Numerical models of the Earth's magnetic field, most commonly in the form of a set of spherical harmonic coefficients, have found applications in fields as disparate as biology, exploration geophysics, land surveying, drilling engineering, navigation, and the study of the Earth's deep interior. A survey, including statistical summaries of these applications are presented. The implications of model abuse will be discussed.

1. Introduction

Geomagnetic models have evolved over the past several centuries. The earliest representations of the Earth's magnetic field are the isogonic charts derived from point observations of magnetic declination (e.g. Halley, 1683). Models such as these remained in use long after the introduction of magnetic intensity units and the mathematical formalism of magnetic field representation developed by Gauss (1841). This formalism was not fully exploited until the advent of electronic computing and automated cartographic techniques. A magnetic model in this wider sense would then include any representation of the Earth's magnetic field whether in the form of charts, mathematical expressions or computer codes.

The profile of the early geomagnetic model user was almost exclusively that of the navigator. Of course, this profile is neglecting the profound intellectual impact which the discovery of this "mysterious force which acts at a distance" must have had on the minds of the men and women of those times. The 17th Century geomagnetic researchers, such as Gilbert and Gellibrand, stimulated by an interest in this mysterious force, generated the hope among many in the seafaring trades that knowledge of the earth's declination variations would prove to be a valuable tool, not only in providing compass corrections, but also as a means to determine longitude. The importance of this second objective led mariners to routinely make declination observations until the advent of steel hulled ships and accurate naval chronometers.

It was the robustness of the magnetic compasses of the 16th, 17th, and 18th centuries, as opposed to the unreliable nature of clocks of the period, which motivated navigators to continue to determine longitude by comparing direct observations of magnetic variation to values on isogonic charts of the period. In an analogous fashion, it is the simplicity and reliability of the magnetic compass which continues to motivate designers of marine and air transportation systems to include magnetic sensors, along with gyroscopes, in their avionic and marine navigation packages. In many cases inertial systems are even initialized using magnetic field information. In harsh environments such as on space platforms and in downhole drilling packages it is the reliableness of magnetic sensors which continues to render magnetic methods useful. It does not appear that the
advent of newer technology, such as laser gyroscopes and global positioning satellite systems will substantially alter the importance which navigators and others must place on magnetic compasses, sensors, and knowledge of the Earth's magnetic field.

2. User Survey

The World Data Center-A (WDC-A) and national organizations have been distributing magnetic field information since the late 19th Century. Until quite recently this information has been in the form of direct observations and compiled charts derived from these observations. More recently, with the wide spread availability of computers, these data have been made available in the form of mathematical models, and supporting computer software. For the last few years, WDC-A has been operating with a computerized Data Request system. This automated system allows us to recover information about users of WDC-A data sets with relative ease. In order to develop a profile of the geomagnetic user community, information on 144 recipients of magnetic field information from October 1, 1987 through June 6, 1989 was assembled.

The 144 users in the study received magnetic field observations, polynomial or spherical harmonic models and supporting software, or tabulated values of magnetic field elements derived from models. These users were assigned to one of twelve, not necessarily mutually exclusive, user categories based on the use of the data or model. Inclusion in a given category was based in most cases on information in our Data Request system. In about a third of the cases the recipient was contacted by phone and asked to volunteer information about the intended application of the data. There was no attempt made to break down research applications into specific research areas. A good portion of these applications were considered sensitive either for corporate or military reasons by the individuals contacted.

It should be noted that this sample does not reflect the total user community. Some of the users represent large multi-system applications. One example of such a users would be the Exxon Oil Corporation who obtained one copy of our geomagnetic synthesis software and a current set of models in 1989. They informed us that they intended to distribute these products to some 300 field offices throughout the world. Most users do not inform us of their intention to re-distribute these products. Other users obtain magnetic models or data from publications, charts, or other distributors. The spherical harmonic coefficient set sanctioned by the International Association of Geomagnetism and Aeronomy and designated as the International Geomagnetic Reference Field (IGRF) is normally published in several journals upon the data set's adoption. One of these journals, "EOS, Transactions of the American Geophysical Union", has a press run of 25,000. This publication is distributed to corporations and academic institutions as well as to individuals.

The number of users who obtain model data from journal sources and other data centers is unknown. Magnetic field models obtained in chart form can be estimated from the chart sales figures of the distributors. The United States Geological Survey has distributed about 2800 charts of magnetic elements since August of 1988, or about 1800 per year. Similar charts are distributed by the Map Sales Office of the U.S. Defense Mapping Agency. They have sold about 3500 magnetic charts since January of 1987 or about 1000 per year. Magnetic field information reaches a far larger number of people in the form of declination information on thousands of different topographic, nautical, and
aeronautical charts. The National Oceanic and Atmospheric Administration's charting services generate current magnetic declination information from models supplied by us for their aeronautical and nautical charts for the United States. Their charts are updated every few years. NOAA distributed about 13 million such charts in 1989. A similar revision cycle is observed by the U.S. Defense Mapping Agency in their preparation of global aeronautical and nautical charts. Geomagnetic field information is included on the 21 million charts distributed by this agency in 1989. Similar types of magnetic field and navigational charts are published and distributed by many other countries. The distribution figures obtained from our data requests therefore represent only a very small sample of the total number of magnetic field data users. It should also be noted that the various user groups noted below apply the magnetic information in quite different ways. A land surveyor, more often than not will employ a single declination determination to reconstruct a geodetic bearing from a magnetic bearing, whereas an exploration geophysicist might appeal to a magnetic field model thousands of times for many geographical regions in the processing of data from magnetic surveys by aircraft and ships.

