

Gravity Gradient Sensor Technology for future planetary missions

Executive summary

Deliverable 5

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1 Overview project

Future ESA missions will be focused on the study of the gravity field of planetary or lunar objects. Mapping of the gravitational field of a celestial body will provide important information about the internal structure and local mass distribution of the object. The gravity field can be described by spherical harmonics and the degree of the harmonics is a measure for the local occurrence of a peculiarity in the field. Lower degree terms can provide information about internal structures as the presence of an internal ocean on Europe and higher order degrees can give the information about the compensation effect of volcanoes.

The first aim of this study is the definition of the scientific objectives of planets and moons of our solar system. We pay attention to Mercury, Venus, the Moon and Mars, the Jovian and Kronian systems and some other planets. If possible we present the required sensitivity for the gravity sensing system needed to study the various objectives. The results are presented in chapter 2, which summarizes the technical note TN2.

Systems with high sensitivity are needed for the accurate measurement of the gravity gradient. Very high sensitivity can be obtained by applying low T_c superconducting sensors that measure the very small relative displacement of test masses. Such a system is operating at liquid helium temperatures and is in general bulky and heavy. Also the system for GOCE is a heavy one.

For future planetary mission one has to account for a relatively small scientific payload. As stated in the ITT, a new generation of low weight systems has to be considered. Recent developments in high T_c superconductivity and micromechanics may lead to new sensors, which are adequate for planetary missions. Furthermore new principles as measuring gravity gradients with ensembles of laser cooled atoms or satellite-to-satellite tracking can be investigated. The study of the opportunities from these new areas is the second main topic of the proposal. We describe the recent developments, estimate the attainable sensitivity and mass. The results are presented in chapter 3, which is the output of TN3 and also partly of D4.

In the final chapter 4 we propose the Research and Development Program for gravity gradient sensors for planetary and lunar missions. On the one hand we describe the program for planetary exploration and on the other hand the program for instrument development. It turns out that the starting projects on Microsat within MicroNed and the roadmap of the Platform Planeetonderzoek Nederland are clearly connected to and support the outcome of this study.

2. Scientific objectives of Gravity Field Mapping Missions and the Gravity-gradient sensor performance requirements

Mars

Since Mariner 12 in 1972, this planet has been studied by a large number of missions including orbiters, landers and rovers. Information on the internal structure has only been obtained by gravity measurements inferred from Doppler-shift tracking of spacecrafts. The inversion of the data obtained by the Mars Global Surveyor mission gives the coefficients of spherical harmonic decomposition of the gravity field up to degree 65.

The gravity anomaly also called the free-air gravity anomaly is defined as the difference between the theoretical value of the vertical component of gravity on an ellipsoid and the measured value on the reference ellipsoid. One can note that the dichotomy (difference of topography between the northern and southern hemispheres) does not show up in the gravity anomaly map. This implies that the topography is fully compensated either by a Pratt (difference in density) or Airy (difference in crustal thickness) model. On the other hand, several volcanoes show very strong gravity anomalies which tend to prove that they are not compensated.

One important discovery is the crustal remnant magnetic field. It would be interesting to see if there is any correlation between these anomalies and mass anomalies. Also, the measurements of the crustal magnetic field at two different altitudes during the Aerobraking phase (150 km) and Mapping Orbit (400 km) show that the wavelength of the anomalies is smaller at the lower altitude. This is important because it proves the interest of having measurement of any potential (magnetic or gravity) close to the surface. Measurements with orbiters can cover the whole planet but are limited in wavelength variations. Measurements on airplanes will cover a small portion of the planet but will resolve short wavelength anomalies. The two kinds of measurements are complementary to each other. Only airborne surveys could check the existence of any correlation between the magnetic anomalies that should be recorded within iron-bearing (and therefore dense) minerals and gravity anomalies. (The ARES proposal for a scout mission proposed to measure magnetic field. It would be interested to investigate the possibility of gradiometers onboard such air planes).

