



Overview of Compass Technology

1 Selecting the Best Technology for Determining Direction

The ability to accurately and autonomously determine direction is fundamental for both navigation and pointing mobile devices. For modern electronic applications, there are three basic alternatives for determining direction, each with its own strengths and limitations. The oldest, most economical and reliable method is measuring geomagnetism using a compass. For applications where dynamic or environmental conditions preclude using a magnetic compass, direction may be determined by measuring the earth's orbital axis using a north seeking gyrocompass. Finally, radio or satellite signals may be used to estimate direction. These manmade signals may be broadcasted deliberately for navigation or for communication purposes. Direction is determined both by evaluating the relative direction of the source of radio signals (radio direction finding); analyzing reflections of radar or sonar off of a target of known position; or by calculating direction based on changes in radio or satellite navigation positions.

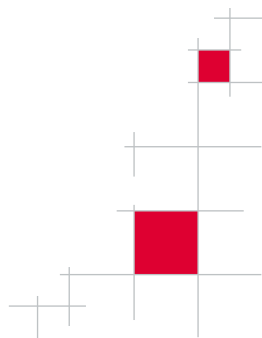
This paper will briefly cover all of the alternatives for determining direction. It will demonstrate why geomagnetism is the most suitable source of direction information in terms of accuracy, reliability, and economy, and will outline considerations in measuring the earth's magnetic field. Conditions which preclude use of geomagnetism will be outlined, and alternatives suggested for applications where a magnetic compass will not work well.

2 Methods of Determining Direction

2.1 Determining Direction by Measuring Geomagnetism Using a Compass

Measuring the direction of the earth's magnetic field is the oldest and most reliable method of determining direction on a continuous basis, albeit with a modern twist. Traditionally this measurement was made by visually observing the tendency of a small piece of magnetized material in a compass to align itself with the earth's magnetic field. Today, direction of the earth's magnetic field is determined electronically. Small changes in induction caused by the relative direction of the earth's magnetic field are measured in specially selected materials as they are being electrically driven in and out of magnetic saturation (described in detail in section 5).

Use of electronic magnetic compasses began during World War II in the wingtips of aircraft. The marriage of this basic technology with the power of the microprocessor in the late 1970's created a new breed of "digital" electronic compasses, capable of extremely accurate and reliable measurements of the local magnetic field.





2.1.1 Advantages of Measuring the Earth's Magnetic Field

No other physical property is so readily available and easily measurable on a consistent basis as the earth's magnetic field. Using it to determine direction does not require visual confirmations of known landmarks or any external source of manmade information. Advances in modern electronics have all but overcome historic limitations in compass design, making the modern electronic compass the most accurate, reliable, and economical tool for determining direction in most applications.

2.1.2 Limitations of Measuring the Earth's Magnetic Field

The earth's magnetic field provides such a reliable source of accurate information, decisions to use something other than a compass to determine direction are usually made only in four very specific situations:

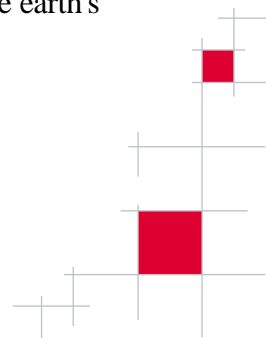
1. The host platform's magnetic field (deviation) is so strong it prevents accurate measurement of the earth's field.
2. The earth's field is too inconsistent to provide accurate information due to natural or manmade magnetic anomalies which distort the local magnetic field in an unpredictable way.
3. The vertical component of the earth's field is much stronger than the horizontal component (dip angle).
4. The dynamic conditions (accelerations) of the application prevent consistent measurement of the earth's horizontal magnetic field with the available compass technology.

These problems must be carefully considered when selecting a direction finding technology for a particular application, so they will be thoroughly reviewed in sections 3 and 4. Fortunately, as described in section 5, modern electronic technology is able to provide solutions which overcome all but the most serious of these limitations.

2.2 Determining Direction by Maintaining a Known Reference Using a Gyro

In situations where the earth's or host platform's magnetic fields or dynamic nature of the application precludes use of a magnetic compass, a mechanical, fiber optic or ring laser gyro is generally the next best alternative as a directional reference. Generically, gyros fall into two broad classes. They will either maintain a known direction by resisting acceleration present when turning, such as the type of gyrocompass often found in airplanes, or they actually indicate the orbital axis of the earth providing a reference of geographic or "True" north, such as a north-seeking gyro in a ship.

The property gyroscopic inertia was first applied to determine geographic direction by Elmer Sperry in 1911, although the gyroscope's tendency to resist forces of change had been known since the mid-1800's. Gyroscopic forces resist changes in position through a phenomenon known as *gyroscopic precession*. When influenced by the forces of the earth's rotation and gravitational pull, known as *Coriolis force*, the gyro tends to align its rotational axis parallel to that of the earth, thereby pointing to true north, the earth's orbital axis.





2.2.1 Advantages of Determining Direction with a Gyro

A well engineered north-seeking gyro will provide a stable, accurate indication of direction for a relatively long period of time. A gyro's performance in highly dynamic conditions is usually more stable and accurate than any type of electronic or mechanical magnetic compass, which must be freely gimbaled to measure the horizontal element of the earth's magnetic field.

2.2.2 Limitations of a Gyro

While offering good dynamic performance, the gyro's complexity adds weight, cost and maintenance requirements to an application. Cost is often the primary concern, as even low end gyros often run \$10,000 or more. Mechanical gyros are generally heavy and often require significant power to run their precision motors. They also have the unfortunate tendency to "tumble" when their gimbaling ranges are exceeded, and may require several hours to reorient themselves or "settle".

