Chapter 1

Earth's magnetic field

It is well to observe the force and virtue and
consequence of discoveries, and these are to be seen
nowhere more conspicuously than in printing,
gunpowder, and the magnet.
Francis Bacon

1.1 Observation of the geomagnetic field

The history of the probing of the Earth's magnetic field is tightly linked to the exploration of the oceans and the discovery of islands and continents. The magnetic field has been known for about 4000 years, having first been noted in China. Although the use of the magnetic field for navigation cannot be unequivocally identified until 1088 in China and nearly 100 years later in Europe [Backus et al., 1996], it was already known by the seamen in medieval times that an iron needle always aligns in one direction, giving the north course. It was also common knowledge that garlic weakened magnets, and even in the 1600's sailors avoided garlic and onions on board ship. This superstition might find its origin in a false transcription of "alio" (other) to "allio" (garlic) of an essay by Pliny (A.D. 23-79) discussing the action of magnets.

The growing interest in compass navigation may have influenced Gilbert somewhat because he wrote *De Magnete* [Gilbert, 1600] at the time the English were preparing to meet the Spanish Armada. *De Magnete* was the first comprehensive study of magnetism. Gilbert dedicated it to those who look for knowledge "not only in books but in things themselves". Since this initial work the Earth's magnetic field has been observed systematically for almost 450 years. Gauss led the effort to set up a global system of magnetic observatories, some of which have been running up to the present day. Geophysical exploration using measurements of the earth's magnetic field was employed earlier than any other geophysical technique. Even to this day, the magnetic methods are one of the most commonly used geophysical tools. This stems from the fact that magnetic observations are obtained relatively easily and cheaply and few corrections must be applied to the observations.

The early navigators observed that the compass does not point to the geographic north

given by celestial investigation. This discrepancy is referred as declination. Also the fact, that the true direction of the magnetic field is not horizontal, the magnetic inclination as it is called, was known to the navigators in the 16th century.
To introduce the geomagnetic elements that describe the magnetic field vector at a certain point on the Earth's surface, we may consider a local Cartesian coordinate system with x pointing to the geographic north, y to the east and z vertically downward. The magnetic elements X, Y, Z are the components of the magnetic field vector $\mathbf{B}$ in this frame, then the declination D is obtained by

$$\tan D = Y/X \,, \tag{1.1}$$

the total force F is

$$F = \sqrt{X^2 + Y^2 + Z^2} \tag{1.2}$$

and the inclination I satifies

$$\tan I = Z/\sqrt{X^2 + Y^2} = Z/H \,, \tag{1.3}$$

where H is the horizontal force.

1.2 The Earth's magnetic field, its temporal variation and its origin

Volcanoes are often active for long periods, and by comparing the magnetization of their lava flows from different times one can learn about changes in the direction of the local magnetic field. As Brunhes studied ancient lava flows in France he found that the magnetization appeared to be reversed [Brunhes, 1906]. Other examples were then found, and Matuyama [1929] examined the evidence and suggested that the magnetic signatures were evidence of actual reversals. Matuyama proposed that long periods existed in the past history of Earth in which the polarity of the magnetic poles was the opposite of what it is now.

Even on shorter time scales, the temporal behavior of the Earth's magnetic field shows a rich temporal variability, both periodic and aperiodic. These characteristics are caused by different mechanisms either external to the Earth's surface or internal.
In 1839, Karl Friedrich Gauss published his method for separation of magnetic field into parts due to external and internal sources by spherical harmonic analysis [Gauss, 1839]. Applying this method to measurements of the Earth's magnetic field, he could show that most of the field was of internal origin, thus confirming Gilbert's early work. The internal part of the geomagnetic field is now referred to as main field and its temporal change as secular variation.
The change of field in time was first detected by Gunter in 1624. He and Gellibrand collected measurements of magnetic declination made at Limehouse near London which showed a systematic decrease in magnetic declination between 1580 and 1634. On the

basis of this study Halley produced a model for the variation in terms of dipole moving generally westward, deep within the earth, making a circuit every 700 years [Halley, 1683, 1692]. He explained this property by an Earth composed of magnetized concentric shells separated by a fluid and rotating relative to each other.

The westward drift is a particular feature of the geomagnetic field originating internal to the Earth's surface. However, this phenomenon does not manifest globally. Figures (1.1) illustrate the westward drift of the zero declination line, the Agonic line, at 100–year intervals from 1590 to 1990. The eastern Agonic line moves in this period steadily westward, whereas the western line approaches the Americas.

