Alpbach Summer School

Final Status Report on the Mercury Orbiter

Alpbach, August 1995

Table of Contents

1. General Introduction..... 03

2. Magnetosphere, Exosphere, Solar Wind and Solar Physics (Group 5)..... 04
2.1. Introducing to Science.....04

2.2. Working Strategy....04
2.3. Scientific Objectives.... 05
2.4. Measurement Requirements.... 08
2.5. Data handling and Data distribution.... 12

3. Geophysics (Group 4).... 14
3.1. Introduction.... 14
3.2. Current knowledge of the physical properties....14
3.3. Geophysical Goals.... 17
3.4. Imaging Systems....19
3.5. Data interpretation and Evaluation.... 23
3.6. Conclusion....26

4. Geochemical Properties of the Hermean Surface (Group 3).... 27
4.1. Introduction.... 27
4.2. Fundamental Questions.... 28
4.3. The Instruments.... 31
4.4. Conclusion.... 40

5. Missions and Operations Design, Fundamental Physics (Group 1)....42
5.1. Introduction.... 42
5.2. Fundamental Physics.... 42
5.3. Solar Sails.... 45
5.4. S/C Autonomy....46
5.4. Enviroment / Instrument-related problems.... 48
5.5. Mission Operation + Encke Option....50
5.6. Mission Time Line....55

6. The Lander Option.... 57
6.1. Mercury Surface Probe.... 57
6.2. The Venus Probe Option.... 58
.
7. System Objects of Spacecraft and Technology (Group 2).... 60
7.1. Introduction.... 60
7.2. Attitude Control System....61
7.3. Propulsion.... 62
7.4. Power system....63
7.5. Thermal Control ans Mechanical Design.... 65
7.6. Communications.... 68
7.7. Conclusion....72

8. General Conclusion.... 72

General Introduction

The deeper we take our investigation of our solar system, its origin and evolution, the more we reveal its complexity and beauty. Today, the field of space science has grown to include almost all scientific fields and the combined effort is a natural requirement in our continued quest for knowledge.

It is practically impossible to extrapolate from the present state of our solar system to the original state of the solar nebula. One can only put constraints on the evolutionary processes by fundamental investigation of the present state. To learn how the present state works one must not only perform a thorough investigation but also use the conclusive knowledge obtained by comparative studies of our solar system. Mercury is in the unique position in both respects.

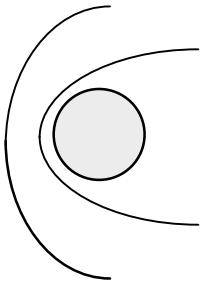
A mission to Mercury can provide information on the evolutionary history of the solar system, since clues about the planetary history can be found from geochemical observations.
The rotational dynamics of Mercury is not well determined. Measurements of several terms of the gravitational potential would improve the knowledge of Mercury´s interior. The structure and temporal variation of the magnetic field is a key to the understanding of dynamo action within the core.
Being the end-member planet closest to the sun brings Mercury into a unique position with a highly dynamic and extreme magnetosphere. The lack of a significant ionosphere put constraints on the origin of the magnetospheric population leaving solar wind particles as an expected major fraction. Moreover, the time scales of magnetospheric processes are ten to hundreds times greater than at Earth making the magnetosphere of Mercury an intriguing object for fundamental studies in magnetospheric plasma physics. It has been thought that the ionosphere plays a central role in processes known as substorms at Earth, but the fact that Mercury have no ability to support any current systems through a conducting ionosphere makes this a key point.

Mercury is important for the characterization of General relativity because its orbit is affected by the space curvature more than any other planet in the solar system. Therefore relativistic effects, like time dilatation, advance of the perihelion or the Shapiro effect are best observed at Mercury.
From the engineering point of view, the hostile environment in the Hermean orbit presents a delicate challenge. Due to the short distance between the planet and the sun of 0.31 AU to 0.47 AU the orbiter will have to face not only high temperatures but also strong radiation. This mission will give us new tools and technologies to manage the special requirements for further exploration of the inner solar system and in particular our central star, the sun.
The installation of an European deep space network as well as the foundation of a center for the distribution of the data among the scientific community is expected to be enforced by the realization of the Mercury orbiter mission.

Solar system exploration is a true interdisciplinary field where both different fields of science as well as science and engineering have to be integrated to form a coherent mission with an optimized scientific return. The extreme conditions at Mercury takes this even further demanding an even higher ability of integration and optimization between different groups of interest. Apart from being a mission with high scientific gain the interdisciplinary benefits will play a significant role in further solar system exploration.
This report is an approach to investigate some aspects of these requirements.

Magnetosphere, Exosphere, Solar Wind and Solar Physics

Laila Andersson, Swedish Institute of Space Physics
Rainer Bauske, Institut für Astrophysik und Extraterrestrische Forschung, Universität Bonn
Pontus C:son Brandt, Swedish Institute of Space Physics
Emil Khalisi, Max-Planck-Institut für Aeronomie
Andreas Klassen, Astrophysikalisches Institut Potsdam
Martin Reber, Physikalisches Institut, Universität Bern
Rune Stadsnes, Department of Physics, University of Bergen

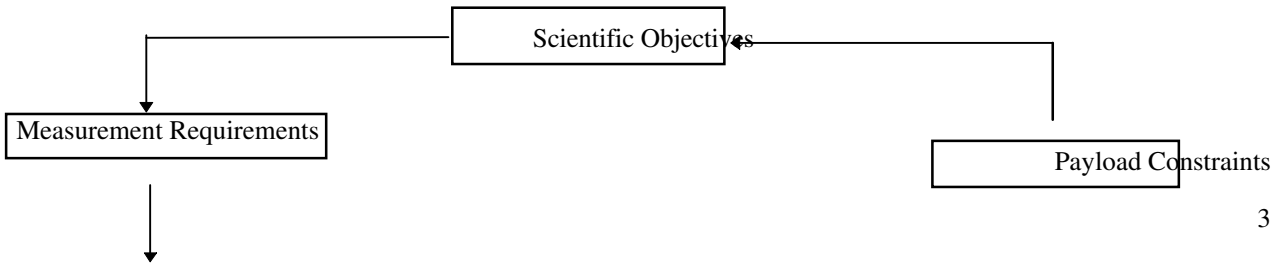


2.1. Introduction to Science

The magnetosphere of Mercury is very different from all other magnetospheres. Twenty years ago Mariner 10 did three flybys at Mercury and discovered its unexpected magnetic field. It is now time for a more comprehensive study of this magnetosphere, which has a nominal position of the magnetopause only 1.4 planetary radii from Mercury on the dayside.
Since Mercury is so close to the sun it is exposed to much denser and hotter solar wind (S/W) plasma than any other planetary magnetosphere in our solar system. Having a weak magnetic field the magnetosphere is small relative to the planet and time scales are hundreds of times faster than on Earth.
Mercury´s atmosphere is very rarefied and there is almost no ionosphere. It will be very interesting to study substorm phenomena and where the magnetospheric currents close when there is no significant ionosphere.

2.2. Working Strategy

The strategy intended to be used is to after having carefully selected key scientific objectives list the requirements put on the measurements, such as energy ranges, time resolution, energy- versus mass resolution etc.. The instruments are designed after these requirements. Integration takes place with other scientific groups and in turn mission integration together with engineers and scientists. The integration will put constraints on the selected instruments and maybe on measurement requirements. Cycle two starts (see graph below).
It is important to note that the driver is science and that from the measurement requirements the instruments will emerge (These are taken as model instruments already existing, e.g. SWICS from Ulysses with required charecteristics and then extrapolated 10 years ahead).
Furthermore, from measurement requirements we get datarate, which is one of the main factors putting constraints on our measurement requirements.



2.3. Scientific Objectives

A set of scientific objectives and key questions has been identified and are listed below.

Magnetosphere

Mercury´s magnetosphere *is* with no doubt a tantalizing object for fundamental magnetospheric research. Mariner 10 studies and ground based studies have shown that an ionospheric layer in the exosphere is not likely to be formed. The ionosphere in a magnetosphere is responsible for the closure of the current systems.

Structure

- What model magnetosphere applies to Mercury (M)?

Dynamics

Since it is probable that M magnetosphere is highly dynamic and time scales of magnetospheric processes are in the order of 100 times faster on M than on Earth. The physics concerning the dynamics is of high interest.

General circulation

- How is the magnetospheric dynamo working? Where do currents close?

Acceleration processes

- Substorms
- Shock acceleration

Sources & Sinks

The overall objective can be narrowed down to separate S/W- from planetary particles.
The magnetospheric population also give information on the sources. There are the following possible *sources* to the magnetospheric population

Surface sputtering

- Exospheric outflow
- S/W entrance through the cusp (polar cap regions)
- Jovian electrons

And *sinks*

- Loss from the planet as pick-up ions
- Charge exchange with exospheric neutrals
- Exospheric loss
- Loss due to surface impacts (planetary sized gyro radius make protons and heavier to impact directly from the interplanetary medium)

Waves

Wave detection will only be in terms characterizing physical properties of the magnetosphere. This goes for the high frequency waves (>100 Hz). Magnetohydrodynamical waves with <10 Hz can be detected with search coil type magnetometers.

Exosphere

The neutral exosphere of Mercury is very rarefied and permanent ionisation may not exist. Here, the questions arise which kinds of particles are present and which are the sources of these particles.

Data from the UV-spectrometer of Mariner 10 and from ground based observations show that the main components in the Mercurys exosphere are H, He, O, Na, and K. We expect a density of 1000 particles per cm^{-3} at 400 km altitude (dayside) for Na and H, other particles are about 2 orders of magnitude less abundant. Various other elements and molecules can be expected in small concentrations (Hunten et al., 1988).

The lower boundary of the exosphere is the solid surface. Solar radiation and direct interaction of the solar wind with this surface leads to sputtering, scattering, and absorption effects. Particles ejected from this boundary into the exosphere will have kinetic energies of 1 - 3 eV. Therefore, neutral particles are not expected to have a Maxwellian velocity distribution. Furthermore the height dependence might be different to that of a ´normal´ exosphere, where the density varies as a function of the exospheric temperature (T-5/2; according to Hunten et al., 1988). Instead, on the dayside the gas temperature of about 150.000 K leads to a scale height which is enlarged by a factor of 6 in comparison to the night side (Ip 1986 and Hunten et al. 1988). After ionisation these particles are influenced by magnetospheric processes which take place on much shorter time scales and spatial scales than in the earth´s magnetosphere.

Estimates of ion densities imply that a permanent ionosphere may not exist (Bauer, 1995). The question to be investigated from the magnetospheric physics point of view is where we can find a conductive layer in order to explain ring currents.

Production and loss processes for the neutrals and ions are not at all understood. The search of less abundant species being in the gas phase such as noble gases and various molecules, e.g. H_2O, CO_2 and CH_4 including their deuterated equivalents gives a clue about the origin and about the alteration processes of the exosphere as well as of the surface.

Surface interactions

Due to weak field, high S/W pressure and lack of any significant ionosphere it can be expected that surface interaction, such as sputtering, plays a significant role in populating the magnetosphere. Interaction with geochemists in this field for best result.

- Source of direct surface impact/sputtering
- Effects on the properties of the surface being important for magnetospheric phenomena
- How can a conductive layer be formed either on or beneath the surface? Effects of photoelectrons at or near the surface?
- How are Alfven waves reflected?

Solar Wind

Lots of basic problems of understanding in solar physics are not answered yet. In spite of analysing the interplanetary space in the inner heliosphere in the 70´s many new questions remain unanswered. Still unknown is the fine-scale composition, especially the density differences of heavy ions in the fast and slow solar wind. The Mercury mission offers another chance to study the solar wind and its phenomena:
- kinetic physics and thermodynamics of the solar wind
- interactions of large scale structures of slow and fast solar wind
- evolution and acceleration of S/W
- development of solar mass ejections (SMEs)

- magnetic clouds
- fast forward shock waves
- helioseismology (TBD)
- Pick-up ions can be considered as a loss process through which magnetospheric particles are lost to interplanetary space. Moreover, pick-up ions can give clues to composition.
- differences from S/W to the earth and the evolution of the heliospheric currrent sheet

Solar Physics

- Investigation of the anisotropy of the X-ray and gamma-ray emission from the sun.
- The total electron contents (TEC) dynamics between the Mercury orbiter and the Earth (ground based station) measuring the rotation of the plane of polarization (Faraday rotation) of the radio emission from the S/C.

Cruise Science

The instruments chosen for measurements in Mercury orbit are also well suited for measurements during the spacecraft-cruise towards Mercury. Solar wind measurements can be done in great detail with the electron and ion composition spectrometers. These spectrometers would also be very useful if one chooses to make a flyby of the comet Encke. The wave instruments will also give information on the processes in the comet and the solar wind.
As one can use the same instruments for cruise science as for Mercury related science, the only limiting factor will be the power available during cruise. There has been many spacecrafts measuring the solar wind, so one should give lower priority to measurements during cruise if there is a power limitation. One could turn the instruments on at the time of the P/Encke flyby, or increase the data-rate at that time if one has a low data-rate during the rest of the cruise.

Comet P/Encke (TBD)
- S/W interaction
- Composition

Venus flyby
- Magnetospheric structure (shock formation)
- Ionospheric composition
- Shock accelerations (Mars comparison)

Mercury flyby
Preinformation of Mercuy and instrument performance

2.4. Measurement Requirements

This section deals with how the measurements should be carried out in order to fulfill the scientific objectives defined above. After having specified the measurement requirements we decided on which instruments to use.

Magnetic field measurements

The magnetometer should give all three components of the field suggesting a 3-axes fluxgate instrument. Furthermore, it should be able to resolve timescales <0.1 s and have a resolution of about 0.1 nT.

Peak ranges from the Mariner 10 mission is 400 nT, but in this case the main driver is the sampling rate (data rate) and not the range, so the range is taken as the range in the ESA proposal to be 4000 nT. Current estimation of mass is 2 kg with a power requirement of 3 W. The data rate with this time resolution would be in the order of 0.1 - 0.2 kbps.
The magnetometer should be placed on a boom about 6m away from the spacecraft in the radial direction to avoid magnetic signatures from the spacecraft itself.

Ion measurements

Ion Composition Spectrometer

The ion composition spectrometer should be able to separate S/W-particles from planetary particles, even when accelerated to 500 keV, which may very well be the case for Mercury. In order to do this we need to resolve about 20 different species (H+, He++ from He+, O+, Na+, K+). The time resolution (the time for one full spectra in one direction with fixed mass) need to be high in the order of seconds, say 0.1 s.
As analogy the MICS is worth mentioning. This is capable of measurements in the range 1 keV - 400 keV and resolving masses from 1 - 50 amu. Further details can be found in the table at the end of this section.
The energy resolution is not of any major concern for the moment. A 10 % energy resolution is believed to be sufficient. A 3D distribution can be obtained by spinning a 180 degree field of view.

Another requirement is the ability to detect and resolve ions with exospheric origin (sputtered ions). This puts greater requirements on mass resolution but less on time resolution.
During what has been referred to as a substorm on M, bursts of 600 keV electrons, 10^7-10^8 cm^-2s-1sr-1, have been observed by Mariner 10. These could effectively work as a plasma gun sweeeping over a significant surface area in the auroral oval region.

As an analogy there is the CAPS instrument on Cassini with an energy range of 1 eV - 30 keV and capable of resolving masses 1 - 50 amu.

In the solar wind energetic particles from SMEs, flares etc are expected in the range between 5 - 400 keV. Their distributions should be sampled in high time resolution. Especially a knowledge of the heavier particles is required, so a spectrometer is needed with a capability to distinguish seperately protons, alpha particles and heavier ions.

Electron measurements

Acceleration processes

For magnetospheric electrons an energy range is to be considered between

E=10 keV - 500 keV (or even higher upto 1 MeV) with Δt=0.1 s / energy sweep

3D distribution with 360° field of view instrument is an option. This can be managed by inserting a 2π-instrument rectangular to the spacecraft's spin axis.

Solar wind electrons have energies ranging from 0.5 eV - 30 keV. Therefore a 2D-direction coverage with 360° field would be sufficient, but high time resolution is necessary. The EEA instrument can perform 5 eV to 30 keV. Alternatively the FREJA MATE spectrometer (weight: 2.5 kg) for example is a 2-π instrument with 32 opening angles, which samples very 10 ms a complete spectrum. The ranges cover the band between 100 eV and 100 keV, which could probably be accommodated to the specified values.

It is possible to include an option to swap polarity of the spectrometer for positron detection. These have been detected in the MeV range on balloon borne experiments and a positron detector has never been flown in the interplanetary space to our knowledge.

Photo electrons from surface and upstream electrons

E=1 eV - 500 eV

Neutrals

Sputtered neutrals

Acceleration of magnetospheric particles and direct impact of S/W onto the surface sputter a significant amount of neutral atoms from the surface (S. Bauer, Private Communication).

Typical sputtered neutrals, He, Na, at 400 km is expected to have concentration of 10^3 cm^-3 and enegies in the order of 1 eV. Since this energy is in the order of the escape energy, sputtered neutrals will have ballistic trajectories, some of them returning to the surface some picked up by the S/W.

Sputtered ions have the unfortunate ability to be accelerated by large potentials set up in the dynamical near tail region (and elsewhere perhaps) and, so, loose their information on initial energy and origin that in turn carries information on the original sputter process. In this case sputtered neutrals have the advantage of conserving their energy except gravitational deflection leading to ballistic trajectories, in some cases returning to the surface.

E=1 eV - 10 keV; resolution m/dm > 100
mass range: 1 - 50 amu/q

Model instrument: Ion- and neutral mass spectrometer (double focussing magnet-type from Giotto; Quadrupole instrument from Galileo-Mission published by Niemann).
Detecting neutrals in this range will also, apart from giving knowledge about surface interaction with magnetospheric particles, reveal geochemical properties of the surface. This is a good example for one of the many issues in this mission, where different fields of science overlap.

Energetic Neutral Atoms (ENA)

Energetic plasma population (10-500 keV) such as radiation belts and S/W injections can be imaged by obtaining the 3D distribution of neutrals. The hot plasma componenents will charge exchange with cold

exospheric neutrals and these will propagate as ENA with conserved momentum and energy and unaffected by gravitiaional and electromagnetic fields.

This is an imaging technique used to obtain global features of the magnetosphere, such as radiation belts, ring currents, injections into the inner magnetosphere (lacking on Mercury). In general to obtain the global dynamics and morphology wherever the charge exchange efficiency is sufficiently high.
For Mercury the charge exchange efficiency varies from 10^-6 - 0.1 (worst and best, day and night side). For Earth conditions this is 10^-4 - 10^-2 (!).