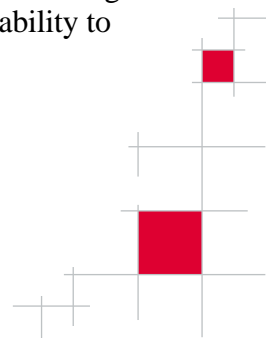
In addition to the acquisition and maintenance concerns, gyros also have performance limitations which must be considered. For accurate readings, adjustments generally must be made to compensate for different geographic latitudes and different speeds. Furthermore, gyros rely on the difference in orientation between their own axis and the earth's axis to maintain a direction, which translates to geographic limitations in northern and southern latitudes where gyros will not work well.

2.3 Determine Direction Electronically Using Electronic Landmarks

Basic electronic navigation aids which determine the relative direction of another physical object using broadcasted or reflected radio or sound waves have been used since shortly after World War I (sonar, radar, radio direction finding). Determining direction by evaluating changes in known position calculated by analyzing deliberately broadcasted signals for the specific purpose of navigation was first used in World War II with Loran, and later with Decca, SatNav, and most recently, GPS. Although these techniques are acceptable in providing redundant confirmations of direction, their inaccuracies in providing real time pointing information preclude their use for most direction determining applications.

2.3.1 Determining Direction with Radio Direction Finding, Sonar, or Radar

Radio direction finding (RDF) involves calculating direction by taking fixes on radio transmissions of known frequencies from towers of known position, and calculating relative direction based on the angle from the tower. With the proper information, this is a fairly reliable means of determining direction. RDF shortcomings involve limitations in signal strength and availability, and the distorting impacts of geographic and physical features between the transmitter and the receiver. Single antenna RDF also suffers from 180 degree ambiguity in determining direction. Sonar and radar transmit sound and radio waves respectively and evaluate signals reflected off any objects the waves pass over, thus providing a method of accurately determining the relative direction of landmarks. The primary problem determining direction using reflected signals is that it requires knowledge of the position of the target and the ability to distinguish the target from other objects which might reflect or distort the broadcasted signals.



2.3.2 Determining Direction with Electronic Navigation Positioning Equipment

Electronic radio or satellite position devices (Loran, Decca, GPS, etc.) determine position by evaluating arrival times or wave characteristics of signals broadcast specifically for navigation from satellites or radio towers of known position. Many of these devices provide, as an "added feature", an indication of direction traveled calculated from the bearing between the current position and the last position recorded in the device's memory. The obvious limitation of this type of information is that it is based on historic data which often is not precise. Changes in direction cannot be calculated until the distance between measurements is sufficient to make the calculation between the two points. Given that the margin of error for navigation equipment ranges from 100's to 1000's of meters, there is a dangerous amount of ambiguity when attempting to use these devices to calculate the vector between two "known" positions. Since rapid turns over a short distance usually go totally undetected, the utility of this method is limited to objects traveling in straight long paths, preferably at high rates of speed to minimize the impact of position ambiguities.

2.4 Summary of Options To Determine Direction

This table summarizes the relative strengths of each approach of determining direction:

	Electronic Compass	Gyro Compass	Radio or Satellite Navigation Device
Property Measured	Earth's Mag. Field	Earth's Rotation	Manmade Signals
Cost	\$50 - \$500	\$5,000 - \$25,000	\$500 - \$5,000
Direction Accuracy	0.5°	1°	5° or worse
Dynamic Performance	Good	Very Good	Poor at slow speeds
Warm-up Time	None	20 minutes to hours	1-5 minutes
Weight	3 ounces	5 lbs. and up	3 lbs.
Direction Repeatability	Excellent	Excellent	Poor
Durability	Excellent	Good	Excellent
Geographic Coverage	80° Magnetic Lat	70° Geographic Lat	Depends on Signal
Need External Signal	No	No	Yes
Power Consumption	100 mA	4.5 Amps	250 mA
Maintenance Required	No	Yes	No

Table 1: Comparison of Direction Determining Technologies

For autonomous direction finding, the earth's magnetic field provides the most accurate, reliable, economically available information. In most situations where a magnetic compass will not provide accurate directional information, a gyro compass or a magnetic compass complimented with a rate gyro for stability is the next best alternative. Generally, calculating direction from changes in position is the least accurate method and is only used when directional accuracy is not an issue or the geographic coverage of magnetic compasses and gyros is insufficient.

3 Using the Earth's Magnetic Field to Determine Direction

To determine whether or not a compass will work in a direction finding application, it is useful to review the basic physics of magnetism and the properties of the earth's magnetic field. This section will demonstrate why local anomalies and the three dimensional nature of the earth's magnetic field create problems in measuring geomagnetism. Section 4 reviews the nature of magnetism and magnetic materials, and how they might create magnetic interference from the host (deviation) which must be taken into consideration when using the earth's field to determine direction.

3.1 Origin of the Earth's Magnetic Field

The most widely accepted theory is that the earth's magnetic field is created by the flowing molten iron of the earth's outer core (1,200 kilometers from the earth's center), churning around the earth's solid inner core. The molten iron of the outer core is extremely hot ($5,800^{\circ}\text{C}$ or the equivalent of the surface of the sun), and under extreme pressure (1 million atmospheres or more). It is very fluid, and conducts electricity better than copper. The earth's rotation propels the molten iron around the inner core, it interacts with the earth's permanent magnetic field, whose origin is unknown but which has been present throughout time. The interaction, working in a manner similar to moving a wire across a magnet, creates a magnetic field which perpetually reinforces the earth's permanent magnetic field in a never ending cycle. The earth's mantle and crust are generally poor conductors, so they neither create nor screen the magnetic fields created at the outer core.