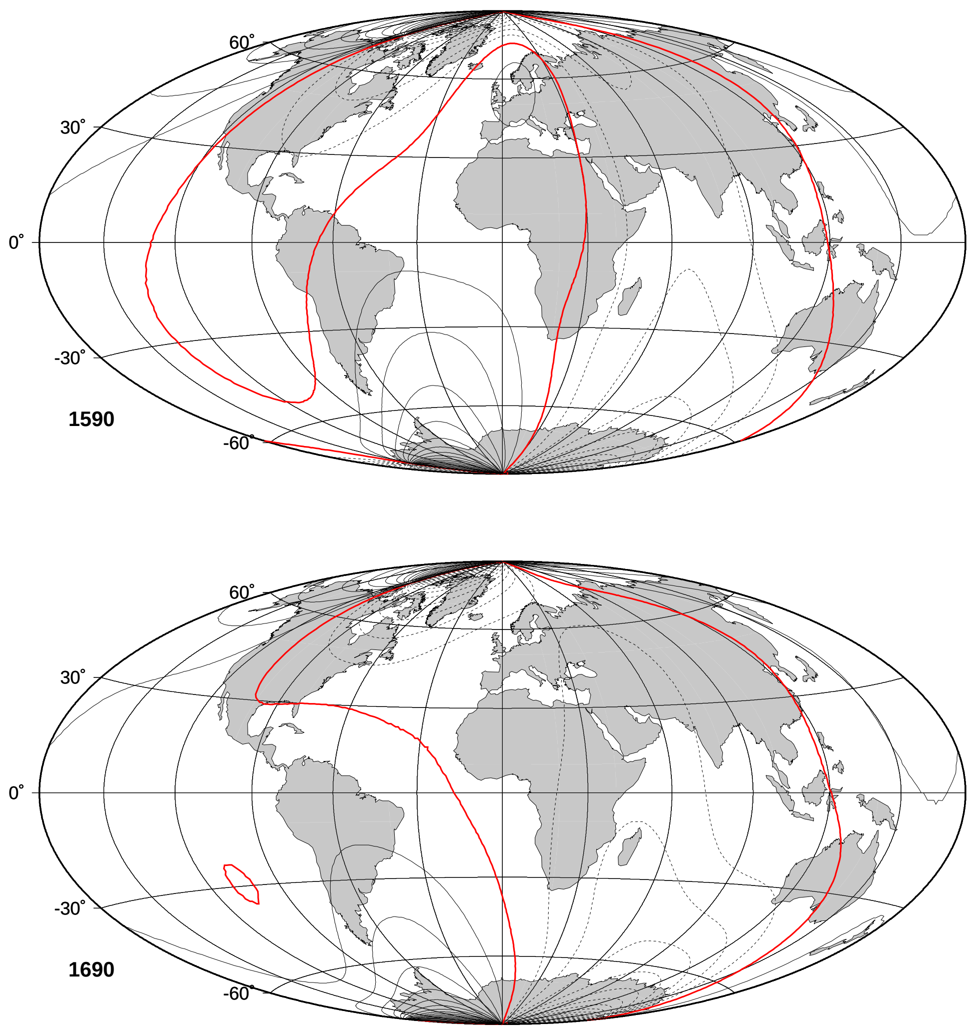

Figure 1.1: Global chart of the Declination (D) derived from *GUFM* [Jackson et al., 2000] for 5 epochs 1590, 1690, 1790, 1890 and 1990 from top to bottom. The red line is the zero Declination line (agonic line). Units are degrees.

