SP-1196 (5)

REPORTS FOR ASSESSMENT

THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Magnetometry Mission

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THE NINE CANDIDATE EARTH EXPLORER MISSIONS

Magnetometry Mission

ESA SP-1196 (5) – The Nine Candidate Earth Explorer Missions –
MAGNETOMETRY MISSION

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1. Introduction

For the post-2000 time frame two general classes of Earth Observation missions have been identified to address user requirements, namely:

> **Earth Explorer Missions** - these are research/demonstration missions with the emphasis on advancing understanding of the different processes which help govern the Earth system. The demonstration of specific new observing techniques also comes under this category.
>
> **Earth Watch Missions** - these are pre-operational missions addressing the requirements of specific application areas in Earth Observation. The responsibility for such missions would be transferred eventually to operational (European) entities and to the private sector.

Nine Earth Explorer missions have been identified as potential candidates for Phase A study and a Report for Assessment has been produced for each of these candidate missions.

This particular Report for Assessment is concerned with the Earth Explorer Magnetometry Mission. It has been prepared by one of the nine Mission Working Groups that have been established to produce these Reports. The four (external non-ESA) members of this particular Group are J. Achache (BRGM, Orléans, France), D. Barraclough (BGS, Edinburgh, UK), E. Friis-Christensen (DMI, Copenhagen, Denmark) and G. Musmann (TUB, Braunschweig, Germany). They were supported by members of the Agency who advised on technical aspects and took the lead in drafting technical/programmatic sections. This report, together with those for the other eight candidate Earth Explorer Missions, is being circulated amongst the Earth Observation research community in anticipation of a Workshop to be held in Spain in May 1996.

The aim of the Magnetometry Mission is to provide continuous monitoring of the magnetic field near the Earth, in particular the part that originates within the Earth's core (the 'main field' and 'secular variation') and the contribution of electric currents in the ionosphere and the magnetosphere (the 'external fields'), together with a determination of the long-wavelength part of the lithospheric magnetic anomaly field. It would contribute to the correction of major deficiencies in our knowledge and understanding of the core structure and motion. The mission would also provide data needed to help realise the objectives of the Studies of the Earth's Deep Interior (SEDI) and of the International Solar-Terrestrial Physics(ISTP) programme and to revise global field models such as the International Geomagnetic Reference Field (IGRF). It would achieve this by means of a) a relatively high-altitude satellite to monitor, over a complete solar cycle, the main field and its secular variation, and the external fields and b) a low-altitude satellite measuring the lithospheric anomaly field.

All the Reports for Assessment follow a common general structure comprising seven chapters. They each start by addressing the scientific justification for a particular mission and move on to detail its specific objectives. This is followed by a detailing of the specification of observation requirements and a listing of the various mission elements required to satisfy the observational requirements. Then consideration is given to the implications of meeting the observational requirements in terms of both the space and ground segment as well as requisite advances in scientific algorithms and processing/assimilation techniques. Finally programmatic aspects are considered.

2. Background and Scientific Justification

2.1. Introduction

Magnetic fields are present everywhere in the Universe and it has been known since 1601, when William Gilbert published the first modern scientific monograph 'De Magnete', that the Earth behaves like a very large magnet. Speculations about the causes of the geomagnetic field have been many and diverse but modern studies have converged on the idea that the major part of the field is produced by electric currents through some form of self-sustaining dynamo operating in the fluid outer core of the Earth (see Figures 2.1 and 2.2). The field produced by the dynamo changes with time, usually rather slowly and steadily, and this is known as the secular variation.

Figure 2.1. The Earth's internal structure. At this scale the outer layer of rock (the crust) cannot be depicted. The mantle is solid on short time scales but convects over geological time. The outer core consists of an electrically conducting fluid and is where the main geomagnetic field is generated. The inner core is solid. (From Bloxham & Gubbins, 1989).

What we measure at or near the surface of the Earth is, however, a composite of this main field and fields caused by the differing magnetisations in the Earth's lithosphere including the upper mantle and the outermost part of the Earth, the crust. Another component of the measured magnetic fields has its origin in electric currents flowing in the conducting part of the atmosphere and in the magnetosphere (see Figure 2.3), and in currents induced in the Earth by these time-varying external fields.

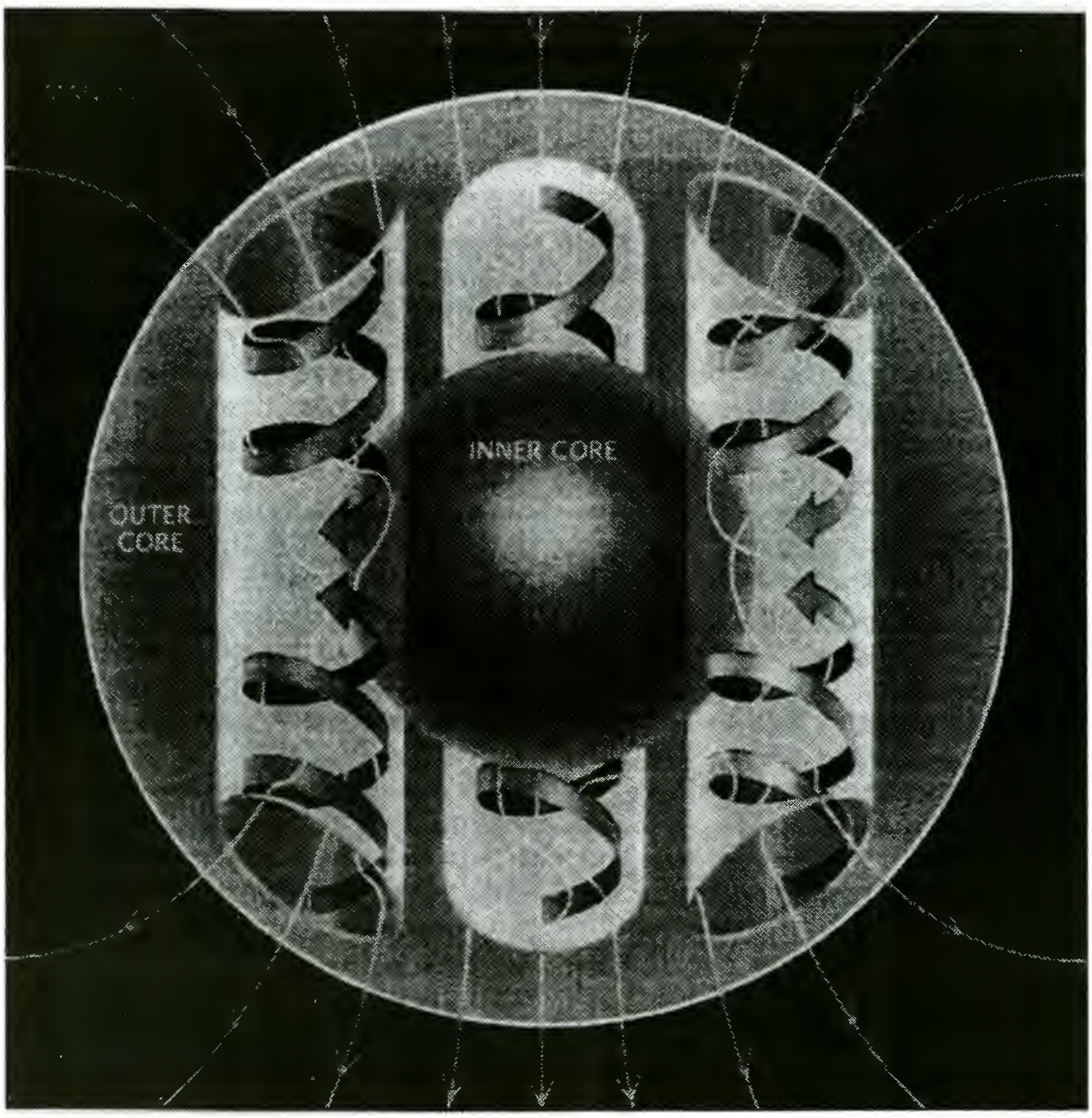


Figure 2.2. *Sketch of possible flow patterns of the fluid in the outer core that could generate the main geomagnetic field. (From Bloxham & Gubbins, 1989).*

Measurements of the geomagnetic field from a satellite may - at first glance - be regarded as in situ measurements. In reality, however, the real value of magnetic measurements is associated with the possibility of interpreting them in terms of their sources. In this respect, therefore, the Magnetometry Mission may be regarded as a remote-sensing mission. The benefit and the challenge of the mission are related to the sophisticated separation of these various sources which each have their specific characteristics in terms of spatial and time variations. *Few other measurements, if any, of a single physical parameter can be used for such a variety of studies related to the Earth, its formation, its dynamics and its environment, stretching all the way to the ultimate source of life on Earth, namely the Sun.*

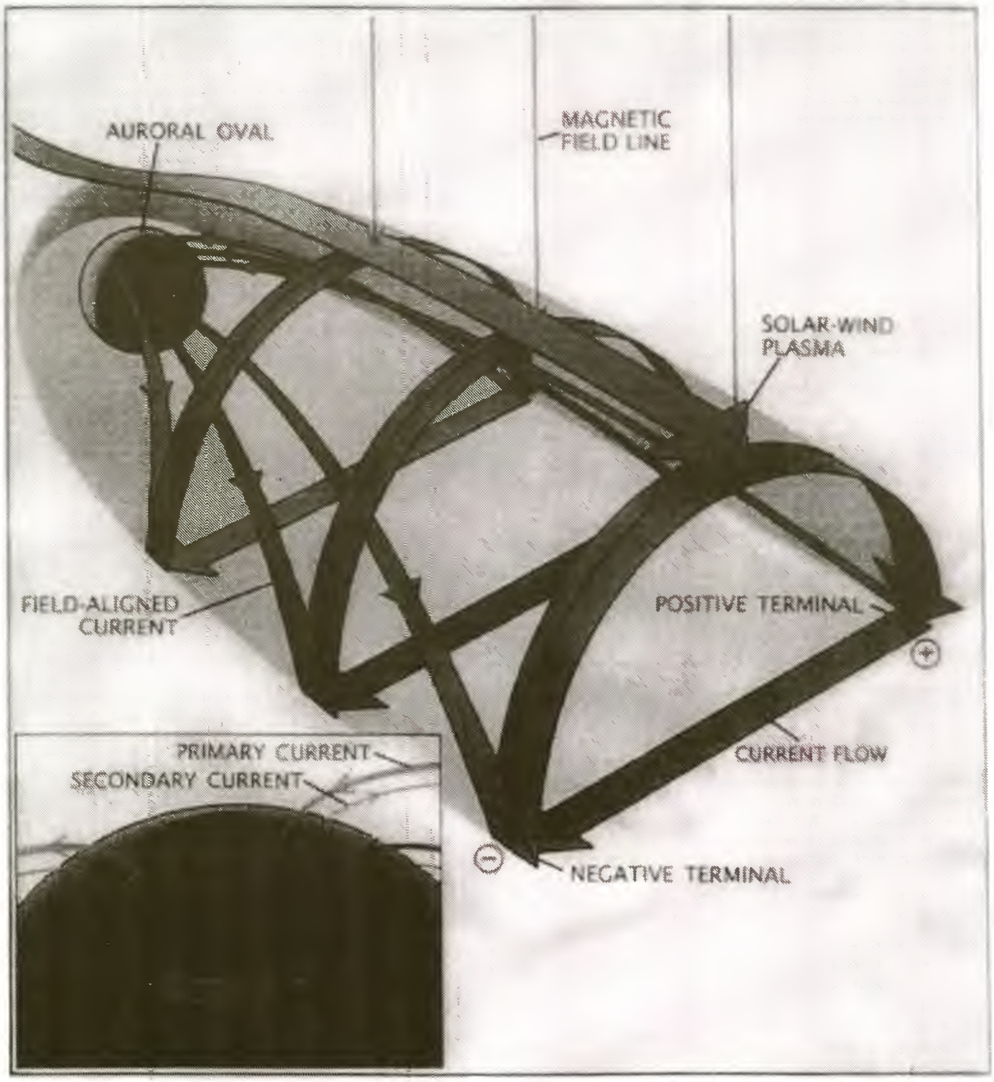


Figure 2.3. *The Earth's magnetosphere. (From Akasofu, 1989).*

The geomagnetic field is, however, not only an issue related to scientific research regarding its origin and related scientific questions regarding the evolution of our planet Earth. It is, in fact, of primary importance for the external environment of the Earth through its role in controlling the radiation belts, and its control of energy and momentum transport from the solar wind to the Earth including near-Earth effects like induced surges in long power lines. Numerous reported, but still poorly understood, correlations between various solar activity parameters and climate variations have recently been related to the flux of high-energy cosmic ray particles from Space and from the Sun. The motion of these charged particles is controlled by the magnetic fields, both the heliospheric magnetic field and the geomagnetic field.

For a number of these reasons an Magnetometry Mission has been part of the ESA Research Objectives for Earth Observation as demonstrated by the proposed Aristoteles gravity and magnetometry mission, which devoted an impressive effort to the investigation of the main field and of the crustal and external fields. The magnetometry part of the mission was so important that it justified orbit altitude and inclination changes. The Aristoteles mission did not happen. The objectives and requirements remain, only now they are more acute.

The 1991 Earth Observation User Consultation meeting insisted on the need for Aristoteles within the frame of the Agency's objectives for Solid Earth research and outlined the requirements for the continuity , namely: the investigation of issues related to the secular variation of the main field by means of Geomagnetic Space Observatories (GSOs) and the investigation of electromagnetic activity possibly associated with earthquakes.

With the decreasing probability of the Aristoteles mission several national initiatives have been promoted to remedy the unsatisfactory situation of a prolonged time span without adequately updated geomagnetic field values and hence a decreased reliability of the geomagnetic field models for use in various research and application areas. The national initiatives undertaken after the demise of the Aristoteles mission, such as the planned Ørsted, Catastrophes and Hazard Monitoring and Prediction (CHAMP) and Satellite de Aplicaciones Cientificas (SAC-C) missions, do not fully meet the Aristoteles objectives, specified by the users at the 1991 and 1994 meetings and restated by the Agency. Of these missions, only the Ørsted satellite (launch planned for March 1997) is solely dedicated to magnetometry measurements. The other two planned missions carrying high-precision magnetic instruments (the German CHAMP and the Argentine satellite SAC-C) are both planned to be launched in 1999 and will have additional science objectives. These initiatives would contribute, together with the Magnetometry Mission, to providing a minimum overall duration of observation time to investigate the secular variation of the main field. These missions will not, however, be sufficient in duration or accuracy and they will not address the objectives related to lithospheric and ionospheric sources.

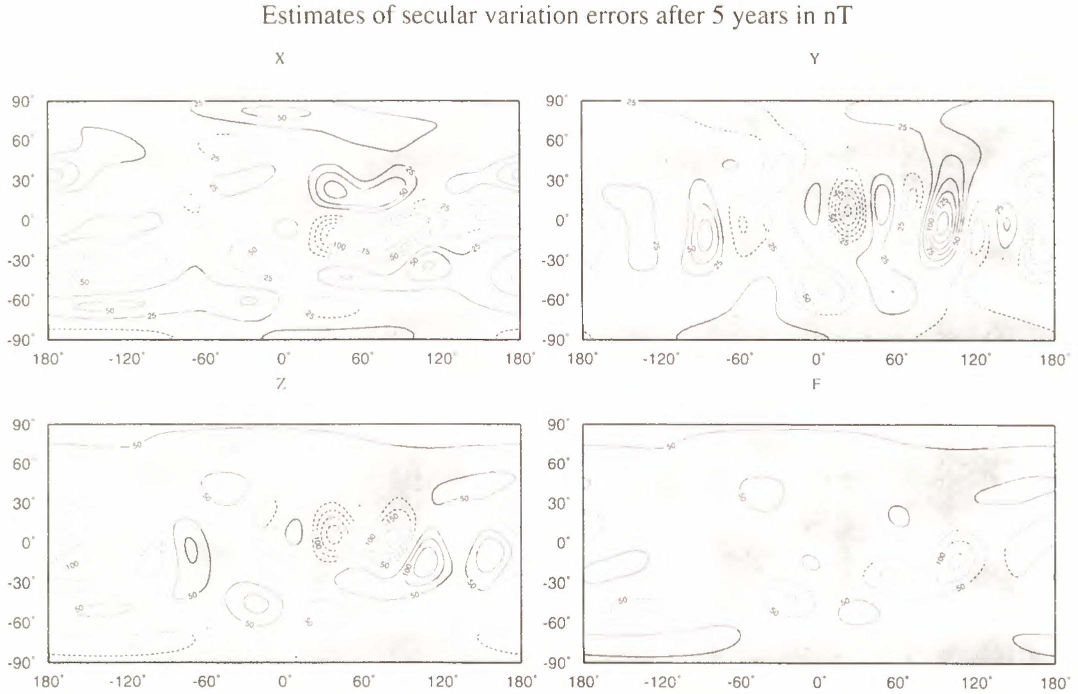
2.2. Main Field and Secular Variation

2.2.1. The Context and Role of the Magnetometry Mission

The main field and, in particular, its secular variation are among the very few means that are available to us for probing the properties of the Earth's outer core and how these change with time. The Magnetometry Mission's primary objective must be to derive an accurate model of the main field and its secular variation. The first comprehensive and accurate magnetic surveys were made by the COSMOS-49 and Polar Orbiting Geophysical Observatory (POGO) flights over the period 1964-1971 recording only the scalar value of the field. While adding vastly to our knowledge of the models at that time, they required surface vector data to correct weaknesses in the resulting models at lower latitudes. Magsat (see Langel et al., 1982), which made geomagnetic observations during late 1979 and the first half of 1980, has been the only satellite so far to have succeeded in measuring the direction of the field with the accuracy needed to produce the high quality vector data needed for global main-field modelling. Magsat was not, however, operational for long enough to provide much information about the secular variation. An abrupt change in the field (a jerk, see Section 2.2.2) also occurred at about this time (1978) and this exacerbates the problem of deriving secular variation information from such a short time series. The main-field models derived using Magsat data therefore provide us with a snapshot of the geomagnetic field at about 1980. These models are the most accurate descriptions that we have of the geomagnetic main field at one particular time.

Because there has been no comparable satellite geomagnetic survey since Magsat, the quality of available main-field information and models has declined over the past fifteen years. We have had to rely very largely on data from the network of magnetic observatories to help us describe and attempt to predict the secular variation and this data set has a notoriously patchy distribution over the surface of the Earth. In regions remote from magnetic observatories the uncertainties in current field models are unacceptably high (they can reach 1° or more in the field direction and several hundred nanoTeslas in field strength) for many uses to which the models are put. For example, almost all the work on recent core motions has been based on Magsat data. Because of their poor distribution and reduced accuracy there has been very little use, for these purposes, of the data that have been collected since 1980.

The errors that can arise because of the difficulties in predicting the secular variation on the basis of data from the poorly distributed network of fixed magnetic observatories are illustrated in Figure 2.4. The four maps show contours of the differences between two recent secular variation models for the same epoch multiplied by five to give an estimate of the errors caused by secular variation uncertainties after five years. The maps are for the north (X), east (Y) and vertical (Z) components of the geomagnetic field and for its total intensity (F).


Estimates of secular variation errors after 5 years in nT

X

Y

Z

F

Figure 2.4. Contours of the differences between two recent secular variation models for the same epoch multiplied by five to give an estimate of the errors caused by secular variation uncertainties after five years. The maps are for the north (X), east (Y) and vertical (Z) components of the geomagnetic field and for its total intensity (F).