E=10 keV - 500 keV

The main problem with this technique in the case of Mercury is that the inner magnetospere is absent. This is where the imaging works best (high neutral density and large ion fluxes).

Optics

A multi spectral spectrometer in the wavlength range from 100 A to 10000 A would provide a wealth of information on the densities of all detectable particle species of the exosphere. Nevertheless a `big` spectrometer has a weight of about 12 kg. Since we are able to detect various particles at the satellite altitudes with other means, we suggest complement measurements by a set of simple optical instruments to get informations on the height variation for the densities of H (122 A), O (1304 A), Na (5890 A, 5896 A) and K (7664 A, 7669 A). Four instruments of this kind flew on board of satellite ASTRID. Here, these spectrometers will be mounted in the spin plane. Therefore their resolutions will depend on the spin rate.

Electrical field measurements

At high densities and low energies antennas can be used as an electron spectrometer as well

The low frequency (1 Hz - 10 kHz) range will be covered with a 3 axis coil magnetometer. This will be mounted on the magnetometer boom. These range will give us information about convection, currents, double layers, boundaries and transportation. For the higher frequency range (up to 6 MHz) two pairs of wired booms are selected. One pair at 30m and the other 10 meters mounted in the spin plane. From this we can intercalibrated some of the instruments and get electron temperature, electron densities. Properties we can study are AKR, radiation belts, solar radiation bursts (flares) and substorms.
Problems with the electric field measurements are due to photo electrons and spacecraft charging. Low frequencies of the electric field will be difficult to do due to s/c spin direction (the wire booms will be in sunlight and shadow). Due to the thermal environment no amplifier and spheres can be put out on the wire booms. The amplifier have to be mounted close to the deployment mechanism. Here the some shielding wire boom - spacecraft have to be made. (Jean-Louis Bougeret, Private Communication)

Wire booms, deployment and pre. ampl. (10+30m)	freq: TNR,HFR	total 1.5 kg
Coils, pre. ampl. 3 axis	Freq: WFA,FFT	less than 1 kg
Electronics		4 kg

Proposed model payload instruments

INSTRUMENT	MESUREMENT RANGE	MASS (kg)	POWER (W)	DATA RATE (kbps)	TIME RESOLUTION (s)	
Magnetometer	+/-4000 nT	2	3	0.1 - 0.2	0.1	6 m boom
Ion Composition Spectrometer 1 (MICS, Viking)	1 - 400 keV/q 1 - 50 amu/q	3.5	4	5	0.1	3D measurements using 180 degrees field of view
Ion Composition Spectrometer 2 (CAPS, Cassini)	1 eV - 30 keV/q 1 - 100 amu/q	2	2	5	0.1	3D
Electron spectrometer	1 eV - 30 keV	3	2	5	0.1	3D
Electron spectrometer	20 keV - 500 keV	2	2	5	0.1	3D
Neutral Mass Spectrometer (Pioneer, Giotto, Galileo)	1 eV . 10 keV 1 -50 amu/q	5	4	0.5	5	high sensitivity m/dm >100
Energetic Neutral Particle Imager (PIPPI, Astrid)	10 - 500 keV	5	4	0.5	5	3D
UV and Optical Telescope	Four wavelengths	0.6	0.3	tbd	tbd	
Wave	1 Hz - 6 Mhz	6.5	7	5	tbd	
Radio beacon	100 Mhz and 200 Mhz	2	1 - 2	passive	impulse emission	
Gamma spectrometer	0.5 - 20 MeV	5 - 10	10	0.5	1	Low priority
X-ray spectrometer	1 - 80 keV	5	4	0.05	1	Low priority

2.5. Data handling and Data distribution

The downlink is a critical point on the Mercury mission. Elsewhere in this report suggestions have been done to increase the downlink volume.
In order to increase the data information sent from the s/c are data processing and compression crucial. This things have to be optimized for the different instruments. Different ways can be done on different instrument example: electron data only sending down three directions (parallel, antiparallel and perpendicular to the magnetic filed). Waves can be analyzed on board (FFT) and look for different signatures in space and only send down when these signatures was measured (neural networks).

All the PI's and CoI's should have the complete data set. When Mercury Orbited will be launched will several high level software for data analyzing being used (such as SDDAS). These high level software need the data to be stored in special data form. The data can being stored in these forms already at the ground control center where the coping of the discs/tapes for the different groups will be made.
The PI's are responsible for making the data or a overwiev of the data available on a server after a time. How long after receiving the data this should have happen and if it will be a common server have to be decided in further investigations. The PI's should have some possible influence of the result of the data being published so no wrong interpretation will be made.

Acknowledgements

We thank for the support by the following people who helped us to complete this work:

M. Blanc

J.-L. Bougeret
M. Coradini
J. Geiss
M.C.E. Huber
R. Schwenn
G. Scoon
D. Southwood

References

Eraker J:H. and Simpson J.A., Accelaration of charged particles in Mercury's magnetosphere, JGR 91, p9973, 1986

Russell C.T., Baker D.N. and Slavin J.A., The magnetosphere of Mercury in: „Mercury" book, eds. Vilas F., Chapman C.R., and Matthews M.S., University of Arizona Press, 1988

Bauer S., Alpbach lecture notes, 1995

Hunten D.M., Morgan T.H., and Shemansky D.E., The Mercury Atmosphere, in Mercury, eds. Vilas F., Chapman C.R., and Matthews M.S., University of Arizona Press, 1988

Ip W.-H., The Sodium Exosphere and Magnetosphere of Mercury, Geophysical Research Letters, 13,423, 1986

Ogilvie K.W., Scudder J.D., Vasyliunas V.M., Hartle .R.E., and Siscoe G.L., Observations at the planet Mercury by the plasma electron experiment: Mariner 10, JGR 82, 1807-1824, 1977

3. Geophysics of Mercury

VERA CONZELMANN, Institut für Planetologie, Westfälische Wilhelms-Universität, Germany
AXEL HAGERMANN, Institut für Planetologie, Westfälische Wilhelms-Universität, Germany
MARCUS GUNNARSSON, Astronomiska Observatoriet, Uppsala Universitet, Sweden
JOHAN WARELL, Astronomiska Observatoriet, Uppsala Universitet, Sweden
THOMAS SIMON, Institut für Astronomie, Universität Wien, Austria
SANDRINE QUÉRÉ, Observatoire Midi Pyrenées, France

3.1. Introduction

The task of the geophysics group was to define areas of research on Mercury and instruments for the detection and measurement of its geophysical properties. The restriction of not being able to drop a soft lander for in-situ measurements on the surface greatly limited the possible geophysical outcome of the mission. All parameters contributing to the knowledge of this aspect of the planet has to be performed with the imaging camera and magnetometer onboard the orbiter and tracking of its motion from ground stations.

3.2. Current knowledge of the physical properties of Mercury

3.2.1. Interior Structure

Mercury has a very high decompressed density compared to the other terrestrial planets. Therefore it is expected to be depleted in volatiles. This would suggest an accretion temperature above 1000 K (Wänke, 1995). The mineral composition of Mercury is currently not known, but its properties would give a clue for the formation of Mercury and could be used to clarify its thermal evolution.
Mercury is differentiated into a metallic core that makes up 65 % of its mass and a silicate mantle, but it is not known, whether the core is at least partly liquid. The moment of inertia factor is not well known. It could be helpful to determine the internal structure of Mercury.

3.2.2. Rotational State

There is a 3:2 resonance of the orbital period to the period of axial rotation. This means, that every 2 Mercurian years, the same side of the planet faces the sun.
Mercury´s shape is very close to a sphere, its oblateness is 1/100 of the Earth´s, which is due to the slow rotational rate. The axis of rotation is not exactly known, but it is almost perpendicular to the orbital plane.

3.2.3. Gravitational Field

The gravitational field is still completely unknown. By calculating J_2 and further terms of the gravitational potential from tracking data of the Orbiter we could get a global map of Mercury´s gravitational potential, determine the size of the core precisely and get a better insight into the density distribution within Mercury.

3.2.4. Surface Conditions

The average surface temperature is about 580 K. Due to the planet´s slow rotation, the surface temperature is very high on the dayside and very low on the nightside (TABLE 1). There are speculations from radar measurements of a possible presence of buried water-ice in the polar regions of Mercury. The modification of rampant craters above a latitude of 35° deduced from Mariner 10 images is most likely the result of fluid flows generated by the liquid water melted at the impact (Balogh, 1995).

The global geomorphology is closely related to shrinkage of the entire planet. Rift structures have been detected by Mariner 10. A global map could be helpful to determine how much the planet has shrunk since its accretion. This would result from the combined effects of differentiation into core and mantle, inner core freeze-out and global cooling of the planet.

The heavily cratered highlands of Mercury have crater size-frequency distributions similar to the Moon and Mars. However, the Mercurian highlands show a marked paucity of craters inferior to 50 km diameter compared to the lunar highlands. This paucity can be explained by intercrater plains formed during the period of late heavy bombardment (about 4 to 4.2 Ga). Mercury's volcanic activity was very intense early in its history (much more than for the Moon) but ended sooner on Mercury (about 3.8 Ga ago) than on the Moon. This is probably the consequence of the formation of Mercury's enormous iron core which caused extensive melting , global expansion and crustal tension during hte period of late heavy bombardment, followed by cooling and global contraction to shut off magma sources early in its history.

3.2.5. Atmosphere

There is a gaseous envelope consisting of H, He, O, Na, K with a column content of less than 10^{11} atoms cm^{-2} and a surface concentration of at the most 10^{4} atoms cm^{-3} (Bauer, 1995). As the atmosphere is most rarefied, there is almost no ionosphere. Nevertheless, it could be dense enough to allow for an auroral zone (Bougeret, 1995).

3.2.6. Magnetic Field

The magnetosphere is unparalleled in the solar system. It is caused by the interaction of the planetary field with the solar wind. Mercury is the sole known example of a magnetized body in the solar system lacking a significant ionosphere. Therefore a much lager fractional volume of the magnetosphere is occupied by the solid planet than on Earth.

There is a weak magnetic field, it´s surface field strength is about 1/100 of the Earth´s surface field strength (Bauer, 1995). It is strong enough to stand the solar wind (Balogh, 1995). The solar wind speed at the distance of Mercury does not differ significantly from that at 1 AU, but its density is 8 times stronger and hotter as well as there is a more intense interplanetary magnetic field. Therefore, the scale size of the Mercurian magnetosphere is about 5% of the terrestrial magnetosphere and one expects short characteristic times for any short-term variations.

The measurements by Mariner 10 delivered no conclusive magnetic field models as there were only few spacecraft trajectories crossing the magnetosphere and due to perturbations from magnetospheric currents. Nevertheless it could give clear evidence of a planetary bow shock as well as a magnetopause (TABLE 1).

The interaction between solar wind and Mercury possibly could be partly determined by the quadrupole terms of the magnetic field.

Magnetometers in orbit could be used to measure the long-term secular variations of surface magnetic fields and thereby answer the question on whether there is an active dynamo mechanism within Mercury. This would require low altitude passes at the periapsis.

The large size of Mercury´s metallic core suggests significant quadrupole moments. Therefore an application of a simple dipole moment could be meaningless. The relative importance of the dipolar term to higher order terms would need to be established with some certainty to set useful constraints on the generation mechanism of the global magnetic field. An intrinsic dynamo process would require the core to be at least partially molten.

TABLE 1 - GEOPHYSICAL PROPERTIES OF MERCURY

density	mean: 5.44 g cm^{-3}	decompressed: 5.3 g cm^{-3}
mass	3.3×10^{24} kg	
radius	2439 km	
core mass	65%	(Earth: 33%, Moon: 5%)
core volume	40%	(Earth: 16%)
silicate phase material	35%	
surface gravity	3.6 N kg^{-1}	
escape velocity	4.2 km s^{-1}	
surface temperature	average: 580 K dayside: > 630 K (perihelion) 575 K (aphelion)	nightside: 95 - 130 K
excentricity	0.206	
orbital period	0.24 years = 87.7 days	
semimajor axis	0.387 AU = 57.9×10^6 km	
orbital plane	inclined 7° with respect to ecliptic	
oblateness	1/100 of the Earth	
spin period	58.6 d	
moment of inertia factor	$I/(M \times R^2)=0.324$	rough estimate
subsolar magnetopause	$1.35 \pm 0.2 R_M$	
bow shock stand-off distance	1.9 ± 0.2 R_M	

3.3. Geophysical Goals

3.3.1. Science from orbit

The imaging camera on the S/C will be used to study the following topics:

- *Crustal movements*. These are vertical and horizontal movements due to seismic activity, thermally compensating movements caused by crust contraction/expansion during the diurnal/annual cycle, and surface disruption due to energetic impacts.

- *Altimetry*. Accomplished by stereoscopic imaging of the surface.
- *Topography*. Accomplished by high resolution imaging of the surface. This is a very important task for the understanding of the topographic and geologic structures. A basic problem is to establish a time-stratigraphic classification scheme to correlate widely-separated gelogic units and provide a framework for interplanetary correlations of geologic time. The geologic history of the planet and impact flux history of the inner solar system can be reconstructed by photogeological analysis of the global relations between rock-stratographic units.

  Regional compression areas can be studied by numerous wrinkle ridges within smooth plains materials. The question of whether there is sub-surface ice near the poles can be answered by studying the morphology of craters in the areas. Such craters would (comparing with the situation on Mars) probably display ejecta blankets with a pattern of "flow" motion, and their distribution would thereby put a limit on the spatial distribution of the ice.

  The study on high resolution images of the NW-SE and NE-SW trending lineaments in the equatorial region, and more E-W oriented lineaments near the poles, will clarify the despinning process in the early history of the planet as the rotation was slowed by solar tides and relaxation of the equatorial bulge. Similarly thrust faults will be studied to clarify if they were created during a slight decrease in the radius of Mercury due to the cooling of the mantle and partial solidification of the core.

  Mercury is the only planet permitting a calibration of the effects of impact velocity and gravity on cratering in a silicate crust depleted of volatiles. It could allow a comparison between volatile-rich and volatile-poor planets and satellites.

Other instruments will provide these data:

- *Gravimetry*. Tracking of the orbiter from ground stations will be useful for the mapping of the gravitational field and identification of mass concentrations in the regolith, and determination of the J_2 coefficient.
- *Internal properties*. The magnetometer situated on the magnetometer boom will be used to study the movement and magnitude of the magnetic field at the periherm point to investigate internal properties of the planet, such as the possibility of a liquid core, and the evolution and generation of the magnetic field.

3.3.2. Venus Flyby

High resolution visual imaging of Venus will not yield additional information on the atmospheric structure or currents compared with Magellan results, as the flyby periods are short and tracking of individual cloud features is best performed in the UV. The knowledge of the J_2 coefficient in the expansion of the gravitational potential can likewise not be improved during the flybys.

The mission comprises probes that will be dropped into the Venusian atmosphere. The instrumentation on each probe has been given very modest dimensions, but the probes should be able to give valuable information on the following topics:

- *Atmospheric structure*. This is done by measurement of temperature and pressure variation with height in the Venusian atmosphere. The vertical temperature gradient is a diagnostic of the atmospheric circulation.
- *Cloud structure*. Done by measuring the optical properties of the clouds. The distribution of clouds has been observed to be very inhomogeneous, countrary to the earlier assumption that the cloud structure everywhere looks like what was seen by the Pioneer Venus probe.
- *Atmospheric composition*. Among the reasons to investigate this is the fact that earlier measurements of the abundance of water vapour are not consistent with each other.
- *Atmospheric electricity*. Electrical discharges could have consequences for the production of certain constituents of the atmosphere. Discharges could be detected by simple equipment such as a radio receiver, maybe together with light and sound detectors.

3.3.3. Comet P1/Encke flyby

Tracking of the motion of the S/C during a flyby of comet P1/Encke would yield information on its mass. High resolution visual unfiltered imaging with the CCD camera would not be useful other than to study the large scale morphology of gas and dust tails. However, mapping of the 3-dimensional distribution of cometary outgassing is possible to perform using carefully selected filters optimized to, e.g. emission of certain ions.

3.3.4. Science using a lander

The only option for this Mercury mission is a hard-impacting lander. No geophysical measurements are possible from such a unit. There is also no possibility of ejecting from it at close range to the surface any radar reflecting foil disks or strips, as the impacting velocity of the objects would be in the order of km s^{-1} (the impacting velocity of the probe is 4 km s^{-1}), sufficient for their vaporization. If the impacting velocity was considerably lower, the reflectors would be used to track a number (optimally three) of surface sites to accurately determine the J_2 coefficient.

A soft lander is (to our immense frustration) impossible due to the large mass of the fuel needed for such a vessel for pre-impact braking and attitude control by use of a set of thrusters. Due to this restriction, in-situ surface measurements crucial to the determination of several basic geophysical problems is impossible. By putting down a lander at a point close to one of the poles with low solar insolation, it would be possible to achieve maximum temperatures less than about 450 K, which is the limiting acceptable temperature for the bonding agent between solar cells. This would allow an extended mission using solar cells as energy generators in combination with a rechearchable battery to allow the lander to produce data for a few days

after sunset. Ideally, a setup of at least three lander would limit the noise in the data and increase the usefulness.

The following areas of geophysical research could be studied with a soft lander:

- *Seismic activity*. Would be performed with a 3-axis seismometer to measure the shear and compressional waves of seismic activity. The estimated weight of a seismometer is 1.5 kg. As a possible back-up unit, a light (about 200 g) and considerably less fragile geophone could be implemented , to measure the amplitude of noise generated by seismic processes.
- *Heat flow*. By using a surface penetrating unit at least 1 m in length the temperature at different depths in the regolith would be measured during a long period of time to study the amplitude of the diurnal/annual heat wave and thereby measure the internal heat flow.
- *Magnetic field*. A magnetometer would measure the strength and direction of the field close to the surface layer to complement orbiter magnetometric measurements and increase the knowledge of the movement, magnitude and origin of the internally generated magnetic field.

3.4. Imaging system

3.4.1. Introduction

The Mercury Orbiter mission of ESA´s Horizon 2000 Plus programme at the rise of the third millenium will be the first possibility to obtain a map of the complete surface of this elusive planet.
After the three flybys of Mercury by Mariner 10 only 45 % of the surface are known. A full high resolution multispectral map will be the basis for a better understanding of the geological history of this planet and its implications for the dynamical processes which formed it. Also the nearly unknown chemical composition of the surface can be investigated by multispectral imaging.