In order to improve our understanding of Mars's gravity field, we propose to use gradiometers onboard of airplanes. However, tests of this method should first be performed on Earth.

Venus

Venus is the planet that resembles the Earth the most. Its radius (6052 km) is only 320 km smaller than that of Earth. Its density is equal to 5.25 (5.52 for the Earth) and can be explained by the lower pressures inside the planet if one takes the same elementary composition. However its atmosphere is very different with large amounts of CO₂ (90 bar at the surface) and clouds that hide its surface in visible wavelengths. Radar images were first obtained by the Soviet Venera 15 and 16 missions in the 80s and the NASA Magellan mission between 1990 and 1994. Its surface is covered with volcanoes but none

of them showed signs of activity during the four years of the mission. Topography and gravity data were obtained by the Magellan mission.

Venus' topography is dominated by two mountains named Aphrodite Terra (equator) and Ishtar Terra (northern latitudes). The topographic features are compensated and the gravity signal is very weak over these areas. The dense atmosphere prevents any spacecraft to orbit the planet at less than 300 km. The minimal wavelength that has been resolved is on the order of 500 km.

The degree two is very small because the Venus' rotation is very small. Therefore, we cannot get a value of the moment of inertia.

It would be very interesting to get higher degree variations to study the compensation of the numerous volcanoes that are present on Venus. This could be the best achieved by gravity measurements in Venus atmosphere. Such measurements may be obtained by gradiometers onboard of balloons or airplanes that would fly into Venus' atmosphere.

Moon

Since the Russian Luna 10 mission in 1966, the gravity field of the Moon has been investigated. The best gravity field has been obtained thanks to the Lunar prospector mission that orbited the Moon on a circular orbit at 100 km from the surface in 1998. It was known that the Moon's shape is not in hydrostatic equilibrium and that several mass concentrations (mascon) existed on the near-side. The Lunar Prospector data revealed three new large mass concentrations (mascons) on the nearside of the moon beneath the impact basins Mare Humboldtianum, Mendel-Ryberg, and Schiller-Zucchius, where the latter basin has no visible mare fill. Although there is no direct measurement of the lunar far-side gravity, LP partially resolves four mascons in the large far-side basins of Hertzprung, Coulomb-Sarton, Freundlich-Sharonov, and Mare Moscoviense. The center of each of these basins contains a gravity maximum relative to the surrounding basin.

- 1 The improved normalized polar moment of inertia (0.3932 ± 0.0002) is consistent with an iron core with a radius of 220 to 450 kilometers depending on the density of the Moon's core that can contain more or less light elements.
- 2 An Airy isostasy model for the crust gives a value of 70 km. But large negative compensation depths are found for the lowland mascon basins. It shows that the Airy model cannot apply everywhere on the Moon.

In order to improve our knowledge of the Moon's internal structure, seismic data are required. Gradiometers in an orbiter may provide a good way of measuring the depth of the mass concentrations.

Mercury

Mercury is going to be observed by two missions in the next decade: the NASA mission Messenger and the ESA mission Bepi Colombo. The former one was launched in August 2004 and will be put in orbit around Mercury in 2011. The Bepi Colombo mission is supposed to be launched in 2011 with an orbit insertion in 2018. Mercury has been observed by Mariner 10 in March 1974 and March 1975 and the pictures have revealed a geological surface covered by impacts.

Models of the internal structure of Mercury have been developed based on the knowledge of the mass, magnetic field and understanding of heat sources and heat transfer (Stevenson et al., 1981) but there are many questions. The thickness of the mantle can vary between 450 and 750 km and that of the liquid iron core between 100 and 1600 km. Finally, the radius of the inner solid core can be anything between 0 and 1500 km.