3.2 Characteristics of the Earth's Magnetic Field

The earth's magnetic field is often visualized as if it were created by a powerful bar magnet in the earth's core. In considering this model, it is easy to understand that a magnetic compass does not point to the earth's magnetic pole, but rather aligns itself with the earth's local magnetic field. The local magnetic field varies greatly in intensity and direction over the surface of the earth, sometimes in a way one would expect with the model to the right, and sometimes in apparent contradiction to the model due to natural and manmade magnetic anomalies. The "poles" themselves are the opposite of what is often assumed. The earth's magnetic north pole is actually located near the geographic south pole. Because opposites attract, the magnetic north pole of a compass needle is attracted to the magnetic south pole of the earth's field, which corresponds to the geographic north pole. What's more, the earth's magnetic north and south poles aren't even 180 degrees apart. These distinctions become important in understanding some of the challenges which must be overcome to accurately measure the earth's magnetic field.

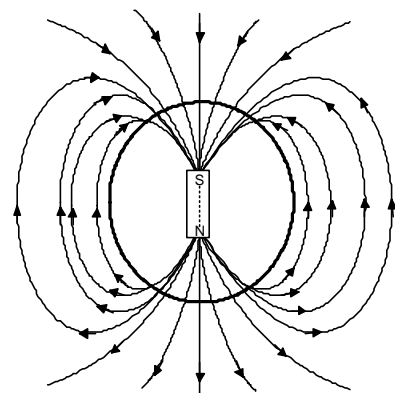


Figure 1: Model of the Earth's Magnetic Field

3.3 Challenges in Measuring the Earth's Magnetic Field

The common "bar magnet" representation in the previous section is useful, but greatly simplified. The exceptions to the generalization are important to understand, because they are the factors which determine whether or not a magnetic compass will provide suitable information for a given application.

The challenges in accurately measuring the earth's magnetic field fall into three broad categories:

1. Those predictable measurement problems associated with the known characteristics of the earth's magnetic field, including variation and magnetic inclination;
2. Unpredictable natural or manmade anomalies which may make the earth's magnetic field an unreliable source of directional information in the particular local area they affect;
3. Those disturbances in the earth's magnetic field created by the host platform on which the magnetic sensor is mounted, which is known as deviation.

3.3.1 Variation

It is well known that the earth's magnetic poles do not correspond with its geographic poles. This 24° difference between the earth's magnetic orientation and orbital axis creates the phenomenon called *variation*. If the earth's magnetic field were perfectly uniform, variation could be explained simply as the difference between the true and magnetic poles. Since the earth's field is not homogeneous, variation is more accurately described as the difference between the local magnetic meridian and the local geographic meridian at any particular point on earth.

Variation really does not present a significant problem for magnetic compasses, provided the user understands that correction factors may be necessary for magnetically determined direction to correspond with geographically calculated direction from a map or chart. This isn't problematic because variation is very predictable and changes at a very slow rate. The magnetic north pole is currently about 700 miles south-west of the geographic or "true" north pole, changing at a rate of about 8 miles per year in a general westerly direction.

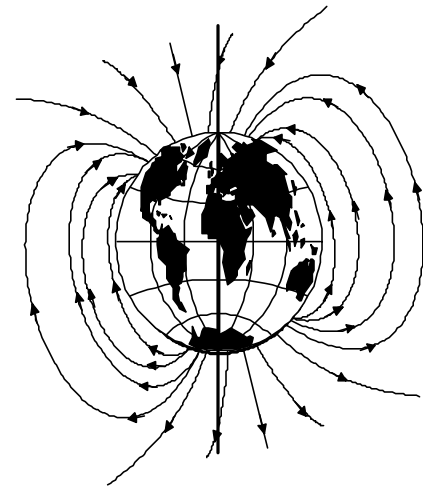


Figure 2: Model of the Effects of Variation on the Earth's Field

3.3.2 Local Magnetic Interference From Natural or Manmade Anomalies

Natural magnetic field disturbances, including large deposits of ore near the earth's surface and even celestial events like sunspots and solar magnetic storms, can have a dramatic impact on the direction of the local magnetic field. Manmade interference, including buildings, bridges, and passing vehicles or passing ships all create their own local fields which influence the direction and intensity of the earth's local field. In some situations, such as those often caused by magnetic anomalies in navigable waters, the

effects are known, can be marked on charts, and generally may be treated like an unusual local variation. In other situations, such as with sunspots or the magnetic interference encountered by a passing vehicle in a large city, the effects are often unpredictable, which presents a problem in that the magnetic field measured may not correspond to direction. Magnetic compasses alone cannot accurately determine direction in situations where unpredictable magnetic anomalies in the environment distort the earth's magnetic field. This limitation can be overcome, and it does not apply to magnetic interference originating from the host platform (deviation), which is relatively permanent, so it can be precisely measured and compensated using modern electronic technology with sophisticated automatic compensation programs.

3.3.3 Inclination or Dip Angle

The earth's magnetic field is a space vector and can be resolved in a horizontal component and a vertical component. Direction corresponds to the earth's horizontal magnetic field, so a magnetic compass must have the ability to isolate and measure the horizontal field separate from the vertical. The illustration to the right shows that the earth's magnetic field is perfectly vertical at the magnetic poles, and perfectly horizontal at the magnetic equator (which corresponds very closely to the geographic equator). Everywhere else there is a combination of vertical and horizontal attraction to differing degrees depending on the orientation on the earth relative to its magnetic poles. This *magnetic dip angle* significantly impacts the performance of a magnetic compass from two standpoints -- geographic coverage and accuracy.

