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ScienceDirect
Advances in Space Research 38 (2006) 672–679
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

MEFISTO – An electric field instrument for BepiColombo/MMO

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Received 2 July 2004; received in revised form 21 February 2005; accepted 2 May 2005

Abstract

MEFISTO, together with the companion instrument WPT, are planning the first-ever in situ measurements of the electric field in the magnetosphere of planet Mercury. The instruments have been selected by JAXA for inclusion in the BepiColombo/MMO payload, as part of the Plasma Wave Investigation coordinated by Kyoto University. The magnetosphere of Mercury was discovered by Mariner 10 in 1974 and will be studied further by Messenger starting in 2011. However, neither spacecraft did or will measure the electric field. Electric fields are crucial in the dynamics of a magnetosphere and for the energy and plasma transport between different regions within the magnetosphere as well as between the magnetosphere and the surrounding regions. The MEFISTO instrument will be capable of measuring electric fields from DC to 3 MHz, and will thus also allow diagnostics of waves at all frequencies of relevance to the Hermean magnetosphere. MEFISTO is a double-probe electric field instrument. The double-probe technique has strong heritage and is well proven on missions such as Viking, Polar, and Cluster. For BepiColombo, a newly developed deployment mechanism is planned which reduces the mass by a factor of about 5 compared to conventional mechanisms for 15 m long booms. We describe the basic characteristics of the instrument and briefly discuss the new developments made to tailor the instrument to flight in Mercury orbit.

Keywords: Mercury; Magnetosphere; Exosphere; Solar system exploration; Electric fields; Space plasma physics

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1. Introduction

MEFISTO (Mercury Electric Field In Situ TOol) is an electric field instrument based on the "hockey puck" principle first employed on Cluster II, but with several

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doi:10.1016/j.asr.2005.05.032

enhancements and adaptations making it suitable for flight in Mercury orbit. The instrument measures one component of the electric field in the spin plane of the spacecraft and will together with the orthogonally mounted WPT (Wire Probe anTenna) sensors (see Fig. 1) provide the electric field vector in the spin plane. MEFISTO also monitors the spacecraft potential which can be used to study density fluctuations and also as input to low-energy particle analysis. The sensors have TiAlN surfaces and are located 1–2 m outwards of the "puck" that houses the pre-amplifiers. The puck is extended by wire booms to a distance of 14–15 m from the spin axis. Both MEFISTO and WPT are part of the Plasma Wave Investigation (PWI) coordinated by Kyoto University (PWI Principal Investigator: Prof. Hiroshi Matsumoto). WPT is based on the same philosophy as the electric field instrument on the Geotail spacecraft (Tsuruda et al., 1994), but with adaptations to the thermal environment at Mercury.

1.1. Main scientific objectives

- Solar wind–magnetosphere–exosphere-surface coupling.
- Field-aligned currents and their closure.
- Plasma convection.
- ULF waves.
- Substorm phenomena.
- Particle acceleration phenomena.
- Magnetospheric and solar MF & HF wave activity.

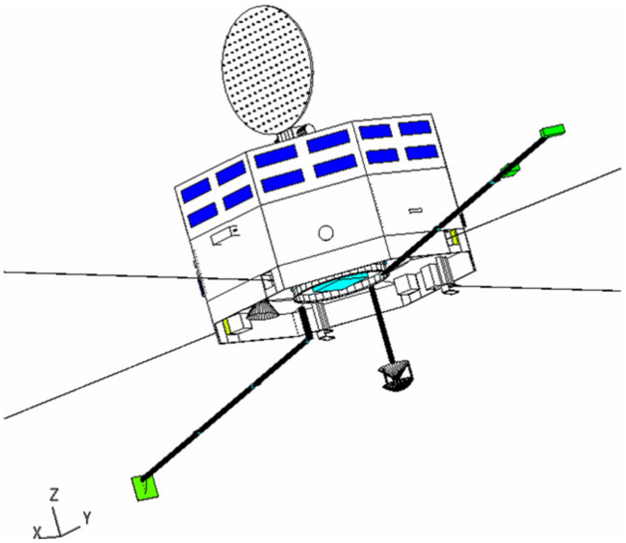

Fig. 1. The MEFISTO and WPT antenna pairs are mounted orthogonally to each other in the spin plane of the spacecraft. At 45° angle to the wire booms are two fixed booms housing the flux-gate and search-coil magnetometers, respectively.