Table 1. Summarizes the results of our user survey.

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Surveying</td>
<td>53</td>
<td>37</td>
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<tr>
<td>Academic Research Organizations</td>
<td>24</td>
<td>17</td>
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<tr>
<td>Governmental Research Organizations</td>
<td>23</td>
<td>16</td>
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<tr>
<td>Exploration Geophysics</td>
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<td>12</td>
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<td>Private Research Organizations</td>
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<td>4</td>
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<tr>
<td>Directional Well Drilling</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Animal Migration Research</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Dish Antenna Orientation</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Avionics Software Development</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Epidemiological Research</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Geographical Information Systems</td>
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<td>1</td>
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<td>Marine Navigational Software</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>144</td>
<td>100</td>
</tr>
</tbody>
</table>

3. Survey Results

It came as no surprise to those of us distributing magnetic field information that far and away the most frequent user that receives data directly from us are land surveyors. Within this category are also included the lawyers who are working with land surveyors to resolve boundary disputes. As a user group the land surveyors are the most likely to have a less than full appreciation for the nature of the magnetic field. Commonly their request for data will be framed within a question like "what was the position of the North magnetic pole in 1929?"

A typical request within this category, was for a reconstructed magnetic variation history for an oyster bed site on the Gulf Coast of Louisiana. In this particular case, one fatality had already occurred in a dispute over oyster raking rights. Ownership had been defined by purely magnetic surveying techniques in 1820. We hope that a new found
appreciation for the nature of secular variation will help to bring peace to that Louisiana fishing community.

Over one-third of the users were classified as researchers, either governmental, academic or private. These users, when they were able to discuss their application, revealed a broad spectrum of applications. The governmental users were more often than not working with some aspect of satellite mission planning. One gentleman from the governmental sector was investigating the feasibility of using a satellite tether as a power generating source. Many people who have expressed hope that low level magnetic surveys might be performed by towing tethered instrument packages from higher orbiting platforms have been discouraged by the prospect of having to deal with the presence of electric and magnetic fields due to the tether. It was interesting that at least one investigator was considering turning this problem into an advantage. He estimated that up to 700 watts of power might be available at the tethers end.

The Earth's core is, from a practical point of view, as remote as many astronomical objects. Heat exchange processes that take place in the core and mantle of the Earth are now suspected as contributors to the overall heat budget of our oceans and atmosphere. Magnetic field information provides one of the few pieces of observational data that can be exploited in research on the Earth's deep interior. The researchers involved in these studies, although few in number, may be in a position to make fundamental contributions to our understanding of the Earth as a total system.

Companies engaged in resource exploration constituted about twelve percent of the study group. Except for research applications, these users are the only group which does not use magnetic field information to deduce attitude or directions. This is also the group of users who are most likely to complain about model field accuracy. Model field errors can be quite obvious when examining large scale compilations of magnetic force elements. An ideal model from these users' point of view would exactly separate the local anomalies of interest to them, from longer wavelength regional fields. This would eliminate the additional step of removing a mathematical surface of some sort in order to isolate the features whose scale is of interest to them. Since these "scales of interest" vary, no single model could accommodate all these users.

One of the most sophisticated applications of magnetic field models can be found among the three percent of the study users who apply magnetic field models to problems which arise in directional drilling. These users are taking advantage of technology developed during the 1960s for use in orienting space platforms. A three component magnetic sensor system is placed in a non-magnetic section of the drilling string. Measured magnetic field directions are then compared with directions derived from a magnetic field model in order to deduce the drilling direction. In some applications these computations are performed by a microprocessor which also resides in this "down hole package". Other drillers perform the calculations at the surface after receiving the down hole magnetic field measurements from "telemetry" transmitted through the mud column. Here the robustness of magnetic field sensors gives these methods a clear advantage over various gyroscopic instruments which are plagued by drift problems caused by the severe mechanical agitation and temperature the instruments must survive. It has proven impossible as yet to design laser gyros which are both small and accurate enough to meet these needs. In recent years a growing number of drilling companies have begun to use hematitic drilling mud in place of the increasingly scarce bentonite, used formerly. The magnetic properties of these mulls is now proving to be a problem for
directional drillers.