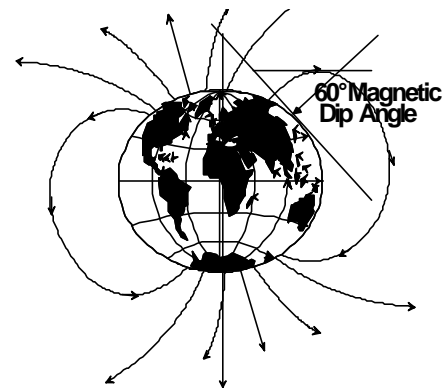


Figure 3: Model Showing the Effects of the Earth's Magnetic Dip

3.3.3.1 Magnetic Dip Angle Effects on Geographic Coverage

At the magnetic poles, the earth's magnetic field is entirely vertical with a dip angle of 90° . There is no horizontal component in the earth's field, so it cannot be used to determine direction. Heading away from the poles towards the magnetic equator, the earth's field gradually becomes more horizontal. At the magnetic equator the earth's magnetic field is entirely horizontal, there is no vertical component of the field, so it has a 0° magnetic dip angle. This change in dip angle is the characteristic of the earth's field which prevents a conventional card compass calibrated from the northern hemisphere from operating in the southern hemisphere. The card will attempt to follow the direction of the earth's field bottoming out against its housing when the vertical component becomes significantly stronger than the horizontal. Modern electronic compasses do not attempt to physically orient themselves to the earth's field. They measure the inductance of the earth's magnetic field in a specially selected core material constantly being driven in and out of magnetic saturation. For this reason, good electronic compasses do not have to be recompensated for changes in magnetic field strength and orientation. KVH's electronic compasses will generally operate well up through 80° magnetic latitude. The chart on the following page shows the lines of magnetic latitude to demonstrate most of the world's inhabited areas are well below the 80° magnetic latitude, so an electronic compass can be used for most applications without much concern about geographic coverage.

3.3.3.2 Magnetic Dip Angle Effects on Accuracy

All compasses which read the earth's magnetic field require some sort of gimbaling to provide the

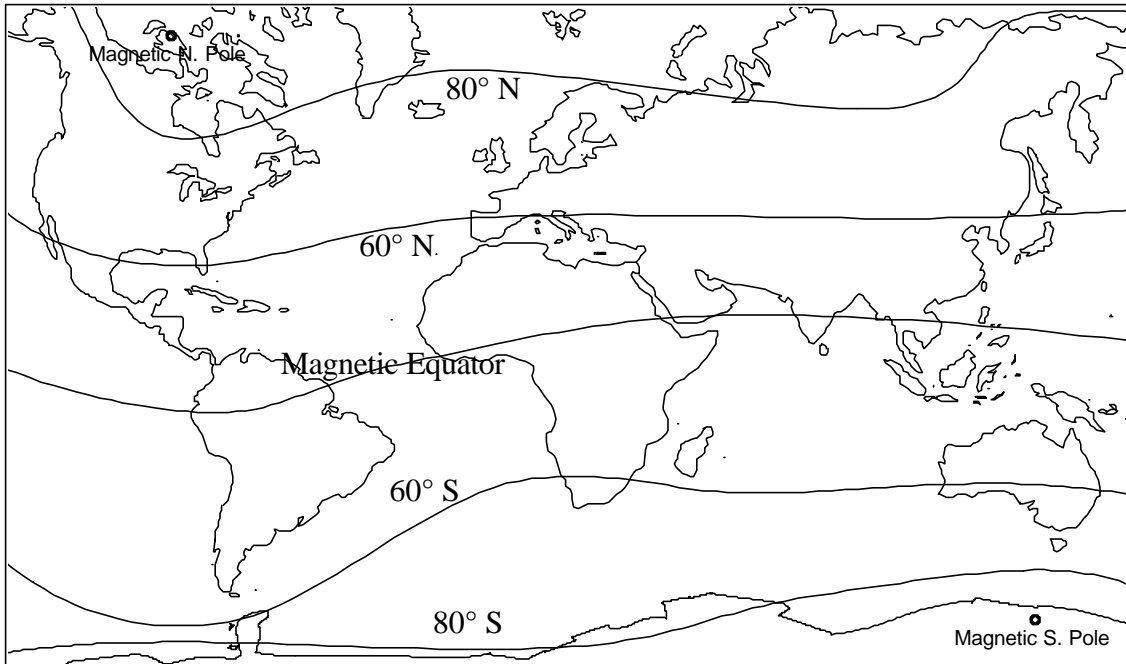


Figure 4: Geographic Coverage of Electronic Compasses Due to Magnetic Dip

freedom of movement necessary to allow either the compass sensor (or card) or an inclinometer to respond to the acceleration of gravity and orient itself with the earth's horizontal field. For a compass without gimbaling, the general rule of thumb is each degree of tilt is roughly 3 degrees of compass error (at 70° magnetic dip angle), although the exact relationship changes at different latitudes. At the magnetic equator, where the earth's field is primarily horizontal, each degree of tilt of the compass sensor has very little impact on the directional accuracy of the compass. In contrast, at high magnetic latitudes, each degree of tilt may be 3-5° of direction error or more, as shown in the following table.

$$\text{Compass Error} = \tan^{-1}[(\sin a) (\tan D) (\cos q)]$$

<u>a = Tilt (or Vertical Reference Error)</u>	<u>D = Magnetic Dip Angle</u>	<u>q = Compass Reading</u>	<u>Heading Error</u>
1°	80°	000°	6°
1°	70°	000°	3°

Figure 5: Effects of Tilt on Magnetic Compass Accuracy



Accelerations, either in the conventional sense or associated with dramatic vibrations or platform instability, may impair the magnetic sensor's ability to remain oriented with the earth's horizontal field. Fluid filled compass sensors and electronic averaging can minimize the effects of acceleration, but to some degree all magnetic compasses tend to be sensitive to dramatic pitch, yaw and roll. In highly dynamic conditions, a rate gyro may be used to complement the magnetic compass providing short term rate of change information to complement the accurate long term information provided by the electronic compass.