The Danish satellite Ørsted, due to be launched in Spring 1997, is planned to provide global vector measurements of the geomagnetic field of even higher accuracy than those from Magsat. It is designed to have an operational lifetime of 14 months and so will give more information about the secular variation than did Magsat. It will also be possible to derive the overall changes in the geomagnetic field since 1980 by comparing models produced from Magsat and Ørsted data. Because of the global coverage of satellite data, these secular-variation models will be more detailed than past and present models can be.

Unless other satellites carry on where Ørsted leaves off, however, we shall soon revert to our present position of having to rely on poorly distributed data of inferior quality. There are other geophysical research satellites in the planning stage carrying magnetic field experiments (SAC-C and CHAMP, for example). These may overlap with Ørsted and continue the surveying work until about the turn of the century. However, if we are to meet the requirement of continuous monitoring of the geomagnetic field from space, it is imperative that another satellite mission providing high quality vector data, such as the Earth Explorer mission under discussion here, be launched as soon as possible after 2000.

2.2.2. The Issues of Interest: the Areas of Research

Core flow, Earth Rotation and Core-Mantle Coupling

The core is a highly conductive medium (conductivity = 10^5 - 10^6 Sm^{-1}) where convection takes place with characteristic velocities of a few kilometres per year (five orders of magnitude larger than plate velocities). Large electric currents are driven in the core by a self-sustaining dynamo process: fluid flowing across magnetic lines of force of the field generates electromagnetic forces which drive electric currents which maintain the magnetic field.

On time scales shorter than about a century the core may be considered as a perfect conductor. The main consequence of this is that the geomagnetic field appears to be frozen into the material in the core. Thus, the magnetic lines of force are advected by the flow of the fluid core material. Because of the skin-effect associated with the high electrical conductivity, such magnetic variations generated at depth in the core are not observed outside the core. Consequently, temporal variations of the main geomagnetic field observed at the surface of the Earth, namely the secular variation, directly reflect the fluid flow in the outermost layer of the core. These boundary conditions, which can only be studied using observations of the geomagnetic field and its secular variation, may then be used to infer the kinematics of the flow in the bulk of the core. Due to the non-uniqueness of the problem, this requires additional assumptions. The secular variation provides a unique observational constraint on dynamo theory and the geodynamo mechanism.

The Earth's rotation presents irregularities with different time scales: fluctuations of the Length Of Day (LOD) with time constants from a few days to a few decades are superimposed on a quasi-linear increasing trend. The long term deceleration is due to braking of the Earth's rotation by tidal forces: its rate is well known from the study of the evolution of the Earth-Moon system and is of the order of 2 ms per century. The shorter-term fluctuations may be split into three parts: a low-frequency variation, a seasonal oscillation and remaining irregularities in the range of a few days to a few years. The seasonal oscillation and irregularities have been convincingly attributed to exchanges of angular momentum with the atmosphere and, in particular, associated with the 1982-83 El Niño/Southern Oscillation event. The low-frequency variation has to be attributed mainly to the exchange of angular momentum between the mantle and the core: no other angular momentum sink is big enough to account for it.

The coupling mechanism between the core and the mantle, although it has been studied for forty years, is still a controversial question. It is of fundamental importance for understanding the decadal variations of the length of day and, to a lesser extent, the motion of the pole (e.g. the Chandler wobble). It is also of primary importance in some dynamo theories where core-mantle coupling is called upon to resolve the indeterminacy of the geostrophic part of the flow. The mechanism of this coupling is, however, not yet definitely elucidated : is the torque coupling the mantle and the core electromagnetic, topographic, or gravitational? The discussion of electromagnetic coupling raises the question of electrical conductivity in the mantle. The discussion of topographic coupling raises the question of core-mantle boundary topography.

It is clear that the strength of the electromagnetic coupling depends on the conductivity profile of the mantle, especially of its deep layers. If we accept the current estimates of this parameter, which have been buttressed by recent high pressure experiments, electromagnetic coupling is not strong enough to account for LOD decade changes. However, the large uncertainties in mantle conductivity values (in particular, that of the D'' layer) as well as the inaccuracy of the estimates of the flow at the core-mantle boundary based on current secular variation data prevent this mechanism from being definitely ruled out.

The second mechanism invoked for core-mantle coupling is topographic coupling resulting from the interaction between the flow in the core and bumps on the core-mantle boundary, if this topography shows departures from axisymmetry. Topographic coupling has been the object of renewed interest since seismologists have attempted to determine the core-mantle topography using travel times of body waves and free oscillations. Geoid anomalies and Earth nutation data have also been used to tackle this problem. The computed topographies are by no means definitive, and large discrepancies still exist between the models proposed by different authors. If the topography is as large as proposed by seismologists (up to 5 km in some models), simple order of magnitude computations show that the torque applied by the core flow is two orders of magnitude larger than the torque on the mantle needed to explain the fluctuations of the length of day, for recent times. Several explanations can be proposed to account for this discrepancy. (I) the topographic torque is nearly balanced by an opposed torque exerted by body forces (gravity or Lorentz forces); (ii) the topography (h) is much smaller than proposed by seismologists (the uncertainty in the estimate of h makes this hypothesis plausible); (iii) most of the topography does not interact with this flow; (iv) order of magnitude estimates based on preliminary estimates of the flow at the core-mantle-boundary are grossly in error.

To tackle this problem, one has to have an accurate determination of the flow of the fluid in the core. As shown above, only geomagnetic studies can provide the necessary information and this requires accurate knowledge of the secular variation which can only be achieved by repeated satellite observations.

Geomagnetic Jerks and Mantle Conductivity

There are two ways of determining the electrical conductivity of the mantle. It can be probed 'from below' using signals originating in the upper core and observed at the surface. This method requires a precise determination of the field, during rapid and isolated events such as geomagnetic jerks. It also requires some a priori assumptions about the kinematics of fluid motion at the top of the core. Although the secular variation usually represents smooth time changes of the main field, episodes of much more abrupt change have occurred in the past. These are known as impulses or jerks (see Figure 2.5 and Courtillot & Le Mouël, 1984).

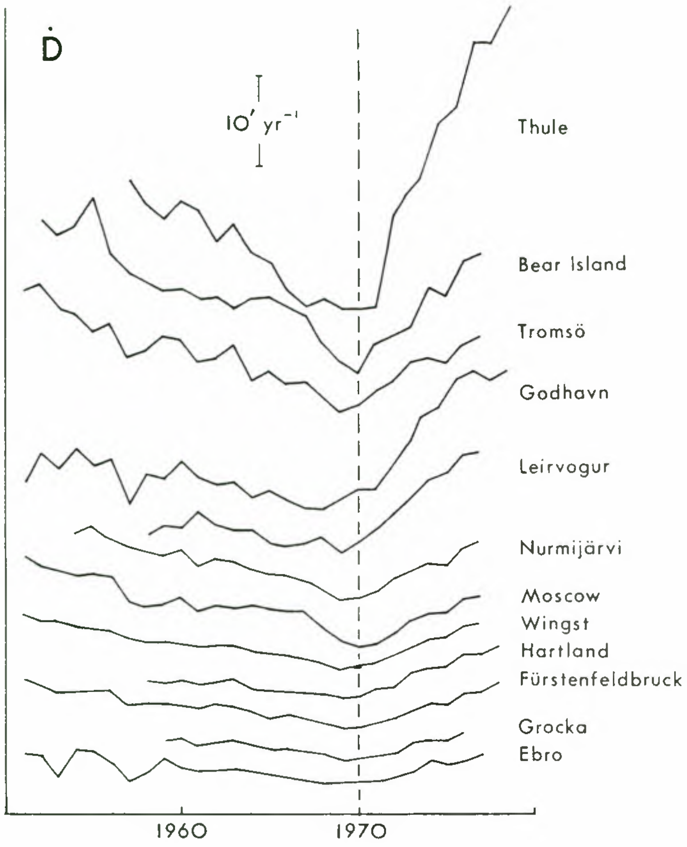


Figure 2.5. *The secular variation in the declination showing a sudden increase in slope (a jerk) at about 1970 for observatories in Greenland and Europe. (From Malin et al., 1983).*

There have been four, or possibly six, such events this century, irregularly spaced in time. They appear to be discontinuities in the second time derivative of the field (the secular acceleration), and they are global in scale.

A typical jerk occurs rapidly (typical frequencies lie between about 1 and 10 cycles per year) and the conducting mantle alters the amplitude and frequency content of what is observed at the Earth's surface and from satellite altitudes by acting as a sort of filter (Backus, 1983). It is only just possible to apply this mantle filter theory to the sparsely distributed data that are currently available from the network of magnetic observatories but, as with all global phenomena, jerks must be studied with a data set that is as uniform and dense as possible in its coverage of the Earth. A combination of ground-based observatory data plus data from the Magnetometry Mission is an approach to this ideal situation and the improvement in our knowledge of the time scales involved will help to refine our estimates of the electrical conductivity of the lower mantle.

Electromagnetic Tomography of the Upper Mantle

Mantle conductivity can also be probed 'from the top' by the analysis of the external and internal (induced) parts of the field at various frequencies. The latter method requires a good knowledge of the time dependence of the field. If measurements are performed for one 11-year solar cycle, it will be possible to obtain the conductivity of the middle and lower mantle without making prior assumptions, such as required in the method 'from below'.

Satellite data typically sample signal periods extending from a few minutes to many months. This encompasses daily variations, broad-band magnetic-storm-related variations between latitudes 45°N and 45°S, auroral substorms at higher latitudes, and pulsations at all latitudes. Because ionospheric current systems will generally be found between the satellite and the Earth's surface, one has to account for these intervening sources in the data analysis. This problem should be explicitly treated as a joint generalized inversion, where both satellite and ground-based data are used to solve simultaneously for the distribution of primary current sources in space and for the induced secondary sources in the solid Earth. The latter, of course, leads to the conductivity as a function of depth and, with refined modelling, to lateral variations in that conductivity.

2.2.3. Conclusion

For all these studies and related applications, accurate and up-to-date global models of the main geomagnetic field and its secular variation are essential. Since the models are global and should have uniform accuracy (in other words, uncertainties that vary little from place to place), the data on which they are based must have a global distribution that is as uniform and dense as possible in terms of accuracy and coverage.

This immediately suggests using a satellite in a polar or near-polar orbit as the data collecting platform and several global magnetic surveys have indeed been performed using satellites over the past thirty years or so. With one exception, however, these have all involved measurements of the strength of the geomagnetic field only and not its direction. Although much information can be derived from such total intensity surveys, geomagnetic field models based solely on total intensity data have serious defects, particularly in equatorial regions. This effect (the Backus or perpendicular-error effect, Backus, 1970; Lowes, 1975) arises because the geomagnetic field at low latitudes is almost entirely horizontal. Observations of the total intensity of the field alone do not, therefore, constrain the vertical component of the field strongly enough and models derived entirely from such observations have significant errors in this component in equatorial regions as demonstrated in Figure 2.6.

The Magnetometry Mission, providing both directional and intensity data of high accuracy, is thus essential if main-field models are to achieve acceptable accuracies over the whole Earth. In order to derive accurate secular variation models and to make significant progress towards solving the problems of separating the effects of core, lithospheric and external fields it is essential to have data spanning a full solar cycle. It is therefore very important that the Magnetometry Mission be designed such that it contributes to continuous observations of the geomagnetic field during a complete sunspot cycle of about eleven years so that there will be an adequate number of intervals when quiet time observations are available and so that the effects of external fields and their variation over a complete cycle can be studied and, where possible, allowed for.

In considering the timing of the mission it is also important to consider the phase of the sunspot cycle. The next sunspot maximum is expected to occur towards the end of 2000. A mission starting a year or so after the start of the new millennium will therefore be making measurements during the early part of the declining phase of the cycle, and this is when many forms of magnetic disturbance have their maximum incidence. This may well be advantageous in studies of the effects of external fields, but it is likely to present additional problems for those studying the main field and those trying to separate out the crustal field.

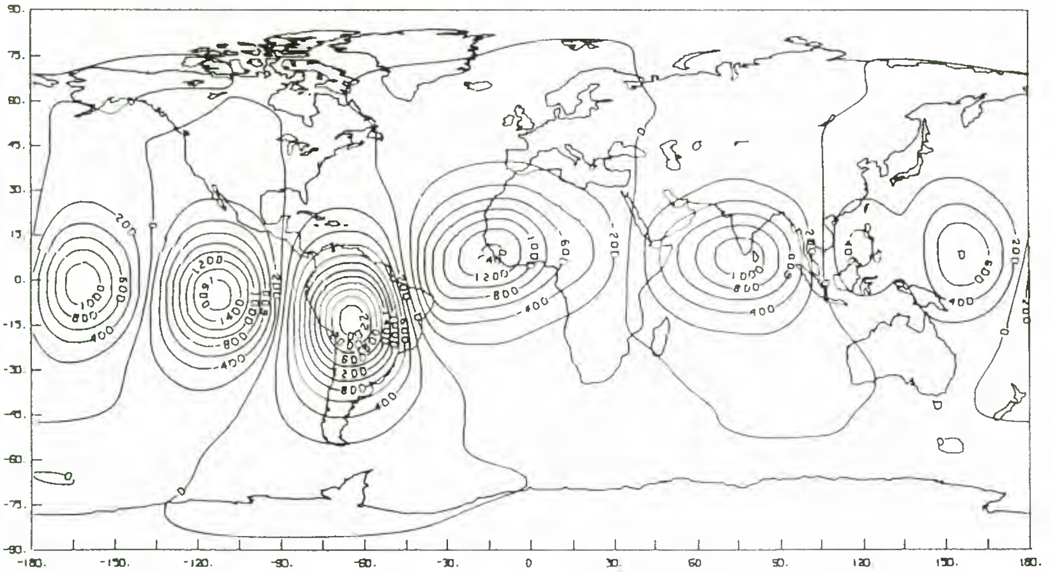


Figure 2.6. The difference in the radial component of the geomagnetic field at the Earth's surface as computed from a model based on Magsat vector data and one based only on Magsat total intensity data. The contour interval is 200 nT. (From Stern et al., 1980).

The availability of high accuracy main-field and secular-variation models on a more-or-less continuous basis from early 1997 (the expected launch of Ørsted) until about 2010 will have far-reaching implications for studies of the interior of the Earth. We might reasonably expect a jerk to occur sometime during this interval. If this does happen, the availability of global observations before, during and after its occurrence should enable us to identify precisely what is happening to the field and thereby to the core during such events. The speed with which the jerk occurs should also be estimated more accurately than for previous jerks and this should help to refine further our estimates of lower-mantle electrical conductivity. This great improvement in our understanding of the fluid motions near the surface of the core, together with the more accurate lower-mantle conductivity estimates, will enable us to make progress with the problem of core-mantle coupling and the precise details of how it excites changes in the length of day and motion of the pole.

2.3. Lithospheric Anomaly Field

2.3.1. The context and Role of the Magnetometry Mission

Plate tectonics satisfactorily describes the first order structure and evolution of the Earth's lithosphere in particular for oceanic plates. By contrast, the history and thermomechanical properties of the continental lithosphere still remain, in many respects, enigmatic. Deformation in the vicinity of intra-continental plate boundaries (e.g., the Alpine-Himalayan belt, the Mediterranean area, the Caucasus, Afar) is far from rigid and is not confined to plate boundaries. The deep structure of the lithosphere below continents is not well known, nor is its relationship with surface tectonics: underplating and delamination below collision mountain belts and high plateaus, or thinning and thickening below sedimentary basins and rifts.

The lithospheric magnetic anomaly field is produced by spatial variations of the magnetisation carried by rocks in the upper layers of the Earth. This magnetisation is partly induced by the ambient field, and therefore proportional to this field and to the susceptibility of the rock. It can also be a remanent magnetisation acquired during the formation of the rock. Remanent magnetisation is characterised by blocking temperatures which may range from a few hundred degrees up to the Curie temperature. This magnetisation may also be reset after the formation of the rock by thermal or chemical alteration. In that sense, remanent magnetisation is a good recorder of any metamorphic, chemical or mechanical event in the past history of a rock.

Indeed, the remanent magnetisation of crustal rocks provides constraints on growth and evolution mechanisms of the Earth's crust. This parameter has allowed geophysicist to demonstrate the concept of continental drift in the 1950's and that of sea-floor spreading in the 1960's. It was, therefore, instrumental in establishing the theory of Plate Tectonics. It is still widely used today to study intra-plate deformation and mountain-building processes as well as oceanic features, e.g. seamounts. As a rule of thumb, remanent magnetisation is considered to be dominant in the upper ten kilometres of the crust. It is also considered to change on a characteristic horizontal scale of a few tens of kilometres (the typical size of a geological formation). One major exception is the Cretaceous Quiet Zone (CQZ) which contains the oceanic crust formed during a period when the Earth's magnetic field displayed no reversal for 30 million years (Ma). The CQZ is thus characterised by a uniform remanent magnetisation extending over thousands of kilometres. Apart from these areas, remanent magnetisation in the crust will, therefore, have little or no expression in the longer wavelengths of the anomaly field which can be measured from satellites.

On the contrary, induced magnetisation is likely to be the dominant type of magnetisation in the deeper layers of the crust (the granulite facies) as well as in the upper mantle. In this case, it has been shown to be predominantly associated with the presence of magnetite, which has a Curie temperature of 578°C. Therefore, the distribution of induced magnetisation in these rocks depends on gradually changing in situ parameters such as mineralogical composition (magnetite content) or in situ temperature and pressure conditions. In particular, magnetisation vanishes above the Curie temperature. Therefore, induced magnetisation at depth in the lithosphere will contribute significantly to broader scale anomalies. The longer wavelengths of the geomagnetic anomaly field (often referred to as the lithospheric anomaly field) which can be best recovered from satellite measurements will then contribute to our understanding of the deep crust and the upper mantle of the lithosphere where induced magnetisation prevails.

Observations of the induced field can help to delineate the composite structure of the old crystalline basement underlying most continental areas and to investigate the chemical and thermal evolution of the continental lithosphere associated with major geodynamical processes such as collision, mountain building, erosion, sedimentation, basin formation and rifting. The investigation of the deep structure of the continental crust is not only of interest for geodynamical studies but is also strongly fostered today by the growing need to prospect for mineral resources at ever greater depths.

Understanding the distribution of magnetisation in the lithosphere requires a comprehensive description of the geomagnetic field over its full spectrum. First of all, since the major source of magnetisation at depth is induced, an accurate knowledge of the main (inducing) field is required for proper modelling of the induced lithospheric anomaly field. It is also required for achieving a proper separation of the lithospheric anomaly field from the core field. The geomagnetic field spectrum derived by Langel and Estes (1982) has formed the basis for the separation of the core and lithospheric contributions to the magnetic field of internal origin. This spectrum exhibits a distinct change of slope near degree $n = 14$ which suggests that the core field is best represented by a spherical harmonic series up to degree and order 13. The residual anomaly field is obtained by subtracting this model from the observed field. Yet, as discussed by several authors, this method, when applied to Magsat data, did not achieve a complete separation and further processing was required to isolate the field associated with lithospheric sources, as well as the core field. At Magsat altitude, the anomaly field is of comparable amplitude to that of the shortest wavelengths of the core field (near $n = 13$). With measurements performed at a lower altitude, the "lithospheric to core ratio" below $n = 13$ will be larger and thus allow for a better determination of the longer wavelengths of the lithospheric field.