3.4.2. Components

The imaging device proposed for Mercury Orbiter, which could be called MUSIC (**Mu**lti**s**pectral **I**maging **C**amera), should consist of the following components:

- external deflection mirror
- shutter mechanism
- optical system
- spectrometer
- 2-dimensional CCD array
- cooling system for the CCD
- mass storage unit
- electronics and data processing unit

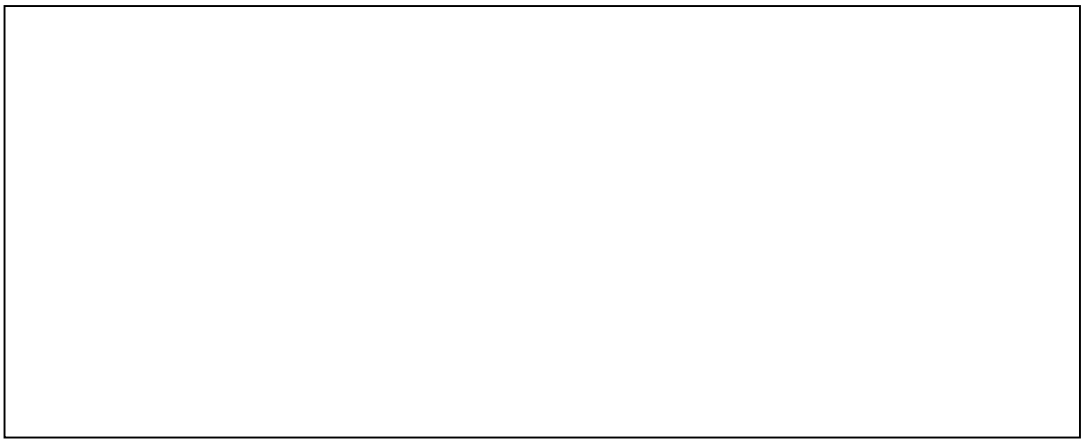


Fig. 1. Schematic sketch of MUSIC design

MUSIC is mounted on the instrumental platform with the optical axis parallel to this plane. The estimated size of the the system is about 15 × 15 × 30 cm. The weight including all mentioned components should not be more than 6 kg. An estimation for the power need is 12 W operating and 4 W standby.

3.4.2.1. External deflection mirror system

Due to the stabilized orientation of the orbiter´s spin axis and the resulting unpleasant observation angles (*Fig. 2*) there is a need for an optical system which deflects the incoming light into the optical path lying parallel to the instrumental platform plane. We recommend the use of simple but smooth planar mirrors[1], which have to be turnable in one axis from 45° to 180°. Power and data lines for the motor and from the sensor measuring the present opening angle lead into the interior of the orbiter.

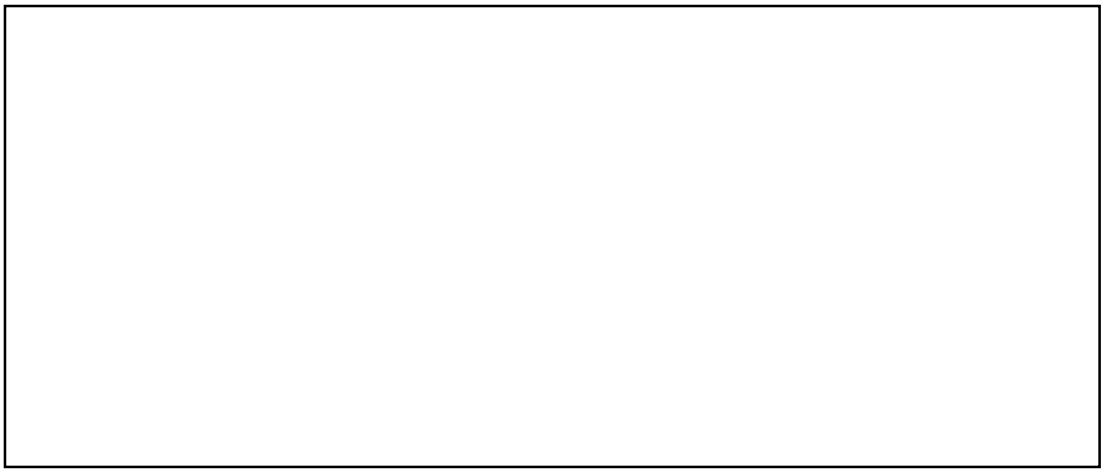


Fig.2. The need for a mirror system

[1] Polarization modifications can be corrected by calculating Fresnel reflection.

3.4.2.2. Shutter mechanism

A simple optical path blocking shutter, which does not have to be highspeed, but as long-lived and as trouble-free as possible, is used to protect MUSIC optics and CCD damage caused by too much light. If the orbiter is in a position allowing sunlight to fall directly into the optical path, the shutter is closed once every spin rotation.

3.4.2.3. Optical system

An optical system with a fixed[2] focal length is used to focus the incoming light onto the CCD in the right scale. A lens system should be preferred to a telescope using mirrors for easier polarization measurements. It should be noted that, because of the large amount of light available, short exposure times are possible and there is no need for big apertures.

3.4.2.4. Spectrometer

For spectroscopic and polarization measurements a wheel containing colour and polarization filters is necessary. The wheel is turned by a stepper motor, quick enough to ensure several exposures during one spin rotation (exposure time at the order of less than 1 msec). The number and spectral resolution of the narrow band filters in the range from 200 to 1100 nm are determined by the features of the spectral components of the most expected minerals like pyroxine or olivine. The observation of clearly defined important spectral features can help to find the chemical composition of the surface without the considerably larger work-load of obtaining SEDs (spectral energy distributions).

3.4.2.4. CCD array (with cooling system)

In contrast to previous studies using panorama stripe scanning by a one dimensional CCD array, we propose the use of a 2-dimensional array for the following reasons:

- A “simultaneous” scan of different channels is much easier to realize with a series of pictures taken by a 2-dimensional array than by line scanning using split light rays.
- The stability of the orbit (precession und nutation modes) is less important for a “still camera”.
- "Hot pixels", defect regions of the CCD, do less harm to pictures taken by a two dimensional array. In this case one pixel corresponds to a region of $10\ m \times 10\ m$, while by line scanning a 10 m broad, but very long, strip would get lost.

The array should be dimensioned that a resolution of 10 m is achievable over the whole orbit stripe near the periherm. This can be done by using different virtual resolutions of the chip, near periaxis a low one is choosen and a higher one when going towards the south pole. The size of the array is determined by this

[2] The scale is not changed by switching the optics, but by using different resolutions of the CCD array.

constraint and the dimension of the optical system. Specifications of the cooling system and the radiation shielding depends on the properties of the CCD. The charge passes through an A/D converter to the MUSIC processing unit.

3.4.2.5. Electronics and processing unit

The cooling of the CCD, mirror system, shutter, filter wheel, mass storage unit and CCD readout are controlled by a processing unit within MUSIC.
Special chips for data reduction (if the CCD array is used for low resolution imaging, the sum of several CCD pixels corresponds to one pixel in the resulting image) and data compression (at least with a factor of 5) ensure that the main CPU of Mercury orbiter is relieved.

3.4.2.6. Mass storage unit

A mass storage unit is used to store the incoming data until it can be sent to the ground stations. It provides space in the order of some or some tens of Gbytes.

3.4.3. Observation strategy

During the first two first two Mercurian years of the orbiting phase the main goal is to collect the data for a complete, in resolution as homogenous as possible, visual surface map. Later regions of special geological interest like the Caloris basin or the "hilled and lineated region" at its antipodal point can be imaged at the maximum resolution. To connect the single pictures overlapping regions are recommended. A vertical overlapping of 50 % at the top and at the bottom and a horizontal overlapping of 10 % on each side gives an overall surface coverage of 220 % and enables the creation of a 3-dimensional map. Using the filter wheel additional images can be taken each spin rotation.

3.4.4. Data rates

Assuming a hermean radius of 2439 km and a (very optimistic) resolution of 100 m^2 per pixel a two dimensional map of Mercury with a dynamical range of 16 bit (65,536 greyscales) takes 12 Tbit of data. Because we have an overlapping factor of 200% in the N-S direction (for stereographic altimetry) and an overlapping factor of 20% in the E-W direction (10% at each frame side for picture linking) the total data amount is 26.4 Tbit.
To this value we have to add the data for the multispectral maps, which can be of much lower resolution, because they will be superimposed to the accurate visual map. If we have 8 channels (colours and polarization), it hardly would need more than another 20 Tbit. Therefore the total data rate for the multispectral imaging of the whole surface would be about

46.4 Tbit of data[3],

[3] a 2 km high stack of 1.4 MB floppy disks

which can be compressed to 1 Tbyte. With todays communication facilities 5.3 Gbyte can be transferred in two Mercurian years, 1 Tbyte is about 190 times too much.

If the communication facilities are not improved within the years until the start of Mercury Orbiter mission, we would have to choose a lower linear resolution of 140 m instead of 10 m for a complete global mapping.

It is well known that computer memory halves in size every two years. In 2004 it will be no problem to store a data amount in the order of Gbytes in the orbiter´s mass storage unit**. Therefore an improvement of the TT&C ground facilities of ESA (upgrading to K-band) is of high importance** not only for this mission, but for all future missions where the present low data rate could turn out to be the weakest point, which restrains the scientific worth of these missions.

3.4.5. "Show-stoppers"

We could think of the following possible failures occuring in MUSIC, which could endanger the mission goals. Most of them can only be countered preventively:

System	failure	remote cure	prophylaxis
external mirror system	gets stuck	☠	
shutter	gets stuck	☠	simple design
spectrometer	motor fails	☠	
CCD array	pixel destruction	☠	radiation shielding
cooling system	fails, CCD damage	☠	
processing unit	software failure	reset	careful testing

3.5. Data interpretation and evaluation

3.5.1. Limited crust movement measurements by image interferometry

The absence of a soft lander prevents us from putting seismological equipment on the surface of Mercury, but a limited possibility of detecting seismicity/tectonic movements remains, in *image interferometry*.

The principle behind this is to let the imager on the orbiter record two high-resolution images of the very same area, from the very same viewing angle, on two different occasions separated by a fairly long time, e.g. 1-2 Mercury years. These images can then be compared and possibly reveal small differences - movements of the crust.

To compare the images, the fourier transform of each image is calculated. This transfers the images from the geometric domain to the frequency domain. Within the frequency domain, the images are processed to determine any differences; the frequencies which are the same on both images are removed, leaving only what has changed between the two exposures. By inverse transformation of this back to the geometric domain, a map showing all movements is obtained.

This procedure requires imaging at very high resolution, in order to detect small movements. It is also very important that the orbital parameters of the orbiter remain constant between the two exposures, and that the images are recorded at the same viewing angle. The angle of insolation, which determines the appearance of the shadowing on the picture, however, is not that important, since the shadowing can be corrected by means of software processing afterwards.

A possible way of achieving this is to record the first images of the selected areas at the suitable times during the first Mercury year, and the second images of the same areas exactly one Mercurian year later. This will also yield the same shadowing.

3.5.2. Gravity field

Mercury's gravity field can be obtained by means of Doppler tracking of the orbiter. This requires a high precision wavelength measurement of the orbiter's radio frequency, a precise determination of its trajectory and continuous tracking and ranging from the Earth.
Obtaining gravity field information does not require any additional instruments on the orbiter itself, except for availability of high precision tracking and data processing capabilities on Earth.

Provided the uncertainty in the determination of the orbiter's position is less than 1 km and neglecting the higher order spherical harmonic coefficients, J_2 can be determined with a minimum accuracy of $\Delta J_2 = 10^{-7}$ (a factor of 200 better than the Mariner 10 data).

Determination of higher order spherical harmonic coefficients will be possible only by orbiting at an altitude of less than 300 km.

3.5.3. Rotational dynamics

Neglecting the possible errors in the tracking of surface features, which will be below 100 m, the uncertainty in the determination of the orbiter position (approximately 1 km) yields a minimum accuracy of 0.14° in the orientation of the polar axis of Mercury, which is only inaccurately known at present.

3.5.4. Surface mapping

Earth based data processing will serve to obtain a topographic map from high resolution images. No additional instruments are needed. A topographic map with a surface resolution of 20 m at periherm and 500 m at apherm will be a good compromise between data rate, weight and surface resolution.

3.5.5. Correlation of topography and gravity field

Doppler tracking and ranging measurements from Earth can be processed to yield a map of Mercury's gravity field. All the data necessary to obtain these data will be transmitted to earth anyway. By comparing topographic and gravity maps of the surface we can draw conclusions with regard to correlations of surface structures and gravity anomalies which may provide information on the planetary interior.

3.5.6. Magnetic field study

Magnetometers separated by a few metres from the orbiter will be used to measure Mercury's magnetic field. From the geophysical point of view the structure of the magnetic field is of particular concern. Mariner 10 data suppose an overall field strength in the order of 500 nT. A three axis magnetometer covering this range with a precision of 0.5% would deliver data with a satisfactory accuracy.

As the duration of the mission is intended to cover 3 Mercurian years, one might be able to detect such long term variations of the magnetic field as polar wandering or secular changes. This is certainly a very optimistic perspective, because short term variations such as magnetic storms may have much greater effects on the magnitude and movement of the magnetic field.

3.6. Conclusion

Having just digested this chapter of the report, the reader will realize that the knowledge of some geophysical properties and the determination of their related parameters would have been accomplished with far greater confidence, accuracy and ease, were a soft landing probe feasible for this mission. The data which is still to be collected about the interior structure and processes of Mercury is certainly several times more voluminous than the amount of data gathered with the current proposal, but we are happy to know that much science still lingers in a close solar orbit for the eager scientists of the upcoming century, when a Mercury mission optimized for a soft landing will hopefully become a reality.

References

Balogh, A.: 1993, *Mercury Orbiter, A mission proposal to ESA to be considered as a candidate for the M3 watching mission*, London

Bauer, S.J.: 1995, *The exosphere of Mercury,* Alpbach summer school

Bougeret, J.L.: 1995, *The magnetosphere of Mercury*, Alpbach summer school

Vilas, F., Chapman, C.R., Matthews, M.S. (Eds.): 1988, *Mercury*, Univ. of Arizona press.

Wänke, H.: 1995, *Mercury: constraints to structure and composition from density and magnetic field*, Alpbach summer school

CHARACTERIZATION OF THE GEOCHEMICAL AND PHYSICAL PROPERTIES OF THE HERMEAN SURFACE

BUSEMANN Henner [(1)], FABIAN Utz [(2)], LELONG Camille [(3)],
SCHLETTI Reto [(4)], SCHREURS Roel [(5)]

(1) Institute for Isotope Geology, ETH Zürich, 8092 Zürich, Switzerland
(2) Max Planck-Institut für Chemie, Becherweg 27, 5128 Mainz, Germany
(3) Observatoire Midi-Pyrenees, UPR234/GRGS, 14 Av. Edouard Belin, 31400 Toulouse, France
(4) Physikalisches Institut , Universität Bern, Sidlerstrasse 5, 3012 Bern, Switzerland
(5) Department of physics and astronomy, Free University, de Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

4.1. Introduction

In order to get a consistent picture of our work, we decided to use the following scheme:

fundamental questions
⇓
concrete questions
⇓
observable quantities
⇓
instrumentation

To each fundamental question, we have added the related concrete questions and observable quantities. In order to keep a better overview, the proposed instrumentation is listed in a separate chapter.

4.2 Fundamental Questions

From a geochemical point of view we have considered the following questions to be fundamental.

4.2.1 Why is the Hermean density so high?

Since 1952 (Urey, 1951 and 1952) it is widely accepted that the high density of Mercury is the result of a large portion of iron in the core. Not only to explain the formation and history of Mercury, but also to get further information on the evolution of the planetary system out of the solar nebula 4.56 billions of years ago, this seems to be the most interesting and, of course, the most important question an orbiter mission should answer.

There are a few models that describe processes in which Mercury acquires a large iron core. It should be possible to favour one of these models by comparing their predictions with measurable Hermean properties.

4.2.1.1 Mantle evaporation models

These models invoke the differing volatilities of iron and silicates to achieve the required iron-silicate fractionation in two phases (Fegley Jr. and Cameron, 1987). An evaporation model was outlined by Cameron (Cameron, 1985a and 1985b). The described process results in extensive chemical fractionations with a large compositional change of the initial silicate magma from solar proportions as a function of the extend of the postulated evaporization.

The final composition of the partly evaporized mantle should be depleted in the alkalis (Na, K), Si, Fe, Mg, and in a smaller amount of Ca and Ti. Furthermore, a depletion of the volatile radioactive element K should be observable. For this purpose, the ratios of Th/U and K/U have to be considered. Enrichment follows for the oxides CaO, MgO, Al_2O_3, and TiO_2 while the oxides FeO and SiO_2, as well as the easily oxidized elements U and Ce are depleted.

4.2.1.2 Collision model

Another hypothesis (Cameron et al., 1988) was developed in analogy with the formation theory of the Moon by a catastrophic impact on proto-Earth. An impact of an object of 1/6 of the mass of Mercury hitting the proto-Mercury with 2.25 times the mass of present Mercury should be able to produce the required density. This theory invokes physical fractionation of irons and silicates, but only little chemical fractionation.

In summary, if the surface of Mercury is of almost original chondritic silicate composition, this fact can be seen as a clue for the impact theory (but, of course, Mercury does not have to be of chondritic composition because of the possible different impact composition and high pressure and temperature processes).

4.2.1.3 Conclusion

In conclusion, the Mercury Orbiter Mission should give complete information about elemental and molecular composition, mineralogy, differentiation of the crust, and distinct viscosities of volcanic magmas due to fractionated composition, and also about morphology and inhomogenities due to a possible impact.

Even if the theories cannot be confirmed, more sophisticated models can be developed by these fundamental composition data. For these reasons, a high resolution elemental analysis by γ- or X-ray

spectrometry is necessary. We propose a γ-ray spectrometer equipped with a high resolution Germanium detector.

Of course, for our needs, a direct measurement of the surface composition by mass spectrometry, even for calibration of remote-sensing measurements, would be desirable for a lander mission.

It is also imaginable to measure ejecta of possible meteorite impacts on Mercury from orbit. In comparison to a number of ten observed falls per year on Earth (with estimated 1% discover-rate), it seems to be unlikely to observe a sufficient number of meteorite impacts. Furthermore, from the geochemical point of view, it seems to be unnecessary to use artificial bullets creating possible craters of 10 meters-diameter.

4.2.2 The history of the Hermean surface

To understand the history and evolution of the Hermean surface, many subjects can be studied by a further completed mapping of Mercury using several methods.