1.2. Heritage

MEFISTO derives from instrument designs successfully flown on a number of earlier missions. At the same time it includes innovative elements to reduce the resources required. The MEFISTO team includes several European and Japanese scientific groups that collectively possess the required expertise and experience. The team is led by the Alfvén Laboratory, Stockholm (Lead Investigator and Lead Engineer (LE) for mechanics) and the Swedish Institute of Space Physics, Uppsala (LE for electronics).

1.3. Instrument capabilities

Maximum field strength	±500 mV/m
Bit resolution	0.015 mV/m
Frequency range	DC – 3 MHz
Spacecraft potential	−100 to +100 V

1.4. Resource requirements

Mass	1.51 kg (incl. nominal harness)
Power	1.28 W (average) 1.68 W (peak)
Volume	288 cm^3 (in main electronics box)

1.5. Other Mercury missions

Only one spacecraft, NASA's Mariner 10, has hitherto visited Mercury. Mariner 10 made two near and one distant fly-by in 1974–1975. The mission was highly successful in making new, unexpected discoveries, but at the same time limited both in terms of instrumentation and orbit. Inasmuch as Mariner 10 provided answers to many central scientific questions, it raised many more. In particular, from the MEFISTO point of view, low-frequency electric field measurements were not made at all. In light of the confirmed existence of a magnetosphere at Mercury, low-frequency electric field measurements are urgently needed to further our understanding of the dynamics of the system.

The NASA Messenger mission was launched in August 2004 and is currently en route to Mercury. Messenger, a Mercury orbiter arriving at the planet in 2011, is a much more comprehensive mission than Mariner 10, but its focus is on the planet itself rather than its magnetosphere. Moreover, Messenger does not carry instrumentation for measuring low-frequency electric fields. Thus, MEFISTO (and the companion instrument, WPT) will make the first-ever in situ measurements of low-frequency electric fields in Mercury's environment.

2. Scientific objectives

Mercury's magnetosphere is quite different from that of the Earth making it interesting to study in its own right, yet they are similar enough to allow comparative studies which are highly likely to provide new knowledge and improved understanding of them both. The electric field describes the plasma transport in a magnetosphere. The electric field also plays an important role in the interaction of the solar wind with the planetary magnetosphere and in the interaction of the magnetosphere with the underlying ionosphere, in the case of Earth, or the underlying planetary surface or its immediate environment, in the case of Mercury. Finally, it is an important parameter for the energy transport between the different regions.

Plasma convection in a magnetosphere is controlled by the DC electric and magnetic fields. Thus, to determine plasma circulation and plasma transport across boundaries, the static component of the electric field needs to be measured. The electric field and plasma flow inside the magnetosphere also give important information on the interaction of the solar wind with the magnetosphere. For example, the saturation mechanism of the transpolar potential that is observed at Earth may work differently at Mercury (cf. Blomberg et al., this issue).

There are indications from Mariner 10 magnetometer data of the existence of field-line resonances at Mercury (Russell, 1989). A field-line resonance is a fundamental response of the planetomagnetic field to the solar wind's interaction with the magnetopause. At Mercury they are interesting also because they depend on the (electromagnetic) reflective properties of the surface and thus may be used to estimate the surface conductivity. This requires simultaneous measurements of the electric and the magnetic fields at low frequency. Some of the "surface" conductivity may reside in a photoelectron cloud just above the surface. By comparing observations in different local time sectors the two components can be separated.

Mariner 10 also observed signatures of field-aligned currents (e.g., Slavin et al., 1997). Studying these with simultaneous measurements of the electric and the magnetic fields will shed additional light not only on the surface conductivity issue but also on the more general, and largely unsolved, question of current closure (e.g., Grard, 1997; Blomberg and Cumnock, 2004). Depending on the details of the low-altitude closure mechanism the correlation between the electric and the magnetic "disturbance fields" will occur for different components, thus enabling diagnostics (Blomberg, 1997).