3.3.3.3 "Northerly Turning Error"

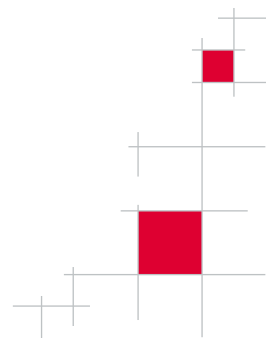
One peculiar phenomenon associated with compass instability and directly related to dip angle is known as "Northerly Turning Error", which occurs when the compass senses the vertical component of the earth's field as opposed to the horizontal. The geometry in the northern latitudes of the dip angle is such that this problem is particularly troublesome heading in a northerly direction in northern latitudes, when the compass will often fail to indicate a turn because the acceleration of the turn provides the compass with vertical field information which corresponds with the direction before the turn. Northerly Turning Error may be easily remedied with the addition of a rate gyro to the system to complement the compass with short term turning information.

3.4 Summary of the Limits of Geomagnetism as a Directional Reference

Generally, most of the surface of the earth is covered by a magnetic field which is relatively consistent and predictable enough to associate with a specific direction. The two primary concerns where the earth's field might not be a good indication of direction are those geographic areas where the horizontal direction-related component of the field is too weak to accurately measure, or those areas where unpredictable magnetic interference from manmade or natural environmental objects distort the local magnetic field in an unpredictable manner.

4 The Nature of Magnetism and Magnetic Materials

Aside from the inconsistencies in the earth's magnetic field which create challenges in determining direction, the magnetic characteristics or deviation of the host platform must be taken into consideration, as they will distort the local magnetic field. The most common oversight of product designers in specifying a magnetic compass sensor for a particular application is not considering the sensor's ability to correct for the host platform's deviation. The meaningful advancements in compass design are not those which make compasses more accurate in the free field of the laboratory, but those which make compasses more accurate after installation in their final application. To fully understand the implications of deviation on successful compass design, it is useful to review materials which might distort the earth's magnetic field.



4.1 What is Magnetism?

Magnetism is the physical force created by moving electrical charges, which is only detectable by its influence on other moving charges. These charges may be associated with electrical current moving through a wire; electrons orbiting around the nucleus of an atom; or charges flowing with the magma in the earth's core. All create identical magnetic fields. Magnetic fields are directional in nature, with the like poles of the magnetic field repelling and the opposite poles attracting each other.

4.2 Nature of Magnetic Materials

Basic physics teaches that electrons, revolving in orbits around the nucleus of an atom, create small current loops. All atoms contain these current loops. Generally, the positive and negative attractions of these current loops balance each other out, either because atoms move randomly without forming strong attractions to each other, or because they join together to form *molecules* which are magnetically balanced, with even numbers of electrons in the outermost valence level.

Elements are compounds made up of a single type of atom. In most elements the atoms move randomly. The strength of their minute magnetic fields are insufficient to overcome chaotic movement created by thermal agitation, so they exhibit no measurable magnetic force. 75% of all elements are *metals*. They generally form compounds with molecules that are ionized (have lost or gained an extra electron). The loss or gain of an electron creates an unbalanced state or polarity in the compound, inducing metallic elements to join together forming natural lattice structures. In most metals the electrons in the metallic ions which form the lattice structure are eventually paired off, resulting in metals which are "magnetically neutral". When the electrons in the metallic ions are not paired off, they have polarity which causes their current loops to become aligned exhibiting magnetic force. Metals exhibiting magnetic force may occur naturally or due to the influence of an external electrical field. Metals which have the ability to exhibit magnetic force are known as *ferromagnetic*. Iron, nickel, cobalt, and gadolinium are the only elements which are ferromagnetic at room temperature, but they are not the only magnetic materials. Various alloys, (compounds formed by molecules made up from two or more different elements) whose components are not ferromagnetic can exhibit magnetic properties when they join to form lattice structures with unpaired electrons.

4.2.1 Permanent magnetism (hard iron)

Ferromagnetic compounds with molecules that have a tendency to spontaneously align themselves in a particular direction creating an external magnetic force in the absence of any external field are said to exhibit *permanent magnetism*. The polar attractions of the molecules overcomes the chaotic influences of thermal energy. Permanent magnets generally are not readily magnetized by induction, but they retain a high percentage of the

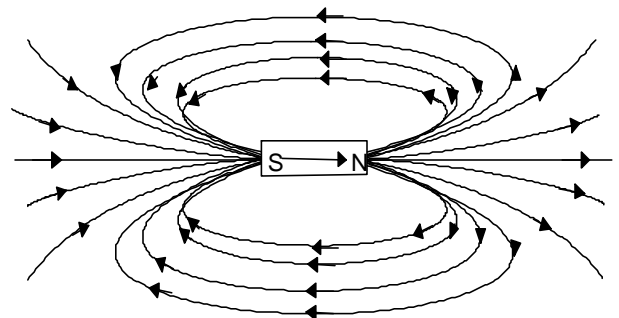


Figure 6: Diagram of Permanent Magnetism

magnetism they acquire, so they are known as "hard iron". Figure 6 illustrates the magnetic characteristics of hard iron.