Magnetosensors have been located in organisms as primitive as bacteria and as evolved as whales. It seems certain that the degree to which magnetic location methods are employed in the animal kingdom has not yet been fully elucidated. Three percent of the users in our survey group were using magnetic field models in animal migration studies. One interesting hypothesis being explored has been proposed by Dr. Peter Klimley (personal communication) of the Bodega Marine Laboratory. In one study area, hammerhead sharks spend their night time hours on the flanks of a seamount. In the early morning hours they move from these areas onto a relatively flat portion of the sea floor where they then descend to a depth close to the ocean bottom. It is at this point that all the hammerheads follow a single path for some distance until they then disperse into areas where they feed. Upon examining surface magnetic anomaly maps, it was discovered that this “single path” coincides with a pronounced linear magnetic anomaly of the type commonly associated with sea floor spreading. One hypothesis is that the sharks are not sensing the strength of the field but rather its gradient. The animals descend from near surface depths in order to reach a point where the Earth’s main field gradient is finally overpowered by the gradient due to the remnant magnetization of the buried mafic rocks. Gradients computed from magnetic field models and the effects of shallow source anomalies are being correlated with the shark’s position and body orientation. Although no magnetosensors have as yet been found in hammerhead sharks this “gradient hypothesis”, if substantiated, may well provide an explanation for the unusual morphology of the animals head.

4. Epidemiological Applications

Quite recently the public debate on the biological effects of extremely low frequency (ELF) electromagnetic fields has heated up. Evidence of such biological effects comes from two quite different types of research. A number of epidemiological studies have asserted that cancer rates in excess of background rates can be statistically associated with populations who live or work close to certain types of alternating power sources (WERTHEIMER and LEEPER, 1979, 1982; MALE et al., 1987). A physical basis for these statistical associations may be emerging from the second type of research. Studies of calcium ion migration rates in baby chicken brain tissues have revealed modulations of these ion outflows as a function of the presence of ELF fields (BLACKMAN et al., 1980). These responses appear to be tuned to narrow frequency bands within the electromagnetic spectrum. The position of these frequency “windows” within the spectrum can be altered by changing the strength of ambient static magnetic fields (e.g. the geomagnetic field). These studies suggest that there may exist a resonance-like relationship between ELF fields, the Earth’s magnetic field and the alteration of certain biochemical reactions, with ensuing implications for the health of organisms. This linkage between the Earth’s magnetic field, ELF fields and alteration of biochemical reactions contributed to a frustrating lack of reproducibility in studies being performed by other researchers in these areas. Magnetic field models are being used to predict the direction and strength of the static field onto which alternating fields from power transformers and power lines are being superimposed. Attention to these coupled effects is evidenced by the number of orders for geomagnetic data from researchers in this field.
5. Abuse

Many of the abuses of magnetic field models are related to failures to update magnetic field models in a timely fashion. The magnitude of the secular variation of the Earth's field varies complexly, both spatially and temporally. Secular variation rates in declination a tenth of a degree per year are not uncommon. In areas adjacent to the magnetic poles, where the field vector approaches a vertical orientation, rates as high as two degrees per year may be observed. Secular variation rates for force components ranges as high as 120 nT per year. A number of years are required for significant errors to accumulate at these rates. However, all too commonly, we have heard about avionic software that used declination values based on, for example in one case, a 1965 model. When one considers that this 1965 model was based on an incomplete set of field determinations made between 1960 and 1965 one can only be consoled by the belief that navigation by magnetic compass is not usually the primary navigational system being employed. We have also heard reports from airline officials that they were motivated to look into the problem because their pilots were complaining. The pilots knew that their supposedly corrected bearings were in error.

Another abuse encountered might be characterized as a false expectation of the accuracy of the values recovered from magnetic field models. These false expectations are usually coupled with unrealistic notions about the accuracy of magnetic compass systems. There are now magnetic compass systems available which give digital readout to the nearest one hundredth of a degree, further encouraging such wishful thinking. The potential for harm in such expectations is perhaps minimal but worrisome nonetheless. Worrisome because these sorts of abuse can be compounded by the errors which are inherent in the modeling process. As a “rule of thumb” these accuracies are often stated as being on the order of one half degree in the angular components and 100 nT in the force components. True model accuracies can not be stated in such simple terms since they are functions of the spatial and temporal distribution of the data sets employed in the model derivations (see Geomagnetic Field Modelling and IGRF Revisions, in Phys. Earth Planet. Inter., Vol. 48, Nos. 3–4, Oct. 1987).

6. Conclusion

Magnetic field models continue to find application in a surprising array of disciplines unrelated to geology and geophysics. The disparate nature of these applications makes it hard to predict the future uses magnetic field models might be put to. Justifications for continued support in the production of models of the geomagnetic field and it's secular variation can use the argument that unforeseen applications will likely appear just as is done by many researchers in basic science.

REFERENCES


HALLEY, E., A theory of the variation of the magnetic compass, Phil. Trans. R. Soc. Lond., 13, 1683.