Observable features are, for example:

- unaltered highlands
- more or less hypothetical volcanism
- former lava flows induced by impacts
- old lava coverage of the plains
- Fe, Mg, and Ti enriched basalts flows
- tectonical traces of the shrinking of the planet
- composition of craters' central peaks and ejecta
- dust coverage.

The age of the Hermean surface can indirectly be determined by counting craters of different sizes in comparison with lunar data.

Thus, elemental and mineralogical compositions of the different Hermean areas are the most meaningful quantities. For this reason, we need a γ-ray spectrometer and, in this case more importantly, a spectro-polarimetric camera.

4.2.3 Is there ice on Mercury? If so, of what kind?

Since there is strong indication of ice on present Mercury in the polar regions (Slade et al., 1992), it is essential to analyse these areas at a higher resolution. The flyby of the north polar region at a distance of 1200 km should be enough. For a similary examination of the south pole, the same distance should be reached.

For this purpose, we suggest to use spectro-polarimetric analysis in order to measure absorption bands of water and polarization properties of ice.

4.2.4 Has there ever been an atmosphere on Mercury?

Mercury has no atmosphere. If there has ever been one, this can be checked by results of erosion processes, for example graben structures, by means of a closer and higher resolution look on Mercury's surface. Once again, a high resolution camera is needed.

It is possible that, because of its higher atomic mass, Xe has not yet completely left the surface of Mercury. To discover Xe and to determine the isotopical composition (wether it is primordial or a fractionated component of solar wind origin) a mass spectrometer would be necessary.

4.2.5 What is the nature of the exosphere?

The Hermean exosphere is mainly composed of H, He, O, Na, and K. H and He have their origin in the solar wind, but O, Na, K, and less abundant elements like Ne, Xe, C, and others that could not be measured yet, have their origin in the surface of the polar regions. These elements are sputtered by solar wind particles. Since their is no atmosphere, the neutral fraction can follow large ballistic trajectories without collisions.

Therefore, mass and energy of the particles can be measured with a neutral mass spectrometer located on the Mercury Orbiter.

Because the "cross section" for sputtering depends on the elements and their chemical compound, the exosphere composition is not representative for the composition of the surface. Even though, we can measure some rare elements that cannot be measured by other techniques, and, moreover, it is possible to draw some conclusions on elemental abundances by using sputtering models.

4.2.6 Possible comet Encke flyby

Because of the acceptable distance and suitable period of the comet Encke, it is thinkable to use the Mercury Orbiter to examine this body. To avoid additional payload mass and costs, and in respect of the importance of the Mercury mission, it seems to be useful to use only the already proposed instruments.

Thus, the composition of the comet's nucleus, the coma, the plasma tail, and the dust tail (consisting mainly of H_2O, NH_3, CH_4, and CO_2) can be measured.

For the evolution of the solar system, it is very important to analyse all other rare elements because the composition might be even more primitive than the C1-chondritical meteorites. Furthermore, the D/H-ratio that might vary from the Earth's value should be measured.

In addition, it could be possible to determinate the activity of the comet using the polarimetric imager.

4.3 The Instruments

In this chapter, we want to describe the three instruments that we propose for the Mercury Orbiter Mission to answer the questions outlined above.

4.3.1 γ –RAY SPECTROMETER (GRS)

When galactic cosmic ray (GCR) particles (i.e. mainly energetic protons) penetrate a planetary surface, a cascade of secondary particles is produced by nuclear reactions. These secondaries are mainly neutrons and pions. As the secondary particles are scattered, moderated and finally absorbed, they excite nuclei in the surface, which de-excite by emission of γ–radiation.
The energy of these γ–quanta is characteristic for the emitting isotope, so γ–rays can be used as diagnostic radiation to determine the isotopical composition of the planetary surface.
This method can be appended to celestial bodies with no or a low density atmosphere and without strong magnetic fields, such as the Moon, Mars, Mercury as well as small bodies like planetoids and comets.

γ–ray spectrometers have been flown on lunar (APOLLO) and Mars (PHOBOS, MARS OBSERVER) missions. The instruments used on APOLLO and PHOBOS were scintillation detectors, whose energy resolution is poor compared to high purity germanium (HPGe) detectors. Because of this, only a few elemental abundances could be measured. The statistical errors of the analysis were rather high.

To measure with a higher precision, a GRS with an HPGe-detector is recommended. This type of instrument, however, needs to be operated at low temperatures. GRSs of this type are also foreseen for lunar (MORO) and comet (ROSETTA) missions.
The Mercury γ–Ray Spectrometer (MGS) should have an anti-coincidence shield of plastic scintillation detectors to screen out signals from charged particles, such as solar wind and GCR particles electronically.

4.3.1.1 Required Measuring Times for some selected Elements

altitude: 400km			Compos. (pref.	rel. error: 0.1	rel. error: 0.2	rel. error: 0.3
Elem.	Energy [keV]	React.	model) [wt-%]	TIME [h]	TIME [h]	TIME [h]
O	6129	(n,nγ)	43.5	4.0	1.01	0.45
Na	440	(n,nγ)	0.25	290	72	32
Mg	1369	(n,nγ)	21.0	1.0	0.21	0.09
Al	2210	(n,nγ)	1.4	2.0E+05	5.1E+04	2.2E+04
Si	1779	(n,nγ)	20.1	0.60	0.15	0.07
Ca	6420	(n,γ)	3.8	571	143	63
Ti	6760	(n,γ)	0.15	806	202	90
Cr	8884	(n,γ)	0.1	2.1E+05	5.4E+04	2.3E+04
Mn	7244	(n,γ)	0.08	9.4E+04	2.4E+04	1.1E+04
Fe	7632	(n,γ)	2.18	22.0	5.0	2.0
K	1461	r	0.12	0.78	0.19	0.09
Th	2614	r	3.8E-05	7.52	1.88	0.84
U	609.3	r	5.0E-05	1.30	0.33	0.14
Sm	439	(n,γ)	7.0E-04	7377	1844	820

The table, outlined above, shows the estimated times that are required to measure the elements of abundances, according to a preferred bulk composition of the Hermean surface from (Goettel, 1986). Abundances of minor elements not given there are taken from the lunar composition given in (Reedy, 1978). The time for the ^{27}Al (n,nγ)-line was estimated from (Reedy, 1978) and laboratory simulation measurements.

The measuring time per orbit is about 35 min, to acquire 1000 h ca. 1700 orbits are necessary, this corresponds to a total mission duration of 960 days.

In case of an extended mission in an orbit with decreased periherm altitude, preferably below 5000 km, the total duration to achieve 1000 h measuring time with the GRS can be reduced.

4.3.1.2 Comparison with different Vaporisation Models

Element	Pref. Mod. [%]	ideal Magma 3000 K [%]	nonideal Magma 2500 K [%]	nonideal Magma 3000 K [%]	nonideal Magma 3500 K [%]
Si	20.1	0.56	15.0	12.1	9.29
Ca	3.80	7.07	10.4	9.79	8.36
Mg	21.0	40.6	20.7	25.4	30.0
Al	1.40	3.28	4.79	4.50	3.81
Fe	2.18	6.46	0.00	0.31	2.64
Ti	0.15	0.30	0.42	0.48	0.36
K*	0.12	0.0	0.0	0.0	0.0
U*	--	0.0	0.0	0.0	0.3
Th*	--	278	401	377	322

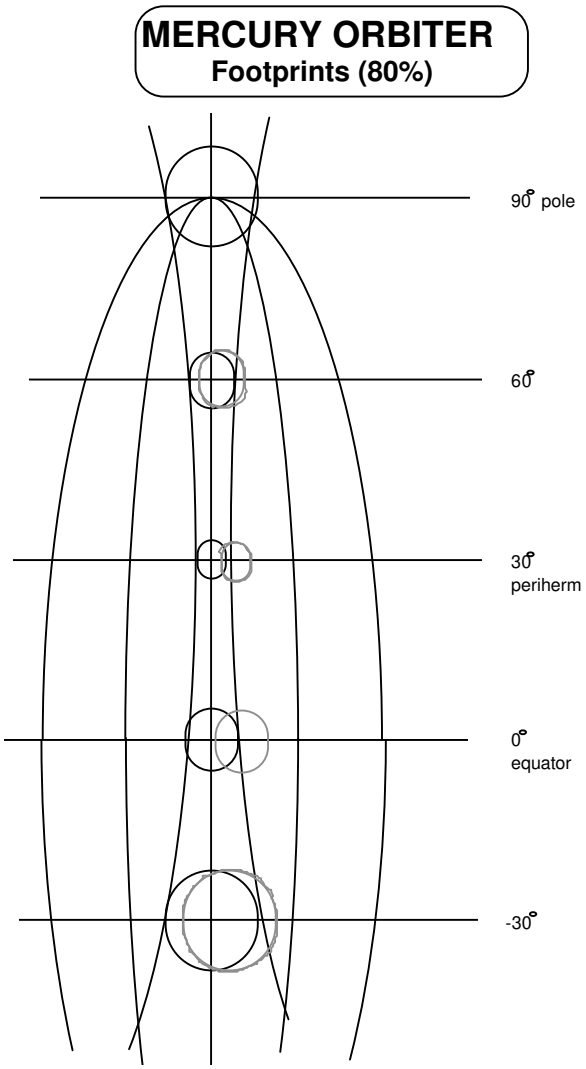
This table shows elemental abundances of the Hermean model composition from (Goettel 1986) (“preferred model“) and four different evaporisation models of Mercury for loss of mantel material, taken from (Cameron et al., 1988).

This shows, that with MGS measurements it is in general possible to distinguish between different compositions estimated in these models.

4.3.1.3 Mapping the Surface Composition

With a γ–ray spectrometer onboard an orbiting spacecraft, the distribution of certain elements can be determined, too. These are elements, that require short integration times due to high abundances or large reaction cross sections, such as Si, Mg, Fe, K, and O.

For this purpose, the Hermean surface should be devided into regions according to morphological landmarks. The part of the surface, that is recorded at a moment (so called ”footprint“), is dependent on the altitude of the orbiter. This is the minimum size of a region for mapping the surface composition. As the altitude during γ–ray measurements varies between 400 and 1200 km, a footprint diameter from 300 km in periherm altitude to about 700 km in 1200 km is expected.



The picture shows the sizes of the MGS footprints in selected latitudes and the related ones of the next orbit that overlap the previous ones.

4.3.1.4 X-Ray Fluorescence Spectrometer (XRS)

X-ray fluorescence is also a diagnostic for the abundances of Al, Si, Mg, Ca, Fe, and probably Ti (Murchie et al., 1995) on Mercury. Except for Al, we expect to measure these elements with the GRS at acceptable precision.

A major difference between planetary x-ray and γ–ray spectroscopy is the fact, that γ–radiation – depending on its energy – is produced within the upper 30 to 50 cm of the surface, while x-rays originate from the uppermost few millimeters of the ground only. This part of the surface may be altered by of solar influence, it may not represent the bulk composition of the planetary crust.
Thus, an x-ray spectrometer is not essential for a determination of the surface composition, as long as a high resolution GRS is used.

4.3.2 SPECTRO-POLARIMETRIC IMAGER (SPCAM)

4.3.2.1 Scientifical purpose

To study the Hermean morphology, we propose a *complete mapping* of Mercury´s surface at a *high resolution* with a CCD-camera.

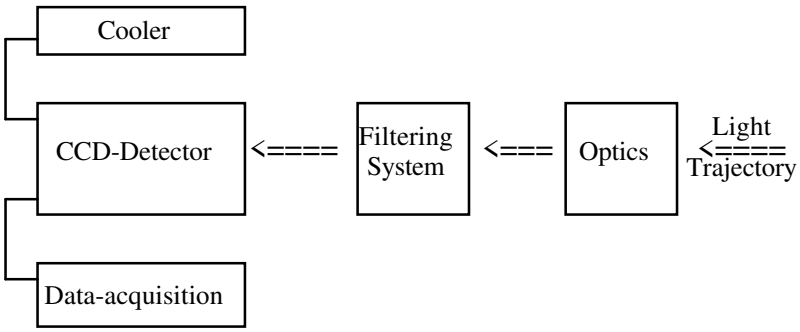
To measure the composition of the Hermean surface in terms of mineralogical distribution (determination and proportions of the mafic and plagioclase elements), we propose *a multi-spectral imaging* method. It will use the same CCD-camera acquiring images of the albedo in many wavelength bands in order to get the spectroscopic information at a very high resolution, and to obtain a geological map of Mercury at such a resolution.

To characterize the physical properties of the surface (recognize the presence of dust, determination of grains size, of rugosity, cristallinity, and alteration of the surface), we propose a *polarimetric imaging* method. There is no need for any other instrument: the same camera again, acquiring polarized images in four directions, could be used.

In the Mercury Orbiter Assessment Study, a multi-spectral camera is already existing. We just propose some modifications to reach our requirements, in order to obtain a spectro-polarimetric imager (SPCAM).

4.3.2.2 Description of the SPCAM

4.3.2.2.1 Basic sheme



4.3.2.2.2 Further explanations

- The CCD-detector should be a matrix of about 1000×1000 pixels, in order to get an image providing a large field of view.
- The cooler has no special characteristics, it is just one of these being usually used for CCD cooling and has already been designed in the Assessment Study.
- The optical system is in fact a telescope. It can be a refractor, if the glass used for lenses does not absorb the studied wavelengths and does not polarize (or depolarize) the light coming through. It can be a reflector with no flat mirror (which would polarize or depolarize), and should better be completely metallic to avoid absorption.
- The filtering system is a set up providing:
  -a position with no filter, collecting the intensity of light in the whole spectrum of light
  -a “spectrometer”

-a “polarimeter”

4.3.2.2.3 Special specifications

◊ The “polarimeter” is a filtering system, constituted by polarizing filters.

- Those polarizing filters have to be very homogeneous and coherent to one another.
- The direction of polarization of each filter must be at 45° of the previous one´s, four filters being needed to get the whole information.
- This set up must allow the camera to acquire an image of the same field of the surface with each of the four filters.
- These images should be in total light and orange light (560 nm), so the polarimeter should contain two sets of four polarizing filters, one of them providing polarizors associated with coloured filters centered at 560 nm.
- We insist that all the optics involved in this camera must not modify the polarization of the light (for example no flat mirrors, no diffractive set up, no prism...)

◊ The “spectrometer” is also a filtering system, constituted by coloured filters. According to former studies of the reflectance spectrum of Mercury and the Moon (see, for example, Vilas, 1988; Pieters, 1983 and 1993), we propose to add the filters chosen in the Assessment Study:

- filters at longer wavelengths to study some significant pyroxene and olivine absorption bands
- filters at the wavelengths of H_2O absorption bands
- some more filters centered in the vicinity of interesting absorption bands, to get a better spectral resolution of these bands

We thus propose the 13 following wavelengths: 350, 400, 450, 560, 730, 820, 900, 950, 1000, 1150, 1200, 1350 nm.

This system has to allow the acquisition of images of the same field of Mercury in each desired wavelength.

4.3.2.2.4 The targets

The morphological features that have to be studied are difficult to fix because of the very uncomplete knowledge of the Hermean surface. We can just propose the following, as a quite non exhaustive list:

- the Caloris Basin, with its highly ridged and fractured floor
- impact craters (dimension, shape, composition of walls and peaks, extend of melt materials)
- secondary craters (dimension, distance from the impact crater)
- ridges and grabens
- fault scarps
- ...

In fact, it can be any unsusual feature and any area offering the possibility to characterize the evolution of the surface (impact, volcanism, tectonics, alteration and dust-reduction...). Anyway, the polar regions are to be observed (in order to detect the possible existence of water).

We propose to use the flybies of Mercury during the two gravitational assists to get a whole map of the Hermean surface at a lower resolution, to choose afterwards which region will be further investigated, by means of morphological, spectral, and polarimetric studies.

4.3.2.2.5 Data acquisition

As explained in the former paragraphs, this method needs to acquire height polarimetric images, thirteen spectral images, so, in total, twenty one images of the *same* area. The exposure time should be of about 5 to 20 ms according to the supposed brightness of the Hermean surface.

It is very important to get these images with the same inclination of incident sunlight and reflectance. So they have to be taken as simultaneously as possible, and it is essential to manage the whole work in one spinning round of the orbiter. In this case, it would be also possible to reiterate the measurements many times on the same area, to check validity, and perhaps to have different angles of view.

For morphological purposes, as many images as possible are required, with all kind of angles of view, incidence and reflectance angles, and so on...

This sets the problem of the spinning movement of the spacecraft, and it would have been much better to allow the camera to follow its target during the complete measurement (moving plateform, three axes equilibrium...). To reduce these problems, it could be easier to use two different cameras. For example, one could be devoted to morphology and polarimetry-imaging, and the other one to spectro-imaging. It could also be possible to envisage to replace the set of one-coloured filters to "palette"-coloured filters, and a sweeping coverage of the field of view. This would reduce the mechanical-moving parts as well.

Due to the amount of data necessary for these studies, some problems are to be taken in consideration, such as data-compressing on board, data-transmission, and data-storage on ground. On the other hand, it will be quite necessary to study very seriously the calibration of the instruments, because of the lack of valued-references about the surface of Mercury.

3.3.2.3 Technical limitations to the use of the SPCAM

4.3.2.3.1 Resolution and Data Transfer

We want to have global coverage of Hermian surface. The radius of Mercury is about 5×10^3 km. Its surface, therefore, is about 3×10^8 km^2. In order to deduce information on the morphology of the surface from the images, it is neccessary to record each pixel more than once. That is, at several angles of solar incidence and at several angles of obliquity. This requires perhaps 10 images.

The intensity information of each pixel will require perhaps 16 bits. Thus each pixel requires 160 bits in total. The resolution that can be reached for global coverage is restricted by the total number of bits that will be allocated for the imager to sent down to Earth, as well as the storage capacity of the orbiter, not by the instrumental resolution that can be reached. This can be demonstrated by the following calculation.