4.2.2 Induced Magnetism (soft iron)

Some elements which do not exhibit any magnetic properties on their own may acquire these properties when brought into the influence of an external magnetic field. This phenomenon is known as *induced magnetism*, and all material in which induced magnetism is present is known as "soft iron". Any mass of ferromagnetic material which is not a permanent magnet will display properties of induced magnetism when exposed to an external magnetic field, including the earth's field. Generally the effect of soft iron on an external magnetic field is to provide a path of lower impedance than the surrounding air, causing the external field to bend into the soft iron as is shown in the illustration to the right. Magnetization present after magnetizing force is removed is known as residual magnetism. It is similar to that of weak hard iron, although its strength gradually changes due to influences of other external fields.

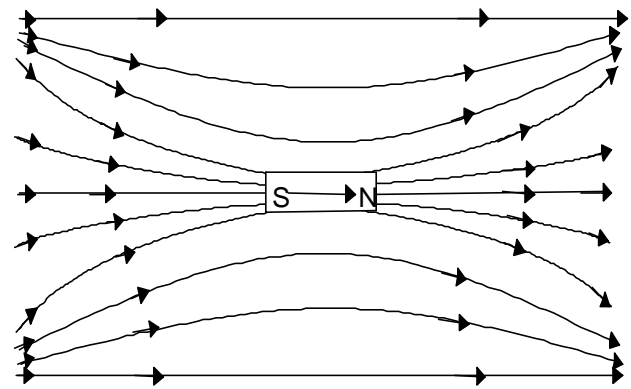


Figure 7: Diagram of Induced Magnetism

4.2.3 Electromagnetism (current passing through wires)

As explained earlier, magnetism is created by moving electrical charges, so it is not surprising that electric currents passing through wires create magnetic fields. This is true even when the wire is a non-magnetic material, such as copper. So long as the current is present, the magnetic field created will be identical to that of a permanent magnet. If the current is consistent, the magnetic field will be consistent. If the current is inconsistent, the field will vary in strength.

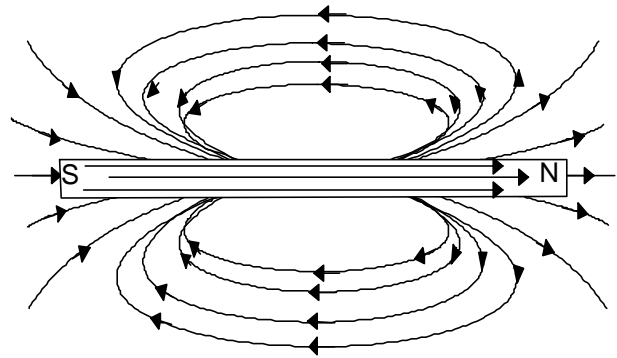


Figure 8: Diagram of Electromagnetism

4.3 Effect of Magnetic Deviation on the Earth's Magnetic Field

Magnetic materials are important to understand because they distort the local magnetic field so that a magnetic compass reading no longer corresponds with direction. The local magnetic field is actually the vectoral sum of the earth's magnetic field, any anomalies present, and the unique magnetic characteristics of the host platform. *Deviation* is the distortion of the earth's magnetic field created by magnetic influences of the host platform. Magnetic fields created by permanent magnets or current carrying wires (hard irons), or by materials which are not magnetic themselves but in which magnetic fields can be



induced (soft irons) are common sources of deviation. Fortunately, since the unique magnetic characteristics of the host platform are constant in relation to the compass, they can be corrected through the familiar process known as *compensation*.

4.3.1 Permanent Magnetism Deviation -- Hard Iron, One Cycle Errors

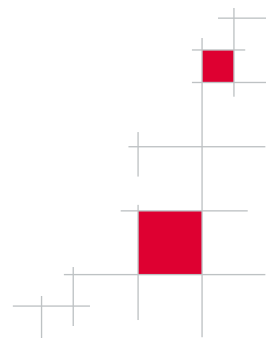
The effect of hard iron or permanent magnetism deviation is a single cycle error -- all readings are distorted in the direction of the magnet, crossing the axis of "no error" at the two points (one complete cycle) where the magnetic vector is aligned with the earth's magnetic field. Hard iron errors may be created by magnets in speakers, generators or DC motors, electrical current in a wire, or even the alignment of the magnetism in the hull of a ship heading the same direction for a long period of time. This relationship is shown in Figure 9.

4.3.2 Soft Iron (Two Cycle) Deviation Errors

Unmagnetized soft iron presents a path of low impedance to magnetic fields. The effect of soft iron is a two cycle error, crossing the axis of "no error" at four points when exactly in line, and exactly perpendicular to the earth's field. Although the overall magnitude of soft iron errors is usually not as great as hard iron errors, they are usually much more difficult to correct because they change in both intensity and direction depending on their orientation to the earth's magnetic field. A major development in KVH's electronic compass technology, and a major difference between the competing brands of electronic compasses, is their ability to measure and correct for soft iron errors (see Figure 10.)