The separation problem is further complicated by the fact that, as seen from a satellite, the ionospheric field, whose sources are located at 110 kilometres altitude, behaves as an 'internal' field. In this respect, the Magsat mission, with a dawn-dusk Sun-synchronous orbit, was particularly poorly suited for this separation. Indeed, ionospheric currents are driven by thermal effects and are therefore predominantly located in the sunlit hemisphere of the Earth. The dawn-dusk terminator where Magsat measurements of the field were performed is then a domain of singular behaviour of these currents. The Ørsted mission, for example, will overcome this problem by providing measurements of the fields at almost all local times. It will however be flown at too high an altitude to provide useful measurements to improve our knowledge of the lithospheric anomaly field and a low-altitude (less than 250 km) non-sun-synchronous mission is still highly necessary. A low-altitude satellite still faces the problem of separating the lithospheric and the ionospheric sources. In fact, the signal from the ionospheric sources will increase more than the signal from the lithospheric sources compared with observations from higher altitudes. This calls for an increased quality of the modelling of the ionospheric currents based on an improved understanding of the external current systems as discussed in Section 2.4.

2.3.2. The Issues of Interest: the Areas of Research

Concerning the lithospheric anomaly field, the research objectives can be grouped in two broad categories. The first aims at improving the determination of the anomaly field at all wavelengths. The second deals with the use of the lithospheric anomaly field for improving our understanding of the structure of the lithosphere.

Determination of the Lithospheric Anomaly Field

The energy density spectrum of the lithospheric anomaly field appears to be almost white down to very low harmonic degrees, corresponding to anomaly wavelengths of the order of the characteristic size of continents. Since, in the spectral band n = 4-11, the amplitude of the core (main) field is significantly larger than any other field, one should not expect to be able to determine either the ionospheric or the lithospheric contributions to the geomagnetic field in this band. Above $n = 11$, however, a Magnetometry Mission, which will perform measurements at two different altitudes with extended lifetime and good coverage of local times will provide a more accurate determination of the field and will help us to separate the three major components of the field. With a combination of a high-altitude, long duration mission and low-altitude mission, short-lived but with high resolving power, our knowledge of both the core and the lithospheric parts of the field can be significantly improved.

Existing studies indicate that neither Magsat data nor aeromagnetic maps are well suited to resolve anomalies in the wavelength range 400-800 km. In addition, there is a systematic amplitude discrepancy between upward continued aeromagnetic data and satellite data at satellite altitude. This mismatch has been observed both for the lithospheric anomaly field and for the main field at specific locations. With satellite measurements performed at a lower altitude than Magsat, one will be able to narrow the gap between aeromagnetic and satellite descriptions of the anomaly field by extending the resolution of the satellite anomaly maps, possibly above $n = 80$ (a wavelength of 500 km). With such a satellite it should be possible to understand the discrepancy.

Magnetic Sources and the Structure of the Lithosphere

The Magsat mission flown at a mean altitude of 420 km has provided the most accurate global set of measurements of the geomagnetic field vector yet measured. These data have shown the existence of a long-wavelength magnetic anomaly field, demonstrating, in particular, that the anomaly field in the oceanic domain appears globally weaker than above continental areas. Yet, they were not adequate for the determination of the vertical distribution of magnetic sources in the lithosphere. This parameter, which can be better reached with a Magnetometry Mission below 250 km altitude, would provide fundamental constraints on the structure, particularly thermal, of the lithosphere.

A ridge-parallel pattern of anomalies in the North Atlantic and Indian oceans suggests that magnetisation variations are related to the age of the lithosphere. A more accurate anomaly field as obtained by the Magnetometry Mission would allow us to try to evaluate how induced magnetisation carried by mantle rocks could provide such a relationship.

In the Pacific and North Atlantic, the long-wavelength magnetic anomalies can be accounted for by the combined effect of 1) the net magnetisation contrast at continental margins, 2) the topography of the ocean floor and 3) the remanent magnetisation of the crust acquired during the Cretaceous Long Normal polarity interval. In continental regions, on the contrary, the origin of magnetic anomalies derived from Magsat data is less clearly understood. Satellite measurements do not allow us to discriminate between variations in magnetic susceptibility and variations of the thickness of the magnetic layer. However, analyses of the magnetic properties of deep-seated continental rocks have evidenced fairly uniform magnetic susceptibilities for upper mantle and lower crustal rocks, at the scale of satellite- derived anomalies. This suggests that lateral variations of the thickness of the magnetic layer should be the prime source of Magsat anomalies.

Magsat observations suggest that abrupt magnetisation contrasts may exist within the continental lithosphere and possibly associated with lithospheric blocks of different age. By comparing high resolution magnetic anomaly maps with models of the continental crust and upper mantle, one should be able to determine whether magnetic anomaly sources are located only in the crust or extend deeper in the upper mantle down to the depth of the Curie isotherm.

2.3.3. Conclusion

Maps of the lithospheric anomaly field have been derived from aeromagnetic and shipborne data for many years, but they are only appropriate for studying small-scale anomalies associated with near-surface geological features. Broad-scale anomalies associated with magnetisation at depth which provide geological information on lithospheric-scale features can only be obtained at high altitude from stratospheric balloons and satellites.

However, because the amplitude of the geomagnetic field decreases according to a power-law with the distance from the sources at a rate which increases with increasing wavenumber, magnetic anomaly maps derived from satellite observations can only provide the longer-wavelength components of the geomagnetic anomaly field. The ground resolution achieved on existing anomaly maps based on Magsat data is of the order of 400 km.

Because of their limited extent, existing aeromagnetic surveys are poorly suited to determine anomalies exceeding 200 km. The assembling of smaller contiguous aeromagnetic surveys to recover the intermediate wavelength anomaly field (200-400 km) has proved to be an elusive task, mostly because of inconsistencies in the normal field defined for each individual survey to extract the anomaly field. These inconsistencies stem from differences in the epoch or the altitude of the surveys, or from discrepancies in the definition of the normal field.

The accurate determination of anomalies in the range 200-400 km thus requires dedicated tools such as wider aeromagnetic surveys, stratospheric balloons or low-altitude satellites. Large-scale aeromagnetic surveys and balloon profiles are likely to remain extremely scarce. Therefore, a low-altitude satellite is the only viable way of measuring this part of the field spectrum and thus bridging the existing gap in our knowledge of the geomagnetic field.

2.4. External Field

2.4.1. The Context and Role of the Magnetometry Mission

During recent years society has become aware of the limitations of our planet and of our dependence on advanced technological systems. The distinction between man-made and natural causes of 'Global Change' has become an important issue, and the concept of a steady Sun, expressed for example in the term 'the solar constant' has been gradually abandoned and transformed into a broadly accepted concept of a constantly varying external environment dominated by processes in the Sun.

At present, the poor understanding of the global processes that determine the coupled interactions between the electromagnetic and corpuscular emissions from the Sun and the neutral and ionised species in the Earth's environment, does not allow prediction of the response of the system to changes in the solar output. As a consequence, several international research programs have recently been initiated to improve our knowledge of the solar-terrestrial system. The Magnetometry Mission would be an extremely important and indispensable contribution to such an undertaking.

If the main geomagnetic field is one of the few observables to probe the interior of the Earth, the external field plays a similar role in understanding the Earth's external environment and the effect of the system most influential on the Earth, the Sun.

The discipline of physics dealing with the conditions and processes in the external environment of the Earth is called Solar-Terrestrial Physics. This discipline has evolved as a result of the direct and in situ measurements in Space between the Earth and the Sun that became available with the launch of the first Earth orbiting satellites in 1957. Solar-Terrestrial Physics comprises several elements dealing with processes on the Sun's surface, the emission of radiation and particles, the formation of the solar wind and its interaction with planetary atmospheres, and the resulting processes in the Earth's atmosphere. Through the highly conducting geomagnetic field lines the near-Earth part of this huge system contains indispensable information about these global processes and precise and continuous measurements by a Magnetometry Mission would therefore provide a significant contribution to the understanding of the state and dynamics of the Earth's external environment.

The initial focus of the discipline of Solar-Terrestrial Physics was directed towards understanding the various local physical processes. With a number of satellite missions in different orbits and with different instrumentation, the various regions of the magnetosphere have been explored and characterised in terms of their physical properties and processes. In this way several plasma regimes of the magnetosphere have been identified: the radiation belts, the plasmasphere, the plasma sheet, the plasma sheet boundary layer, the entry layer on the day side, the low latitude boundary layer, and the plasma mantle. Still, however, it is not known how these regimes are connected to the near-Earth field lines and how they interact in the combined global magnetospheric system.

In recognition of this, the focus of research has recently shifted to be more directed towards understanding the global aspects of the whole Sun-Earth physical system including solar variations and direct effects in the atmosphere and on the surface of the Earth as for instance expressed in the Solar-Terrestrial Energy Programme (STEP) sponsored by the International Council of Scientific Unions (ICSU) and the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). In conjunction with this mainly ground-based programme the space agencies of Europe, USA, Japan and Russia have defined a co-ordinated satellite programme, ISTP dealing with a particular aspect of this physics, namely those elements that can be addressed by satellites in the solar-wind and in the outer magnetosphere. Parts of this program include the ESA Cluster and Solar Heliospheric Observatory (SOHO) missions, the National Administration for Space and Aeronautics (NASA) Wind and Polar satellites, the Japanese Geotail satellite and the Russian Interball satellite mission.

Still, a missing component in this co-ordinated programme is the detailed and absolute measurements of the magnetic field variations to be made by near-Earth satellites. The Magnetometry Mission would be an appropriate element to cover the complete solar-terrestrial system. It would not only allow the study of structures and processes at low altitudes and their relations to the Earth's external environment, but would also allow improved exploitation of the data from other missions planned for studies of other regions of the Sun-Earth system.

Magnetic field measurements describe, however, only one aspect of the complex physical system. Energetic particles including electrons from 30 keV to 1 MeV, and protons and alpha-particles from 200 keV to 100 MeV are good indicators of the boundary between dipole-like geomagnetic field-lines and open magnetic field-lines, i.e. field-lines connecting to the interplanetary medium.

Combined studies including in situ measurements of energetic particles and ground-based observations of precipitating particles will provide improved knowledge about the dynamical features associated with magnetospheric processes. The level of particle flux provided by a particle instrument may also be used in the selection of suitable quiet intervals for the derivation of geomagnetic field models and as a monitor of solar activity.

The electrodynamics of the upper atmosphere is determined by the electric field structure, the conductivity and the electric currents. These parameters are mutually dependent. Ideally all three parameters should be measured. By means of the vector magnetometer measurements a good estimate of the electric currents can be obtained. A promising tool providing information about the electric conductivity is to create tomographic maps of the electron density by means of occultation data from a dual-frequency Global Positioning System (GPS) receiver. Finally the science return of external field studies would greatly benefit from direct measurements of the electric field at the satellite location. This could relatively easily be accommodated by the inclusion of an ion driftmeter.

The Magnetometry Mission would allow the bridging of the very important gap in the fundamental knowledge of Solar-Terrestrial Physics, namely the origin of the structures and dynamic processes in the proximity of the Earth. This also has important implications for the studies of the Earth's lithosphere. With its improved accuracy and spatial and temporal coverage, the Magnetometry Mission would build on the results of Ørsted, SAC-C and CHAMP improving the results and avoiding their limitations thus allowing generalised progress in several essential areas.

2.4.2. The Issues of Interest: the Areas of Research

Solar Wind - Magnetosphere Interactions

The question of how solar wind plasma, momentum and energy are transferred to the magnetosphere is one of the fundamental problems of magnetospheric physics. A necessary requirement for solving this problem is the understanding of the magnetopause and boundary layer processes. It is today realised that a major obstacle in reaching this understanding is the lack of a sufficient number of simultaneous observations of these regions and their ionospheric projections. A concerted effort using ground-based and dedicated satellite observations will contribute to solving the intriguing question of possible merging between magnetic fields of solar and terrestrial origin.

One of the most direct effects of the solar wind - magnetosphere interaction is seen in the day side of the magnetosphere and ionosphere. The combined three-dimensional current system here changes dramatically and immediately according to the variations in the solar wind and must therefore be regarded as the most fundamental part of the response of the magnetosphere. The understanding of the relationships between the current systems in this region and their dependence on the external conditions in the solar wind, will significantly enhance our understanding the coupling between the solar wind and the magnetosphere.

Magnetosphere-Ionosphere Coupling

The geomagnetic field lines act as the link between the outer part of the magnetosphere and the lowest part, namely the ionosphere. This link is sustained by electric currents that can easily flow along the geomagnetic field lines because of the highly anisotropic conductivity in the magnetosphere. The only direct measurements of these currents are in the form of magnetic field measurements on board low-altitude polar-orbiting satellites. Measurements from such satellites have provided indispensable information that has made it possible to describe in gross terms, but not yet to understand, the coupling between the magnetosphere and the ionosphere.

An indirect effect of the interaction between the solar wind and the magnetosphere is the occurrence of magnetospheric substorms that take place at intervals of, typically, a few hours. Substorms are thought to result from unloading of energy from the solar wind. This energy is stored in the tail of the magnetosphere and the unloading processes are associated with strong localised field-aligned current sheets, particularly in the midnight sector.

During particularly strong ejections of solar energy and mass the activity in the magnetosphere may be enhanced for several days. These conditions are called magnetic storms and involve the entire magnetosphere in a very complex way. Magnetic storms is one of the strongest manifestations of the energy transfer from the solar wind to the Earth and the understanding of such events is therefore of special importance for 'Space Weather' investigations.

Ionospheric Currents

The ionosphere is conducting and is therefore able to carry electric currents. These currents have their origin in electric fields generated by a number of different mechanisms. In the polar regions these fields are primarily of magnetospheric origin and the motion of ionospheric ions may, during high geomagnetic activity, be a considerable source of upper atmospheric heating. At lower latitudes there exists a permanent system of electric currents that is caused by the motion of the neutral atmosphere, which is designated as the *Sq* system. The system consists of two large vortices in the sunlit part of the atmosphere, a counter-clockwise cell in the northern hemisphere and a clockwise cell in the southern hemisphere. Near the magnetic equator where the horizontal magnetic field lines inhibit the normal discharge or polarisation electric fields, a large electric field is established that drives a strong electric current along the day-side equatorial part of the ionosphere, the Equatorial Electro-Jet (EEJ), an intensified current flowing along the magnetic equator during the day at about 105 km altitude. The EEJ is accompanied by meridional currents which cause toroidal magnetic fields up to about 100 nT which can only be detected between 100 km altitude and 300 km. The magnetic effect of the EEJ is a significant part of the magnetic signal measured both on the ground and at near-Earth satellite altitude.

The Magnetometry Mission will be particularly well suited to study the three-dimensional current system including the ionospheric part of the system. The measurements of a low-altitude satellite will provide unprecedented measurements of the ionospheric part. The simultaneously operating high-altitude satellite, at selected times even on nearly connecting magnetic field-lines, will provide measurements of the field-aligned part whereas existing ground-based facilities will be used to complete the set of measurements and to provide the boundary conditions for the interpretations.

Modelling

In addition to studies of selected events using the full range of data, satellite and ground-based, the long operational life time and the absolute accuracy of a Magnetometry Mission will also allow a statistical analysis of the distribution of the external magnetic field as a function of local time, season, conditions in the solar wind and in the magnetotail (substorm activity). Such an updated empirical near-Earth model of magnetospheric response to given average solar wind conditions is an important tool which may be used to test the theoretical models of solar wind - magnetosphere interaction.

2.4.3. Conclusion

One of the primary goals in Solar-Terrestrial Physics is to understand the transfer of energy and momentum from the solar wind to the magnetosphere and how this energy is subsequently released in the magnetosphere and the upper atmosphere. The electric currents associated with the motion of charged particles in the magnetosphere and ionosphere reflect directly the energy flow, and the complete knowledge of the dynamics and spatial distribution of these currents will therefore constitute a crucial part of the basis for understanding the process. The strongest current sheets project down to the ionosphere along the so-called auroral oval and may best be observed using polar-orbiting satellites because these satellites will intersect the current sheets four times in each orbit.

The Magnetometry Mission will specifically provide high precision measurements of the complex electric current sheets at all local times. The noon region is known to respond immediately to changes in the conditions in the solar wind, and in particular to the interplanetary magnetic field. No other satellites have yet made high-precision magnetometer measurements in this local time sector. The Danish Ørsted geomagnetic satellite planned to be launched in March 1997 will make such measurements during an operational lifetime of one year. The present mission will, however, be able to cover all local-time ranges and would, in addition, take advantage of a second satellite providing simultaneous measurements. At regular intervals it will be possible to get simultaneous measurements at different altitudes on the same local-time meridian.

2.5. The Potential Application Areas

As noted in Section 2.1, geomagnetic measurements are always observations of the composite field originating from sources inside the Earth: the core, the mantle and the crust and outside the Earth: the ionosphere and the magnetosphere. The importance of the main field in studies of constituents of the geomagnetic field is obvious, since this represents, typically, over 98% of the observed signal at the surface of the Earth. In addition to the wide range of research topics that can be addressed with geomagnetic data, these are also indispensable for a variety of operational functions and applications. The applications fall into two main categories. The first comprises applications that depend on accurate models of the slowly varying component of the main geomagnetic field. The second is related to the rapid time-varying part of the field due to external sources, which are related to the ever changing transfer of energy and momentum from the solar plasma and electromagnetic radiation.

2.5.1. Application of Geomagnetic Field Models

The International Geomagnetic Reference Field (IGRF)

For many purposes in the fields of ionospheric, magnetospheric and cosmic-ray physics and in studies of crustal fields, particularly in exploration geophysics, an internationally produced and agreed global model of the main field and its secular variation, IGRF is widely used. It is generally recognised that values computed from the current version of the IGRF are most accurate for times near those when Magsat was in orbit, around 1980. The IGRF is revised every four or six years and the data from the Ørsted and subsequent missions are therefore expected to ensure that the next revision, in 1999 or 2001, will be even more accurate around this time than the current version is around 1980. The two revisions after that, in 2005 and 2009, will similarly benefit from the results of the Magnetometry Mission.

Studies of Lithospheric Magnetisation

In Section 2.3 mention has already been made of the part of the geomagnetic field that results from the differing magnetisation of crustal and upper mantle rocks. In studies of this anomaly field using satellite data, the lithospheric signal is a small proportion of the measured values. The first and very important step in the analysis is the removal of an accurate estimate of the core field. Although this is easily done for scale sizes smaller than about 3000 km ($n > 13$), the signal for larger sizes contains both lithospheric and core components. A longer period of vector data collection than those provided by Magsat and the planned Ørsted, CHAMP and SAC-C missions is needed for this research, and this will be achieved by the Magnetometry Mission. Furthermore, much of the lithospheric signal observed at satellite altitudes is due to magnetisation of rocks induced by the present-day main field and an accurate and up-to-date knowledge of the main field is important for the correct processing and interpretation of such data.

A knowledge of the crustal field is important not only scientifically in its own right, but for the insights it can give to the exploration geophysicist in the search for mineral and hydrocarbon deposits. In areas where the basement is concealed by sedimentary cover, magnetic anomaly maps have shown to be an important component in the diagnostics of mineral resources. Airborne magnetic surveys have recently been successfully used in mapping faults sometimes missed by early seismic studies. The observation from space of the long-wavelength anomaly field will help to tie together adjacent aeromagnetic surveys. It is also instrumental in understanding structure of the basement and its implications for emplacement mechanisms of mineral resources. Furthermore, the investigation of the deep structure of the continental crust has received increased attention today due to the growing need to prospect for mineral resources at ever greater depths.

Geomagnetic Field Models as Tools in Magnetospheric, Ionospheric and Climate Investigations

The main geomagnetic field controls the motion of charged particles in the magnetosphere and ionosphere, including the trajectories of incoming cosmic-ray flux. Several specialised co-ordinate systems have been derived to help organise data collected in these regions of the atmosphere and these are all ultimately based on a knowledge of the geomagnetic main field. It is often necessary, in these studies, to be able to follow the path of a particular geomagnetic field line from one hemisphere of the

Earth to the other. For example, the South Atlantic Anomaly of low magnetic fields has a significant effect on the distribution of the energetic particles in the near-Earth part of the radiation belts.