From the model of the internal structure, we can compute the values of the moment of inertia and the value of J_2 . One surprising result is that the value of J_2 calculated for the different models is much smaller than the one measured by the Mariner flybys and reported in literature. The models give values of J_2 between 3.8 and $4.5 \cdot 10^{-6}$ for a wide range of density profiles. The value measured by Mariner is on the order of $6 \cdot 10^{-5}$, which is more than one order of magnitude larger. However, one must keep in mind that we have only a couple flybys to constrain Mercury's J_2 value. The next missions to Mercury should be able to answer those questions by measuring the magnetic field and the gravity field by LoS measurements. Based on these results the scientific objectives for a gravity gradiometer mission can be defined.

Jovian system

The Jovian system has been studied by the NASA mission Galileo between 1995 and 2000. One of the most important results is that the Galilean satellites (Io, Europa, Ganymede and Callisto) are differentiated. Models of the internal structure of these satellites have been developed recently based on interpretation of tectonics, magnetic field, and moment of inertia (J_2)

The main question that forthcoming missions must address is the presence of an ocean within Europa and the determination of its depth thickness and may be composition. Other issues include the characteristics of the core and the existence of volcanism in the silicate core. Europa has an eccentricity which is maintained thanks to the 1,2,4 Lagrange resonance between Io, Europa and Ganymede. The H₂O/silicate ratio of Europa is much smaller (density much larger) than that of the larger satellites Ganymede and Callisto. Also, Europa is quite close to Jupiter and models of tidal heating suggest that this is a major source of internal heating which may prevent the satellite from a complete freezing. Because Europa has an induced magnetic field and an active tectonics, it is supposed that it hides a deep ocean. The depth of this ocean is very much debated. It has been shown how the values of Love numbers k_5 and k_2 depend on the presence of an ocean, on the thickness of the ocean, and on the viscosity of the ice shell. As reported in TN2, the Love number k_2 varies from 0 (no ocean) to 0.4 (shallow depth ocean). This value could be measured if a probe orbits Europa. Such a probe is envisaged for a survey in 2020 in cooperation with NASA. Although LoS measurements could be performed, gravity gradients would also provide a good way to measuring Europa's gravity field

Kronian system

Saturn's system is being studied by the NASA/ESA Cassini-Huygens mission. Although no gravity data have yet been released, it is envisaged that Titan, Saturn's largest icy satellite, is differentiated. Titan is the only satellite that has a thick atmosphere. Such an atmosphere does not allow for a small altitude of probes. On the

other hand, it makes possible a mission with balloons and/or airplanes that could carry gradiometers in order to obtain good measurements of the gravity field.

Other planets

Future missions to asteroids and outer planets will address the question of the internal structure of these bodies.

Between Mars and Jupiter, several asteroids orbit around the Sun. Among those, Ceres and Vesta will be studied by the Dawn mission. Vesta is a dense asteroid and several meteorites (HED meteorites) are thought to come from this asteroid. Their study shows that they are differentiated. But this must be checked by future missions.

Other planets (Uranus, Neptune, Pluto) may be studied in the future. The New Horizons mission will study Pluto. No plan exists for either Uranus or Neptune.

3. Gravity-Gradient Sensor concepts and related technologies

In this chapter we describe our conclusions from the study concerning the gravity gradient sensor technology for future planetary missions. From the TN2 study, we use quite rough data as a necessary gravity gradient sensitivity of about $1 \text{ mE}/\sqrt{\text{Hz}}$. The height of the orbiter above the planet surface is crucial for the lateral resolving power. Higher order components of the gravity gradient tensor can be better studied at lower height.

We have shown that the sensitivity for a gravity gradient sensor is directly proportional to the factor $T/m\text{b}^2$, with T the temperature, m the test mass and b the base line of the system. A lower temperature, a higher test mass and a larger base line result in a better resolution. Small size gravity gradient sensor systems, as is the starting point for planetary missions, imply a reduced sensitivity. A lower T introduces the additional weight of the cooling system.

The noise contribution is determined by the mechanical noise and the sensor noise. We have shown that the mechanical resonance frequency is very important. This resonance frequency should be of the order of 40 mHz and force feedback has to be applied to make the system faster.