There have been speculations about the possibility of magnetospheric substorms at Mercury, based on observations of energetic particles in the magnetotail (e.g., Baker et al., 1986). The energetic particles are presumed to be accelerated by induced electric fields related to magnetic reconfiguration of the magnetotail. Also here, electric field measurements will play a clarifying role. Substorms, if they occur, would have vastly different scales involved, both spatial and temporal, compared to Earth. At Mercury the time-scale of substorms would be minutes rather than hours. This opens up new possibilities for understanding the relative significance of the driven versus loading–unloading components.

Energy transport within the Hermean magnetosphere is governed, at least partly, by plasma wave activity, in particular Alfvénic activity. Alfvén waves arise where dynamic processes occur. They can transport energy, in the form of electromagnetic energy, large distances before dissipating it through kinetic, inertial, or wave breaking processes. BepiColombo will be the first mission to Mercury where the detailed physics can be studied, i.e., energy transport, acceleration processes, and dissipation.

A number of wave emission processes are expected. Hermean kilometric radiation (HKR) well below 1 MHz may be emitted from the "auroral" acceleration regions that are known to exist at Mercury, and have a similar cause as the Auroral kilometric radiation (AKR) near Earth. It is interesting to note that radio emissions originating near Mercury below about 50–80 kHz will be trapped inside (reflected back into) the Hermean magnetospheric cavity due to the dense ambient solar wind (30–70 cm^{-3}). Moreover, it has been suggested that the possible existence of radiation belts around Mercury can be inferred from the emission of synchrotron radiation with a peak around a few MHz.

Because of the expected dipole offset, interhemispheric charge flow may arise along Mercury's magnetic field (Blomberg and Cumnock, 2004). Such a charge flow will lead to weak field-aligned currents connecting the hemispheres or to a parallel electric potential distributed along the field lines or a combination of both.

By monitoring bursts of solar radio emissions that indicate the solar disturbance level, it is possible to investigate the whole chain of events from the Sun to the processes directly responsible for magnetospheric storms and substorms at Mercury. Specific activity on the Sun can then be related to specific activity in the Hermean magnetosphere. The time delay is somewhat less than one day for, for example, a solar coronal mass ejection to reach Mercury. It will be possible to compare space weather effects on Mercury with those on Earth, both directly when Earth and Mercury are close to each other in heliospheric longitude, and indirectly when they are separated in longitude.

MEFISTO will continuously monitor the satellite potential. In addition to providing input to the analysis of low-energy particle data, the satellite potential can be used to estimate the local plasma density. It is particularly sensitive to plasma density fluctuations and can, thus, be used to monitor the plasma environment with high time resolution. The technique is well established and has been used on several past satellites (e.g., Pedersen, 1995).

These are but a few examples of scientific issues that can be addressed with the MEFISTO electric field instrumentation on BepiColombo MMO. A thorough literature survey, including a brief review, is found in Cumnock and Blomberg (2003). Expected amplitude and frequency ranges are discussed by Blomberg et al. (this issue).

3. Instrument performance and science operations

MEFISTO employs the "hockey puck" principle, first flown on Cluster, to ensure optimum measurements at low frequencies. At the same time, the instrument will measure AC fields up to 3 MHz with good sensitivity. Fig. 2 shows the sensitivity as a function of frequency. This figure also clearly illustrates how MEFISTO and WPT nicely complement each other to provide for very high sensitivity over the entire frequency range of interest. Except in cases where extreme sensitivity is needed at low or high frequency, respectively, both instruments will function well and a vector measurement (in the spin plane) will be possible.

Spacecraft constraints do not allow a measurement of the axial component of the electric field. The assumption that the quasi-static component of the electric field parallel to the magnetic field is negligible can often be used to estimate the missing (axial) electric field component. The assumption breaks down when the spin axis is nearly perpendicular to the magnetic field or in studies where a direct measurement of the parallel electric field is desired. At times, this may complicate data analysis for certain scientific purposes. Overall, it is not a severe restriction.