A controversial topic in atmospheric science is the possible connection between the geomagnetic field on one hand and climate and weather on the other. It has been suggested that the changes in the rates of rotation of the Earth may be involved in some way (Courtillot et al., 1982). Global studies, which are essential for the climatological aspects of this topic, need accurate global information about the main field and its secular variation.

A potential source of climate variations is the varying cosmic ray flux that in the atmosphere creates ionisation changes which affect microphysical processes, such as the nucleation and growth of ice particles in high-level clouds (Tinsley, 1994). Generally, cosmic rays are categorised into two sources: a continuous flux of Galactic Cosmic Rays (GCR) that is characterised by very high energies, and Solar Cosmic Rays (SCR) of typically lower energies that are associated with solar eruptions. The particle fluxes, in particular the lower energy part, are highly dependent on the magnitude and distribution of the geomagnetic field.

Use in Navigation

A recently developed navigational use of geomagnetic information, which is assuming increasing importance, is in the drilling of deviated (i.e. non-vertical) wells in the oil and gas industries. It is common for 50 or more deviated wells to be drilled from a single rig and it is therefore necessary to be able to control the dip and azimuth of the drilling tool to within close tolerances. Gyroscopic devices can be used to supply this information but they are sensitive to vibration and drilling operations must therefore be suspended whilst measurements are made. This is expensive and the preferred method of navigating the drill string is, in most cases, by using the geomagnetic field as the source of directional reference. Magnetic sensors are located in a non-magnetic Section of the drill string, not far from the drill bit, and it is possible to make navigational measurements whilst drilling is in progress. Accurate and up-to-date geomagnetic field information is of course, essential and accuracy requirements are much more stringent than in traditional forms of navigation, and are becoming more so.

In terms of more traditional navigational uses, whilst it is true that modern navigation aids rely more and more on terrestrial and satellite-based techniques involving the transmission and reception of electromagnetic waves, it is still a legal requirement in most countries that ships and aircraft carry a magnetic compass (and magnetic charts) as a back-up system in case the more complicated systems break down or are jammed in times of war.

2.5.2. Applications Related to the External Part of the Magnetic Field

Space Weather

The space environment is populated by charged particles controlled by the electric and magnetic field. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to serious economic losses as recognised for instance, in the Strategic Plan, a report prepared in 1995 by the Committee for Space Environment Forecasting (CSEF) of the Office of the Federal Co-ordinator for Meteorological

Services and Supporting Research (OFCM). The Magnetometry Mission would also allow progress in these application areas.

In addition to the geomagnetic field, also the solar wind magnetic field has a large modulating effect on the cosmic ray flux. During high solar activity the increased number of magnetic irregularities will impede the flux significantly, dependent on the actual energy ranges in question. This large variation has been proposed to be the key to the reported correlations between solar variability and climate changes. Fluctuations of the geomagnetic field on a global scale directly reflect variations in the solar wind. Measurements in the solar wind are only available for the last three decades, but an understanding of how the solar wind and magnetosphere interact, may enable us to use the geomagnetic fluctuations recorded at magnetic observatories during the last 130 years to infer solar wind conditions during this time. This would allow an independent test of the hypothesis of a direct climatic effect of the varying cosmic ray flux.

Contamination of Estimated Main and Lithospheric Fields by External Field Contributions

As mentioned in Section 2.3 an appropriate separation of the lithospheric and ionospheric contributions is a major obstacle for the determination of the main and lithospheric parts of the geomagnetic field. Whilst a decrease of satellite altitude will increase the signal from the lithospheric sources significantly, the signal from the ionospheric field would be even more enhanced. Therefore, in order to optimise the advantage of a low-altitude orbit it is necessary to improve our models of the ionospheric currents, based on an improved understanding of ionospheric dynamics and the relation to magnetospheric sources.

The quality of magnetic surveys is influenced by the level of magnetic activity. The possibility of predicting this is therefore of immediate interest for those planning such campaigns. Necessary for prediction capability is the existence of good models and good data collected in real-time or with a small time delay. One of the objectives of the Magnetometry Mission is to improve present models of solar wind-magnetosphere interaction, which is the source of magnetic activity measured on the surface of the Earth. It will also be used to investigate whether the geomagnetic field data may be used directly, together with various other data, in real-time models of the effect of the distribution of electric currents.

3. Research Objectives

3.1. Introduction

The following is a presentation of the specific research topics that will be studied using data from the Magnetometry Mission.

3.2. Main Field and Secular Variation

3.2.1. Global Modelling of the Main Geomagnetic Field and its Secular Variation

Throughout the mission careful selections will be made of sets of data that have been measured during magnetically very quiet times and still have good global coverage. The quiet-time selection procedure will minimise the contributions from electric currents flowing in the ionosphere and magnetosphere. Ionospheric current effects will be minimised by selecting quiet time data collected near local midnight when the electrical conductivity of the ionosphere, and therefore the intensity of any electrical currents flowing there, are as small as possible. The effects of magnetospheric currents will be minimised by selecting only data measured when one or more of the indices that measure magnetic disturbance have values below a preset level. Candidate disturbance indices include the *Kp* and *Dst* indices.

Using these data sets, together with appropriate observations made on and near the Earth's surface, a series of global models of the main geomagnetic field and its secular variation will be produced at intervals throughout the mission. The standard method of global geomagnetic field modelling is currently based on spherical harmonic analysis. Research will, however, also be conducted into alternative methodologies.

Two strategies can be used to extract secular variation information from data sets such as that provided by the Magnetometry Mission. In the first alternative subsets of the data, each spanning the shortest time sufficient to give a good global data distribution, are selected. Each subset is analysed to give a series of 'snapshot' main-field models centred at the mid-points of the individual time intervals. A secular variation model can then be derived by studying the time dependence of the individual coefficients of this series of main-field models. The second technique involves using selected data spanning the entire mission and producing, simultaneously, a main-field model at the mid-epoch of the mission and a model of the secular variation, assumed constant, over the interval spanned by the data. If the length of the mission is sufficient it may also be possible to investigate the feasibility of modelling the time variation of the secular variation (secular acceleration).

For studies of the Earth's core, it is essential that the field models used are contaminated as little as possible by fields originating in the Earth's crust or in the upper atmosphere. For these models, it may be necessary to use selection procedures that are more stringent than those described above or to augment them with other techniques for selecting and correcting the data.

An important part of all the modelling work will be the production of realistic estimates of uncertainties in the models and the field component values derived from them.

3.2.2. Secular Variation in the Recent Past

By combining data from this mission with the results obtained from Ørsted and from any other post-Ørsted missions, a study will be made of how the main geomagnetic field has changed since the launch of Ørsted. It is planned to carry out a similar investigation as part of the Ørsted research programme, combining Ørsted data with those from Magsat. The two sets of results will together give an accurate description of how the geomagnetic field has changed since 1980.

3.2.3. Jerks

A careful search will be made to detect any jerks that may occur during the lifetime of the satellite. If any are found satellite and ground-based data will be analysed to discover when the jerk happened and what the dominant time scales of the process were. Attempts will be made, using recently developed techniques such as wavelet transform analysis (Alexandrescu et al., 1995), to elucidate the precise nature of any jerks, for example whether they represent a discontinuity in the second time derivative of the geomagnetic field or something more complex. The global nature of the satellite data set will also allow investigations of the implications for lower mantle electrical conductivity . The question of whether a particular jerk is a true signal from the core or whether its source lies above the Earth's surface (as has been suggested for some jerk-like signals) will also be studied.

3.2.4. Core processes

From the main-field and secular variation models that have been discussed in Section 3.2.1 it will be possible, using a variety of assumptions about the general nature of core fluid flow, to derive possible flow patterns for the fluid near the surface of the core. If any jerks are detected during the mission, their study, as described in Section 3.2.3, will help to refine some of the parameters needed in these investigations.

The derived fluid flow patterns will be used to study how the core and mantle are coupled. In particular, an attempt will be made to ascertain which of the two most likely mechanisms, electromagnetic or topographic coupling, is dominant or whether both are important. Excitations of changes in the length of day and motion of the pole by exchange of angular momentum between the core and mantle will also be investigated. Crucial for these studies is the long time series of high-quality geomagnetic field data that the Magnetometry Mission will provide in addition to the Magsat observations and the measurements from the planned intermediate geomagnetic field missions like Ørsted.

3.2.5. Prediction of Secular Variation

For many applications it is necessary to be able to predict how the main field will change in the near future (up to five years ahead). At present this is done almost entirely on the basis of the behaviour of the field in the recent past, assuming that what is about to happen is likely to be similar to what has just happened. Studies will be conducted using the data from this mission to try to improve the accuracy of prediction, hopefully by including in the forecasting method some of the improvements in our knowledge of core processes resulting from the studies discussed in Section 3.2.4.

3.2.6. Requirements for Data Accuracy

Studies of the spatial power spectrum of the geomagnetic field (for example, Langel & Estes, 1982) have shown that, at the Earth's surface, the field from the core dominates for values of the spherical harmonic degree (n) less than 13, whereas the crustal field has the greater power for n greater than 15 or 16. It is therefore not realistic to produce spherical harmonic models of the main field with n greater than about 13 (although, for models that are to be used to investigate processes in the core, special techniques, usually involving the use of *a priori* information, are employed to estimate the higher degree coefficients).

The $n = 13$ coefficients of models of the present-day field have values of a few nanoTeslas. (Barton, 1996). Taking 10 nT as the amplitude of the field of degree 13, this will be reduced to 1 nT at an altitude h (in km) above the Earth's surface, where

$$[\frac{a}{a+h}]^{n+2} = 1/10$$

because of the $(a/r)^{n+2}$ dependence of the harmonics in the expansions of the field components. Taking a as 6371.2 km (the mean radius of the Earth) and n as 13 gives h » 1060 km. This is therefore the maximum altitude for the Magnetometry Mission if accurate main-field models are to be produced up to and including a maximum spherical harmonic degree of 13, given a measurement accuracy of 1 nT.

3.2.7. Requirements for Other Data

Data from the existing networks of magnetic observatories and repeat stations will be essential to the main-field and secular variation studies.

As mentioned in Section 3.2.1, indices of magnetic disturbance such as *Kp* and *Dst* will be used for data selection and it is imperative that the observatories that presently contribute the data on which these indices are based continue to do this, and in as near real time as possible for the duration of the Magnetometry Mission.

It will be important to verify secular variation models produced from the Magnetometry Mission data with estimates of the local secular variation based on selected ground-based observations corrected for possible induction effects using simultaneous satellite observations. Since observatory data are the most reliable source of secular variation information it is essential that such data continue to be received from the observatory network throughout the Magnetometry Mission. In addition, information about induction effects will enable estimates to be made of the electrical conductivity of the upper mantle.

3.3. Lithospheric Anomaly Field

3.3.1. Determination of the Long-Wavelength Lithospheric Anomaly Field. Separation between Core, Ionospheric and Lithospheric Fields.

A Magnetometry Mission, which would perform measurements at two different altitudes with extended lifetime and better coverage of local times will provide a more accurate determination of the field and will help us to separate the three major components of the field. A comparison of the spectra of the main and lithospheric fields observed by Magsat (at an average altitude of 370 km) has shown the 'Lithospheric to Core Ratio' (LCR- the ratio of the energy associated with these two fields) to be of the order of 20% at $n = 13$, 5% at degree 12 and less than 2% at degree 11.

Measurements performed at high altitude for a sufficient lifetime can provide an accurate determination of the core field up to $n = 13$ where the LCR is very low (attenuation of the lithospheric field with altitude is greater). This model can then be used to remove the main field contribution to measurements performed at a lower altitude even though the LCR is higher at this altitude. With such a combination of high and low altitude measurements our knowledge of both the core and the lithospheric parts of the field can be significantly improved. Although the two types of measurements need to be close in time, they do not need to be strictly simultaneous considering the shortest characteristic time scales of secular variation (a few months).

Analyses of Magsat data have shown that the ionospheric field has significant energy at low degrees (associated with the solar daily variation, SR) and in the range $n = 10$-20, from the equatorial electrojet in particular. With a good coverage of the field at different local times, and with one satellite being close to the sources, one may expect to be able to separate the lithospheric field from the local-time-dependent ionospheric field.

3.3.2. Determination of the Short-Wavelength Lithospheric Field. Bridging the Gap between Satellite and Aeromagnetic Mapping

Several attempts to compare surface and satellite observations have been performed over South Africa, the conterminous US and the USSR using broadscale aeromagnetic surveys and over oceanic areas using sea-surface magnetic data. These studies have all shown that there is virtually no overlap in the spatial frequency information of Magsat-derived lithospheric anomaly maps (shortest wavelengths near 800 km) and surface data. Aeromagnetic maps usually do not resolve anomalies larger than 200 km. There is some indication of overlap between the compiled aeromagnetic map of North America and the Magsat anomaly field in the range $n = 45$-57 (700-900 km wavelength, or 350-450 km anomalies). Furthermore, there is a systematic amplitude discrepancy between satellite data downward continued to ground-level and surface data. This mismatch has been observed both for the lithospheric anomaly field and for the main field at specific locations. This latter observation has been attributed to the presence of local standing anomalies near magnetic observatories.

With satellite measurements performed by a Magnetometry Mission at an altitude of 250 km, one will be able to extend the resolution of anomaly maps above $n = 80$. Anomalies as short as 250 km could then be accurately observed from satellite and compared with their corresponding signature in large-scale aeromagnetic maps. Because of the different ambiguities mentioned above, it is absolutely necessary to cross-check satellite and surface data to validate a posteriori the processing techniques applied to satellite field measurements in order to isolate the lithospheric anomaly field.

3.3.3. Magnetic Sources in the Oceanic Lithosphere

The long-wavelength magnetic anomaly field derived from Magsat observations consistently show a contrast between continental and oceanic domains: the anomaly field in the oceanic domain appears globally weaker than above continental areas. Furthermore, the signal-to-noise ratio seems to be below 1 over most of the oceans. Only a few anomalies in oceanic basins have warranted geophysical interpretation, being generally attributed to local topography contrasts. These anomalies are consistent with local magnetisation contrasts, assuming that all the magnetisation is induced by the main field, associated either with submarine structures and plateaus of characteristic continental affinity (e.g., the Lord Howe Rise in the Pacific or the Florida Straits block in the Atlantic) or with thickened oceanic crust (e.g., the Kerguelen plateau and Broken ridge in the Indian Ocean). The poor accuracy of these maps in the oceanic domain has precluded documentation of these relationships on a global scale.

The hypothesis that mantle rocks may carry magnetisation has been discussed by many workers. This hypothesis implies that the upper mantle might acquire some magnetisation (whether remanent or induced) while cooling down away from the mid-ocean ridge. Thus a relationship might exist between magnetisation (and consequently magnetic anomalies) and the age of the lithosphere.

The ridge-parallel pattern of anomalies observed on Magsat-derived maps alternatively suggests that magnetisation variations may be related to the age of the oceanic crust. It has been suggested that remanent magnetisation in the upper crust could be a possible source for these anomalies in the North Atlantic.

In these regions, homogeneous remanent magnetisation was acquired during the 30 Ma period of normal geomagnetic polarity know as the Cretaceous Long Normal (CLN) polarity interval. In the CQZ, the sea floor is uniformly magnetised over several hundred kilometres in the direction of spreading and over thousands of kilometres parallel to the ridge direction. Such structures should then contribute significantly to the lithospheric anomaly field. However, the current accuracy of anomaly maps is not adequate to obtain a precise estimate of the Natural Remanent Magnetisation (NRM) carried by the oceanic crust. A properly designed Magnetometry Mission (i.e., allowing for the separation of ionospheric and lithospheric components with a proper choice of the orbit precession rate and an orbit below 250 km) would enhance the accuracy of the lithospheric anomaly field and allow us to efficiently separate the respective contributions of induced and remanent magnetisation to the field of the oceanic lithosphere.

3.3.4. Magnetisation Discontinuities in the Continental Lithosphere. The Depth of Magnetic Sources.

The most characteristic features of Magsat anomaly maps are elongated anomalies extending over several thousand kilometres. Two such elongated NW-SE paired anomalies are observed above central Europe from southern Scandinavia. In eastern Eurasia, three anomalies elongated in a NE-SW direction are observed with similar amplitude and scale. The most prominent is a large belt of negative anomalies which extends from the southern Caspian Sea to Sakhalin island in the Pacific reaching a maximum above the Himalayas, the Karakorum and southern Tibet.

Dipolar elongated anomalies such as those described above have been observed in the magnetic anomaly field derived from Magsat data near continental margins. These anomalies can be modelled by an abrupt magnetisation contrast between two domains of uniform magnetisation. This phenomenon could arise from the truncation of the low order terms of the spherical harmonic models of the field, a procedure required to remove the main field originating in the core and isolate the anomaly field of lithospheric origin. The existence of a magnetisation contrast at the transition from continental to oceanic lithosphere has been suggested and is consistent with the distribution and amplitude of many observed Magsat anomalies near continental margins. These observations suggest that abrupt magnetisation contrasts may exist within the continental lithosphere. High resolution magnetic anomaly maps provided by a Magnetometry Mission should be compared with seismic tomographic models of the continental crust and upper mantle which are becoming widely available with increasing resolution. This should lead us to determine the extent of magnetic sources in the lithosphere which then could be compared with the depth of the Curie isotherm. Continental geotherms calculated for the Appalachians and the Eastern Canadian Shield indicate that the 600°C isotherm is located at 100 km below the Canadian shield and at 70 km below the younger Appalachian province. Thermal oceanic models place the 600°C isotherm near 40 km depth for a lithosphere older than 70 Ma. These values are somewhat different from the currently accepted depth of magnetic sources in the continental lithosphere.

3.4. External Field

Whilst a model of the main geomagnetic field is derived from satellite measurements eliminating as far as possible the contribution from the lithospheric and external sources, there is also a great need for adequate magnetic field models incorporating the contribution from external currents. For example there is a great interest in being able to map the position in the geomagnetic tail where a magnetic substorm is initiated but how such a position maps along the geomagnetic field lines to the ionosphere is not known with great precision. One of the difficulties with such models is the dynamics of the external field which means that the mapping in fact changes with time, corresponding to the varying effect of the interaction between the solar wind and the geomagnetic field. A necessary requirement for good external field models is good observational data and a good understanding of the physics of the three-dimensional current systems in the magnetosphere and ionosphere. The high-precision data provided by the Magnetometry Mission will be used to enhance our understanding in the following research areas.

3.4.1. The Global Coupled Sun-Earth System

Although the solar wind - magnetosphere interaction is a very dynamic process there are several indications that the dynamics may be described, at least to the first order, as transitions between a number of 'ground-states', each defined by the average condition corresponding to a specific combination of solar wind parameters. These ground-states, or average states, can be derived from a statistical analysis of the distribution of the external geomagnetic field as a function of local time, season, conditions in the solar wind and in the magnetotail (substorm activity). An empirical model of the magnetospheric response to given average solar wind conditions is an important tool which can be used to test the theoretical models that describe the interaction between the solar wind and the magnetosphere.

The absolute accuracy of the magnetic measurements made by the Magnetometry Mission during its relatively long operational period will provide an excellent opportunity to obtain an updated empirical near-Earth model of the external field variations in all local time sectors.