Apart from the gradient approach in one instrument we like to emphasize that the study of separate linked accelerometers is very worthwhile. In this case the base line can be increased considerably using a few or more simple accelerometers. This means formation flying of an array of small satellites. This is one of the main topics of the microsatellite program within MicroNed. This MISAT study will be executed by over 20 PhD students. The UT group will be heavily involved in this program.

We now summarize the results from our study on gravity sensor systems based on superconductivity, MEMS technology and atom interferometry. These results have been the outcome of TN3. In D4 we have designed a prototype gravity gradiometer based on a single wafer approach. We discuss this work in the MEMS-based systems in a section below. We also describe here the results from the comparison of gravity gradiometry and Line-of-Sight as was extensively discussed in D4.

Superconducting systems

In the low T_c approach we come to the conclusion that SGGM are possible as has also been shown in the practical examples. There are no constraints with respect to the technology. Readout with SQUIDs of sufficient sensitivity can be realized. Coils for levitation and appropriate superconducting joints are available. A gravity gradient resolution of the order of $1 \text{ mE}/\sqrt{\text{Hz}}$ can be realized with test masses of the order of 1 kg and a base line of 0.2 m. From the cooling description we see that these systems have a weight of the order of 100 kg.

If the research concerning MgB_2 has developed much further we believe that also here the realization of a system operating at about 35 K is possible. Most probably the total weight of such a system will be of the order of 10 kg.

In an earlier study we described a system based on high T_c materials. In this case a system with a sensitivity of a few $\text{mE}/\sqrt{\text{Hz}}$ using test masses of 0.5 kg each with a base

line of 0.1 m looks realizable although several practical issues have to be solved. The cooling system can be of the order of 1 kg.

MEMS-based systems

We can conclude that a micro-machined accelerometer with sensitivity in the order of 10^{-12} m/s² is extremely hard to obtain. We see that the noise floor is defined by the thermal motion of the proof mass, independent of the read-out mechanism, which can either be capacitive, optical or based on electron tunneling. Therefore, the proof mass should be as large as possible. Using thick silicon wafers a silicon proof mass size of 4 x 4 x 1 cm results in a mass of 37 gram. In that case very low damping in combination with electronic control of the spring constant and force feedback is needed. For a proof mass of 37 gram we have the following system parameters (the bandwidth is controlled by the loop gain in the force feedback loop): spring constant is $2 \cdot 10^{-3}$ N/m, quality factor is 100,000 and the mechanical resonance frequency 0.04 Hz.

For a hybrid design, i.e. with a separate proof mass attached to a silicon support and read-out structure, a much larger proof mass is possible. In that case a proof mass in the order of 100 to 200 gram should result in performance levels similar to the non-MEMS designs. The main advantage of using MEMS is then the high fabrication accuracy allowing very symmetrical structures and low off-axis sensitivity.

The performance of an array of sensors is defined by the total size of the proof mass. This may be an important advantage for using MEMS technology, since batch fabrication offers the possibility to fabricate many identical devices in a single fabrication run. For a total test mass of 100 g a stack of 20 100-mm wafers with accelerometer devices could be sufficient. Using modern 300-mm wafers only 2 or 3 wafers are sufficient. In this case one can also consider gravity gradient detection within the wafer.

We designed a prototype gravity gradiometer based on different single Si wafers. We used standard 100 mm-wafers with a thickness of 0.5 mm, a 100 mm wafer with the exceptional thickness of 10 mm, and a modern 300 mm-wafer with a thickness of 0.8 mm. The calculation results are very similar to the accelerometer ones. Also now we need a very low resonance frequency in order to have the sensor noise below the mechanical noise. We find a cross-over point at a frequency of about 0.04 Hz. Applying force feedback gives again the possibility of having sampling times of 1 second. We have shown that a gradient sensitivity of the order of 1 mE/ $\sqrt{\text{Hz}}$ is feasible.

In all cases, cooling down the proof mass and suspension structures offers the possibility to further reduce the noise-floor.

