacing predicted ones. As a consequence the catalogue of events as it is presented at the time of publication of the article may change. However, it has been checked that these possible changes (shift in start/stop times of some events) are limited, and, for example, on the same scale as the shift induced by varying the cone aperture of a few degrees (for "Cone" configuration), or the solar wind velocity by a few 10 km/s (for "Parker" configuration).

List of the SPICE kernels:

- BepiColombo: ESA/ESAC https://doi.org/10.5270/esa-dwuc9bs
- Solar Orbiter: ESA/ESAC https://doi.org/10.5270/esa-kt1577e
- Parker Solar Probe: https://sppgway.jhuapl.edu/lpredict_ephem and https://sppgway.jhuapl.edu/recon_ephem
- STEREO-A: https://sohowww.nascom.nasa.gov/solarsoft/stereo/gen/data/spice/depm/ahead/
- Planets: NASA/NAIF https://naif.jpl.nasa.gov/naif/

The websites of the different tools and movies are:

- CDPP: http://www.cdpp.eu/
- AMDA: http://amda.cdpp.eu/
- 3D View: http://3dview.irap.omp.eu/
- Magnetic Connectivity: http://connect-tool.irap.omp.eu/
- Heliopropa: http://heliopropa.irap.omp.eu
- Bepi-CoObs WG Amda manual
- Solar Orbiter's Science Operation Center: https://issues.cosmos.esa.int/solarorbiterwiki/display/SOSP/Solar+Orbiter+SOC+Public

BepiColombo planning - the generated catalogue and the down-selected list of events are available in:

- AMDA: "Shared catalogue" directory http://amda.cdpp.eu/
- BepiColombo's Cruise Science: https://www.cosmos.esa.int/web/bepicolombo-yssg-cs

Solar Orbiter planning - the future planning during the cruise phase of Solar Orbiter is available in:

- https://issues.cosmos.esa.int/solarorbiterwiki/display/SOSP/Cruise+Phase

AUTHOR CONTRIBUTIONS

All the co-authors have contributed in discussing the science topics, operational instruments and geometries for identifying the potential coordinated observations. In addition, LH, VG, and SA have investigated the potential windows of opportunities using the AMDA tool.

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