Apart from the system of global-scale currents involved in the interaction between the solar wind and the magnetosphere, more localised processes occur in the outer magnetosphere. These processes may be associated with small-scale current systems, which couple to the ionosphere. Each of these is related in a distinctive way to the very nature of the source, be it Flux Transfer Events (FTEs), impulsive plasma penetration, Kelvin-Helmholtz instability, or magnetospheric responses to sudden changes in solar wind.

The study of the ionospheric response to the variety of different signals that pass the magnetospheric boundary layers may provide crucial information about the coupling mechanisms. On account of the dynamic and localised nature of these processes the controversies regarding their origin may not be solved by spacecraft data alone, but require the inclusion of ionospheric measurements by means of high-resolution ground-based observations such as ionospheric remote sensing using coherent and incoherent scatter radar techniques, observation of particle precipitation patterns using imaging riometers and all-sky camera or television, and magnetometer arrays to measure ionospheric current systems.

3.4.2. The Coupled Magnetosphere-Ionosphere System

The direct effect of solar wind - magnetosphere interaction is particularly seen in the noon sector. However, a very conspicuous result of this interaction is the occurrence of magnetospheric substorms that take place at intervals of, typically, a few hours. Increased energy transfer to the magnetosphere takes place during times of southward directed interplanetary magnetic field, i.e. oppositely directed to the geomagnetic field lines at the magnetopause. During such conditions the intervals between the substorms is shorter indicating that they are caused by unloading of accumulated energy in some not yet fully understood local processes that take place in the tail of the magnetosphere. Substorms are associated with strong field aligned current sheets, particularly in the midnight sector, which can be measured directly by magnetometer measurements on polar-orbiting satellites.

During magnetic storms the whole magnetosphere is perturbed. One aspect of magnetic storms is the prolonged increase of the ring current having its origin in the Van Allen radiation belts. A magnetic storm consists of a multitude of phenomena taking place simultaneously at different local times. Magnetic storms, although they have some common features as mentioned above, all seem to be very different in their spatial distribution and in their evolution in time. Presumably the actual state of the magnetosphere at the time of the initiation of the storm plays a large role. Observations of field-aligned currents in the midnight sector during a long-duration mission as the Magnetometry Mission will therefore provide an extended database of magnetic storms and their associated field-aligned current sheets that is needed in order to sort out the specific characteristics of the various magnetic storms, and how these characteristics relate to their causes on the Sun's surface.

3.4.3. Ionospheric Structure and Processes

In the polar regions the electric fields, which drive the ionospheric currents, are primarily of magnetospheric origin. These currents are particularly strong during active solar conditions. But even during quiet magnetospheric conditions there is a permanent system of electric currents that is caused by the motion of the neutral atmosphere. This motion affects the ionised particles in the upper atmosphere and a global ionospheric current system, the Sq system, is established. The system consists of two large vortices in the sunlit part of the atmosphere, one counter-clockwise cell in the northern hemisphere and a clockwise cell in the southern hemisphere. The current intensity is about 100 000 amperes, which is less than in the polar current systems of magnetospheric origin. But because the spatial extent of this system is so large, it has a magnetic effect, which is a crucial part of the measured field at satellite altitudes. The atmospheric winds that drive these currents are partly due to the diurnal variation of the absorption of ultraviolet radiation in the thermosphere. In addition, there exists a component, which is due to atmospheric tidal motions of solar and lunar origin.

An unsolved problem is the closure of the ionospheric current systems. At high geomagnetic latitude it is known that a considerable part of the current closes via field-aligned currents in the magnetosphere. The currents may therefore only be understood as part of a complex three-dimensional current system. Whereas the currents along the field lines can only be measured directly by means of polar-orbiting satellites, the ionospheric part of the system will also be observable from dedicated ground magnetometer networks. At middle latitudes simulation models of ionospheric wind-dynamo effects have predicted the existence of currents flowing along geomagnetic-field lines between the northern and southern hemispheres, driven by asymmetric winds and conductivities in the two hemispheres, especially around the solstices. The predicted magnetic effects of these currents are on the order of 10 nT, which should be distinguishable from lithospheric fields in satellite magnetometer data upon careful analysis. Detecting these fields would be a test of ionospheric dynamo theory, and can help provide a quantitative measure of wind asymmetries between the two hemispheres. Their quantification may also prove to be important for the accurate determination of the main field.

At lower latitudes the results from Magsat indicated that currents in the ionospheric F region produce measurable magnetic perturbations. Unfortunately, the limited local-time coverage of the Magsat mission did not allow a comprehensive analysis of this effect. A satellite below 250 km altitude would be flying through these F-region currents, and would enable their global patterns to be mapped out after careful separation of lithospheric fields. These patterns could then be interpreted in terms of F-region conductivities and winds, which have not been well quantified on a global basis. A low-altitude magnetometry satellite would also be able to make relatively detailed measurements of the equatorial electrojet. The meridional profile of magnetic variations associated with the electrojet are closely related to the wind structure in the 90-160 km height region, as well as to global ionospheric electric fields, and thus their measurement would provide further information about ionospheric winds and electric fields as a function of longitude and local time. A good determination of these ionospheric-current effects at low latitudes will also be important in the determination of lithospheric fields.

3.4.4. Induced Currents in the Lithosphere

An important effect of the large-scale ionospheric current system and its systematic variation on a daily scale (and longer term variations as well) is the induced current in the lithosphere, to a depth of about 1000 km. The refined modelling of these currents by means of highly accurate magnetic measurements at different altitudes in space and on the ground will be used to increase our knowledge about the conductivity distribution in the lithosphere and will allow a better description of the external source field.

3.5. Summary of Research Objectives

The research objectives to be pursued by the Magnetometry Mission fall in the three broad categories already identified:

- main magnetic field and its secular variation;
- lithospheric magnetic anomaly field;
- external fields in the magnetosphere and the ionosphere.

Accurate modelling of the main field, i.e. the first 13 harmonics in its spherical harmonic expansion, will represent an important contribution to research on the deep interior of the Earth. Provided that the proposed mission, together with the immediately preceding ones such as Ørsted and CHAMP, achieve a complete coverage of a solar cycle, secular variations originating from the Earth's interior will be isolated and correlations with e.g. the Length of Day established. A minimum satellite altitude will be needed to guarantee mission duration and separation of the main field from the external and anomaly fields.

The second category of mission objectives is expected to provide a significant enhancement of research on the oceanic lithosphere, separating contributions of induced and remanent magnetisation. In combination with seismic tomography, magnetisation discontinuities within the continental lithosphere will be investigated. These mission objectives impose a requirement to resolve the magnetic field on a much shorter spatial scale than for the determination of the main field, and this will in turn require the use of a second satellite in a lower orbit.

Both the higher and the lower satellites will be used for the fulfilment of the third category of mission objectives, i.e. the determination of external fields. The higher and the lower satellites will respectively provide better information on magnetic field-aligned currents and ionospheric current systems, the latter with a sufficient duration although much shorter than the former. Measurements by the Magnetometry Mission will support research on the coupling between the Earth's ionosphere, its magnetosphere and the solar wind. A better understanding of ionospheric structure and processes will also result from the proposed mission.

3.6. Optional Scientific Research Objectives

Taking into account the multitude of science objectives associated with this mission, it is obvious that some of these could be enhanced by including additional experiments provided they can be included without affecting the basic requirements regarding the high-precision measurements of the magnetic field vector.

The 1991 Earth Observation User Consultation meeting indicated interest in testing whether electromagnetic earthquake precursors exist and might be measurable from space. The present knowledge of this research area does not justify a dedicated mission with this objective. However, because the confirmation of the existence of any earthquake precursor signal would be highly beneficial for a future warning system, it might be worthwhile to augment the Magnetometry Mission to include such investigations. A modern vector magnetometer is already able to measure part of the electromagnetic spectrum of interest, namely the geomagnetic field at frequencies below 100 Hz with sufficiently high sensitivity. A more complete mission would result from the inclusion of the Very Low Frequency (VLF) band (above 100 Hz). This could be accommodated by including a search coil as an optional instrument.

One of the science objectives of the Magnetometry Mission is the study of external fields. The external field is a manifestation of the currents flowing in the upper atmosphere/ionosphere, and along magnetic field lines in the auroral oval. The current in the upper atmosphere, while carried by charged particles (ionospheric particles) is dynamically coupled to the neutral atmosphere through collisions. Thus currents heat the atmosphere during magnetically disturbed conditions, setting in motion large-scale wind systems, with velocities reaching more than 300 m/s. The motion of the neutral atmosphere in turn affects the current systems and the Joule heating experienced by the neutral atmosphere.

The scientific output of external field studies would greatly benefit from additional observations of the conductivity, which can only be done indirectly. It is determined, primarily, by the solar ultraviolet flux, but important ionisation at high latitudes is also generated by the precipitation of energetic particles. Observations of the electron and proton fluxes with energies down to 1 keV will provide a significant input for the estimation of the conductivity structure in the upper atmosphere and should be seriously considered as optional measurements on the low-altitude satellite.

Operational models of thermospheric density and composition, such as Mass Spectrometer Incoherent Scatter (MSIS), provide densities with an accuracy of about 15% at low latitudes and for geomagnetically quiet magnetic times, but uncertainties at high latitudes during geomagnetic storms often exceed 50%. The poor accuracy, in particular during magnetically disturbed conditions, affect satellite lifetime predictions, and is one of the important issues to be addressed within an ESA space weather initiative.

The reason for the unsatisfactory performance of models are many. They include lack of sufficient sensor accuracy and inappropriate assumptions in the extrapolation procedures used to extend the empirical model to altitudes were data are sparse. It is therefore useful for many atmospheric studies to measure the state variables of the upper atmosphere: density, temperature, composition, and winds. In this respect, the orbit of a low-altitude satellite of the Magnetometry Mission provides a rare opportunity to study upper atmospheric dynamics. The extremely low altitude of the satellite, its relatively long lifetime, and the high inclination orbit, allows an unprecedented and comprehensive in situ study of the neutral part of the atmosphere provided suitable instruments could be accommodated.

4. Observation Requirements

4.1. Introduction

The seventeen years gap in satellite Earth magnetic field measurements since Magsat will be partly closed by the Danish Ørsted, the German CHAMP and the Argentine SAC-C satellite.

The Ørsted mission is scheduled for a launch in spring 1997 having an elliptical polar orbit with 97° inclination and a nominal lifetime of 14 months. The (calibrated) accuracy of the vector magnetometer (including the star imager) is expected to be about 4nT per component or better, respectively 1nT for the scalar magnetometer. CHAMP is a gravity and magnetic field experiment spacecraft planned to be flown in mid 1999 as a 5 years mission in a 500 km circular orbit with 90° inclination and a decrease in altitude towards the end of the mission down to 300 km. The vector magnetic field accuracy is designed to be of the order of the Ørsted satellite. The SAC-C spacecraft, planned to be launched in 1998 into a sunsynchronous circular orbit of initially 580 km altitude (finally 400 km after 3 years) with an orbital plane drift of 30 min in local time over 3 years, 97.7° inclination, will carry a duplicated Ørsted Flux Gate Sensor and Star Imager thus having a measurement accuracy of about 4 nT per component.

Besides those missions there was a detailed ESA study (Aristoteles) on an Earth's Gravity and Magnetic field mission. This mission, however, was never approved.

The planned national missions will mainly contribute together with the Magnetometry Mission to a minimum appropriate period of observation of a full solar cycle - to investigate the secular variation of the main field. These missions will however not be sufficient in duration, altitude, local-time coverage and inclination to address the scientific objectives and requirements of the Magnetometry Mission related to external fields and in altitude related to lithospheric fields. The objectives and requirements as discussed in Chapter 2 and Chapter 3 therefore demand a partly simultaneous presence of two satellites in a polar orbit with different altitudes (600 to 1060 km, and below 250 km) and full local-time coverage.

4.2. Orbit Requirements

4.2.1. Altitude

The orbit altitude requirements are dominated by the main field investigation and its secular variation and by the lithospheric structure (anomaly) measurements. The spatial resolution decreases with the increase of satellite altitude. As a zero order approximation it can be assumed that the maximum spatial resolution of magnetic fields on the Earth's surface as measured in space equals the satellite's altitude (Langel and Estes, 1982).

The requirement for accurate main field measurement therefore is to select an altitude as low as possible to get the highest spatial resolution but to select a minimum altitude where the relatively short wavelength and small amplitude lithospheric and ionospheric field contribution can be tolerated as 'noise' in the data. As discussed in Chapter 3 main field and secular variation studies require spatial resolutions corresponding to a maximum spherical harmonic degree of 13. In order to resolve this high degree term of the main field, the orbit altitude with the maximum possible measurement accuracy of 1 nT must be below 1060 km, because at this altitude a typical value of 10 nT at the Earth's surface for the $n = 13$ coefficients is decreased below about 1 nT. Because of the lifetime requirements for long term monitoring of the field for main field and secular variation studies of at least 5 years or one solar cycle in conjunction with the other national missions, a minimum altitude of 500-600 km is recommended.

This recommended altitude, however, is too high to get a reasonable resolution for lithospheric anomalies and a required improvement versus the Magsat results (350-550 km). For this latter purpose the altitude should be below 250 km with 200 km as a design goal. With an altitude of 250 km lithospheric anomalies up to a degree of about $n = 80$ in spherical harmonics can be detected.

The above requirements are best met by a mission consisting of two satellites designated as Geomagnetic Space Observatory - High (GSO-H) in a high altitude orbit and Geomagnetic Space Observatory - Low (GSO-L) in a low altitude orbit.

4.2.2. Local Time Coverage, Geographical Coverage, and Orbit Inclination

The magnetic field at the Earth's surface or at satellite altitude is a combination of core, lithospheric and external fields with the core fields dominating with more than 90% of the field, depending on the altitude of measurements. The lithospheric field is independent of local time. The external field in equatorial and polar regions, however, caused by ionospheric and magnetospheric currents strongly depends on the Sun's activity and position, which means local time. These local time dependent fields, in general, vary between several nT and several hundred nT in magnitude. To separate the local time dependent fields requires a multi-times full coverage of local time for various solar activity conditions.

This complete local time and geographical coverage can be achieved with a polar orbit, where a complete local time coverage is achieved every 6 months. Therefore a high inclination is preferred for all main field, lithospheric, and external field studies.

4.3. Mission Duration

The mission duration of the GSO-H is driven by the observation of the secular variation. A decade of observation is the minimum appropriate time to observe the steady variation of the field and to have a high probability to detect one or more jerks if available statistics of these remarkable events are correct. Taking into account the planned Ørsted, CHAMP and SAC-C missions, the lifetime of the Magnetometry Mission must be at least 5 years. This duration is also advantageous for external field studies because those fields are driven by the solar activity.

The mission duration of GSO-L is driven by the need to sample all local times and to obtain a sufficiently dense and uniform coverage (at least about 100 km at the equator) of the whole surface of the Earth. Because the lithospheric fields are nearly constant, this requirement can be met with a satellite lifetime of 6 months

Only such a combination of high and low altitude measurements with the same polar orbit and proper selection of simultaneous measurements as well as periods of different local-time coverage will provide unprecedented measurements of the field and thus allowing the best possible separation of the standing lithospheric field from the local-time dependent ionospheric field and from the irregularly changing core field. The identical inclination and local time of the two satellites for about six months will provide intercalibration possibilities between both spacecraft which will improve the overall measurement accuracy. The periodic radial alignment by two satellites will also provide unique observations of meridional currents associated with the Equatorial Electrojet.

4.4. Accuracy Requirements for the Magnetic Field Data

The highest accuracy requirements on the vector magnetic field data are based on the scientific objectives and the data analysis for main field measurements and separation as discussed in Chapter 3 which includes the requirements for core motion, secular variation, jerks, LOD and IGRF calculations.

The main field dominates at the Earth's surface for values of the spherical harmonic degree $n < 13$. In the Earth's field models the amplitude of the field of degree $n = 13$ has a typical values of about 10 nT at the surface which decreases to about 1 nT at 1060 km or 2.6 nT at 600 km altitude. The accuracy requirement design goal is therefore better than 1.5 nT per component. This accuracy is very satisfactory for lithospheric as well as for external field studies.

Given the power law attenuation of the field with altitude, as given in Section 3.2.6, increasing the accuracy (signal to noise ratio) by a factor of 3-4 compared to Magsat (Magsat accuracy was 5-6 nT) increases the maximum harmonic degree n to which the field can be determined (cut off harmonic degree) at a given altitude (in the range 250-500) at least by $n = 20$. This confirms that the Magnetometry Mission can provide an accurate description of the magnetic field up to at least $n = 80$ as stated in Section 2.3.2.

In addition, the above accuracy is consistent with the requirement for retrieving the various constituents: core, crust and external.

In terms of resolution the design driver is the study of field-aligned currents. This needs a resolution of about 0.2 nT together with a high time resolution of 100 samples per second.

4.5. Error Sources

The 1.5 nT accuracy on each component has to be distributed between the various error sources discussed below.

4.5.1. Instrument Errors

The vector magnetometer errors can be estimated as follows:

calibration coil	0.1 nT	(equivalent to 0.5 arc sec)
calibration accuracy per component	0.2 nT	(equivalent to 1 arc sec)
internal sensor axis misalignment	(equivalent to 0.25nT)	1 arc sec
instrument error	0.5 nT	(offset stability, temperature correction)
inter-calibration	0.5 - 1 nT	with scalar magnetometer

These alignment and calibration errors result in an rss error of 0.8-1.2nT. The intercalibration error was estimated assuming the absolute error the scalar magnetometer used for calibration is 1-1.2 nT.

4.5.2. Spacecraft and Instrument Fields

Another source of inaccuracy for the vector magnetometer is the spacecraft field contamination. From the experience with other spacecraft like Ulysses, Giotto, CLUSTER and CASSINI/Huygens, a spacecraft field (DC) of 0.4 nT at 8 m distance from the spacecraft centre of mass is required This corresponds to a worst case overall magnetic moment of the spacecraft of 1 Am^2 at the centre of the spacecraft.

A DC spacecraft magnetic field error budget can be estimated:

		at Vector Magnetometer [nT]
Spacecraft field	(design goal for radial component)	0.4
Torquer Coils	calibrated induced field	0.04
Ni-Cd battery	induced field	0.1-0.2
Thrusters	(compensated)	-
Star Imager	calibrated	-
Total error	**0.5nT**	**rss 0.4-0.5 nT**

4.5.3. Timing and Position Errors

The error caused by the timing and position inaccuracies should be negligible compared to the magnetic field measurement accuracies.

The timing error of each measurement corresponds to a position error of the satellite. With a satellite velocity between 7-8 km/s and an overall timing accuracy of 1ms the equivalent position error along track is 7-8 m. This position error can be translated into magnetic field error if the different maximum field gradients of the Earth's magnetic field are considered.

Langel [1991] has calculated the maximum field gradients per km in a 300 km circular polar orbit. These gradients are equivalent to a satellite orbital position error of 1 km. They are shown below in nT per km in a 300 km orbit.

	Vertical	along track	cross track
B_r	-28.0	-13.3	6.8
B_θ	1.8	-6.5	23.4
B_θ	8.4	-2.0	23.3
B	-28.0	-6.1	5.7

The timing error of 1 ms (equivalent to 7-8 m along track) therefore corresponds to a field error of approximately 0.1 nT. With the available GPS receivers position measurement accuracies of cm in all three directions can be obtained. Therefore the induced error is negligible.

4.5.4. Attitude Error and Total Error Budget

Measuring the vector components of the magnetic field on board a spacecraft requires a transformation from the magnetometer coordinate system to the inertial reference frame. This requires an accurate knowledge of the attitude of the vector magnetometer provided by star imagers mounted on an optical bench together with the vector magnetometer. The required accuracy of the attitude system can be estimated from the total error budget, which shows that in order to meet the 1.5 nT objective the attitude error should be 0.75 nT (equivalent to 2.5 arc s at 60000 nT ambient field).