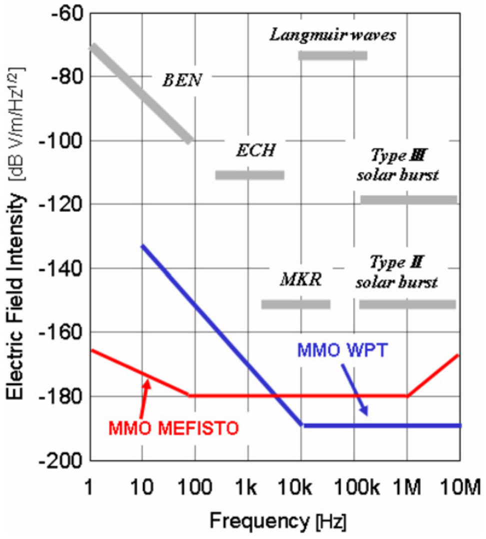

Fig. 2. MEFISTO (and WPT) sensitivity as a function of frequency.

The MEFISTO output is fed into several different receivers. At the low-frequency end, the potential difference is fed into EWO-EFD (Electric Field Detector) for filtering with a cutoff at 30 Hz and subsequent sampling. In the medium-frequency range, the individual probe potentials are fed into EWO-WFC/OFA for filtering at 20 or 120 kHz. The filter output can be either sampled by WFC (wave form capture) or spectral analyzed by OFA (on-board frequency analyser). The unit name EWO derives from EFD, WFC, and OFA. At the high-frequency end the probe signals are analyzed by SORBET (Moncuquet et al., this issue) up to 3 MHz.

Since the telemetry-rate from Mercury is restricted and also varies with the relative locations of Earth and Mercury, a variety of different operational modes are planned. High-speed data collection will be possible by using the on-board mass memory for temporary data storage. At the lowest data collection rate, sharp boundaries in the plasma will not be well resolved. At higher data rates electrostatic shocks, for example, should be well resolved. Autonomous burst triggering will be used to identify suitable regions for high-rate data collection. The electric field induced by the spacecraft motion will be less than some mV/m and therefore not present any problem for the data analysis. The spacecraft is spin-stabilized at 15 rpm, and its attitude is determined from star and sun sensors. Expected measurements are also discussed by Blomberg et al. (this issue).

At regular intervals, the current–voltage characteristic of the probes will be determined by sweeping the bias current (see below) and registering the corresponding probe potential. From the characteristic the optimal bias current setting can be determined, ensuring good low-frequency measurements. In addition, the AM^{2}P instrument (Trotignon et al., this issue) will intermittently inject a stepped sequence of current at different frequencies from which the probes' AC response can be calibrated.

4. Principle of measurement

MEFISTO is a double-probe electric field instrument (e.g., Fahleson, 1967). The basic principle of the measurement is identical to that of a voltmeter: the potential difference between two terminals is measured. In the case of a laboratory measurement where highly conductive clamps are used, ensuring good electrical contact between the probe and the point whose potential we want to examine is trivial. However, in tenuous space plasmas the probe–plasma coupling is a delicate problem. We want the potentials of the respective probes to deviate from that of the local plasma surrounding by the same amount, so that the difference is representative of the potential difference in the unperturbed plasma. If we succeed in this, the electric field component along the direction of the booms is readily obtained as the potential difference divided by the separation distance of the probes.

In order to bring the probes outside the region electrostatically perturbed by the spacecraft, it is desirable to have very long booms. The MEFISTO baseline probe-to-probe separation of 32 m allows measurements of fields as weak as fractions of a mV/m in all but the most tenuous plasmas.