The average resolution, dependent on the altitude of the space craft, is about 50×50 m^2. If all of the surface would be imaged at this resolution, there would at least be

$$3\times10^8 \text{ km}^2/0.05\times0.05 \text{ km}^2 = 1.2\times10^{11} \text{ pixels.}$$

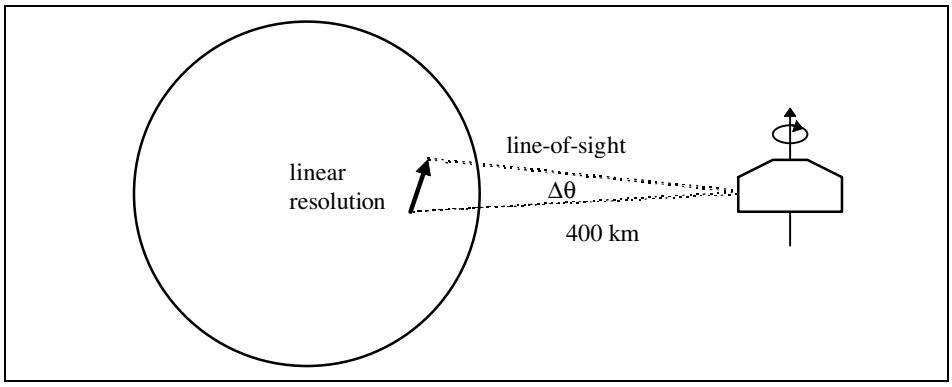
Each of them would require 160 bits, thus a global picture would require 2×10^{13} bits. At a transfer rate of 8 kbit/s this takes 2.5×10^{9} s. Which is about 30000 days. Data compression will not be able to get this number sufficiently down.

Therefore, it is neccessary to perform global coverage at much lower resolution, and a number of interesting areas at maximum resolution. Of course it will be preferable to decide which areas this must be only after the global map is available.

The instrumentation group, for the time being, offers us 8×10^{11} bits of data to be send down to Earth during the time of orbiting. Since we propose two imagers, presumably 4×10^{11} bits are available for each of them. Half of it could be used for global coverage, half of it for detailed images of selected areas.

Global coverage:

bits available	2×10^{11}	
bits per pixel	16	
angles of solar incidence	3	(shadows of elevated objects)
viewing directions	2	(stereoscopic view)
number of pixels	**2×10^{9}**	($2\times10^{11}/(16\times3\times2)$)
radius of Mercury	5×10^{3} km	
surface area	3×10^{8} km^2	



global resolution	**400×400 m^2**	(3×10^{8} km^2 **/2×10^{9}**)

For the detailed imaging the calculation is the other way round.

required resolution	50×50 m^2	
number of pixels	**2×10^{9}**	
covered area	5×10^{6}km	
percentage of total area	**1.7%**	(5×10^{6} km^2/3×10^{8} km^2)

During gravitational assist there is the possibility to take images. The resolution will not be high, but it is useful to have some global infomation at an early stage. The availability of data-storage onboard the orbiter. Data-transfer rate is a minor problem here, because there will be time for transfer in-between gravitational assists and insertion into orbit.

4.3.2.3.2 Resolution and Frequency of Spinning

The present type of orbiter will be a spinning space craft. If the imager can not be oriented independently, its line-of-sight will sweep over the surface corresponding to the revolving orbiter. This sets an upper-limit to the exposure time, given certain resolution demands. At an altitude of 400 km this time can be estimated as follows.

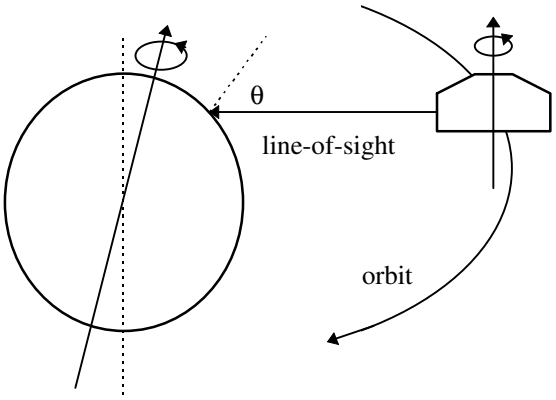
We allow the line-of-sight to move 50 m. The corresponding $\Delta\theta$ will be:

$$\arctan[50/4\cdot10^5] \approx 50/4\cdot10^5 = 2\cdot10^{-4}.$$

This corresponds to a certain time, depending on the spinning velocity of the orbiter. This velocity may be 10 rpm. In that case, the angular velocity is $2\pi/6 \approx 1$ rad/s. The exposure time will thus be $2\cdot10^{-4}$ s. This is probably to short for a CCD-array. Therefore it is advisable to allow the imager to move in the horizontal direction, relative to the orbiter.

4.3.2.3.3 Latitude and Angle of Obliquity

The current proposal comprises an orbiter with spinning axis perpendicular to the ecliptic plane. Since the inclination of the rotation axis of Mercury is only 7°, this means that an imager mounted to the side of the orbiter, can not look straight down.



Since it is necessary to take images at nadir regions, especially at the poles, the imager must be able to be tilted in the vertical directions. The range would be +83° to −83° in order to take images of all the planet at nadir regions. When the imager is also used as spectrometer, nadir observations are necessary to get a data-set in which measurements can be compared and analyzed.

4.3.3 Neutral-Gas Mass Spectrometer (NGMS)

To measure the exosphere's composition, we need a mass spectrometer for low energetic neutral particles (up to 100 eV). The resolution $m/\Delta m$ should be at least high enough to separate O, Na, and K which are the most abundant elements originate from the Hermean surface. This can be archived with a resolution of 4. For measuring elements that have not be found in Hermean exosphere yet, a resolution of 50 to100 should be enough.

The expected fluxes in 400 km altitude are very low, 10^8 cm^{-2} s^{-1} for Na, and much lower for for some other elements. So either a high efficient ionization technique, like surface ionization (~ 10 %) (P.Wurz et al. 1995), or long integration times are needed.

An imaging instrument would not make sense because the sputtered particles are distributed isotropically in space, and the regions where the solar wind reaches the surface might be to large. But the measurement of the energy distribution of the particles, which depends on the element, will furnish information about the interaction of the surface with the solar wind particles.

For geochemical purpose, short time scales are not necessary, maybe just for detecting Na-clouds over the polar regions, but for understanding the dynamics of the system solar wind-magnetosphere-surface, short time scales are essential.

Several kinds of mass spectrometer that already have been flown in space missions can be used. Which one is the best is also dependent on other applications in the orbit, especially for plasma physics.

4.4 Conclusion

Being a scientific group, we have basically been concerned with the topics of scientific investigation of Mercury, and related observable quantities.

We have tried to propose a complete set of instrumentation, under the restrictions of an orbiter without a soft lander. The absence of a lander sets serious limitations to the acquirement of knowledge of the Hermian surface, but seems to be a determined fact.

The requirements of the proposed set of instrumentation in terms of power consumption and data transfer rates were not thoroughly investigated, but only touched upon in connection to the imager. This is both due to lack of time, and to the limited knowledge of the instrumentation that is available, and of its expected future development.

More extensive interaction with the instrumentalists and the other scientific groups should be taken, in order to make requirements posed by research and limitations set by the instruments meet.

REFERENCES

Cameron, A. G. W. (1985a) Icarus **64**, 285-294

Cameron, A. G.W. (1985b) in: Protostars and Planets II, eds. D. C. Black and M. S. Matthews (Tuscon: University of Arizona Press), 1073-1099

Cameron, A. G. W. (1988) in: Mercury, eds. F. Viley, R. Chapman, and M. S. Matthews (Tuscon: University of Arizona Press), 692-708

Fegley B. Jr., Cameron, A. G. W. (1987) Earth Planet. Sci. Lett. **82**, 207-222

Goettel, K. A. in: Mercury, eds. F. Viley, R. Chapman, and M. S. Matthews (Tuscon: University of Arizona Press), 613-621

Murchie S. L. et al (1995) Encounter with Eros, the Near Earth Asteroid Rendezvous Mission, Lunar and Planetary Information Bulletin

Pieters C. M. (1983) J. Geophys. Res. **88**, 9534-9544

Pieters C. M. (1993), in: Remote Geochemical Analysis, elemental and mineralogical analysis, eds. C. M. Pieters and J. P. A. Englert (Cambridge university Press), 309-412

Reedy R. C. (1978) Proc. 9. Lunar and Planet. Sci. Conf., pp 2961

Slade M. A., Butler B. J., Muhleman D. O. (1992) Science **258**, 635-640

Urey, H. C. (1951) Geochim. Cosmochim. Acta **1**, 209-277

Urey, H. C. (1952) The planets: Their origin and development (New Haven: Yale University Press)
Vilas F. (1988) in: Mercury, eds. F. Viley, R. Chapman, and M. S. Matthews (Tuscon: University of Arizona Press), 56-76
Wurz P. et al. (1995) Optical engineering, July, Special issue: "Swiss imaging instruments"

5. Missions and Operations Design, Fundamental Physics

Andrew J. BALL, University of Kent, Unit for Space Sciences
Werner BENGER, Leopold-Franzens-Universität Innsbruck, Inst. f. Astronomie
Norbert FRISCHAUF, Technische Universität Wien, Inst. f. Kernphysik
Gernot E. GRÖMER, Leopold-Franzens-Universität Innsbruck, Inst. f. Astronomie
Simon HEFTI, Universität Bern, Inst. f. Planetologie
Wolfgang JAIS, Leopold-Franzens-Universität Innsbruck, Inst. f. Astronomie
Ener Orlando SALINAS, Stockholm University, Fysikum

5.1. Introduction

As a first part, four experiments related to Fundamental Physics have been described.
The Operations and Mission Design Groups task was also to work out the spacecrafts path trough space, including the swing by manoeuvres as well as develloping alternativ options for the whole mission. In cooperation with the engineering team the final possibilities for the orbiters technical arrangment have been designed.

Hence, the following aspects were taken into consideration:

1- two options concerning Fundamental Physics
2- a solar sail option for propulsion purposes
3- software security and s/c autonomy
4- possible spacecraft malfunctions as well as
5- the orbit calculations including a possible Flyby at comet Encke

5.2. Fundamental Physics

5.2.1. Test of relativity

The special as well as the general relativity can be tested with the Mercury Orbiter using Mercury's and the s/c's proper motion and the higher gravitational potential, respectively.
An atomic clock could be carried on board the Mercury Orbiter to verify the theory of General Relativity, which predicts that at a distance r_1 from a mass M a clock at rest will run slower than a clock at distance r_0 ($r_0 > r_1$). When $\Delta\tau(r_1)$ denotes the time interval between two beeps emitted at distance r_1 and $\Delta\tau(r_0)$ denotes the time interval measured at r_0, the following relationship

holds:

$$\Delta\tau(r_0) = \sqrt{(1- 2m/r_0) / (1-2m/r_1)}\ \Delta\tau(r_1)$$

This means that on Earth a longer time interval will be measured:

$$\Delta\tau(r_0) > \Delta\tau(r_1)$$

In numbers:

$m = GM/c^2 = 1476.18$ m (Mass of the Sun in metres)
$r_0 = 1AU = 149.5$ Mio. km (Distance from Earth to Sun)
$r_1 = 0.39AU = 58.3$ Mio. km (Distance from Mercury to Sun)

Therefore:

$$\Delta\tau(r_0) / \Delta\tau(r_1) = 1.000\ 000\ 015\ 4 = 1 + 1.54\text{ppb}$$

The time signal measured on Earth would last $1.54\ 10^{-9}$ longer than at a static position at Mercury's orbit. This small increment would correspond to 0.048 seconds per year or one additional second in 20.5 years.

This experiment does not necessarily need an atomic clock to measure the exact time which has elapsed since launch, but it requires some very stable frequency generator with an error of at least 1ppb (e.g. a quarz oscillator would typically yield 10^{-6}, an atomic clock 10^{-15}). If such a precision is not possible, then an atomic clock would be required to track the accumulation of the time dilatation. Additionally it enables the determination of the Shapiro effect.

However, beside the general relativistic effect of space curvature one may not neglect the effect of special relativistic time dilatation due to the motion of the Mercury Orbiter relative to the Earth.
A rough upper limit for the relative speed is 50km/s (48km/s for Mercury Orbit + 4 km/s for the Mercury Orbiter), which results in a special relativistic time dilatation of

$$\Delta t_{Earth} = \Delta t_{Mercury} \Big/ \sqrt{1 - v^2/c^2}$$

effectively yielding an exaggeration of ca. 14ppb; so the special relativistic effect due to the relative speed may exceed the general relativistic effect of space curvature by a factor of roughly 10.
So this short estimation shows that during the real experiment exact calculations have to be done to distinguish between the special and the general relativistic effect.

5.2.2. Measurement of the distance of Mercury-Earth

To improve the precision of distance measurements between Earth and Mercury we thought about the possibility of dropping optical reflectors on the surface of Mercury, as was done by the Apollo missions on the Moon.
It would not be too great a problem to land such reflectors since there are no critical parts like electronics (which could at least survive 10 000g) and so the deceleration zone could be quite small. Some ideas were to use airbags or foambags, which could easily be blown up in the interplanetary vacuum. Such accessories could provide a deceleration zone of a few metres; to stop down from 4km/s (the orbital velocity of the spacecraft) with 10 000g would require a deceleration zone of 80m, which is comparable to the size of the

Echo satellites, launched by NASA in the 60's. Without any electronics the deceleration zone could be even shorter.

We estimate the reflector light beeing of 31st magnitude, assuming the diameter increase of the laser beam due to diffraction at the laser aperture. A laser beam of λ=500nm with an inital diameter of 1m will reach a diameter of 50km at a distance of 100 Mio. km, resulting in an intensity of 10^{-10} of the original one. When the light is sent back to Earth by a reflector of 1m diameter also, the reflected beam will have an intensity of 10^{-20} of the original one (where atmospheric effects have been neglected). Now if the signal laser had a power of 1W, the reflection of magnitude 31 (as can be seen from the formulae below) could hardly be detected, additionally if one considers the small elongation between Mercury and the Sun. Therefore it is questionable if the reflected light could be detected from Earth and if the usage of optical light would be a real improvement over the use of radar measurements.

Formulae:

d .....Laser aperture (1m)
λ.....Wavelength (500nm)
α.....Diffraction angle

$$\alpha = \lambda/d$$

D..... Distance Emitter (Earth) - Reflector(Mercury) (100 Mio. km)
L..... Beam diameter at reflector

$$L = \alpha \cdot D = \lambda D/d = 50 \text{ km}$$

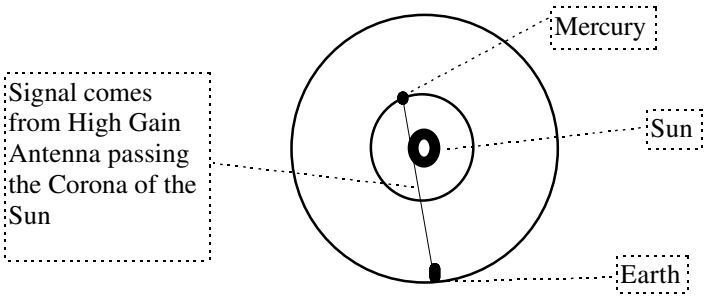
I_{Earth}..... Laser Intensity at Earth
$I_{Reflector}$ ..... Beam Intensity at the Reflector

$$I_{Reflector} = I_{Earth}\ d^2 / L^2 \approx 10^{-10}\ I_{Earth}$$

m_{Sun} ..... Magnitudine of the Sun (-26.8)
I_{Sun} ..... Intensity of the Sunlight (1365 W/m^2)
I_{Laser} ..... Intensity of the reflected laser beam (10^{-20} W/m^2)
m_{Laser} ..... Magnitudine of the laser reflex

$$m_{Laser} = m_{Sun} - 2.5 \log (I_{Laser} / I_{Sun})$$

5.2.3. Corona Experiment with High Gain Antenna



By analysis of the polarization of the radio signal propagating through the solar corona it is possible to determine

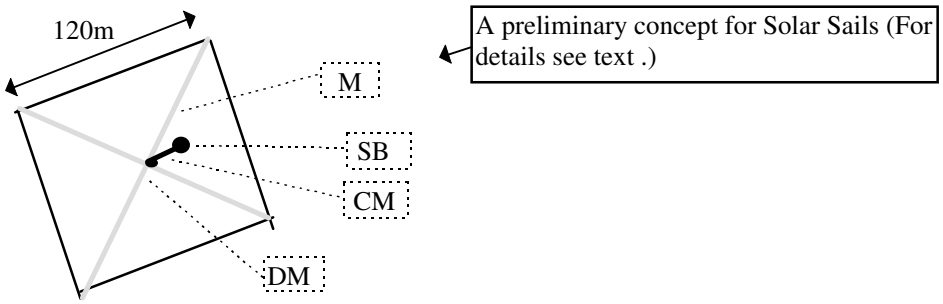
- electron density = ion density of the Corona
- electron temperature

In addition the magnetic field, the dynamics of the corona and flare events can be deduced from these measurements using models of the solar corona.

5.2.3. Geodesy of Mercury

Using the deviation of the s/c's orbit from a standard orbit caused by mass concentrations (Masscons) on Mercury these Masscons can be detected.
Mass concentrations are regions of a higher gravitational field already found on the surface of the Moon and may also exist on the surface of Mercury. Scientists estimate that Mascons have their origin in a great meteor bombardment 4.5 billion years ago. Mascons will influence the velocity and the trajectory of a Spacecraft moving in an orbit around Mercury. It is possible to measure this small effect with the High Gain Antenna by using the Doppler Effect. For more detailed Information see the Report of the Geophysics Group.

5.3. The Solar Sail Approach



Several solar sail concepts have been studied for the Mercury Orbiter. In one design option Spacecraft consists of a central mast (CM), a deployment module (DM), the Spacecraft bus (SB) and a central mast (CM) conecting the DM and the bus. The surface of the DM facing to the sun can be covered with solar cells, possible gallium-arsenide cells, because they can withstand high temperatures and have a higher efficience than silica cells.
All structural components may be constructed of composite materials, because they reduce the weight of the spacecraft.

sail	film(200nm), 2.84g/m^2	40kg
	reflector(10nm), 0.27g/m^2	4kg
4masts	l = 80m	62kg
central mast	l = 10m	4kg
Spacecraft Bus	Structure	50kg
	Thermal control (Peltier-Elements)	20kg
	Computers	10kg
Deployment module	Structure	50kg
	Mechanics/Engines (for Navigation)	50kg
	Thermal/control (Peltier-Elements)	20kg

Scientific payload		50kg
total		**360kg**

(figure 3.2.: Mass budgetation)

Acceleration due to solar pressure at 1 AU distance is

$$f_{sp} = 2\eta S_C/c(1/R)^2 A/m\cos^2(\beta)e_n$$

where η is the sail reflecting efficiency (maybe 89%), S_C is the Solar Constant ($1367 W/m^2$), c is the speed of light, R is distance from the Sun expressed in AU, A is the area of the sail ($14400 m^2$), m is the mass of the Spacecraft and β the angle between sail normal and sun radiation. The acceleration of the sail itself is about 0.3 mm/s^2 m^2. This is about half the acceleration due to the gravitational field of the Sun about 1 AU distance.