Instrument errors	1.2nT rss	acc. to 4.5.1
Spacecraft fields	0.5 T rss	acc. to 4.5.2
Timing and position errors	0.13nT rss	acc. to 4.5.3
Attitude errors	0.75 T rss	
Total error	**1.5 nT rss**	

With proper control of the spacecraft DC field during development, the proposed intercalibration with a scalar magnetometer and the possible intercalibration periods with the second satellite (simultaneous measurements) a design goal of 1nT per component will be feasible.

4.6. Sampling Period and Spatial Resolution

For satellite altitudes of about 250-300 km the characteristic anomaly scale size (half amplitude width of the anomaly) which can be detected is about 250-300 km and greater. With an orbital velocity of about 8 km/s a sample rate of 1 per s for the vector magnetometer would be appropriate. However, the time resolution requirements are driven by the interpretation of the time varying ionospheric currents, for which a sampling rate of 10 samples per second is appropriate and the fine structure of external magnetic field variations caused by field-aligned currents at higher magnetic latitudes. Here structures with scale sizes between 10 to 100 m have been reported which correspond to a time resolution of 100 vectors per second. Consequently, the sampling rate for the vector magnetometer should be 10 samples per second for latitudes say below 50° and 100 samples per second for higher latitudes.

4.7. Supporting Measurements

To complete the science return of the mission two instruments, a Charged Particle Detector (CPD) and an Ion Drift Meter (IDM) have been included in the baseline. The following table summarises their relevance to the mission objectives.

Mission objective	Observable	Relevance	Instrument	Range	Performance
Field-Aligned Currents	Particle fluxes	Monitoring solar activity Sorting out of magnetic field lines	Charged particle detectors (CPD's)	Electrons 30 keV - 1 MeV Protons, alpha 200 keV - 100 MeV	
Ionospheric currents	Ion velocities	Monitoring the electrodynamics of ionosphere	Ion drift meter (IDM)	- 4 km/s +4 km/ s	± 50 m/s 1 Hz sampling

4.8. Optional Observations

4.8.1. EEP - Electromagnetic Earthquake Probe

Recent magnetic Extreme Low Frequency (ELF) observations on ground and from space (Aureol-3) in the frequency band from 100 Hz to several tens of kHz (Parrot and Mogilevsky, 1989) have shown that magnetic oscillations may be generated from earthquake epicentre regions before or after the earthquake. With the above satellite, a few positive correlations between earthquakes with $M_s = 5$ and electric and magnetic sensor signals have been observed.

Other studies based on DE-2 satellite electric field data do not show a correlation between shocks and electric signal activity because the stronger electric noise level on the spacecraft may have masked the EEP signal. Considering the importance of earthquake warning, we propose the addition of a single three component magnetic search coil to investigate the EEP phenomena.

The GSO-H spacecraft provides the most appropriate lifetime, coverage and orbit to perform a pilot investigation.

In case EEP science objectives are included in the mission, the sampling rate for the vector magnetometer should be increased to 100 samples per second also at lower latitudes (< 50°).

4.8.2. State and Dynamics of the Upper Atmosphere

As mentioned in Chapter 3 the external field studies may benefit from the inclusion of additional instruments that can measure the state variables of the upper atmosphere: density, temperature, composition, and winds. Atmospheric parameters can be observed with several combinations of instruments. An instrument package may include an ion/neutral spectrometer, possibly coupled with a retarding potential analyser (RPA) to determine temperatures, and an accelerometer. The requirements to the instrumentation is that atmospheric density can be determined within 5 %. This should be possible with flight-proven instruments. In summary we propose the following optional instruments for the GSO-L spacecraft.

Particle Spectrometer:	Energetic particle precipitation (E > 1 keV)
Electrostatic Triaxial Accelerometer:	Neutral density and winds
Quadropole Ion/Neutral Mass Spectrometer:	Ion and neutral density, composition, wind
+ Retarding Potential Analyser (RPA):	Temperatures

4.9. Ground Based Observations

Magnetic field data from existing networks of magnetic observatories will be required to ensure the full realisation of mission objectives. Annual and monthly mean values will be needed so that secular-variation information from the satellite data can be verified against what is observed at the surface. Data with a higher time resolution (minute values or even more frequent) will be needed to assist the separation of external fields from the satellite data. Disturbance indices such as Kp, Ap, Dst, AE normally produced from magnetic observatory data will be widely used for data selection and interpretation purposes.

Detailed surface and near-surface measurements of the crustal anomaly field will be needed to compare with the longer-wavelength anomaly field measured by the satellite.

4.10. Conclusion

The following table summarises the primary observational requirements.

	Field component accuracy (nT)	**Spatial resolution half wavelength (km)**	**Sampling rate (Hz)**
Main field modelling	1.5	1500	10
Length of day, jerks, secular variations, and core motion	1.5	1500	10
Lithospheric structures	1.5	250	1
Ionospheric currents	1.5	100	10
Field aligned currents	1.5 (0.2)	0.01	100

(Number in brackets indicates resolution, i.e. relative accuracy)

The sampling rates of 10 Hz specified for studies of the main field, secular variation and lithospheric anomalies are needed for an accurate removal of external field effects from the observed signal.

5. Mission Elements

5.1. General

The Magnetometry Mission is intended to ensure the indispensable continuity of observations of the main magnetic field and of the external fields extending the sequence Ørsted - CHAMP (SAC-C) to cover together a complete solar cycle, i.e. the minimum time span for the proper investigation of issues related to the secular variation of the main field and to external fields. This mission should also provide a global and homogeneous data set on the lithospheric magnetic anomaly field. The numerous research and also application oriented areas that should benefit from this mission imply a large scientific community. This community is already organised around the Ørsted mission, precursor of the high altitude satellite of the Magnetometry Mission, i.e. the GSO-H. The community is already global and growing and will gain even more momentum around the CHAMP and SAC-C missions.

5.2. Space Segment

Taking into account the requirements listed in Chapter 4 and the expected results of the planned national missions, the space segment of the Magnetometry Mission would include two satellites GSO, at different altitudes:

GSO-H	Main field and secular variation and external fields; 600 km altitude, 90° inclination, 5 years lifetime.
GSO-L	Lithospheric anomaly and external fields; 250 km altitude or lower, 90° inclination, 6 months lifetime.

In both cases the payload would be composed by the same set of instruments:

– *Vector Magnetometer:*	Measurement of the three components of the magnetic field
– *Scalar Magnetometer:*	Calibration of the vector magnetometer
– *Charged Particle Detectors:*	Particle flows associated with solar activity
– *Ion Drift Meter:*	Derivation of the electric field
– *Global Navigation Satellite System (GNSS) Receiver:*	Timing and localisation of magnetic field measurements; ionospheric research; GRAS (GNSS Receiver for Atmospheric Sounding) is assumed
– *Star Imager:*	Transformation of magnetic field measurements to reference coordinates

To address the additional research objectives (Section 3.6), complementary instruments would be embarked on the GSO-H and GSO-L. The GSO-H, with its longer lifetime, would be the preferred carrier for the investigation of electromagnetic activity associated to events, e.g earthquakes:

Charged Particle Detectors	The baseline Charged Particle Detector set has to be complemented with additional detectors for lower level energy, 1 keV
Earthquake Electromagnetic Probe (EEP)	Sensor to monitor electromagnetic activity at satellite location in the range 10 Hz to 1 MHz to investigate possible association to earthquakes

The GSO-L, with its lower altitude, would be the appropriate carrier for the instrumentation devoted to the investigation of the upper atmosphere:

Accelerometer	3 axis accelerometer to infer neutral density and winds
Spectrometer	Quadruple Ion/Neutral Mass Spectrometer to measure ion and neutral density, composition and wind. It includes a Retarding Potential Analyser.

5.3. Ground Segment

The ground segment concept includes the following elements:

- a command and data acquisition station at suitable Northern latitude;
- a mission operations and satellite control element;
- a processing and archiving element that performs preprocessing of data and provides archiving facilities;
- a science data centre that continues processing to obtain geophysical products.

Ground observations would support the space based observations with a series of measurements provided by magnetometer arrays, imaging riometers, radars, ionosondes and all-sky cameras. The ground observations would continue to provide indices of magnetic disturbances like Kp and Dst to support the selection of space data sets. In addition the IGS network of geodetic quality GPS receivers would also support the mission.

5.4. Contribution from and to Other Missions

The Magnetometry Mission would form a sequence with the Ørsted and CHAMP and SAC-C missions spanning a complete solar cycle of observations, which is the minimum appropriate duration for a magnetometry mission. Other missions that explore electromagnetic activity from space could be of interest, e.g. for the establishment of theories related to correlation between earthquakes and electromagnetic activity. Future solar and magnetosphere missions are also relevant to the Magnetometry Mission and would in turn benefit from this mission. The ionospheric research objectives of the Earth Explorer Atmospheric Profiling Mission are also related.

6. System Concept

6.1. General

Figure 6.1 shows the main constituents of the Magnetometry Mission. The two satellites and their essential instruments are shown. The main blocks of the ground segment are also outlined.

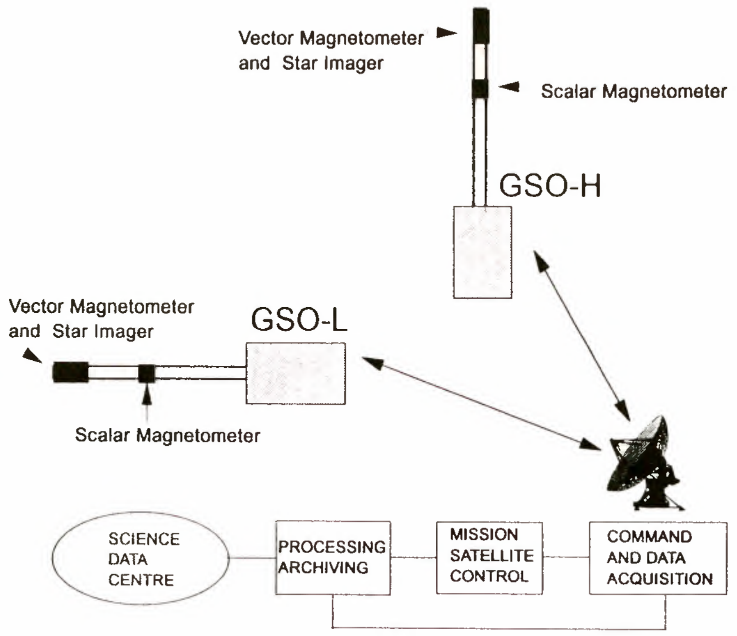


Figure 6.1. *The constituents of the Magnetometry Mission*

6.2. Payload

The payload concept of each of the two satellites includes a vector magnetometer, a scalar magnetometer, a charged particle detector, an IDM, a GPS/GLONASS receiver and a star imager. Figure 6.2 shows their observational objectives and synergies.

6.2.1. Vector Magnetometer

This is the essential instrument of the mission. It measures the three components of the magnetic field at the satellite's location. It has to be co-located with the star imager on an optical bench for extremely accurate attitude determination. This bench would be located at the tip of an 8 m boom to guarantee magnetic cleanliness.

The instrument would be a fluxgate magnetometer similar to that used for Ørsted. It includes a compact spherical coil (CSC) sensor to obtain quasi-perfect spherical isotropy. The processing and power electronics and the interfaces complete the instrument.

The main performance characteristics are:

- Absolute accuracy: 0.5 nT
- Resolution: 0.1 nT

- Linearity: 0.05 nT
- Dynamic Range: +/- 65000 nT
- Operating frequency: up to 100 Hz

This performance meets, with margins, the requirements established in Chapter 4.

The vector magnetometer can be derived from the Ørsted magnetometer. Potential improvements already under way include the replacement of analog circuitry by a digital signal processor. The performance of such an instrument would be limited by the intrinsic accuracy of the sensor. A reduction of one order of magnitude in the noise can be expected.

The instrument will have a mass below 1.5 kg, require less than 1.8 W and generate 5.4 kbps at high sampling rate, 100 Hz.

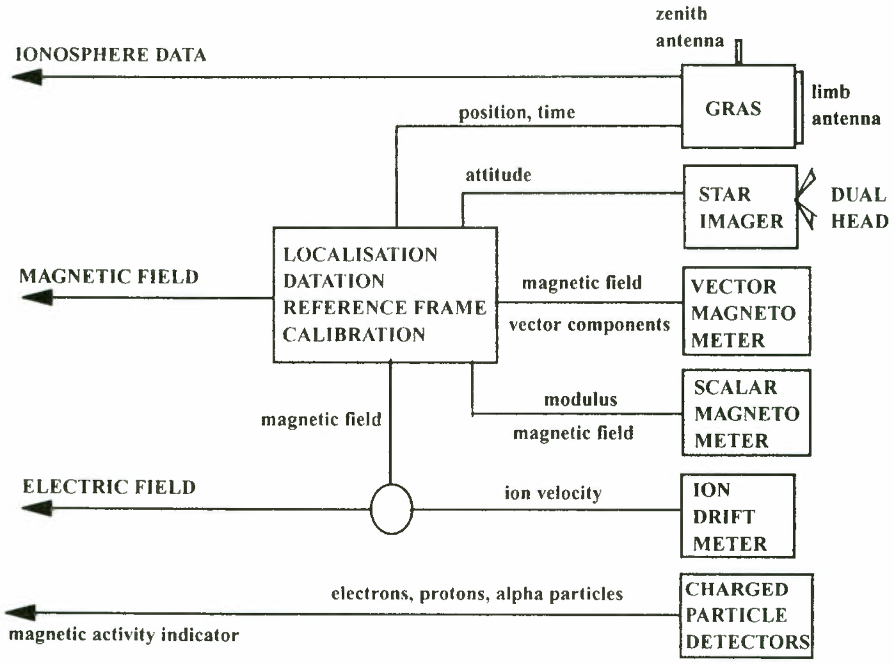


Figure 6.2. *The payload: functions and synergies*

6.2.2. Scalar Magnetometer

This instrument would provide the modulus of the magnetic field at the satellite location and can be used to calibrate the drift of the vector magnetometer. It would be mounted on the same boom as the vector magnetometer but 2 m closer to the satellite to avoid interference.

Three types of scalar magnetometers have been considered for this mission: optically pumped magnetometers as flown on Magsat, proton precession magnetometers using the Overhausser effect as planned for Ørsted and CHAMP and the new generation of proton free precession magnetometers. A proton free precession magnetometer, the most common type of scalar magnetometer for ground applications, is proposed for its simplicity and expected performance. The sensor in this magnetometer is toroidal enabling it to operate in all field directions and produces a slow decaying AC signal with a frequency which depends only on the external magnetic field. This signal is analysed in a signal processor with a time base related to UTC. The GPS/GLONASS receiver (GRAS) is used to monitor the quality of this frequency reference.

The main performance characteristics are:

- Absolute accuracy: 0.25 nT
- Resolution: 0.1 nT
- Dynamic Range: 15000 nT - 60000 nT
- Operating frequency: will be operated every minute

This performance meets, with margins, the requirements of Chapter 4.

This type of scalar magnetometer is universally used on ground and flight versions are under development including improvements of the DC/RF polarisation to reduce excitation power and increase the sampling frequency.

The scalar magnetometer will have less than 1.5 kg of mass, require less than 3.4 W of power and generate less than 0.1 kbps.

6.2.3. Charged Particle Detectors

A set of CPDs would be included in the payload to measure the flow of electrons, protons and alpha particles. The objective is to assess the suitability of the magnetometer observations for external field (dynamic times) or internal field (quiet times) studies.

The CPDs can detect the following energy levels:

Electrons: 30 keV - 1 MeV
Protons: 200 keV - 100 MeV
Alpha Particles: 600 keV - 124 MeV

The instrument would have a total mass of less than 2.8 kg, consume less than 1.3 W and generate 2.4 kbps of data.

The CPDs for this mission could be based on the instruments of Ørsted with higher sensitivity and appropriate interfaces.

6.2.4. Ion Drift Meter

An IDM measures the vector drift velocity of ambient ions which allows the derivation of the ambient electric field. The detector of the IDM should be mounted on the ram side of the satellite. It measures the angle of the incoming ion flux by means of a segmented anode. The IDM includes a retarding potential analyser to obtain the ion velocity parallel to the IDM direction of view. These observations and the knowledge of the spacecraft's attitude would allow the derivation of the ion velocity in Earth-centred coordinates and thereby the electric field vector (from the relation between electric and magnetic fields and ion velocity).

The performance characteristics are:

- Accuracy: better than 50 m/s, equivalent to 2.5 mV/m in electric field accuracy
- Range: +/- 4000 m/s
- Sampling rate: 1 Hz

The IDM has an estimated total mass of 0.5 Kg including detector and electronics, consumes 0.5 W and generates 0.7 kbps of data. The IDM is a simple instrument that could be provided by several groups in Europe and abroad.

6.2.5. GPS/GLONASS Receiver

The GPS/GLONASS receiver would have a dual function, as a satellite facility and as a science instrument. The GRAS has been selected. Its main characteristics are summarised below.

- Number of parallel dual frequency channels: 12
- Carrier phase noise at 10 Hz output rate: < 1 mm rms
- Code phase (pseudo-range) noise at 1 Hz output rate: < 25 cm rms (GPS)
  < 50 cm rms (GLONASS)

Two antennas are required, one for position determination oriented to zenith, and a second one for ionospheric sounding, oriented to the limb. With these characteristics the derived performances fully meet the requirements established in Chapter 4.

As a satellite facility, the receiver is required for timing and geolocalisation of the magnetometer measurements. Concerning timing, the 1 ms requirement of Chapter 4 can be met easily (by about a factor of at least 100). This would reduce the equivalent position error to 7-8 cm and the contribution to the magnetic field error accordingly. For position determination the accuracy achievable onboard in real time will be better than 100 m which is enough to enter in the ephemeris and magnetic field models used with the sun sensors and the magnetometers for attitude estimation. After processing the accuracy will be at the cm level and the related magnetic field error will be negligible.

As a science instrument the receiver could be used for ionospheric sounding by tracking the signals of the GPS/GLONASS satellites going to occultation. These observations complement those of the Magnetometers, IDM and CPDs by measuring total electron contents (TEC) and electron density. The ionospheric sounding mission of GRAS is described in the Report for Assessment of the Earth Explorer Atmospheric Profiling Mission.

The present estimates for GRAS are: 3 kg of mass (excluding antennas), 15 W of power consumption and data rate of 10 kbps. The power and data rate estimates assume that GRAS is fully used for atmospheric sounding. These values are much lower if only position determination and timing are required. Laboratory models of GRAS have been already successfully tested. The development is continuing.

The mass of the antennas can be chosen to be compatible with available satellite resources. Smaller antennas will restrict the number of atmospheric profiles obtainable.

6.2.6. Star Imager

The star imager is needed to determine the absolute orientation in celestial coordinates. A dual head sensor would be used, located at the tip of the boom and sharing the optical bench with the vector magnetometer. The sensor has to have two unobstructed views to allow operation also with the sun in the field of view of one of the two heads. High accuracy is achieved by matching star patterns with a very high quality star catalogue.

The performance characteristics are:

- Accuracy: better than 2 arc sec
- Output frequency: one update every 0.5 s
- Allowed rotation rate: up to 0.5°/s

The sensor will have a total mass of 2.4 kg, consumes 5.3 W and generates 0.1 kbps of data.