For optimal measurements over a wide frequency range the pre-amplifiers need to be located as close as possible to the probe. Historically, the pre-amps have often been mounted inside the probe itself. This necessitates a multi-conductor boom cable extending from spacecraft to probe. A new development was flown for the first time on Cluster (Gustafsson et al., 2001). There, the pre-amps were located in a separate housing (called ‘‘hockey puck’’ because of its shape) at a distance of 1.5 m from the probe. The ‘‘puck’’ was extended from the spacecraft body by a multi-conductor boom cable, whereas the probe was separated from the ‘‘puck’’ by a thin single wire. The Cluster design has proved to yield measurements of very high quality, likely because of the thin single wire, minimizing the perturbations of the probe potential caused by the boom cable. We are planning to use a similar design for MEFISTO. There is another important reason for this choice: by separating the measurement probe from the pre-amps we can chose a probe surface material optimizing the electrical contact with the surrounding plasma at the same time as choosing a ‘‘puck’’ surface material providing an acceptable thermal environment for the pre-amp electronics. Because of the proximity to the Sun this is of crucial importance for Mercury-orbiting spacecraft.

To optimize the operating point of the probe potential with respect to the plasma, the probe can be fed with a bias current. At Mercury, the photoemission is by far the dominant current in sunlight. Different bias currents will be needed in sunlight and in planetary shadow, to avoid saturation of the probes. If the bias current is chosen such that the probes are kept close to the local potential of the surrounding plasma, the spacecraft potential may be monitored by recording the average potential of the two probes. Since the average of the two probe potentials is representative of the unperturbed potential at the location of the spacecraft body, the negative of this average will be a measure of the spacecraft potential.

Fig. 3 illustrates the MEFISTO sensor configuration. The red sections, probe and sensor wire, form the sensor. The ‘‘puck’’ has two electrically insulated external surfaces. The potentials of these two surfaces can be set individually, the exact values being an operational decision once in Hermean orbit. Our baseline assumption is that the outer ‘‘puck’’ surface will be kept a few volts positive with respect to the probe in order to retract photoelectrons emitted by the ‘‘puck’’, and that the inner ‘‘puck’’ surface will be kept at about 10 V negative with respect to the spacecraft body, in order to repel photoelectrons emitted by the boom and by the spacecraft body. The outside of the boom cable will be connected to spacecraft ground.

5. Electronics

The MEFISTO analogue and digital circuitry mounted on one circuit board in the PWI box, and in the two MEFISTO boom units consists of:

- Two identical E-field pre-amplifiers mounted in each ‘‘puck’’, connected to the main electronic board through 13 m long nine-wire boom cables.
- Two sets of analogue circuitry for current generator control.
- Four drivers for the potential controlled surfaces on the ‘‘pucks’’.
- A common floating ground driver for both probes.
- Two DC signal buffers and one AC signal buffer for each probe.
- Six level shifters to bring analogue signal control from main satellite ground reference to floating ground.
- A field programmable gate arrays (FPGA) controller providing the specialized digital interface with the PWI, motor control, and analogue electronics.
- A dedicated DC/DC converter for floating voltage handling and for floating voltage circuitry power supply.
- Two motor control units.

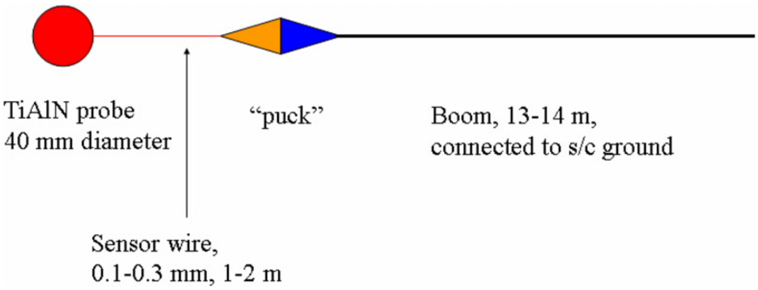

Fig. 3. The MEFISTO sensor configuration.

6. Probes – electrical and thermal properties

The MEFISTO sensors will consist of $Ti_xAl_yN_z$-coated 4 cm diameter spherical sensors, each with a mass of 50 g. The nitridation of the Ti_xAl_y-alloyed spheres can be made in two ways, either by stochastically sputtering nitrogen on the spheres or by baking the spheres in a nitrogen atmosphere at high temperature. The sensor should be kept as cold as possible in order not to overheat the preamplifier electronics in the ''puck''.