At a 0.3 AU the Solar flux reaches 10.5 S_C. The corresponding sail temperature is approximately 230°C for perpendicular incidence of the sunlight. Since reflection and reradiation are not considered, the actual sail temperature will increase. Therefore the orbit around Mercury is essential for the surviveability of the Spacecraft.

Trajectory analysis

We propose to launch the Mercury Orbiter using solar sails on an Ariane 5. For the cruise to Mercury orbit starting at 1^AE the solar light pressure is used to decelerate the s/c. This results in spiraling down to the planet. Deceleration is maximal for beta = 35°.
We estimate a transfer time of two years, but shorter transfer time is also possible.
Mercury orbit: It is possible to reach equatorial and polar orbits**.**

5.4. S/C Autonomy

S/C autonomy is foreseen in order to recover from possible anomalies occuring during cruise, manoeuvres and Mercury orbit. Several levels of autonomy are selectable by ground command. For example, the S/C must be able to accomplish a started manoeuvre even when the ground station cannot continue to control the maneuvre for some reason. In this case, the envisaged action would be to stop the main engine and/or thrusters after a given time. Of course, such a high level of autonomy is not commanded for normal cruise.
Analysis of possible anomalies from which the S/C can recover by itself shows that only

- positioning / navigation and
- payload control / mission operations

can be handled by the autonomy system. Autonomy does not help in the case of subsystem malfunction, since the subsystem cannot be repaired. Therefore, emergency and backup modes must be foreseen for such events.
We identify the following problems which can be handled by the S/C:

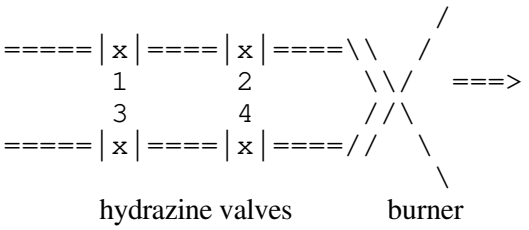
- in- / decreasing power from the solar panels
- batteries are discharged too much
- S/C is getting too hot / cold
- S/C is spinning too fast / slow
- anomalous operation of main engine and/or thrusters
- loosing contact with ground.

In every case the nature, severity and possible duration of the anomaly must be identified. The reason for the depletion of the battery may be that the S/C is actually in the shadow of Mercury. In this case of course no action will be performed. In the case of a severe problem being found the remaining time must be estimated until S/C parameters such as temperature or battery discharge will reach critical values. Depending on this time the S/C will go to a "safe mode" or wait for commands from ground. After the conclusion of the investigation on the origin of the occured failure, the selected strategy to recover is executed.
In many of these situations the "safe mode" will include switching off all non-essential loads. For the handling of the scientific instruments we propose the following: in case of a malfunction of the instrument itself, the specific instrument will be switched off. The malfunction can be detected by monitoring the crucial housekeeping values of that instrument such as voltage, current and temperature. In case of a S/C anomaly as mentioned above, the scientific instruments will be switched off according to a steadily maintained priority list which indicates the most important measurements for a given time and position from the scientist's point of view. Of course the highest priority is given to the maintainance of the operational S/C in any case.

Avoiding software errors

From previous missions we know about the crucial role that software plays in space missions so that it is worth while to think about its improvement. As a fact, *errorless software cannot be expected*.
We discuss a few ideas on how software can be made more reliable:

- Foresee enough time to develop the software. This point includes a sharp time schedule, since software used on S/C is strongly hardware dependent and therefore needs the hardware for the testing.
- Make sure that the same software is used at every stage of hardware developement, including for a specific subsystem or scientific instrument: the operation on the bench, the integration test on the S/C and the operation in flight.
- Introduce hardware limits which inhibit wrong commands. As an example, a system to avoid uncontrolled burn of main engines or thrusters is shown in figure .



[Figure N]

Valves 2 and 4 are the devices which control the hydrazine flow under normal conditions, while valves 1 and 3 are normally open. Valves 1 and 3 act as hardware limits in the sense that they can be closed if the burning duration exceeds a given time.

- Introduce 'red covers' in the software. For safety reasons some parts of a software are not really executed during the tests of the S/C. As an example, the command to turn on the main engine will not be transmitted to the hardware during tests. Of course, these parts of the software must be activated *before* launch. The idea is to use an easily recognizable marker for such parts of the software as critical mechanical parts are marked with red paint.
- Foresee a check within any routine to validate its parameters. With this check, the execution of a randomly generated, misleading command is avoided. Such wrong commands are caused by 'bit flips' due to energetic radiation or by a software error. The

checks include: range checking of the parameters and validation of the command by a command header and a checksum.

Software testing procedure

We propose to test the software in three steps: first every routine's performance must be tested. Second, the performance of an integrated subset of routines is tested. It seems that modern programming concepts such as 'object-orientated programming' include such a hierachy. These tools can certainly help to develop space proved software, but they cannot avoid all errors. Third, the integrated software must be tested by generating variing input data for the software while the critical S/C parameters as dV, current and spin rate are monitored.
Carry on as many tests as possible.

5.5. Enviromental / Instrument-related problems

Apart from exact designing a spacecraft mission, there will always be the possibility of malfunctions due to internal problems or obstacles provided by nature.
According to statistics, spacecraft malfunctions are caused by the following reasons:

SUBSYSTEM	Percentage
Telemetry, Command and Control	24.6
Guidance and Navigation	13.6
Electric Power	13.2
Data System	9.1
Thermal Control	5.6
Propulsion	3.7
Structures	3.5
Spacecraft Bus Total	**73.3**
Visual / IR -sensors	13.1
Communication Payload	5.2
Special Payloads	4.9
Navigation Payloads	3.5
Payload Total	**26.7**

(Source: Larson, 1992)

Left side: Statistics of known spacecraft malfunctions divided into payload and spacecraft structure.

5.4.2. Instrument related Problems

Magnetic cleanliness: the magnetometer has to be positioned on an external facility in order to avoid magnetic turbulences and interference with the spacecrafts internal systems.

Fuel malfunction: Hydrazine has to be held at appropiate temperatures, the same applies to the batteries. In conclusion developed thermostats are required.

During Launch: The spacecraft has to endure 4.25 g (at +100s after launch) and 3.8 g (at +580s after launch) during the launch operations at maximum. The maximum acoustic vibrations will not exceed 139 dB.
On reaching Mercury, the thrusters will provide a acceleration of less than 0.2 g, so no additional requirements concerning the stability of the structure are necessary.
(Source: "Ariane 5 - users manual")

Software security: see part 2.

5.4.3. Enviromental Problems

Space Debris - a man made risk
95% of all space hardware is non-operational. The identification and observation of the > 7000 bodies greater than 10cm is provided by a huge network of ground stations. The number of non-trackable objects is estimated between 40 000 and 80 000 pieces, correlating with a mass between 1.6 to 2.0 Million kg moving at a speed of 10 km/s. (Peak velocities are computed to be up to 14 km/s.)

Concerning the short time the Mercury Orbiter will spend near Earth, no debris avoidance techniques seem to be required.

System-generated Electronmagnetic Pulses (SGEMP's)
Another possibility for system malfunction is the hard photon emission from the Sun, occuring with eruptive events on the Sun. These flux increases are governed by flares and coronal mass ejections (CME). Due to hard X-ray and γ-ray radiation, internal fluxes of electrons in the spacecraft hardware are a serious hazard. These currents and large voltages may cause serious malfunctions related to the electronic parts.
A further source for these high frequency signals are scientific instrument failures, as high voltage break downs.

A possible avoidance strategy would be to enclose the sensible parts (integrated circuits,...) within a metallic (e.g. aluminium) cage to keep out strong fluxes. If an event occurs, an emergency mechanism could be activated to separate electronic components (assuming a very fast diagnosis of such a case). Of course there should remain the possibility for reconnecting the troubled parts.

Micrometeorites
There seems to be no requirement for special shielding or even active anti-collision techniques, exept for a possible Encke-encounter, when the spacecraft is in direct contact with the comet's tail. (See also part #4)

Temperatures
Concerning the radiation from the planet itself as well as from the sun (about 50% of the total computed infrared flux) sophisticated thermal controls are required. A more detailed description of the solutions has been done by the engineering team.

5.6. Mission Operation

In the first assesment studies a launch date of 7/7/2004 was proposed, including an arrival at 22/4/2008. The cruise to Mercury includes two Venus and Mercury gravity assists to save propellant. This offers an opportunity to make some measurements on the planet Venus during the flybys.

By crosschecking the s/c trajectory with the orbits of certain asteroids and comets, we have found a "very cheap" (in terms of fuel) possibility to encounter comet Encke.
This flyby requires a shift of the s/c launch to January 2009 and a small Δv manouvre of 140 m/s.
To calculate the needed fuel for the Δv manoeuvre, one can use the following rocket equation:

$\Delta v = w \ln (m_0/m_b)$

w ... velocity of the exhausted propellant
(Hydrazine propulsion: 3150 m/s)
m_0 ... initial s/c mass before ignition (1138kg)
m_b ... derived s/c mass after ignition

Evaluation of this equation leads to a $\Delta m = m_0 - m_b = 49.5$ kg.
This means that only 49.5 kg fuel are needed for the Δv manouvre, which is comparable to the fuel needed during cruise navigation and launch window. The encounter will take place in October 2013 at a solar distance of 0,38 AU, so the comet is close to its perihelion.
Mercury will be reached in January 2014, so the cruise phase will be extended by 1.7 years (in comparison to the original schedule), which has influences on costs and reliability.

5.6.1. Encke Flyby

There are two possibilities to take a close look at comet Encke:

a) A close flyby, requiring an additional Δv manoeuvre with 140 m/s and increasing the initial cruise phase by at least 1.7 years. Encke will be reached in October 2013, shortly before its perihelion (launch date: January 2009). The distance between Earth and Mercury will be 1.1 - 1.2 AU, so we have 2-3 kBps for TT&C, elongation is also at maximum ≈ 20°.
b) A more distant encounter with a closest distance of $13.8 \cdot 10^6$ km (≈ 0.09 AU) observed from Mercury orbit during the final mission in April 2010 (launch date: 2007).

a) obviously has a greater scientific return, since the distance can be reduced to hundreds of kilometres. On the other hand the launch date needs to be shifted much more and the costs are also increased, due to a longer cruise phase of 1.7 years. We consider a) to be more "scientifically valuable" , so it is worked out on the following pages.
b) is easier to achieve than a), since it only needs a launch of the s/c in 2007 - everything else is naturally. However the scientific return is probalbly low. At least optical observations of the comet during its perihelion phase be possible. The brightness of the comet will be more than 2.44 mag, derived from the following calculation:

$$m = 10 \log r + 5 \log d + m_0 = 2.44 \text{ mag}$$

m ... observable brightness in magnitudes
r ... sundistance in AU (≈ 0.35 AU)
d ... distance of the comet to the s/c (≈ 0.1 AU)
m_0 ... "absolute" magnitude of the comet (Encke ≈ 12 mag)

So it would be bright enough for the camera!
Also the comet could be observed for 20-30 days passing from behind and above (in respect to the Sun) to below and in front.
The implications on mission planning are only to shift the launch date to 2007!!!

Some other Encke flyby at a later time might be possible, though we did not have time to check. Other comets were also crosschecked (e.g. P/Honda-Mrkos-Pajdusakova), but none of them would be as easy to reach as P/Encke!
Comparison of the orbital parameters of Mercury and P/Encke:

	Mercury	**Encke**
Eccentricity e	0.2056	0.85
Perihelion distance q	0.31 AU	0.34 AU
Angle of ascending node Ω	48.33°	334°
Angle of perihelion ω	29.11°	186°
Inclination i	7°	12°

5.6.2. Scientific Goals

Why should we give the s/c a small kick to reach this comet?

There are several reasons to do this:

- We have only a very small database on comets from measurements of P/Halley, P/Giacobini-Zinner and P/Grigg-Skjellerup. Also only one cometary nucleus has been imaged - P/Halley by GIOTTO. So there remain a lot of questions:
  - Are cometary jets (observed by GIOTTO at Halley´s comet) common?
  - Are there differences in composition and dimensions of the nuclei (rotation, history)?
  - Is the gas and dust production rate comparable (extended sources)?
  - What temperature does the nucleus have?
  - Is the isotope ratio comparable to other comets (history)?
- P/Encke is a very old comet (period only 3.3 a ⇒ many perihelions), until 1970 47 appearances had been observed from Earth. So maybe it is in an intermediate state between a comet and an asteroid!
- The interaction between the solar wind and a comet had never been observed at this small solar distance (0.38 AU).
- P/Encke is fairly visible from the Earth. Even under very good circumstances it reaches only 5-6 mag (just at naked eye limit) and its elongation from the sun is also very small. So it may be possible that certain features have remainded undetectable from our point of view (is there really nearly no gas and dust tail and only a coma, shaped like a droplet. Are there some mass fluctuations, etc.).

5.6.3. Encke Flyby Trajectory

To determine the best s/c trajectory during the encounter, one has to consider the best operational distances for the different experiments:

- Nucleus dimensions: Multi Spectral Camera
- Jet detection: Multi Spectral Camera
- Ion chemistry: Ion spectrometer, Plasma analysers
- Chemistry on Neutrals: Neutral mass spectrometer, Plasma analysers
- Electron density: Electron analyser
- Electron temperature: Electron analyser
- Comet - S/W interaction: Ion spectrometer, Plasma analysers, Magnetometer
- Isotopic ratios: Ion spectrometer, Plasma analysers
- Bulk velocity: Plasma analysers

Since the camera has a resolution of 10 m at a periherm distance of 400 km, the following table is derived for increasing distance to the nucleus:

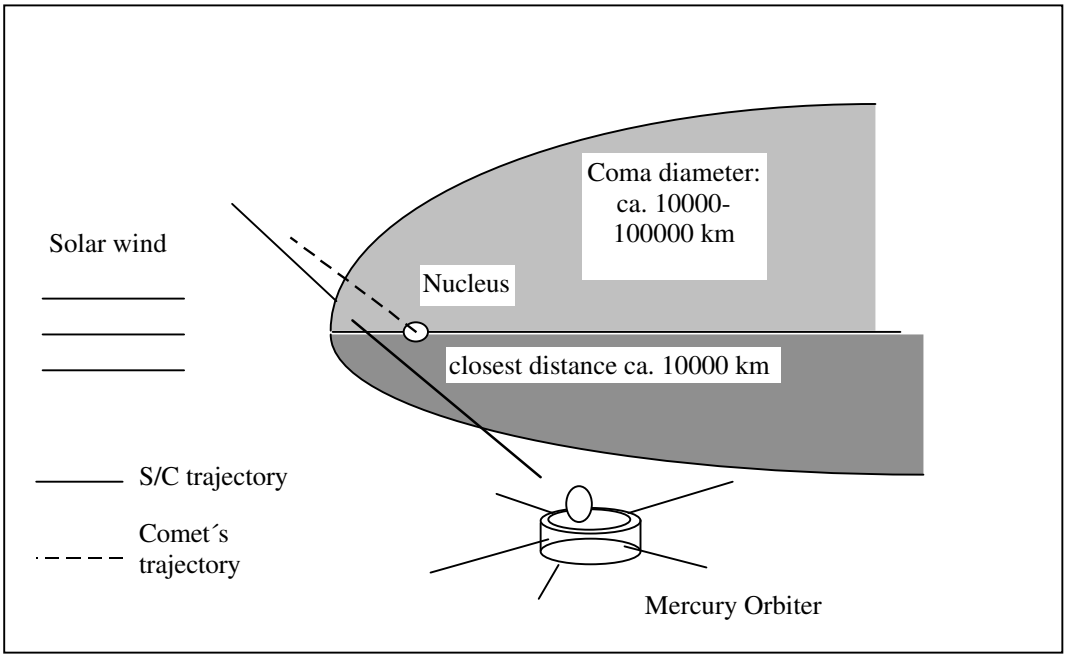
Distance	Resolution
400 km	10 m
800 km	20 m
1000 km	25 m
2000 km	50 m
5000 km	125 m
10000 km	250 m
20000 km	500 m

If one estimates the nucleus to have a diameter of about 7.5 km, a distance of 3000 km would lead to a resolution of 75 m on the surface. This means that the nucleus will cover at least 100 pixels.
The best operational distances of the other experiments are based upon the *Contact surface*. The Contact surface marks the region, where the environment is influenced only by the comet. This means that any particles from the solar wind will be held out of this region.
To calculate the Contact surface, one can use the following equation:

$$R_{c/s}{}^2 = \frac{mi \;\; kin\sqrt{k_{ph}/k_{rec}}\; Q^{3/2}}{m_{sw}\; 16\pi^{3/2}\sqrt{\nu_n}\; n_{sw}\; \nu^2{}_{sw}}$$

This leads to a $R_{c/s} \approx 4500$ km for P/Halley and a $R_{c/s} \approx 500$ km for P/Encke. To estimate the distance of the bow shock, we used the value measured by P/Halley and divided it by 10 (this is the ratio of the contact surfaces). So we got a value of $\approx 50\,000$ km
So why not pass the nucleus at 400 km distance and have very good measurements?
The problem is, that one wants the s/c to survive the comet encounter to go ahead to Mercury!
Recalling GIOTTO, which was hit by a substantial dust particle at about 800 km distance, it would be wise to pass the nucleus no closer than 10000 km. This distance sounds big, but don´t forget, that the encounter will happen at 0.38 AU distance from the Sun.
The closer the distance the more active the comet is, however P/Encke is an old comet and may no longer be very active. So maybe we can decrease the “dangerous” distance to some 1000 km. Further calculations on the mass loss rate in gas and dust depending on the models of P/Halley and the other comets could lead to another dangerous distance.
Another point to consider is the relative velocity of the comet and the s/c, in our case it reaches 38.5 km/s, which is quite high compared to the v_{rel} of 10 km/s during Grigg-Skjellerup encounter, but low compared to the v_{rel} of $\approx$ 70 km/s during the Halley flyby.

By taking all this data into account we consider the following trajectory to be the best one:



The s/c approaches the nucleus from behind in such a way as to pass it on the sunlit side (with a relative velocity of 38.5 km/s). The camera shows the nucleus with a resolution of about 250 m, so the picture will cover ca. 30 pixels. Even if we won´t be able to see a lot of surface features, it should be possible to determine the nucleus dimensions and its rotation axis and period.