4.3.3 The Unique Deviation Problem Created by Electromagnetism

Magnetic fields created by electromagnetism create some of the most difficult deviation problems, because they often change unpredictably in value as power consumption on the load increases or changes occur in the transmission rates of communications and data on radio or computer wires. This type of deviation is generally controlled by mounting the directional sensor in a location away from the influences of electromagnetism. If this is not practical, it can be controlled to a great degree if precautions are taken when building the host product. In wires carrying an alternating current, it is generally safe to assume the alternating pulses create magnetic fields of equal and opposite directions which effectively cancel each other out. Using DC power with two wires carrying current to the load, the polarity of the field around the wire is related to the direction of the current, so twisting the two wires together will effectively cancel out the field produced by the wire. The tighter the twist, the more thoroughly the fields will be canceled. In communications and other wiring, twisting may or may not cancel fields out depending on the symmetry of the signals going each direction through the wire.



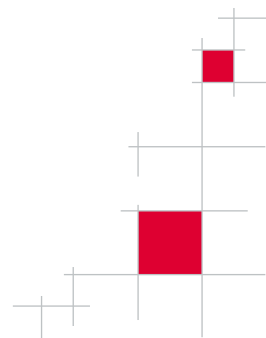


4.4 Correcting for Deviation in Magnetic Compasses

In order to use a magnetic compass to provide an accurate indication of direction, it is necessary to isolate the measurement of the earth's magnetic field from those unique magnetic characteristics of the host platform. The most common mistake of product designers utilizing directional sensors is to evaluate the performance of the magnetic compass subsystem before its final installation in the host platform where it will actually be used. A magnetic sensor's "accuracy" is directly related to its ability to isolate and compensate for the magnetic deviation of the host.

In the old days of card compass technology, compensation was accomplished with compensating magnets (hard iron errors) or cast iron spheres (soft iron errors) which were artfully placed in an attempt to mimic the forces of deviation in the equal and opposite direction. This method was time consuming and often inaccurate. Compensating magnets changed their own magnetic characteristics over time. Most electronic compasses use what is known as a rate of turn method of measuring deviation, which requires rotating the host platform at a constant rate through 360° (a full circle). The resulting readings differ from the theoretical perfect circle by an amount that is assumed to be deviation. The rate of turn method is flawed because it fails to adequately correct for the unique sources of hard and soft iron deviation, which change their characteristics based on the intensity and dip angle of the earth's magnetic field.

KVH Industries has developed compass technology that is capable of directly measuring and automatically compensating for the distorting influences of both hard and soft iron deviation. This method is so effective, it has been documented by the U.S. Military to work on main battle tanks and aircraft carriers. The procedure is possible because the earth's magnetic field (including any local anomalies) is relatively constant at any particular location. The magnetic characteristics of the host platform are also constant. When the unique magnetic field of the host platform is under the influence of the earth's magnetic field, the magnetic compass reading taken on the host will be the vectoral sum of all magnetic fields present. As was demonstrated, the fields interact in a significantly different manner depending on the relative orientation of the host platform's magnetic field to the earth's magnetic field. By rotating the host platform in a circle so that measurements of its field can be taken at every different point of interaction with the earth's field, hard and soft iron sources of deviation on the host platform are identified, measured and compensated. KVH's microprocessor based electronic compass can create sophisticated mathematical models which isolate both hard and soft iron errors. Once the errors have been identified, they can be taken into consideration so that the final measurement of the local magnetic field corresponds extremely close to the earth's field without the deviating influence of the host platform.