The attitude transfer between the star imager and the vector magnetometer is achieved by means of an optical bench. The high attitude estimation accuracy provides a notable reduction of the error budget with respect to Magsat and even with respect to Ørsted.

6.2.7. Optional Instruments

In addition to the essential payload the following optional instruments are considered for the potential implementation options addressed in Section 6.7.

Earthquake Electromagnetic Probe (EEP)

The EEP is a possible option to detect electromagnetic activity in the range from 10 Hz to 1 MHz. The EEP would complement the magnetometers which cover the frequency range from DC to 100 Hz. The objective would be to investigate the potential association of electromagnetic activity with earthquakes.

The proposed EEP concept consists of the sensor and its pre-amplifier, located at the tip of a 2 m boom, and the wave analyser. The EEP covers the 10 Hz to 1 MHz range in two frequency regions and overlaps with the vector magnetometer in the 10-100 Hz frequency range. The sensor is a coil of 400 turns of aluminium wire arranged in 4 sections of 100 turns each separated a few mm to avoid stray capacitance. The coil area is 0.1 m^2 and the total mass of the sensor is less than 1 kg including support structure. 1 kg is also assumed for the pre-amplifier and other interface electronics. The power consumption is estimated to be 2 W.

The performance characteristics of this concept are:

- Low frequency band: 10 Hz (0 dB) - 15 kHz (40 dB)
  Sensitivity: @ 10 Hz: 7.93 pT/ sqrt(Hz)
  @ 10 kHz: 5.12 fT/sqrt(Hz)
  Dynamic range: 135 dB

- High frequency band: 10 kHz (+50 dB) to 1 MHz (42 dB)
  Sensitivity: @ 100 kHz: 4.36 pT/sqrt(Hz)
  @ 1 MHz: 11.2 fT /sqrt(Hz)
  Dynamic range: 125 dB

The wave analyser function would be performed by the on-board data handling system. Additional resources are estimated in 1 kg, 2 W. The analyser would sample in 8 channels the EEP and the magnetometer output at 1 Hz. The rate could be increased in burst mode upon ground command. On average the additional data rate from the EEP would be 0.2 kbps.

Accelerometer

The accelerometer would measure the vector components of the drag forces on the satellite. These forces are related to the satellite velocity and the atmospheric density and winds. The scientific return would be enhanced by the addition of a mass spectrometer. The main performance characteristics of a potential accelerometer candidate are:

- Accuracy for across track winds: better than 50 m/s
- Accuracy for density: better than 5%
- Measurement range: 0.01 m/s^{-2}

- Resolution: 10^{-7} m/s^{-2}
- Sample rate: 1Hz

The accelerometer would have to be installed as close as possible to the centre of mass of the satellite. Its mass would be less than 6 kg and require less than 4 W of electrical power. It would generate 0.1 kbps of data.

Neutral Mass Spectrometer

This instrument would measure neutral cross-track winds, temperatures and composition. The main performance characteristics would be:

- Accuracy, cross track winds: better than 50 m/s
- Density: better than 10%
- Sample rate: 1 Hz

The instrument would have to be accommodated on the ram side of the spacecraft. Its mass would be less than 6 kg, require less than 12 W and generate 0.6 kbps of data.

6.3. Mission and Operations Profile

6.3.1. GSO-H Mission Profile

The GSO-H would be placed on a polar orbit of 600 km altitude and 90° inclination. This orbit sees all local solar times in a 6 month period. With the configuration and inertia properties of the baseline concept described in Section 6.4, the GSO-H will stay 5 years in a 50 km altitude band without any orbit maintenance (assuming launch close to the worst solar activity conditions). Figure 6.3 shows the estimated orbit decay. This figure also shows that it would be possible to span the time from before the solar maximum until after the solar minimum.

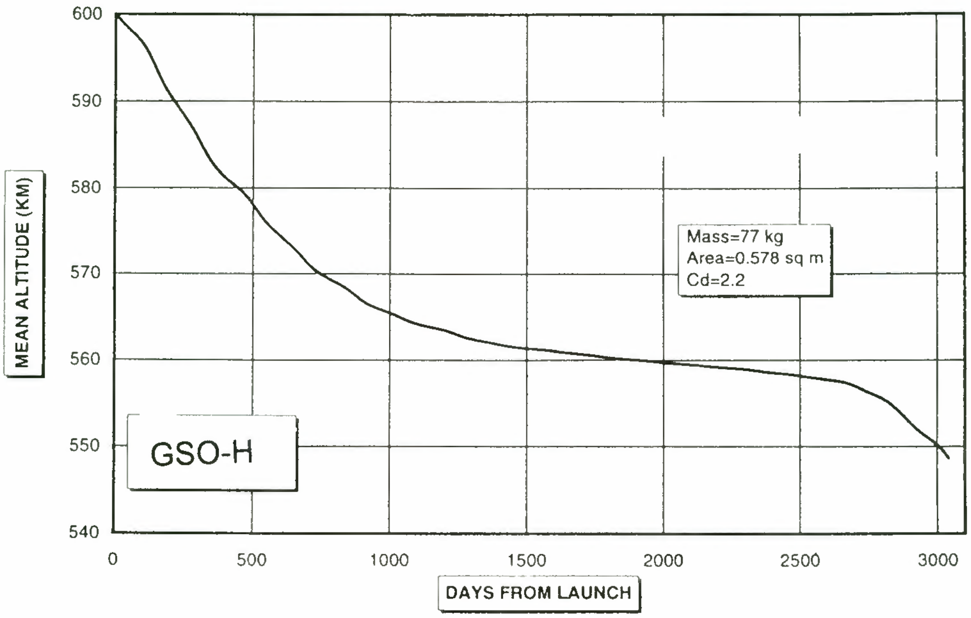


Figure 6.3. *GSO-H: orbit decay, launch date 1 June 2000*

Stabilisation by gravity gradient supported by magnetotorquers can be envisaged. Figure 6.4 shows the GSO-H flying attitude, boom towards zenith.

No attitude manoeuvres are foreseen after the initial detumbling phase, except to optimise power generation in the worst orbital conditions (around noon - midnight conditions towards the end of life). The attitude control system will have the capability to recover the operational attitude if for any reason the gravity gradient stabilised attitude was lost.

The GSO-H is planned for a nominal mission duration of 5 years but clearly, a longer lifetime can be reasonably expected.

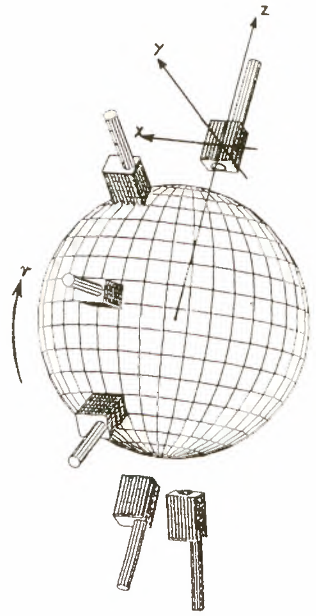


Figure 6.4. *GSO-H: flight attitude*

6.3.2. GSO-L Mission Profile

The GSO-L would operate in an orbit of 90° inclination and less than 250 km of altitude. The initial altitude after separation from the launcher would be 280 km. This has been selected to provide sufficient time for commissioning and to cater for launcher injection errors. The nominal operational altitude is 230 km and has been defined so as to guarantee a period of 7 days of uncontrolled decay before the minimum design operational altitude, 200 km, is reached. These 7 days would be the time available to recover a major failure. The operational altitude would be acquired after commissioning by natural decay caused by drag. To accelerate this decay the satellite attitude could be changed to increase the drag. The GSO-L is therefore designed to operate at 200 km altitude and above.

Figure 6.5 shows the orbital decay assuming maximum solar activity, launch in mid 2003 and the configuration and inertia properties presented in Section 6.4. Launch delays would result in lower solar activity and in consequence in slower decay. The worst case estimate of delta V to keep the spacecraft at 200 km for 6 months is 879 m/s (equivalent to 63 kg of hydrazine).

The attitude would be Earth pointed, in the so called "comet mode" with the boom trailing behind the satellite body as shown in Figure 6.6. No attitude manoeuvres are nominally foreseen.

The duration of the planned mission is 8 months assuming 6 months of operations and 2 months for commissioning and potential campaigns.

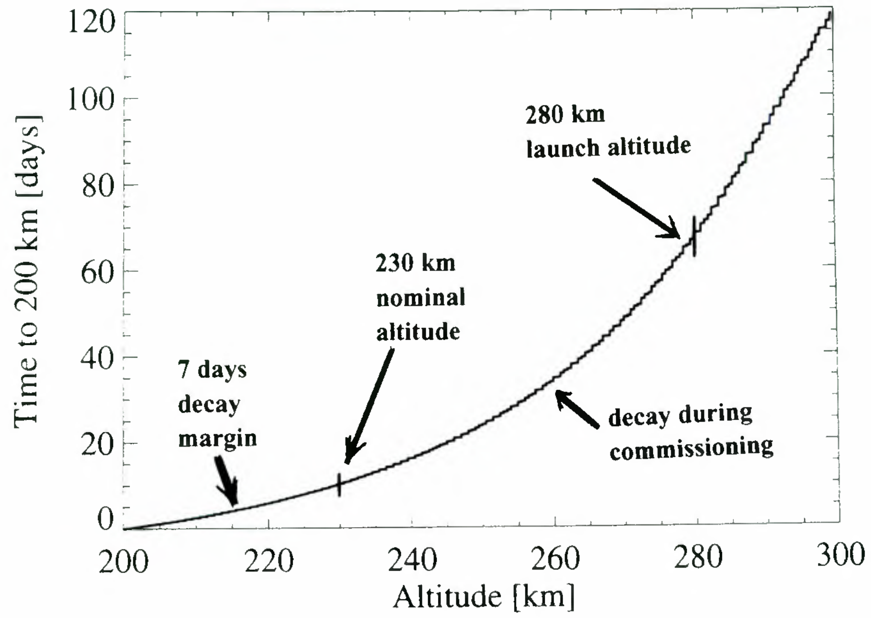


Figure 6.5. GSO-L orbit decay

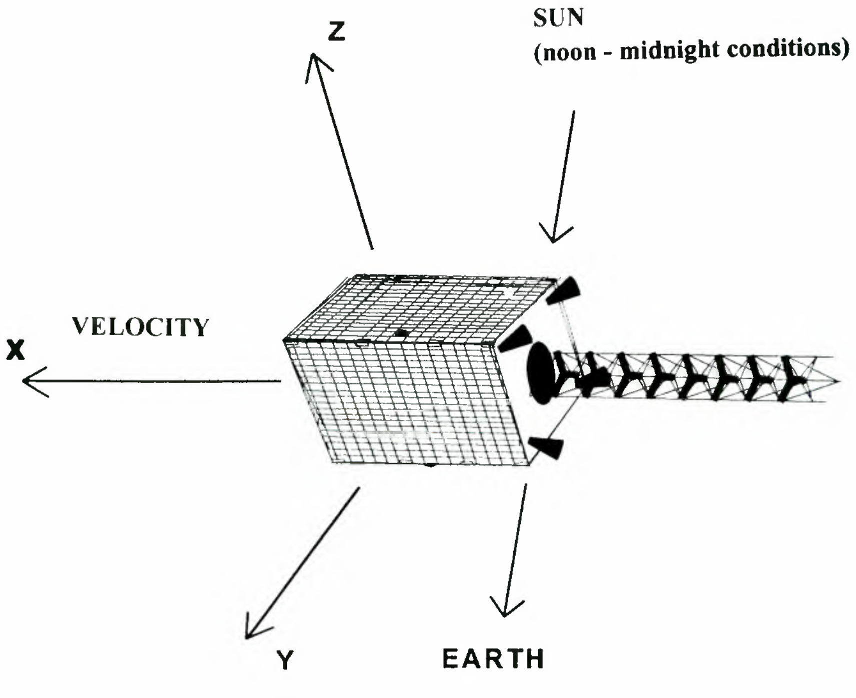


Figure 6.6. GSO-L flight attitude

6.3.3. Operations

The operations of the GSO-H and GSO-L concept are extremely simple. A single nominal operational mode is envisaged with all instruments operating continuously. Two submodes have been identified which differ in the sampling rate of the vector magnetometer: 100 Hz for latitudes above 50° and 10 Hz elsewhere. The switch over is automatically commanded according to the satellite location as estimated by GRAS.

In addition, a campaign mode has been introduced to allow dedicated observations of special events, e.g. earthquakes. In the campaign mode the sampling rates of the magnetometers and the CPDs would be increased within the limitations of the onboard resources.

6.4. Spacecraft

The most demanding satellite is the GSO-L. Due to the very low altitude of its orbit the GSO-L concept requires propulsion and full active attitude control which are not needed at the orbit of the GSO-H. The Earth Explorer Magnetometry Mission could be implemented with two identical satellites driven by the requirements of the GSO-L. However, if timeliness is taken into account, the GSO-H should be available as soon as possible to back-up CHAMP and to guarantee no interruption of observations. The GSO-L would benefit from a later launch, mid 2003, when the worst of the solar activity should be over. This suggests for the GSO-H a quick development, which implies simplification. A concept based on Ørsted is therefore suggested. Another reason to keep the GSO-H as simple as possible is the potential utilisation in constellations if the interest for a system to monitor electromagnetic activity for earthquake detection is confirmed. Nevertheless a high level of commonality is guaranteed between the GSO-H and GSO-L concept, in particular the complete payload, including the boom and the optical bench, the platform mechanical and thermal design concepts and the complete electrical power, command and data handling and communication systems. The main differences are that the GSO-L requires a propulsion module and a more complex attitude control system.

6.4.1. GSO-H

Configuration

The proposed configuration has been driven by the Ariane-5 Auxiliary Structure for Auxiliary Payloads (ASAP) envelope which was selected to reduce costs and to maximise future launch opportunities. For this first Magnetometry Mission a dedicated launch is however likely to be required. The other major configuration constraints are derived from the selected attitude stabilisation concept, gravity gradient, the accommodation of the boom and from the thermal and power generation requirements. The resulting satellite configuration is shown in Figure 6.7 and can be seen to be a parallelepiped with solar cells on the lateral and zenith sides (which also has the opening for the deployment of the boom).

Mechanical and Thermal

The structure concept is derived from the Ørsted satellite. A combination of aluminium and non metallic materials allows it to benefit from simplicity of manufacturing and to minimise magnetic disturbances.

The main mechanism is the 8 m boom that supports the optical bench with the vector magnetometer and the star imager, at the tip, and the scalar magnetometer, 2 m inwards. The boom length is driven by magnetic cleanliness requirements and the overall arrangement by the gravity gradient stabilisation concept. The proposed boom is a coilable lattice design of non magnetic material. The total mass is 4.4 kg. It is stowed inside the satellite body and deployed in orbit under ground command.

An optical bench guarantees the transfer of attitude measurements between the star imager and the vector magnetometer with an accuracy better than 1 arcs.

The thermal control system is passive. The internal surfaces of the structure and the internal boxes are black painted for radiative coupling. All heat dissipating equipment except the boom-mounted instruments are conductively coupled to the structure. The overall result is a single integrated thermal mass with long time constant. Radiation to the environment occurs through all sides but mainly through the nadir face which is exposed to Earth's albedo and infrared radiation and therefore requires selective painting. The boom mounted instruments are thermally isolated.

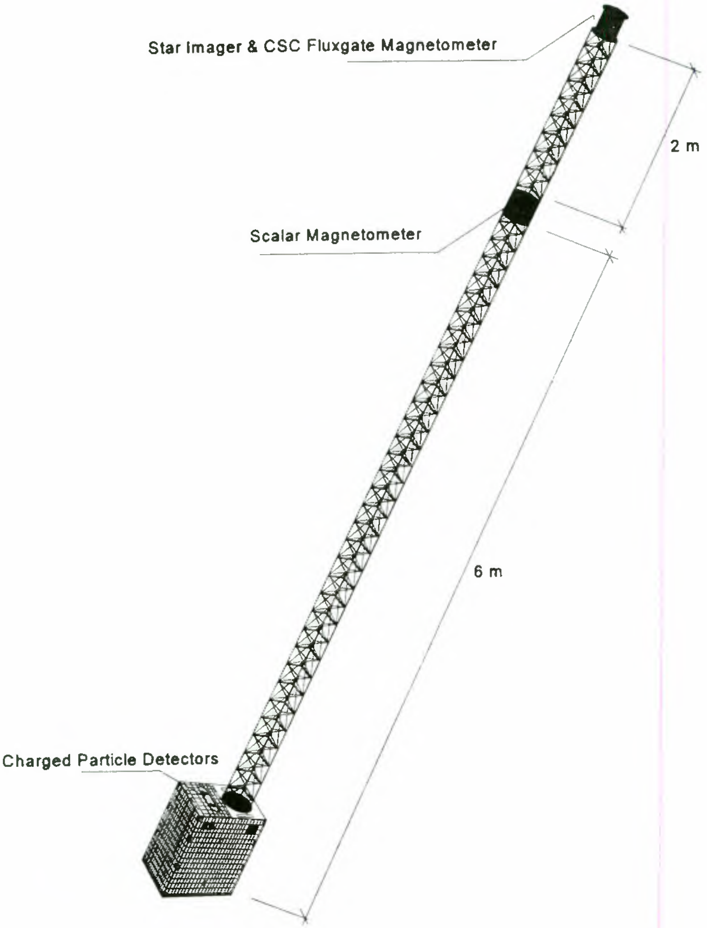


Figure 6.7. *GSO-H configuration concept*

Electric Power

The electric power system concept consists of the solar array, the battery and battery charge regulators, dc/dc converters and power distribution units. Panels of GaInP/GaAs cells (efficiency 22%) are mounted on all lateral sides and on part of the zenith side. They provide enough power to operate the satellite and charge the battery.

Propulsion

At the altitude considered no orbit maintenance would be required during the 5 years lifetime. As attitude control is achieved by gravity gradient and magnetotorquers, the GSO-H has no propulsion system.

Attitude and Orbit Control

The Attitude and Orbit Control System (AOCS) concept performs orbit and attitude estimation and attitude control. Orbit control is not required. Orbit estimation is provided by GRAS with the performances mentioned in Section 6.2.

Attitude stabilisation and control is achieved by a combination of passive means, gravity gradient, and actuation by magnetotorquers. Attitude estimation is provided by the star imager in nominal conditions and by sun sensors and the vector magnetometer in non-nominal conditions.

Command, Data Handling and Communications

The Command and Data Handling System (CDHS) concept is controlled by the on-board computer. It is structured around a serial bus and interfaces with all payload and platform elements.

The time reference is provided by GRAS. The instruments themselves perform time stamping of the science data and 'packetisation' before forwarding the packets onto the bus. All science and housekeeping data are stored in a mass memory storage waiting for transmission to ground.

The total data rate would be 16 kbps assuming the instrument data rates of Section 6.2 and an additional 20 % for housekeeping data, overheads and coding. It is also assumed that the vector magnetometer, the CPDs and GRAS (for descending occultations) are fully used and no data compression is applied.

If data compression is used and the sampling requirements of Chapter 4 are considered, (i.e. the vector magnetometer and the CPDs are operated in burst mode only above 50° of latitude, and GRAS is used only for position determination and datation), the data rate is reduced considerably.

The on-board data storage (0.5 Gb) and the data downlink rate (1 Mbps) have been defined assuming that a ground station like Kiruna is used and no loss of scientific data is allowed. As uplink data a rate of 4 kbps is assumed. Communications are in S-band.