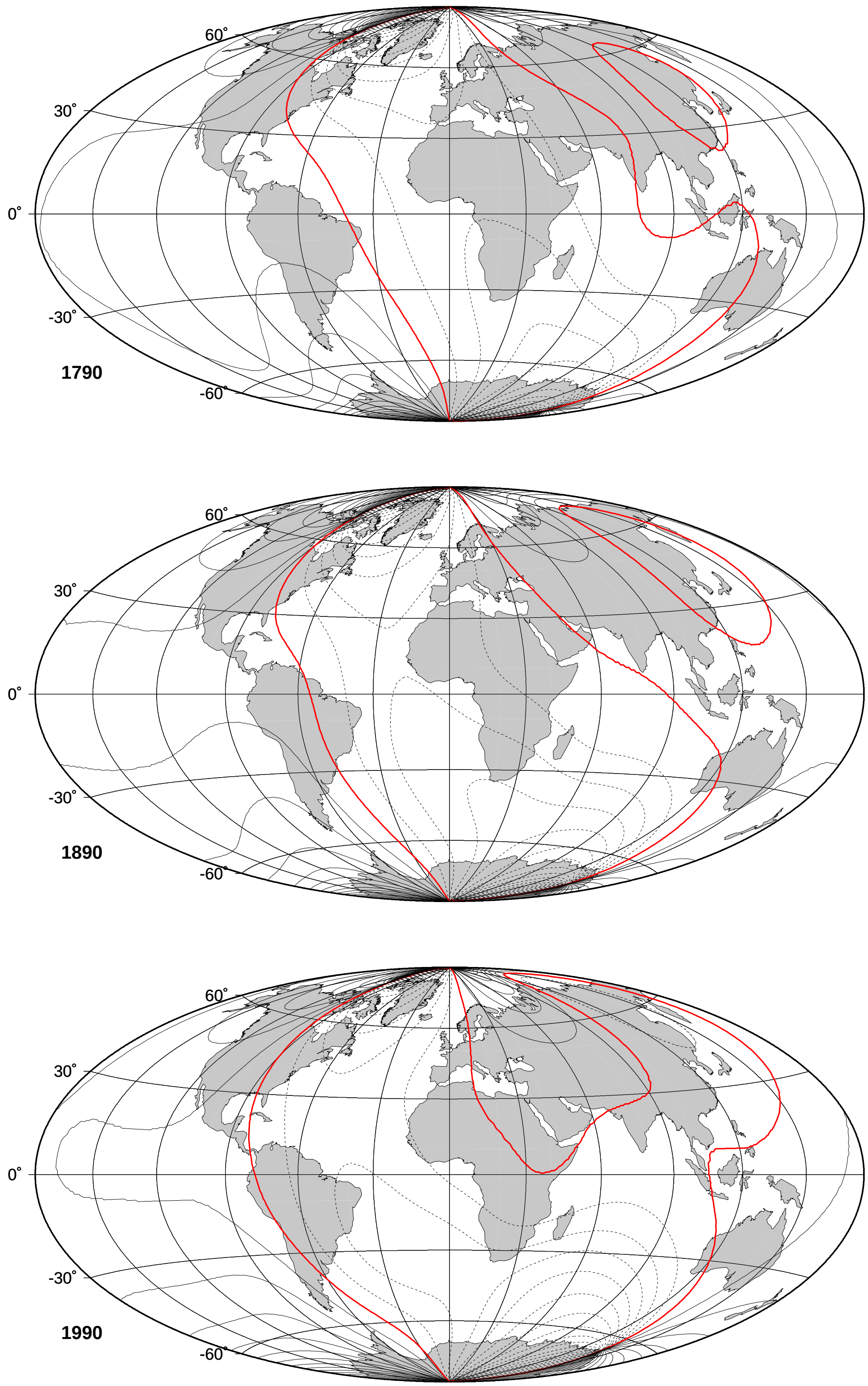

Figure 1.1: Concluded.

From discussion of fig.(1.1), part of the field seems to drift and part not. Langel [1987] discusses several methods to quantify the westward drift. The basic assumption therein is that the entire temporal change of the field is due to the westward drift. Following [Langel, 1987, p. 445, method 2], a crude estimate of the drift can be achieved by minimizing

$$\chi = \sum_i [C(\theta, \phi_i, t_2) - C(\theta, \phi_i + \Delta\phi, t_1)]^2 \tag{1.4}$$

with respect to $\Delta\phi$, the drift between two times t_1 and t_2. Here, C is any main field or secular variation component for a fixed latitude θ and longitudes ϕ_i. The drift rate is then given by

$$\dot{\phi} = \Delta\phi / \Delta t\,. \tag{1.5}$$

For the period 1980 – 2000 the westward drift depends on the latitude, as shown in figure (1.2). The averaged drift rate is 0.11°/year (see for further discussion section 4.1.3). The westward drift is by no means steady in time: rather, it shows a complex transient