5.6.4. Implications of the Flyby for the Mission

There will be some points which one has to consider in planning the mission, due to the flyby:

- Potential changes to the eclipse profile. This has to be further investigated, because it has implications on dimensioning the required battery size.
- Longer flight duration (at least 1.7 years, depending on the s/c trajectory after the 4th MGA). This has to be taken into account when designing the electronic subsystem.
- Increased operations cost, due to longer cruise

5.6.5. Orbit Design and Control

The chosen scenario requires several Venus and Mercury gravity assists to decelerate the s/c strong enough to reach orbit around Mercury. It requires:

a) Launch of s/c: January 2009
b) 1st Venus gravity assist (VGA) around Apr. 2009
c) 2nd VGA around May 2010
d) 1st Mercury gravity assist (MGA) around Aug. 2010
e) 2nd MGA around May 2011

f) 3rd MGA around July 2012
g) Encke flyby around Oct. 2013
h) Δv = 140 m/s to reach Encke
i) 4th MGA around Jan 2014
j) Mercury arrival - Mission start
k) Optionally extended mission

Between the 1st and the 2nd VGA: Resonance orbit with 1:2
Between the 1st and the 2nd MGA: Resonance orbit with 2:3
Between the 2nd and the 3rd MGA: Resonance orbit with 2:3
Between the 3rd and the 4th MGA: Resonance orbit with 3:4
Optionally after the 4th MGA: Resonance orbit with 6:5 (less fuel needed)

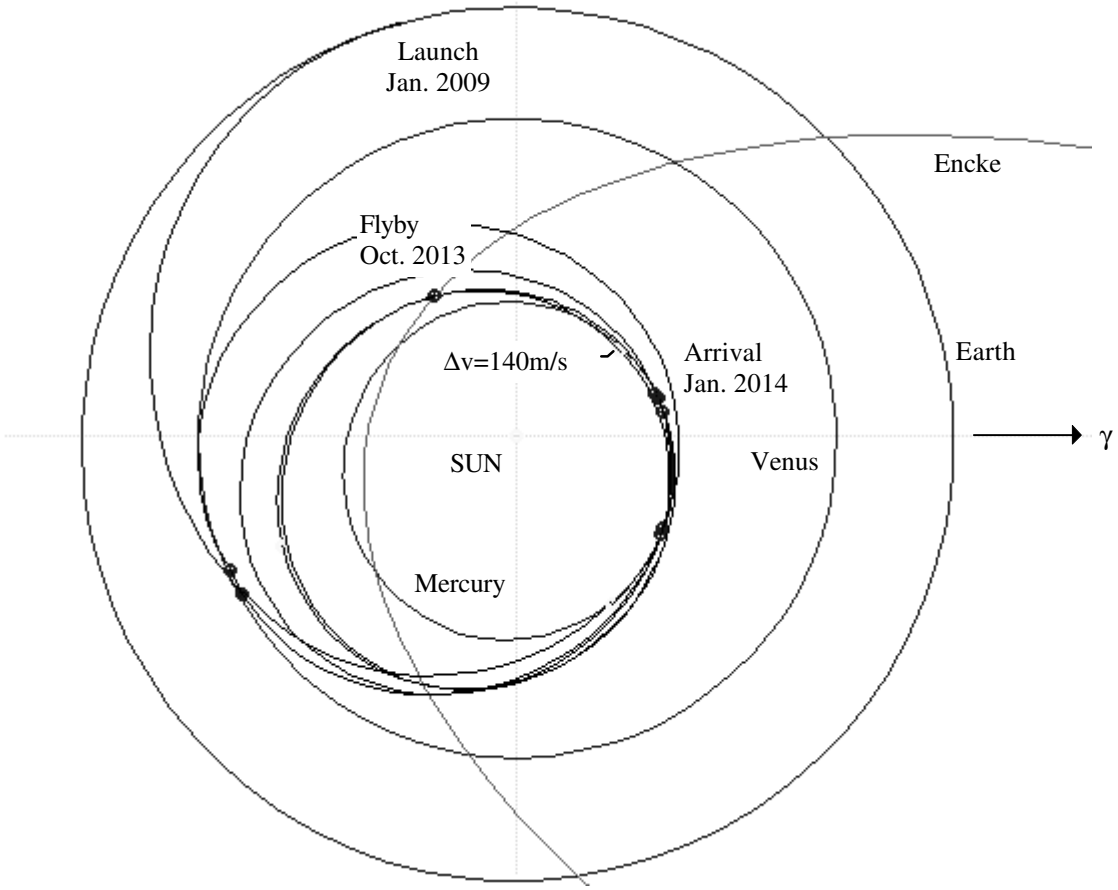
No changes will be made to the s/c orbit around Mercury, so we can refer to the ESA-Assesment Study (also for the TT&C Datarates).
All datas were derived from a program, which was operated by Yves Langevin (Thank's!!).

5.6.6. Extended Mission

Since the mapping of the Hermean south pole is not quite accurate, due to the higher altitude, it was stated by the scientitists that it would be good if one could circularise the orbit.
If one estimates that we have 15% fuel left after the baseline mission (≈120 kg), we can make a Δv manouvre at periherm to lower the apherm (Δv = 557 m/s). Using Kepler´s equations we can lower the apherm to an altitude of 2342 km and derive an orbital period of about 2.7 h.
The north pole will be passed at 720.8 km, south pole at 1643 km, in comparison to the original orbit, where the s/c passed the south pole at about 5288 km.

5.7. Mission Time Line

a) Launch of s/c
b) Activation of OFF-LOAD Device of HGA
c) TT&C test:
   Test of all subsystems
d) Deployment of all booms and wire antennas
e) TT&C test:
   Monitored adjustment of s/c solar aspect angle (accuracy, reaction time)
f) Communication test with HGA circuit
g) Activation and Checkout of the scientific instruments, being used during the different phases (cruising, VGA, MGA, Encke flyby)



References:

- Voigt, H.H.: “Abriß der Astronomie”, BI-Wiss.Verl. Mannheim, Wien, 1988
- Stanek, B.: “Raumfahrt Lexikon”, Hallwag. Bern, 1983
- Strom, R.: “Mercury, the elusive planet” Cambridge University Press, 1987
- Allen, C.W.:”Astrophysical Quantities”, third edition. The Athlone Press, 1973
- Vilas, F., Capman, C,R, Mattews, M.S., editors: “Mercury”, the University of Arizona Press.
- Talk of Jean-Pierre Blaser (Paul Scherrer Institute, Vilingen): “Planetary Missions, Opportunities for Fundamental Physics Experiments”.
- many very creative discussions with our tutors
- Chapman, R. J.:”The clementine lunar orbiter project” paper presented at the Alpbach Summer School 95.
- Larson, W.J.:”Space mission analysis and design”, Kluwer Academic Publishers, 1992.

6. The Lander Options

6.1 Mercury Surface Probes

It is proposed that two small surface probes be deployed towards Mercury. Each would perform both active and passive studies of the magnetospheric plasma using Langmuir probes and chemical release. Due to the severe problems associated with soft-landing a probe on the planet's surface, these probes would be purely ballistic, impacting the surface with a speed of several kms^{-1}. Remote analysis of the impact plume can be carried out using cameras on the orbiter, allowing the elemental composition of the surface material to be determined.
A large fraction of the mass of these probes would be solid material. This makes the impact on Mercury more easily visible from the orbiter and provides sufficient thermal inertia and insulation to maintain the active payload's temperature below its critical level for the duration of the descent. Graphite may prove to be a suitable material, due to its physical properties, low cost and relatively simple emission spectrum (which produces less contamination of the impact plume spectrum).
Once the first global mapping sequence has been completed, a trade-off is required between impact site and trajectory through the magnetosphere. Ejection speed from the orbiter would be predetermined by the design of the spring release mechanism, while the direction can be chosen by re-orienting the orbiter.
One possible scenario is probe release at apherm of the nominal orbit with a speed of 35 ms^{-1} in the -v direction, and impact at periherm 6.6 hours later.
During descent, a chemical tracer (such as barium) would be released into the magnetosphere and monitored by the camera on the orbiter. Chemical release could be achieved by an electrically-initiated "firework" device. Release rate would depend on the shape of the grain, as with a solid rocket motor.
Basic plasma analysis would be carried out using Langmuir probes mounted on the surface of the projectile. Data would be transmitted to the orbiter by means of a low gain antenna, using the same system as for the proposed Venus probes.
The scientific objectives of the Mercury probes are as follows:-

Active analysis of the plasma environment during descent through the magnetosphere

Monitoring of the magnetospheric dynamics by chemical release

Determination of surface composition at the impact site (search for volatiles at the poles)

These objectives will be met using probes with the following characteristics:-
Mass: 15-20 kg (impact energy, thermal inertia)

Energy: 50Wh (battery power)

Communications: 50 bps via low gain antenna

Structure: Hollow sphere

Deployment: Pyrotechnically initiated spring mechanism

Payload: Langmuir probes, chemical release device, impact mass

Stabilisation: Possibly deployment-induced spin

Propulsion: None (though chemical release will produce thrust)

Thermal control: Insulation & thermal inertia

Lifetime: 7 hours

6.2. The Venus Probe Option

The current mission trajectory includes two Venus gravity assists, providing opportunities for scientific investigations. In addition to operating experiments on the orbiter, two small probes could be deployed into the Venusian atmosphere during the first flyby. Only basic parameters (including temperature, pressure & acceleration) would be studied, with a payload mass of no more than 1 kg per probe. In this way a basic analysis can be performed without significant impact on the spacecraft's primary mission. While such measurements have been made before, new data is always of benefit, especially since the Venusian atmosphere is still poorly characterised.
The mass budget for each Venus probe is shown below. The estimates are based on previous Venus probe designs.

Item	Mass /kg
Deceleration module	4
Pressure Vessel Structure	3
Thermal Control	4
TT&C	1.3
CDMS1.2	
Power	2
Science Instruments	1
Separation Mechanism	1.3
Total Mass Excluding Margin	17.8
Total Mass Including Margin (20%)	21.4

The probes would be released almost simultaneously several days before encounter. Descent through the atmosphere would take about one hour, during which time each probe would transmit data to the orbiter via a low gain antenna.
A basic power supply and checkout connection would be provided from launch of the orbiter to probe deployment. Probe activation would occur autonomously on detection of a threshold deceleration in the upper Venusian atmosphere.

7. System Objects of Spacecraft and Technology

Regine Bolter, Technical University Graz, Inst. f. Computer Graphics
Klaus Enninghorst, Universität Bonn, Inst. f. Astrophysik und extraterr. Forschung
Alois Goller, Technical University Graz, Inst. f. Computer Graphics
Mathias Michaelis, Universität Bern, Physikalisches Institut
Torsten Poppe, Max-Planck-Society, Res. Unit. Dust in Starforming Regions
Martin Tajmar, Technische Universität Wien, Allg. Elektrotechnik und Elektronik

7.1. Introduction

Our group reviewed and evaluated the present concepts of the Mercury Orbiter mission and assessed the major trade-offs. Possible mass reductions were discussed as well as alternatives concepts for propulsion, stabilization, power concept, thermal control, structure design, and telemetry, telecommand and control (TT&C) under consideration of technologies becoming available in the very near future. Since the transmission of scientific data is the most important objective of the mission, special attention was payed to the possible enhancement of the downlink data rate.The science teams intend to implement the following payload on the spacecraft:

Instrument	Measurement Range	Mass (kg)	Power (W)	Data Rate (kbps)	Remarks	Group (*)
Oszillator (Atomic Clock)	Frequency : 100 MHz	2	Combined with radio beacon. Fundamental physics.			1
Neutral mass spektrometer	Energy: 1eV - 10keV Massrange: 1 - 100 u Resolution: 100	6	3	0.3	ev. cooled ionisation surface	3, 5
Radiobeacon	Frequ. f1 = 100 MHz Frequ. f2 = 200 MHz	2	2	No	Column density of electrons.	5
Magnetometer	±4000nT, res. 0.1nT 0 - 50Hz, 3 axis.	3	3	0.4		5
Multispectral Imager (2x)	resolution: 10m at periapsis, 250<λ<1000nm	2x5	2x12	2x6	Cooled CCD (-35°C) ±83° movable.	3, 4
Gamma spectrometer and neutron, proton detector	0.5MeV<E<8.0MeV	10	10	1.4	Ge crystal working at 100K => cooling problems !	3, 5
Plasma ions 3-D ions spectrometer	5eV - 30keV	5	5	1		5
3-D electron analyser	5eV - 30keV	2	4	0.4		5
Waves : search coil, AC electric fields	1 Hz - 100 kHz 10kHz - 640kHz 0.5 MHz - 20MHz	16	7	1		5

X-ray spectrometer	from < 1keV to 7keV FOV = 1.8° (FWHM)	5	4	0.2	Although this may done by γ-Spektr., it is more sure to take it.	5
High energy electron detector	15keV - 1 MeV	1	1	0.4		
Medium energy ion detector	15keV - 4 MeV	2	2	0.4		
UV imaging detector	He Lyman-α (304 A)	2	2	0.2		
Dust detector	mass range 1E-16 to 1E-6 g	2	2	0.05		
Photometers		1.5	2.5	0.2		
Ion gun (spacecraft potential control)		2	3	0.02		5
Total		**71.5**	**74.5**	**17.97**		
Total of present study		**49.4**	**43.8**	**6.12**		

(*) 1 : Fundamental physics, mission scenario and operations
2 : System aspects and technology
3 : Geochemistry
4 : Geophysics
5 : Plasma, exosphere and solar physics

These additional requirements have to be fulfilled as well as the requirements concerning attitude control and structure design including the possible accomodation of an additional instrument probe.

7.2. Attitude Control System

Stabilisation

There are two stabilisation possibilities
- spin stabilisation
- 3-axis stabilisation

Because of the special conditions in Mercury orbit, 3-axis stabilisation has many disadvantages:
- The payload antennas cannot be expanded by centrifugal force due to the spinning spacecraft. If there is no spin, another solution for this problem must be found
- Plasma instruments need spin. If the spacecraft is not spinning, a spinning platform has to be added to mount those instruments
- Thermal problem: When the spacecraft does not spin, the whole heat is concentrated on one area

⇒ Mercury orbiter must be spin stabilized (with the proposed 6-10 rpm)

Control system

The control system consists of the following components
- Sun sensor (0.85 kg, 0.110 W)
- Star mapper (4,5 kg, 0.700 W)
- Attitude determination and control electronics (7.7kg, 1.7 W)
- Accelerometers for monitoring the spin rate (0.7 kg)

This corresponds to an ACS (Attitude Control System) mass budget of 17 kg with 15% margin and a required power consumption of maximum 7 Watt.

7.3. Propulsion

Fuel

The fuel consists of 2 components (bi-propellant)
- Hydrazin (fuel)
- N_2O_4 (oxidizer)

The whole mass is 945 kg including 15% margin.

Alternative: Mono-propellant system

- Advantage: More simple fuel system
- Disadvantage: Less specific impuls (more fuel is needed)

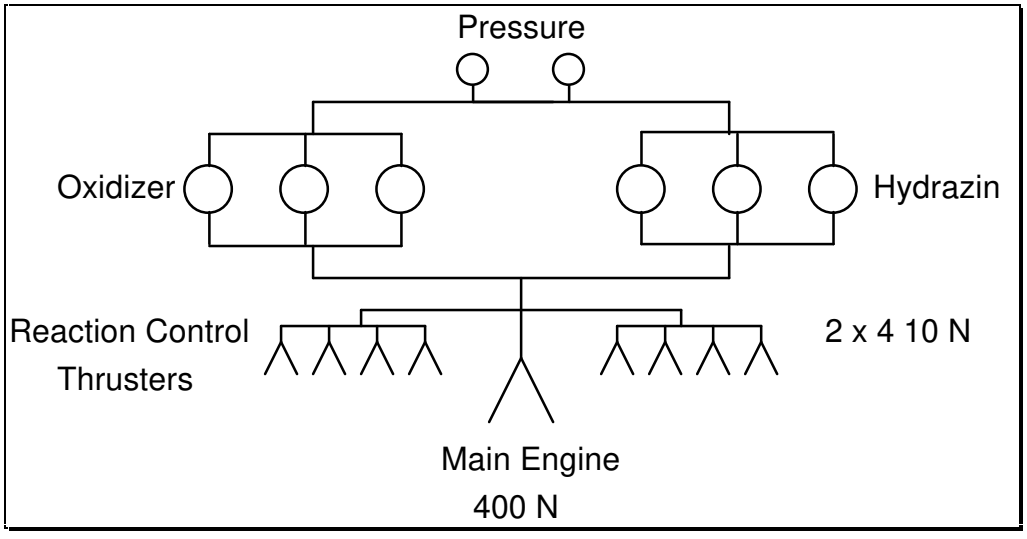
Tanks

- 2 (fuel and oxidizer) * 3- This has an stabilation advantage (spin) because of the moment of inertia.
- For pressure: The tank is filled with Helium which is necessary to press the fuel into the engines (instead of pumps).

The diameter of the spherical tanks is 66 cm, the filling ratio 90%. We recommend for both tanks a composit of wounded fiber which is lighter than any metal.

Engine

- Main engine (400 N): For orbit control
- Reaction Control Thrusters (2 x 4 10 N): For attitude control and some orbit control manoeuvers



For the Mercury Orbiter a chemical bi-propellant propulsion system is currently planned which has a big advantage: If the main engine fails, the small thrusters can use the fuel and can also do orbit manoeuvers (This has happend at the Hipparocs mission). The whole mass budget is 88 kg with 15% margin.

Alternative - Electric propulsion

For example the European RIT-35 engine: This is an ion-propulsion engine which provides a thrust of about 100 mN at an electrical power of 5 kW. Fuel (Xenon) is ionized and electrically accelerated, whereby much higher speeds are obtained compared to chemical methods (higher specific impulse). The problem is the low mass density, which means that only small thrusts are possible. Compared to our situation we have the following:

Advantage:
Higher specific impulse, which saves a lot of fuel, mass and money.
Disadvantages:

- High electrical power is needed (3 - 5 kW). This means that we would need a different power system than solar arrays (currently planned).
- Long burn times - small thrusts: This would be a problem for the planned orbit insertion and attitude manoeuvers - a new trajectory must be calculated.
- It has not been used for interplanetary missions up to now but only for orbit controls on satellites - qualification status.