Satellite budgets

The estimates for the mass and power budgets are:

	Mass (kg)	Power (W)
Payload	16	20
Platform	57	44
Margin	4 (5%)	6 (10%)
Total	77	70

The mass estimate for the payload includes the boom. The power estimate for the payload assumes reduced use of the sounding function of GRAS. The margins of 5% for mass and 10% for power, are acceptable considering the similarity with Ørsted. The mass limitation is 80 kg imposed by the Ariane-5 ASAP. This constraint could be relaxed if a dedicated launcher is used. The power limitation is imposed by the solar array area and it varies from 90 W to 70 W depending on season, local solar time and duration in orbit. Larger solar array areas could be used if the Ariane-5 ASAP constraints are relaxed.

6.4.2. GSO-L

The low orbit of the GSO-L imposes special constraints on the satellite configuration and systems because of the particular orbit and attitude control requirements.

Configuration

The satellite configuration concept is mainly driven by the launcher envelope (Pegasus XL is assumed) and by the accommodation of the propulsion system and of the 8 m boom. The launcher envelope is fully used to maximise the solar array area with body mounted panels. Internal accommodation and integration considerations lead to a two-module configuration: a propulsion module, housing mainly the combined fuel and pressurant tank, and an observation module that includes the canister of the boom, the batteries and the electronic boxes of the various subsystems. The configuration is shown in Figure 6.8.

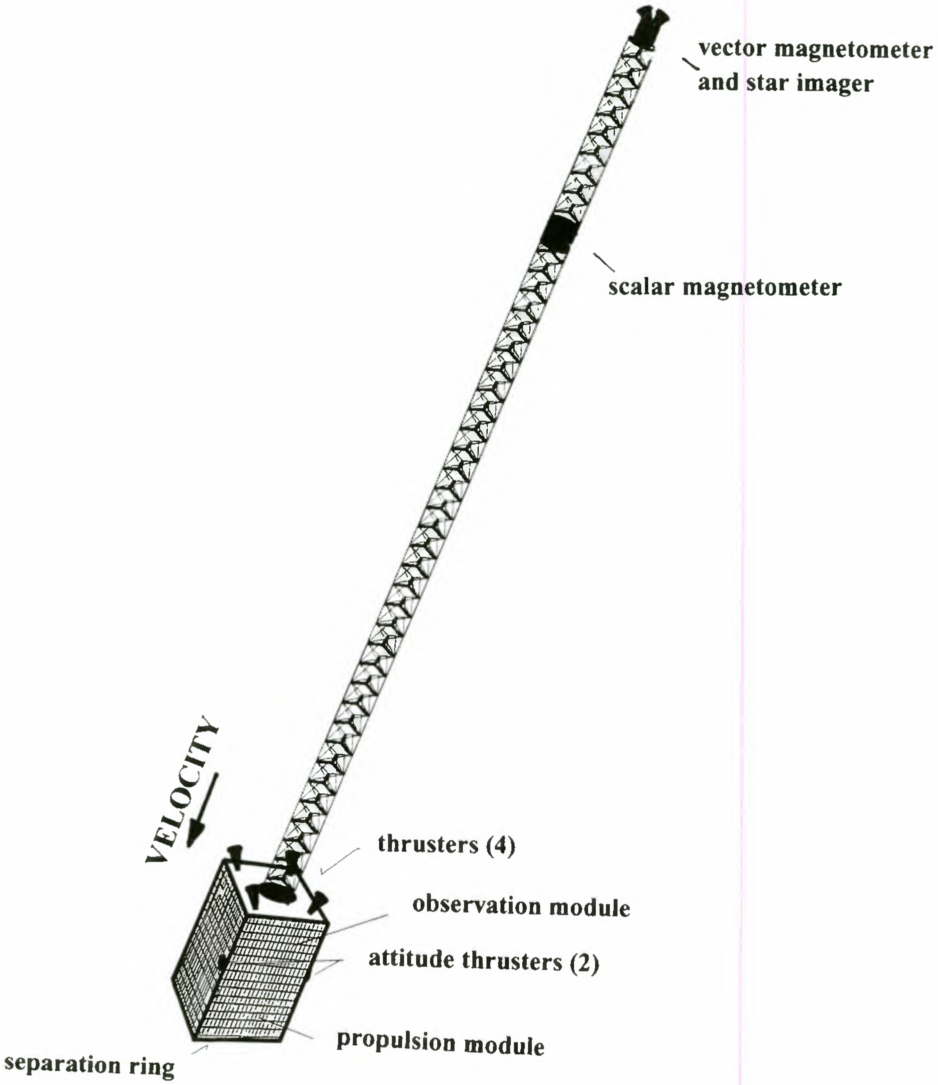


Figure 6.8. *GSO-L configuration concept*

Mechanical and thermal

The structural and thermal design principles proposed for the GSO-H are equally applicable for the GSO-L. The same 8 m boom and optical bench are proposed.

Electric Power

The electric power system concept is the same as for the GSO-H. The body mounted GaInP/GaAs cells provide 200 W in the worst illumination conditions. This is enough to provide power to all satellite equipments and payload and charge the batteries.

Propulsion

The Propulsion system concept includes a single tank for pressurant and propellant. It contains 85 kg of propellant which are fed to a set of four 1 N thrusters. Two additional thrusters may be required for desaturation of the reaction wheels.

Attitude and Orbit Control

Orbit estimation would, as for the GSO-H, be based on GRAS. Orbit control is required to counteract the approximate 4 km /day decay. Maintenance is foreseen every orbit without changes in attitude or interruption of operations.

The attitude determination strategy has to take into account the requirements of the complete attitude control loop. The system is therefore more complex than for the GSO-H and will use gyros and earth/sun sensors for nominal operations.

The GSO-L could fly in two attitudes, boom leading or boom trailing. The analysis of the stability of both attitudes has led to prefer the boom trailing option as it provides some degree of passive stabilisation and permits the scheduling of attitude corrections simultaneously with orbit corrections thus increasing the cleanliness and quietness of the satellite.

To achieve passive stabilisation the aerodynamic torque in pitch can be used to maintain the satellite alignment along the velocity vector overcoming gravity gradient and other disturbances. This strategy requires that the distance between centre-of-mass and centre-of-pressure does not fall outside certain limits. Preliminary analyses show that this condition is met until the end of the mission, tank depleted, and for different atmospheric density values, by proper accommodation of the satellite elements. The system designed for the boom trailing configuration would also be able to maintain the boom leading configuration.

Command, Data Handling and Communications

The concept is the same as for the GSO-H.

Satellite budgets

	Mass (kg)	**Power (W)**
Payload	16	20
Platform	150	144
Subtotal satellite	166	164
With 10% margin	185	16
Propellant	85	-
Total satellite	270	180

The payload mass estimate includes the boom. The payload power estimate assumes reduced use of the GRAS sounding function.

6.5. Ground Segment and Data Processing

The ground segment requirements for the Magnetometry Mission are similar to the Ørsted mission. The presence of two satellites in orbit during at least six months could require some additional capabilities. A functional block diagram is shown in Figure 6.9 including the four main functional elements:

- a command and data acquisition element;
- a mission operations and satellite control element;
- a processing and archiving element;
- a science data centre.

The following processing levels are identified:

- Level 0: raw data, time ordered and without overlaps;
- Level 1a: data 'depacketised', calibration and geometric corrections computed and appended but not applied;
- Level 1b: data with calibration and geometric corrections applied and geolocalised;
- Level 2: geophysical variables.

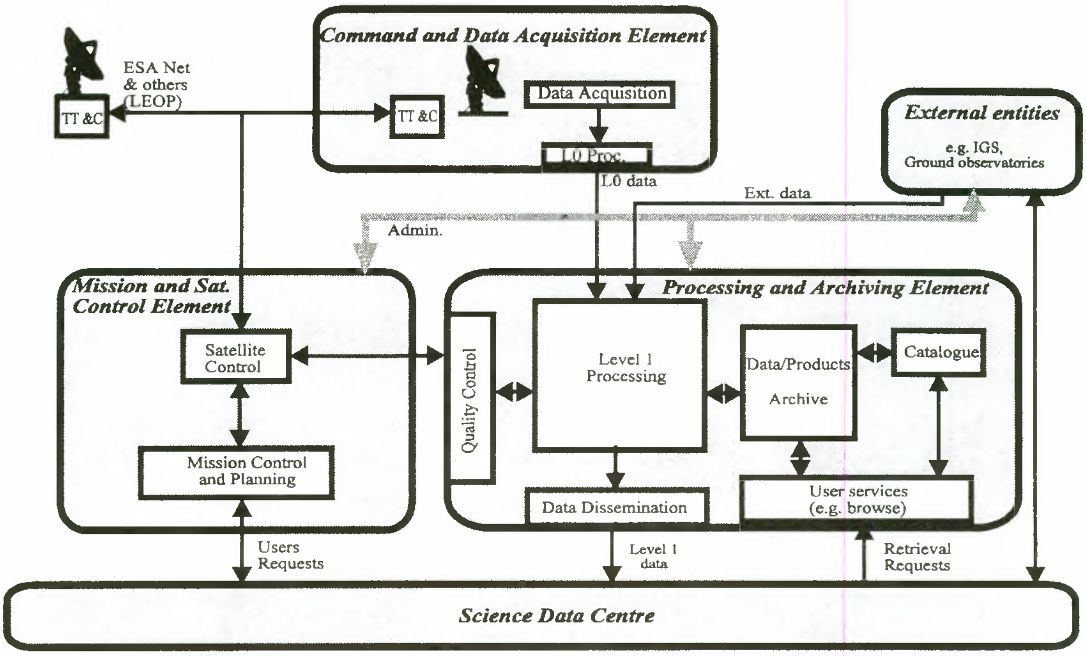


Figure 6.9. *Ground segment overview*

Command and Data Acquisition

A single station at Northern latitude, e.g. Kiruna, could be used to communicate with the satellite for command and data acquisition. The station would provide processing to Level 0 and short term data buffering, e.g. for one week.

Mission Operations and Satellite Control

This element would control the mission operations and the satellites and monitor the operation of the ground segment.

The satellite concept will have high autonomy which is inherent to their simplicity. Control sessions would be scheduled every 72 h for verification purposes. Telemetry would be automatically analysed after every station pass and alarms would be triggered automatically upon detection of anomalies.

Due to the low data rate of the missions the requirements on ground communication links are low.

Processing and Archiving

This element would receive the Level 0 data from the Command and Data Acquisition Station and process them to Levels 1a, 1b. Level 1 data will be delivered in weekly batches to the Science Data Centre (SDC).

Archiving would be at Level 1a and would be maintained for ten years after the end of the mission. Data retrieval would be upon request. Catalogue and browsing facilities could be available. The response time should be less than one week in magnetic medium or faster on line via ground network. Standard services would be available on line based on access to WWW. This element would also guarantee the data interface and consistency with other missions.

Science Data Centre

The SDC would perform processing from Level 2, merging the data from this mission with other space and ground data. Some Level 2 products may also be archived.

Relation with other missions

The study of the main field and its secular variation for a complete solar cycle can be performed by the sequence Ørsted, CHAMP (SAC-C), GSO-H. This represents a unique opportunity. It is necessary to establish coordination procedures for the coherent utilisation of the data from these missions.

Calibration of GSO-L data and exploitation of Ørsted and CHAMP data on the structures identified by the GSO-L also require coordination of data utilisation procedures.

The study of the external fields will benefit from the data collected by other missions performing ionospheric sounding with GRAS.

6.6. Launcher Considerations

The GSO-H element of the Magnetometry Mission could be launched in a dedicated launch with a Pegasus or Start 1 launcher. However, it has been designed to be compatible with the Ariane-5 ASAP. The objective is to keep the costs low and to guarantee a series of launch opportunities. It is expected that such opportunities will exist as a companion in launches of the SPOT, METOP, Helios series of satellites. These satellites go to sun-synchronous orbits of around 800 km altitude, local time between 09:00 and 10:00 h, i.e. far from the dawn-dusk conditions which are not desirable for magnetometry observations.

The GSO-L requires also a dedicated launch. Pegasus XL has been considered. A combined launch could be envisaged as both satellites go to the same orbit plane. In this case Eurockot could be used as the reference launcher.

6.7. Implementation Options

For the GSO-H the option would be the addition of the Earthquake Electromagnetic Probe (EEP) described in Section 6.2. The satellite would follow the principles of the GSO-H and a possible configuration concept is shown in Figure 6.10.

In the depicted concept an additional 2 m boom is required to support the EEP and keep it away from the satellite to avoid that the sensitive coil sensor picks-up noise from the platform. A shorter version of the coilable lattice boom used for the magnetometers is assumed.

The attitude stabilisation and control concept would need to be revisited, but the dual boom configuration could be used to improve passive stabilisation.

The wave analyser functions can be entrusted to the on-board computer. The additional data rate is estimated to be below 0.2 kbps, thus the data handling and communications systems of the GSO-H are basically suitable for this option.

The resulting satellite mass is 115 kg including 10 % margin. The power estimate (with 20 % margin) is 90 W.

The accommodation in the GSO-L of the optional instruments listed in Section 6.2 can be considered to lay within the available margins.

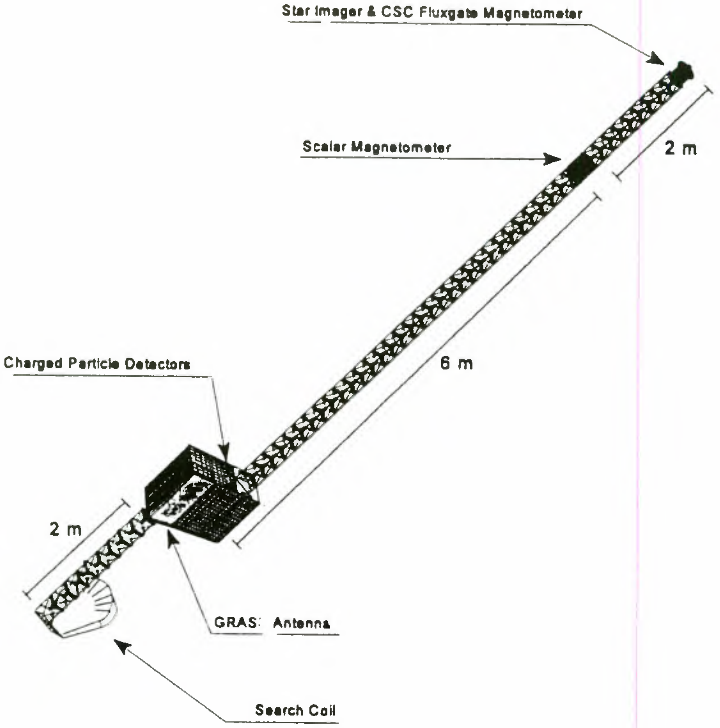


Figure 6.10. *GSO concept with earthquake electromagnetic probe*

7. Programmatics

7.1. General

The Magnetometry Mission would be implemented in the frame of an ESA Earth Explorer Programme of research missions if selected after phase A studies carried out within the frame of the Agency's Earth Observation Preparatory Programme.

7.2. Critical Areas and Open Issues

No critical areas have been identified during the preliminary assessment of the mission. In fact it is expected that the instruments will continue to be improved steadily, towards higher performance and lower demands in resources and cost.

The concept for the GSO-H is very simple so it can be built quickly at low cost and risk. This approach would allow the GSO-H to be made available in time to continue CHAMP observations. The GSO-L is also simple but of higher complexity. In both cases no technical problems have been identified.

The ground segment does not present any major challenge. A scientific community has been already organised around the Ørsted project and will continue for the CHAMP mission. It can be expected that by the time of the Magnetometry Mission processing algorithms will be well developed.

7.3. Related Missions and Timeliness

The Magnetometry Mission is related to the European Ørsted and CHAMP missions and to the Argentinean SAC-C. The sequence Ørsted, CHAMP, SAC-C will provide several years of uninterrupted observations of the Earth's main magnetic field. The time scale of the observations however should be at least one solar cycle. The Earth Explorer Magnetometry Mission, with the GSO-H element would extend the observations to complete the period thus achieving the global scientific objectives.

However, none of the above national missions address properly the lithospheric anomaly field issues. The GSO-L element of the Explorer would focus on this aspect.

Future research on the interior of the Earth would benefit from the synergy between high-resolution models of gravity and magnetic fields.

Activity in the area of relation between electromagnetic observations from satellites and earthquakes have to be followed. Correlation with GSO-H observations will have to be studied.

At least the GSO-H element of the Magnetometry Mission should be ready to be launched to coincide with the last operational years of CHAMP. The GSO-L element should be launched as soon as possible but would benefit from a launch in 2003 far enough from the maximum solar activity of the next solar cycle.

7.4. International Cooperation

The Magnetometry Mission could be opened to international cooperation. This will be specially important to harmonise the data structures with the Ørsted and CHAMP missions. Cooperation should also be established in the frame of the already existing international coordination in the areas of Solar Terrestrial Physics with the solar and magnetospheric missions. Cooperation would also be important in the domain of space weather initiatives. A new area is the study of electromagnetic activity associated to earthquakes. The Magnetometry Mission could contribute to such studies.

7.5. Enhancement of European Capabilities and Applications Potential

The scientific results of this mission would be of direct relevance to the various areas mentioned in Chapter 2. In this section the potential application for space based observations after the Earth Explorer mission is considered.

As established in Chapter 2 there is growing interest in the continuous monitoring of the Earth's external environment and initiatives are emerging in the USA and Europe for space weather systems which are of interest, not only for science, but also for applications in the areas of communications, electric power distribution, space and ground navigation, spacecraft environment modelling and others including also the understanding of electromagnetic activity potentially associated to earthquakes. For this reason, the GSO-H element of the Explorer has been conceived simple and affordable, compatible with the Ariane-5 ASAP.

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List of Acronyms

AOCS	Attitude and Orbit Control System
ASAP	(Ariane) Auxialiary Structure for Auxiliary Payloads
BGS	British Geological Survey
BRGM	Bureau de Recherches Géologiques et Minières
CDHS	Command and Data Handling System
CHAMP	Catastrophes and Hazard Monitoring and Prediction
CLN	Cretaceous Long Normal
CPD	Charged Particles Detector
CQZ	Cretaceous Quiet Zone
CSEF	(US) Committee for Space Environment Forecasting
DMI	Danish Meteorological Institute
EEJ	Equatorial Electro-Jet
EEP	Electromagnetic Earthquake Probe
ELF	Extreme Low Frequency
FTE	Flux Transfer Events
GCR	Galactic Cosmic Rays
GLONASS	(R) Global Navigation Satellite System
GNSS	Global Navigation Satellite System (based on GPS and GLONASS)
GPS	(US) Global Positioning System
GRAS	GNSS Receiver for Atmospheric Sounding
GSO-H	Geomagnetic Space Observatory - High
GSO-L	Geomagnetic Space Observatory - Low
ICSU	International Council of Scientific Unions
IDM	Ion Drift Meter
IGRF	International Geomagnetic Reference Field
ISTP	International Solar-Terrestrial Physics programme
LCR	Lithospheric to Core Ratio
LOD	Length Of Day
METOP	Meteorological Operational Satellite Programme
MSIS	Mass-Spectrometer Incoherent Scatter
NRM	Natural Remanent Magnetisation
OFCM	(US) Office of the Federal Co-ordinator for Meteorological Services and Supporting Research
POGO	(US) Polar Orbiting Geophysical Observatory
SAC	Satellite de Aplicaciones Científicas
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics
SCR	Solar Cosmic Rays
SEDI	Studies of the Earth's Deep Interior
SOHO	Solar Heliospheric Observatory
STEP	Solar-Terrestrial Energy Programme

SDC	Science Data Centre
TEC	Total Electron Content
TUB	Technische Universität Braunschweig
VLF	Very Low Frequency

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