The electrical properties of the electric field sensors are, of course, of crucial importance to the performance of MEFISTO. The electrical work function homogeneity is a measure of how smooth a surface of an electrical sensor is and determines to a large degree the resolution of the experiment. The mechanical manufacturing method of the spherical sensor is another important factor. The electrical work function determines how prone a surface is to EMF effects, which may cause hysteresis in the voltage–current characteristic of the probe when the bias current is swept.

The electrical work function, along with adhesion and thermal stability properties, was extensively tested in the laboratory for the TiN-surface coating used on the Langmuir probe on the Cassini/Huygens mission to Saturn (Veszelei and Veszelei, 1993; Wahlström et al., 1992). Actual in-flight data are shown in Fig. 4, illustrating the superior performance compared to previously used graphite (DAG) surface coatings. TiN was applied on the Cassini Langmuir sensor by the high-temperature nitridation method. TiN was also used for the electrical sensors (Blomberg et al., 2004) and the Langmuir probes (Holback et al., 2001) on Astrid-2 with excellent results. Although similar tests have not been carried out for $Ti_xAl_yN_z$-alloys, with the exception of thermal properties of sputtered samples (Brogren et al., 2000), the electrical, chemical, and mechanical properties are expected to be quite similar to those of a pure TiN surface coating. The TiN surface coating has the following properties:

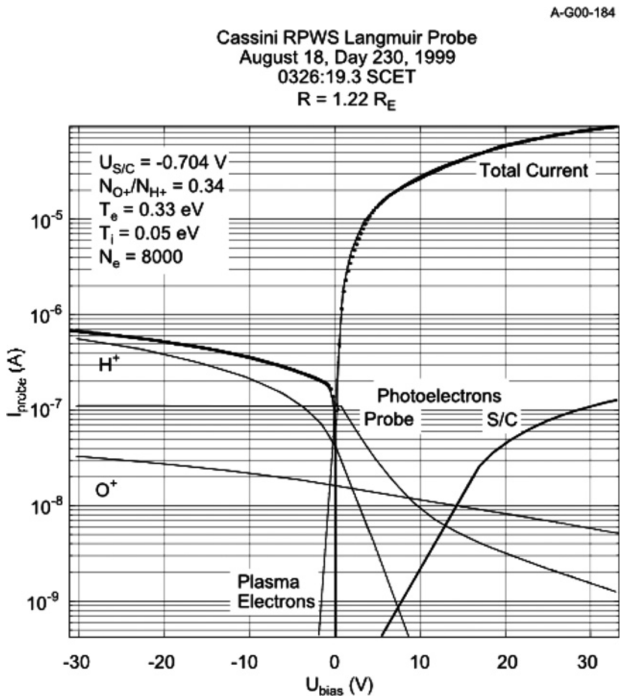

Fig. 4. Two superposed Cassini Langmuir probe sweeps along with model calculations taken during the Earth flyby at an altitude of approximately 1200 km. No electrical hysteresis can be detected in the voltage–current characteristic for this TiN-coated sensor (Kurth et al., 2001).

- Electrical work function rms variation of only 0.15 meV.
- Chemically inert, especially to atomic oxygen radicals.
- Mechanically very hard and durable surface.
- Easy handling and cleaning. Sputter cleaning may be possible in-flight by applying a high negative bias voltage.

The equilibrium temperature, T, is dependent on the ratio of the average solar absorption, α, and the averaged, temperature dependent, thermal emittance, $\varepsilon(T)$. The pure TiN-coated surface is not suitable for the Mercury environment for thermal reasons. However, by carefully selecting the composition of the alloy the effect of the infrared radiation from Mercury can be minimized for optimal thermal control of the sensor. A factor 3–4 improvement over TiN coating is expected.

7. Boom mechanics and extension mechanism

The boom unit provides storage and deployment of the wire boom, the puck, and the probe. Mechanically, the wire acts as a boom; electrically, it acts as a carrier of the electrical connections between the probe at the end of the wire and the experiment unit in the spacecraft body. The boom wire, stored between two concentric cylinders, is fed using a mechanism driven by an electrical motor located at the rear end of the boom unit. This mechanism lifts the wire from its storage between the cylinders and pushes it out along the center axis of the two cylinders. The wire deployment speed can be up to approximately 25 mm/s.