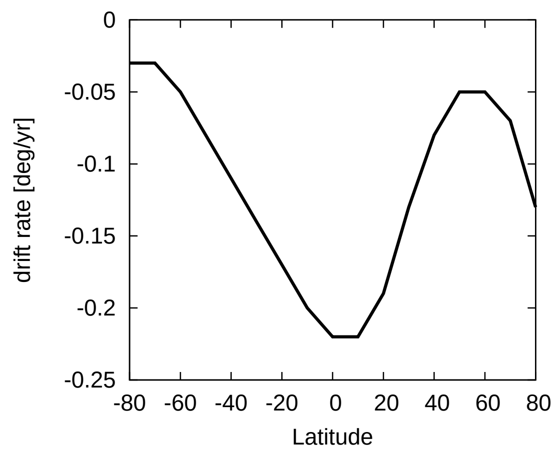

Figure 1.2: Westward drift for different latitudes during the period 1980 – 2000. After [Langel, 1987, p. 445, method 2].

behaviour, which seems to be related to what is known as geomagnetic jerks. Such jerks are event-like features which show up as a change of sign of the slope of the secular variation, a discontinuity in the second time derivative of the field, most clearly seen in the east (Y) component of the geomagnetic field. For the last 100 years at least seven jerks have been reported (1912, 1925, 1969, 1978, 1983, 1991 and 1999), some of them of global extent. The 1969 event (first described by Courtillot et al. [1978]) was widely investigated; on the basis of observatory records Courtillot et al. [1978] and Malin & Hodder [1982] showed its global extent, although it was not evident in all field components. This fact and the coinstantaneous occurrence of jerks and Sun spot maxima hinder the understanding of the causative processes for jerks, as the lively discussion between Alldredge and McLeod in the 1980's shows [Alldredge, 1984; McLeod, 1985; Backus et al., 1987].

In addition to long term behavior and short term events the geomagnetic field also exhibits periodic variations. Most of the variations have been identified as external, including the single solar cycle, its harmonics [Currie, 1966, 1976] and a quasi-biennial variation generated by solar activity [Sugiura & Poros, 1977]. The origin of variations with a near 22–year period is less clear. As Alldredge [1977] pointed out, the origin of these variations cannot be external because they occur at only a subset of observatories and do not have a common phase. Even longer periods have been found in geomagnetic observatory measurements. The most interesting, a 60–year period [Slaucitajis & Winch, 1965; Currie, 1973], which could be associated to torsional oscillation in the core [Braginskii, 1970].

An apparent periodicity of nearly 60 years occurs also in the decadal change of the length of days (Λ). Vestine [1953] and Vestine & Kahle [1968] showed an evidence for a correlation between Λ and the westward drift, and also it seems that a slow down of the mantle or spin up of the core precede a jerk [Kahle et al., 1969; Davis & Whaler, 1997].

The origin of the Earth's magnetic field is most likely due to dynamo action in the Earth's interior, where the field is generated by motions of a conducting fluid [Larmor, 1919]. These motions are driven by the heat loss of the inner core to maintain a convective dissipation of heat to the mantle.

The origin of secular variation could be either due to MAC–wave dynamo [see Finlay & Jackson, 2003; Finlay, 2004b, for recent discussion] or due to fluid flows at the core–mantle boundary. MAC–waves are magnetohydrodynamic waves which are dependent on magnetic, Archimedean (buoyancy) and Coriolis force, therefore MAC-waves. They occur on diffusive time scales ($\geq$ 300 years) and might account to the long term secular variation and westward drift. As this thesis will point out, core–surface flows have the ability to account for the most of the short term secular variation. An interaction of MAC-waves and core–surface flows is very conceivable.

1.3 Outline of this thesis

In this study I focus on the secular variation over the period 1980-2000. This time interval is bracketed by high-quality satellite vector data (from MAGSAT in 1980 and ØRSTED and CHAMP in 2000). My aim is to model the magnetic field and secular variation simultaneously throughout this period by a fit to all available data. The use of the two satellite epochs as "bookends" will enable a higher resolution of secular variation modelling than has been possible to date. In particular, we hope to answer the question as to whether we can see subdecadal or shorter period variation in the internal field, which in turn will provide important constraints on processes in the core.

As already mentioned, an important feature of the secular variation is the occurrence of geomagnetic jerks. In chapter 2 I will analyze how much of the jerk signal for the best known jerk in 1969 and the secular variation can be modeled by external variation;

this study is undertaken for three geomagnetic observatories Eskadalemuir, Hermanus and Kakioka.

Chapter 3 gives the description of data, data processing and satellite models used for simultaneous time–dependent modelling of main field and secular variation. Also the modelling approach is developed in this chapter. In chapter 4 the time–dependent model is inverted to assess the fluid motion at the core–mantle boundary. Herein different assumptions of the nature of the flow and their prediction of secular variation and the angular momentum budget are analysed. The fifth chapter summarizes the findings and provides some prospects.