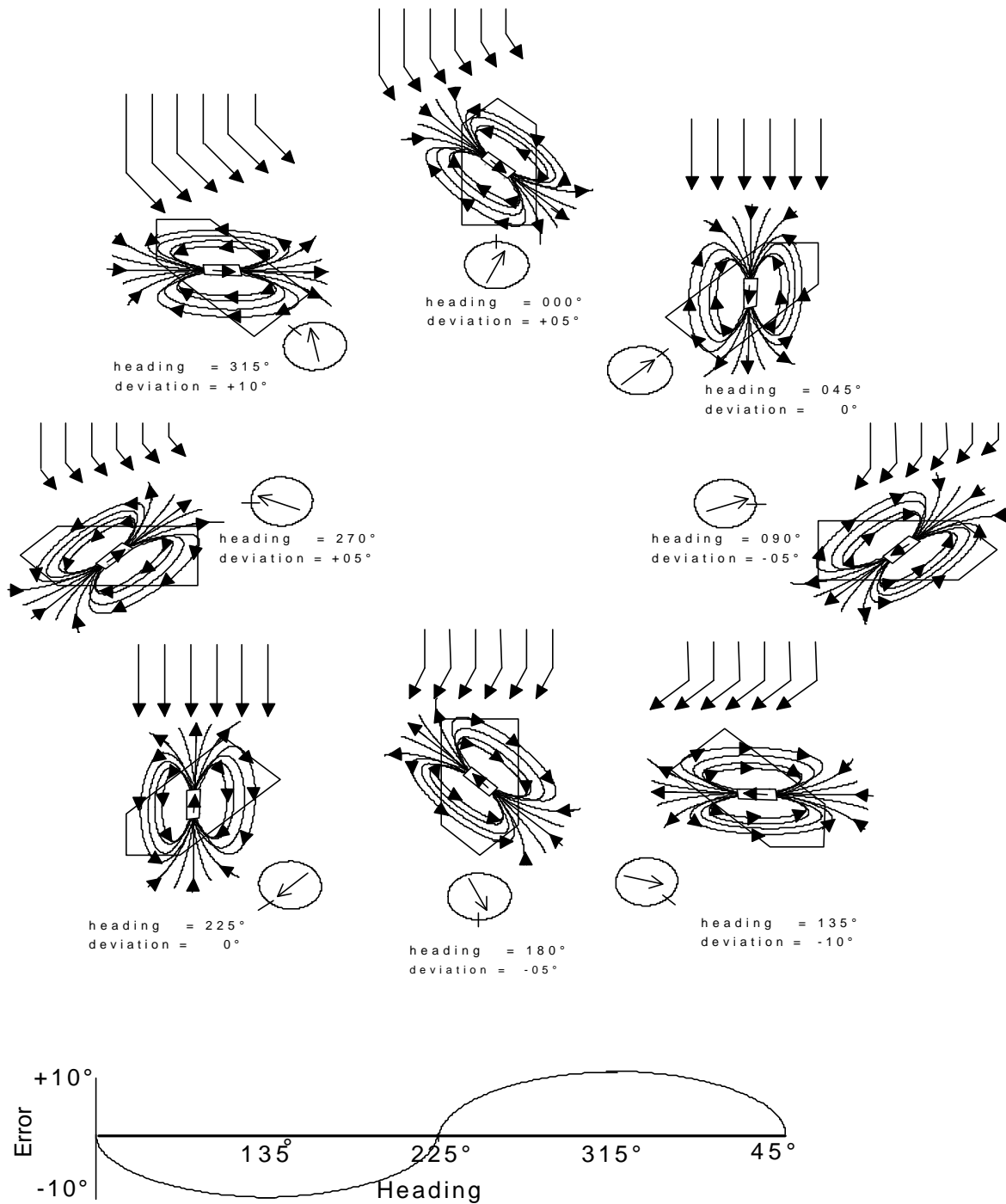


Figure 9: Diagram of a "Hard Iron" Source of Deviation

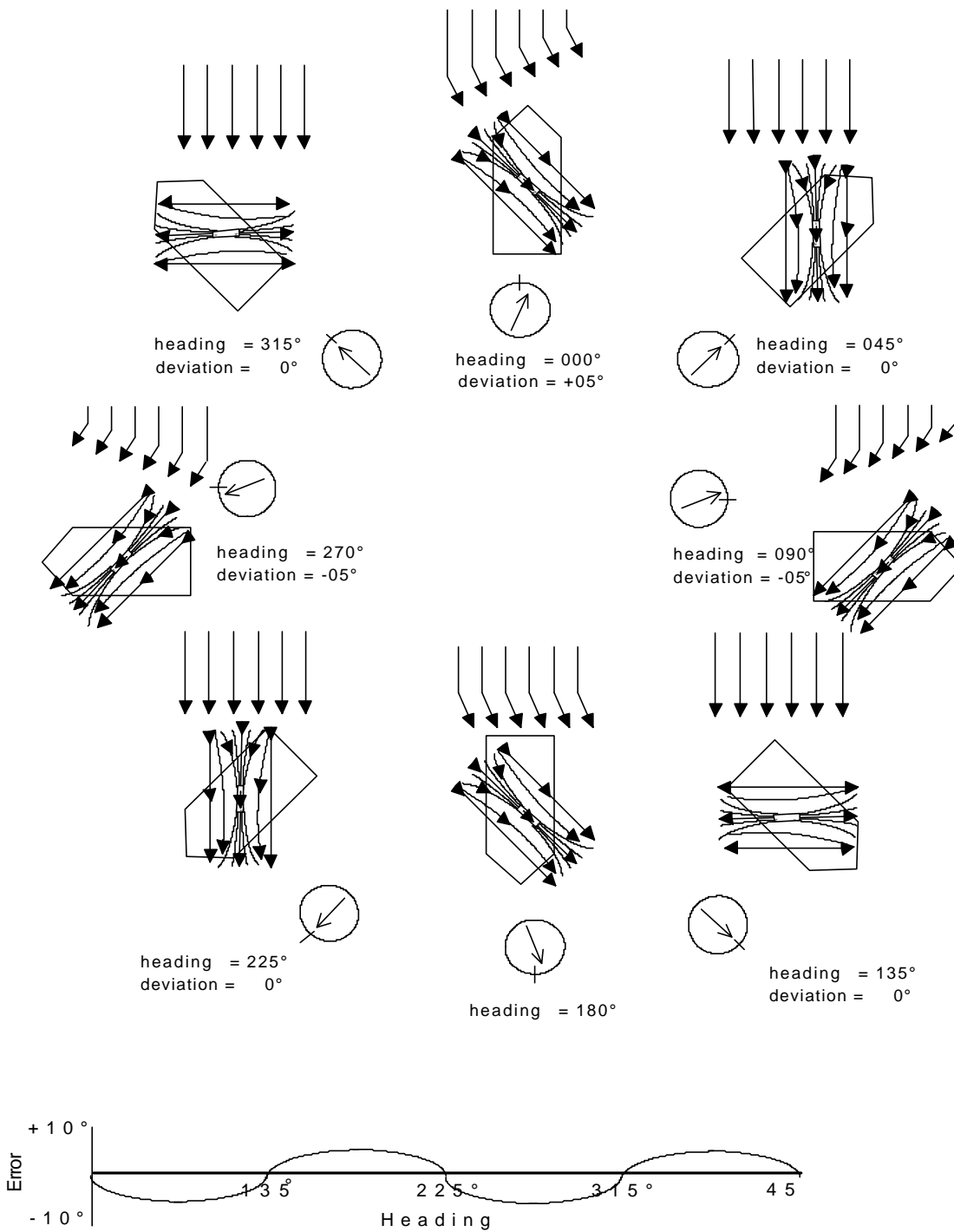


Figure 10: Diagram of a "Soft Iron" Source of Deviation