The two boom units are mounted on the lower deck through a square hole in the lower spacecraft panel. The front surfaces of the boom units are aligned with the outer surface of the lower panel. Fig. 5 illustrates a boom deployment unit.

The mass of each puck is 50 g, each of the two boom cables is 79 g, the boom deployment units are 380 g each. Thus, excluding platform harness, the total mass of the boom system (incl. probe, 50 g) is 559 g per unit.

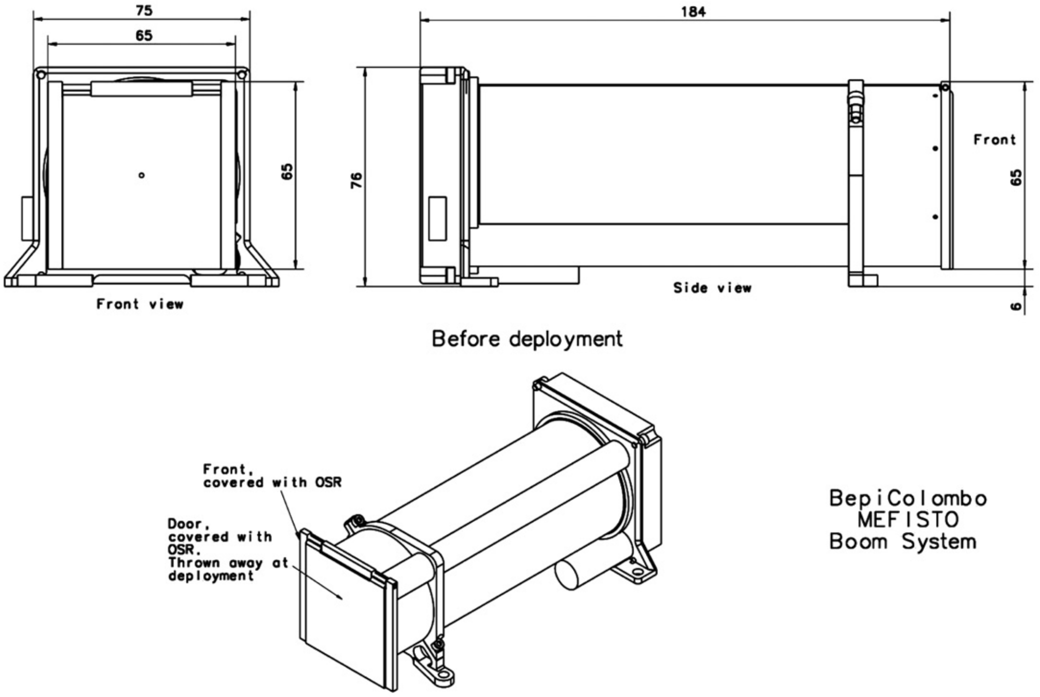

Fig. 5. The MEFISTO boom unit.

This is approximately a factor 5 less than the mass of conventional mechanisms for the same boom length.

8. Summary

There are an abundance of magnetospheric phenomena that are particular to Mercury that we propose to study. There are also many phenomena familiar from the Terrestrial magnetosphere that we will learn a lot more about from studying them in a magnetosphere with vastly different scale sizes, and subjected to different boundary conditions both at its lower, planetary border, and at its upper, interplanetary border. We expect to expand our knowledge about the magnetosphere of Mercury in particular as well as planetary magnetospheres in general.

The instrument proposed for these studies is based on the double-probe principle which has successfully been used on several earlier missions. A number of new developments have been done to adapt the instrument to flight in the thermally harsh environment of planet Mercury as well as to meet the stringent mass limitations for the payload elements.

Acknowledgments

The authors are grateful to Per-Arne Lindqvist, Mats André, Michiko Morooka, Göran Olsson, Sverker Christenson, Bjørn Lybekk, Kauko Lappalainen, and Anssi Mälkki for their contributions to the project. We thank the referees for constructive comments on the paper.

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