Laser cooled systems

Atom interferometry is a technology very promising for space instrumentation. A gravity gradiometer consists of two atom-interferometer accelerometers separated by a distance that is the baseline. The two acceleration measurements are performed simultaneously using the same Raman laser beams, so that the common mode noise and uncertainties are cancelled.

A sensor for gravity gradient based on atom interferometry could achieve a sensitivity below 1 mE/ $\sqrt{\text{Hz}}$ using 10s interrogation time. The technology is based on lasers and vacuum that is already well known and has proven to be reliable in space.

The limitations in size for the instrument will be determined mainly by the baseline. Vacuum chambers for the atom clouds could be of the order of 10 cm in diameter. It is believed that the total mass of the instrument could be some tens of kg. The interrogation time will be limited to about 11s to avoid the matter wave to travel more than 10cm. The absolute gravity value with this time should be $g < 10^{-4} \text{ m/s}^2$. That means that the instrument could not be proved on ground unless the interrogation times are reduced to some 10^{-3} s.

Both Cs and Rb atoms are used in laser cooled atom interferometry. We think that Rb atoms will be the final choice.

Comparison of Line-of-Sight and Gravity Gradient Sensing.

Based on literature we made a comparison between two missions investigating the Earth gravity field: GOCE and GRACE. GOCE will be equipped with a classical gravity gradiometer. GRACE, which was launched August 2002, consists of two satellites orbiting close after each other with a separation between 100 and 400km. By measuring the distance-variations between these two satellites, the gravity field can be retrieved. This method of gravity field retrieval is similar to the LoS-method, so the conclusions are useful for us. This comparison was made with the assumption that GRACE will stay in orbit for 5 years, whereas GOCE will be in orbit for 9 months.

The errors in the spherical harmonics of the gravity field recovered from the different missions are compared to each other and to Kaula's rule of thumb. Although the comparison is rather qualitative, it clearly shows the different behaviour for GG and LoS. LoS is better to determine the lower orders, whereas GG is good to determine the higher orders. The crossover point depends on the planet and the distance of the orbiter to the surface. The closer the satellite can orbit the planet the better local information can be obtained and we expect that the crossover point will shift to lower orders.

Because airplanes and balloons can get closer to the surface, even better results are to be expected from those types of missions, if the same sensor sensitivities can be reached for sensors on board of airplanes/balloons. The velocity of these vehicles will be much lower than that of the orbiter so higher order components of the gravity field can be obtained much more easily. The mapped area is then reduced so one has to choose a particular scientific object.

In general one can state that LoS and GG are complementary techniques and the combination of both techniques is a desirable approach for coming planetary missions.

4. R&D Program for Gravity-Gradient Sensors for planetary/lunar missions

In this chapter we propose a research program for gravity gradiometry. We distinguish two areas being:

- Program for the **planetary exploration**
- Program for **instrument development**

Program for planetary exploration

A better understanding of the internal structure of planets and satellites is the next step to planetary exploration. The atmosphere and surface properties of most planets and satellites have been largely studied and are pretty well known although there are always questions that need to be solved. But the internal structure is almost unknown for each planet and if we want to improve our knowledge of planet formation and evolution, it will become necessary to determine the present internal structure of planets and satellites. Seismic devices are difficult to implement although they have been proposed for Mars. Gravity field mapping is interesting because it may provide an easier way, or a complementary way, to determine the internal structure.

The next missions that are envisaged in the Cosmic vision program concern Europa and Mars. Further away, a new mission to Titan will be envisaged but one must digest the results that are being acquired by the Cassini mission before designing the next mission. We can also envisage missions to Venus. We have therefore three planets with atmospheres (Mars, Venus, Titan) and it would be interesting to investigate the possibility of having gradiometers onboard of automatic airplanes (UAV, unmanned aerial vehicles). Such tests could be performed on Earth in areas where gravity anomalies are known. Such a device could actually be interesting for the Earth itself. For Europa and the Moon, the only way is to set up the gradiometer onboard the orbiter.