7.4. Power systems

The power consumption for each part is

Payload	80 W
Transmission	80 W
Thermal Control	20 W
Spacecraft Control	10 W
Attitude Control	7 W
Total (+15% Margin)	226 W

Solar arrays

Because of the big solar constant at Mercury (up to 15 kW/m^2) the current plan is to use solar arrays. The required properties are:

- Applicable to high temperatures (150°C)
- Working at shallow sun aspect angels (10°)
- High efficiency

Conclusion: GaAs solar cells. They are designed for a theoretical efficiency of 26% and they can work at high temperatures with 20%. The specific costs are 3000 $/W.

Normal solar cells made out of Si are cheaper (20%) but cannot resist the required temperature and not designed for shallow illumination angles.

In combinition with solar cells a battery is needed to work also when the spacecraft is in the Sun eclipse (max. 110 min). The current battery is a NiH_2-type, which has 35 Wh/kg and so the weight is, calculated for a required power of 200 W, 12 kg.

Alternative: Li/Polymer battery-type (under development). Because of the energy density of 150 Wh/kg, the weight would only be 3 kg which means a mass reduction of 9 kg (+ fuel and 15% margin = 36 kg!).

Radio-Isotopes Thermal Generator

The main advantage is that the power supply does not depend on the position of the sun and therefore no battery is required. But there are also some disadvantages:

- Radiation can have an influence on the measurements and the electronics
- They produce a lot of heat
- It is very expensive (specific costs 16000 $/W)
- The efficiency is very low (2%)

Currently, there is a lot of development going on to increase the efficiency (up to 7-10%) which would also reduce the heat production. Maybe this would be an alternative for future missions, although there is a problem of political acceptance.

Nuclear Reactors

Additional to the advantages mentioned above nuclear reactors have a power/cost ratio which is very good (specific costs of 600 $/W). The problem is that there are no reactors available for such small powers (they start at 25 kW). The efficiency is also very low and it produces a lot of heat.

If we use electrical propulsion we would have to make

- big solar arrays
- or nuclear power systems. In that case we would suggest a nuclear reactor because of the power production and the low costs.

7.5. Thermal Control and Mechanical Design

Thermal Considerations

The hostile radiation environment is a major design driver for a Mercury Orbiter. The sun intensity varys from 6.3 kW/m^2 to 15.5 kW/m^2 due to the high excentricity of the Mercury orbit. The Hermean surface infrared emission is even worse for design. A standard method of thermal control, i.e. the use of surfaces with white colour or second surface mirrors, is not effective for the Mercury radiation in the infrared.

As anticipated, for thermal reasons a spinning cylindrical spacecraft design is planned. This distributes the heating equally onto the side. For the side a multi layer insulation is proposed which has a high reflectivity

in the visible and can withstand temperatures of 250 °C. For the proposed orbit around Mercury the north pointing and south pointing ends of the spacecraft get a different radiation from mercury. It is roughly estimated to have a maximum of 1 kW/m^2 on the north and a 2 kW/m^2 on the south. This maximum occurs close to but not at periherm of Orbiter and aphelion of Mercury. Therefore solar arrays and the high gain antenna should be on the north end during the entire mission.

A flat shape of the Mercury Orbiter will reduce the area exposed to the sunlight. The electrically dissipated energy and the conducted heat into the spacecraft are radiated into space on the top and bottom of the spacecraft. Because of the Hermean radiation the cooling areas must temporarily be shut by louvers. To provide an inside temperature of 300 K, the size for louvers to radiate 500 W

is roughly 1 m^2, which must be accomodated each on the top and bottom. If a stronger cooling for some instruments is required, the design of these instruments must perform the cooling without exceeding the foreseen power limits for the payload.

The temperature of the solar arrays must not exceed 150 °C. Because of the temporarily strong radiation from Mercury, the sun radiation onto the solar arrays should not exceed 1 kW/m^2 averaged for one spin rotation. Assuming an efficiency of 15% at high temperature and shallow illumination angles, a solar array of 2 m^2 is required for 300 W. The solar array must therefore be lit in a shallow angle. A small tilt of spin axis adjusts the exposed solar array area to the varying sun intensity.

The louvers and solar arrays need 3 m^2 of the 6 m^2 north pointing area. So there is enough space also for the antenna.

The use of solar pannels is refused.The possible advantage, a panel backside radiation cooling, would not work during the entire orbit due to the strong infrared radiation from Mercury. This would lead to a complicated design with louvers on the backside of deployable panels.

Despun Antenna Platform

The high gain antenna must be despun to point to Earth. In order to use standard techniques for despun antenna platforms, the bearings should be placed inside the cool interior of the spacecraft connected to the platform by a tube of low heat conductivity

A feed through for the high frequency high power signal can be avoided by placing the sender on the spinning spacecraft and reflecting the signal in the spin axis onto the antenna.

Since the spin axis is orientated due to thermal and solar power reasons and the Mercury orbit plane has a high inclination of 7 °, there must be a tilt mechanism for the antenna. We suggest a higher tilt angle than +-4 °, maybe +-10 °. This is to avoid restrictions in launch date and life time of the orbiter. Furthermore, a larger tilt angle allows to compensate a possible bending of the antenna caused by temperature gradients. The communication should work in any constellation of Earth and Mercury and any slight tilt of spin axis due to thermal and power reasons. Thus, a 180 ° tilt of the spin axis can be avoided in order never to expose the antenna and the solar arrays to the hot south end of the orbiter.

The antenna and the tiltable secondary reflector are exposed to the most hostile environment any part of the orbiter has to face. They do not spin and can get radiation from Sun, Mercury, and the Mercury Orbiter. A porous mesh antenna with a high reflectivity in the visible may be the solution. A feed through for the tilt mechanism is required which is simpler as the avoided RF feed through. The despun platform is seen as the most difficult subject of mechanical design.

Scientific instuments cannot be placed on the platform, since no thermal control and no power supply can be provided.

Structure

For the cylindrical spinning spacecraft we propose an hexagonal star shaped inside structure of plates. The plates provide strength and mounting possibilities. In an iterational process the arrangement of all inside components must be determined to keep the moment of inertia axis in the symmetry axis. The mounting plates allow such an iterational design process. Their vertical orientation corresponds to the direction of the mechanical load during the launch. A tube in the center accomodates the bearing of the despun platform and the RF sender.

The structure is made of aluminium for reasons of high heat conductivity and light weight design. Inside it is painted black also to provide a rather equal inside temperature. Titanium must be avoided because of the

gamma ray spectrometer. The six ball shaped tanks for propellant and the pressure gas tanks are made of light weight kevlar wound composites. The diameter of the tanks is about 700 mm; to allow instruments being placed on the entire circumference a heighth of 1 m for the cylindrical shape is chosen.

The mounting of the spacecraft on the rocket should be close to the heaviest components, the tanks, to reduce the required mechanical strength of the structure.

Since there are no unusual stiffness requirements for the structure as there were for the Cluster project, the Mercury Orbiter can do with a lighter structure of estimated 120 kg, compared with a mass of 144 kg in the present proposal.

Possible Future Improvements

In respect of thermal and mechanical design there are improvements which can be made by new technical developement. The use of electromissive devices (e.g. Type ESTHER, DORNIER) can replace the louvers, this can lead to mass saving and increasing reliability by avoiding moving parts.

The use of high temperature bearings and high temperature vacuum lubrification would significantly simplify the despun platform design and reduce mass. Especially it should be looked for new materials for the bearings. The major problem will probably be the life time of bearings with a lubrification of solid material (graphite, molybdendisulfide)

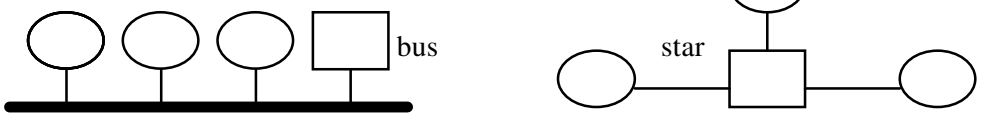
(See also figures enclosed)

7.6. Communications

Communications occur between all spacecraft (S/C) devices (sensors, housekeeping processor, actors) to provide the requested autonomy, between payload devices and S/C computers to forward control and data signals, and between the S/C and the groundstation (G/S) for telemetry, telecommanding and control (TT&C) as well as for the downlink transmission of all scientific data.

S/C Internal Communication

Topology



Contrary to the currently used bus topology, a star has the following advantages:

- no collisions, thus simple protocol
- more than one communication at one time
- problems with one payload device do not affect others

To implement this star topology, fiber glass links can be used having additional features:

- less mass
- less metal that disturbes sensitive payload sensors
- higher internal communication bandwidth
- electrical decoupling (no grounding problems, no influences due to EMPs)

Data Preprocessing

Nowadays data preprocessing is performed in each payload device. Major advantages are clearly defined interfaces and a simpler systems development. Nevertheless, our approach is one central processor, which performs all required preprocessing tasks. A lot of advantages occur:

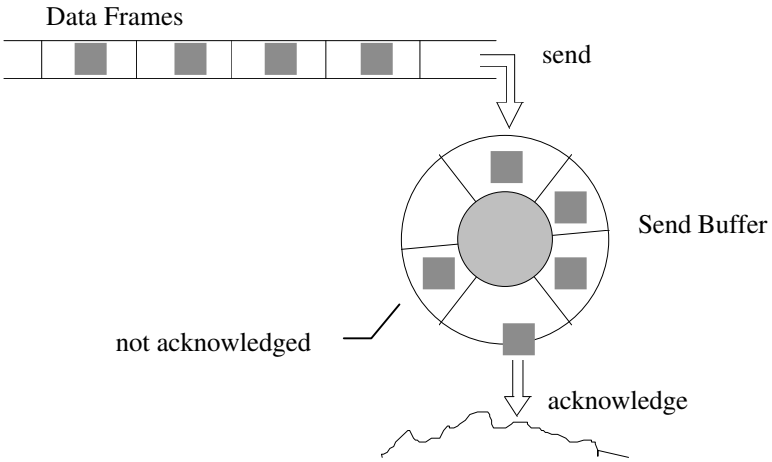
- mass reduction
- fault tolerancy, various algorithms can run on the same DSP
- all digital electronic devices are in one box; thus can be easily shielded against EMP
- thermal constraints are easy to meet
- software code reusage
- scope checking must be performed on uncompressed data
- advanced preprocessing and compression algorithms are possible due to timesharing of DSPs and/or the main processor

Compression

To achieve the highest possible compression rate, data from each payload device should be handled seperately, although this implies more complex algorithms and thus more computing power. First of all, for each payload device one has to decide if lossy compression is applicable and at which degree [2].

Protocols

To ensure an error-free communication to the G/S, a protocol has to be incorporated. We suggest packeting of the data stream (including framing information and CRC), and the implementation of a windowing-mechanism (*selective retransmission* with variable frame sizes, i.e. a data packet is deleted after receiving the corresponding acknowledge from G/S).



Windowing Mechanism with selective retransmission

Memory & Backup

Additionally to the main memory used for preprocessing and compression, a backup system has to be designed to collect all data items obtined from several payload devices. The size of this memory must be large enough, so that occultations, temporarily too high datarates from payload devices, and transmission failures can be handled. To save mass, power consumption and volume, as well as to avoid complicated mechanical components, DRAMs should be used instead of conventional tape recorders.

Computing Performance

In order to serve all requirements stated above, a powerful, three times fault redundant processing system should be used. It is impossible to design error-free software. Thus, different software should run on those three processors. This provides not only hardware- but also software fault tolerancy.

Uplink & Downlink

The higher the frequency, the higher the achieveable data transmission rate. But increasing the carrier frequency leads to a more complicated hardware handling. Whilst for commanding (uplink) a bitrate of about 20 bit/s is sufficient [3], the downlink bitrate determines the amount of scientific data.

Frequency [GHz]	Wave Length [cm]	Band	Comments
2	15	S	available at ESA now
8.42	3.563	X	available at ESA after ROSETTA mission [1]
15	2	K	G/S had to be upgraded

The total amout of compressed, scientific data can be calculated as follows [3]:

$$\mathbf{A_{tot} = R + t = (EIRP + L_S + L_a + G/T - k - E_b/N_0 - \varepsilon) + t} \qquad \text{[all in dB]}$$

A_{tot}	total transmitted (compressed) data	L_a	atmospheric attenuation
R	data rate	G/T	figure of merit of the receiver
t	transmission time	k	Boltzmann konstant
EIRP	emitted isotropic radiated power	E_b/N_0	coding requirement
L_S	free space loss	ε	various other losses, margin

EIRP includes the S/C HGA gain and the transmit power. The S/C HGA has a diameter of 1.4 m and a gain of 37.8 dBi at X-Band [2]. One way to increase EIRP is to enlarge the antenna which implies more mass. Increasing the frequency results in a denser grid, implying more mass, thermal problems and additional shadows onto the solar panels.

G/T depends on the ground based equipment. Higher frequency and larger antenna diameter improves this term.

E_b/N_0 depends on the coding algorithm, modulation and communications link reliability. We suggest to use the best available technique, regardless of ist complexity. Momentarily it is BPSK with Reed-Solomon (255,233) encoding and Viterbi (r=0.5, k=7) decoding [3].

With one G/S communication is possible at most 8 hours/day. Using three well-distributed G/S would allow communication 24 hours/day. These G/S are not available now, and operation is three times more expensive.

configuration	bitrate [kbit/s]	total amount of data [Gbyte]
standard (X-Band, 15 m G/S, 20W transmit power, 1.4 m S/C HGA)	8.0	7.9
24 m G/S antenna (Weilhem)	20.5	20.3
34 m G/S antenna (NASA-DSN)	41.0	40.7
70 m G/S antenna (NASA-DSN)	174.2	172.5
1.8 m S/C HGA	13.2	13.1
0.8 m S/C HGA	2.62	2.6
40 W transmit power	16.0	15.8
3 G/Ss	8.0	23.7
K-Band	25.3	25.1
proposal 1 (24 m G/S, 1.8 m S/C HGA)	33.6	33.3
proposal 2 (34 m G/S, 40 W transmit power)	82.0	81.4
proposal 3 (K-Band, 40 W transmit power, 3 G/Ss)	50.6	50.1
proposal 4 (K-Band, 70 m G/S, 40 W transmit power, 1.8 m S/C HGA, 3 G/Ss)	1816	5394

Combining all improvements, a total amount of 5.4 Tbyte of compressed data can be received. However, this big amount of data seems very unrealistic. Regardless of the total amount of data obtained, an European Data Center is mandatory. This center must provide post-processing, storage (archiving) and distribution.

Autonomy

A certain amount of S/C autonomy is required, because the communication between the Mercury Orbiter and a station on Earth lasts at least 20 minutes. In addition, the S/C is not always reachable (e.g. Mercury or Sun are between orbiter and G/S). Thus, the S/C should be able to handle the following points:

Attitude Determination and Control

Due to a number of reasons (e.g. thermal control, communication, angle of direction of the cameras) the attitude of the S/C must be kept within a small range around the nominal position, which is perpendicular to Mercury's orbital plane. The attitude is determined by star and sun mapper and accelerometers, the attitude manoeuvres are performed by 10 small thrusters. Minor corrections to keep spin axis orientation and spin rate in the nominal range should be managed autonomously by the on board computer. If major deviations occures, the S/C must avoid to loose too much propellant in senseless manouvres. Thus, before correcting unexpected deviations, the on board computer must consult the Earth. A malfunction of the attitude sensors has to be considered as well.

Thermal Control

Autonomous thermal control includes the monitoring of the temperature using several sensors which are distributed within the whole S/C and to direct the position of the louvres.

Power Management

The performance of the solar cells, the charge condition of the batteries, and the power consumption of payload instruments and other devices must be controlled. If a 'power-to-low-failure' occures, the on board computer must switch off devices in that way that the survival is guaranteed according to the following priorities: S/C - communication - payload. It has to be considered that the importance of maintaining the measurements depends on the actual position of the S/C (e.g. in the dark no cameras are needed). Since one of the mission objectives is the complete mapping of the surface, the continously function of the cameras is given a high priority. If a malfunction of one payload (e.g. it becomes too hot or a short circuit occurs) endagers the whole S/C, this instrument must be switched off immediately, probably switched on again after it has cooled down.

Communication Control

The communication control includes the alignment of the high gain antenna according to the orbit configuration as well as the management of the communication with the G/S. If a loss of communication occurs, the on board computer should try to set up the communication once more with the HGA, then switch to the MGA, if that fails too, switch to the LGA. The LGA only allows the transmission of a few bits per seconds, but has the highest reliability, in particular with respect to alignment problems.

7.7. Conclusion

After having received the requirements of the science teams, we were confronted with the demand for an increased payload mass and the need for a more efficient data transmission. A solution could be outlined for both mass and data rate. The available payload mass can be increased by reducing the weight of the structure of the S/C by 20%. The data rate can be increased by making use of K-band transmission instead of X-band. To clearify the details of these concepts and to make the demands of the science teams and the proposed system design really coherent, many more iteration steps would be neccessary.
The presented assessment study of the Mercury Orbiter mission was critically rewieved. A lot of alternative solutions were discussed showing the process of making trade-offs between the different constrains.

References

[1] George Scoon, private communication
[2] L. Popken, TT&C Capacity Assesment for Mercury, November 93
[3] Athena Educational Group, Space Mission Analysis and Design Short Course, Chapter III, March 95

8. General Conclusion

The following points can be concluded as a result of this study:

- The engineering challenges of the hostile environment at Mercury can be solved.
- The expected amount of data will require some improvements of the groundbased infrastructure of ESA, the upgrade of the antenna stations to K-band communication and the foundation of an European Space Science Data Center is highly recommended.
- The scientific gain will improve our knowledge on Mercury, in particular its composition, its structure, and its magnetosphere. This is expected to give a feedback to other fields of study when comparing Mercury with other planets leading to a deeper understanding of the formation and the evolution of the solar system and not the least to a better knowledge of the magnetosphere of the Earth. Since disturbances in telecommunication are induced by geomagnetic storms, an improved forecast of such events can save a lot of trouble and a lot of money.

Thus, the participants of this course all do agree:

A Mercury Orbiter mission is required and it is feasible.

The critical inspection of the assessment study of the Mercury Orbiter, considering some of the major tradeoffs between scientific requirements and technical possibilities, as well as the development of some new ideas, gave 31 young scientists the opportunity to learn the ***whats***, the ***whys*** and the ***hows*** of the iteration process which is necessary to design and to implement a successful mission.
Beside this, we all enjoyed the stimulating working atmosphere in the congress centre and in the 'Böglerhof' and the beautiful landscape of Alpbach and would like to express our thanks to the all the people who are involved in organisation and excecution of the 1995 Alpbach Summer School.