Therefore we propose:

- for Europa, to build a gradiometer that would allow a better understanding of the domes and icy rafts that seem to float away from each other,
- for the Moon, the same exercise than for Europa could be set in order to better understand the mascons, especially on the far side which is poorly known.
- missions to Mars, Titan and Venus that would use airplanes
- to set up a program with people who can help us with flying drones
- to test the data acquired by gradiometers on balloons

Program for instrument development

We propose research in three different areas:

- gravity gradiometers based on MEMS and hybrid MEMS
- multi-sensor multi-satellites systems
- laser cooled atom interferometry

1) Development of a gravity gradiometer based on MEMS and hybrid MEMS technology

We have shown that the sensitivity of a gravity gradiometer is determined by the weight of the test masses, the base line, the operation temperature, the mechanical quality factor and operation frequency of the system. Also the readout of the displacement of the masses is crucial to obtain high sensitivity. We designed a prototype gradiometer using one single silicon wafer and we found moderate sensitivity in case of sampling times of 1 second. We showed that this sensitivity can be improved by lowering the resonance frequency. Even the range of a few $\text{mE}/\sqrt{\text{Hz}}$ is feasible. The sensitivity can also be improved by choosing larger wafer sizes in order to increase the base line. Furthermore the sensitivity can be improved by applying hybrid MEMS technology, where an additional test mass is attached to the membrane mass. We believe that such a gravity gradiometer is a very promising instrument for future planetary missions.

We propose to set up a development program for designing, fabrication and testing of micro-machined gravity gradiometers based on MEMS and hybrid MEMS technology. The study should include all the relevant parameters mentioned above. Attention has to be paid to various approaches to realize very weak springs and also to the use of floating masses. The readout can be performed capacitively and then attention has to be paid to the materials for the electrodes, studying charge trapping by capacitance –voltage measurements and time effects. The readout electronics can be finally integrated on the silicon wafer. This item is already extensively discussed with SRON (Utrecht). Also alternative readout techniques as interferometry have to be considered.

A spin off of the project are accelerometers and seismometers. The latter devices can be used at the surface of the planet.

In first instance we consider the gravity gradiometer instrument placed in an orbiter. We also emphasize that the instrument can be placed in an aerial vehicle to come closer to the surface of the planet.

A part of the above program will be financed in the microsatellite (MISAT) program of MicroNed. Unfortunately the MISAT financing for fabrication is rather limited and the project would certainly benefit from an additional funding by ESA.

Gravity Gradiometry using Micro System Technology has been selected as one of the two important instrument developments for coming space missions by the National Platform Planet research in The Netherlands. A possible mission could be ExoMars but it is questionable if the development of a space qualified instrument can be performed in that limited time schedule. A later mission or the Mars Sample Return mission can be appropriate.

2) Study of multi-sensor multi-satellite systems

Formation flying and multiple sensor actuator systems is one of the main research topics within the MISAT program of MicroNed. Within this program a project has been granted being multi-sensor multi-satellite systems. The sensing functions of the units of the formation are distance, gravity and magnetic field sensing. The constellation of the flying formation will also be considered in order to obtain optimal information about gravity and magnetic field mapping.

The gravity sensing will be performed by accelerometers that are quite similar to the gravity gradiometer systems as mentioned in the research program described above. The information will be coupled with the distance sensing data.

For magnetic field sensing we will investigate miniaturized flux gate sensors in planar technology, GMR-based sensors (possible in seesaw MEMS) and techniques based on high T_c superconductivity.

The first phase of this project will be financed by the MicroNed program but again this is a limited amount of money and the program would benefit from additional ESA support.

3) Laser cooled atom interferometry

We described atom interferometry as a technology which is very promising for space instrumentation. It is feasible that a sensitivity of a few mE/√Hz can be reached using interrogation times of 10 seconds. The limitations in size will be mainly determined by the baseline. Vacuum chambers for the atom clouds could be of the order of 10 cm. It is believed that the mass of the instrument could be some tens of kg.

A research program for a study for applying atom interferometry for future planetary missions is advised.