

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**INVESTIGATION ON THE EFFECT OF GEOMAGNETIC FIELD ON SAFE
AIR NAVIGATION**



M.Sc. THESIS

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Department of Geomatics Engineering

Geomatics Engineering Programme

DECEMBER 2018

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**JEOMANYETİK ALANIN GÜVENLİ HAVA NAVİGASYONU ÜZERİNE
ETKİLERİNİN ARAŞTIRILMASI**

YÜKSEK LİSANS TEZİ

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To my soulmate and family,



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ABBREVIATIONS

ADF	: Automatic Direction Finder
AGL	: Above Ground Level
APU	: Auxiliary Power Unit
CHAMP	: Challenging Minisatellite Payload
CONAE	: Comisión Nacional de Actividades Espaciales
DI	: Declination – Inclination
DME	: Distance Measuring Equipment
EBBR	: ICAO Code of Brussels National Airport
GFZ	: Deutsche Geo Forschungs Zentrum Potsdam
GNSS	: Global Navigation Satellite System
GPS	: Global Positioning System
IAGA	: International Association of Geomagnetism and Aeronomy
IATA	: International Air Transport Association
ICAO	: International Civil Aviation Organization
IFR	: Instrument Flight Rules
IGRF	: International Geomagnetic Reference Field
ILS	: Instrument Landing System
INS	: Inertial Navigation System
IRS	: Inertial Reference System
IVAO	: International Virtual Aviation Organization
LF	: Low Frequency
LFSB	: ICAO Code of EuroAirport Basel Mulhouse Freiburg Airport
LOC	: Localizer
LPPR	: ICAO Code of Porto Francisco Sa Carneiro Airport
LPPT	: ICAO Code of Lisbon Airport
LTBA	: ICAO Code of Istanbul Ataturk International Airport
MF	: Medium Frequency
NASA	: National Aeronautics and Space Administration
NDB	: Non Directional Beacon
NOAA	: National Oceanic and Atmospheric Administration

RNAV	: Area Navigation
SAC – C	: Satelite of Aplicaciones Cientificas – C
SI	: International System of Unit
SID	: Standard Instrument Departure
STAR	: Standard Terminal Arrival
THY	: Türk Hava Yolları
USGS	: United States Geological Survey
VHF	: Very High Frequency
VOR	: VHF Omnidirectional Radio Range
WGS84	: World Geodetic System



SYMBOLS

A_p	: Index of maximum 24 – hour disturbance for storm events
B	: Geomagnetic field
CH	: Compass heading
CN	: Compass north
cts	: U.S. cents
DEV	: Deviation
D	: Declination
E	: East
E	: Electrical field
F	: Intensity of the total field
FL	: Flight Level
ft	: Feet
gal	: U.S. gallon
H	: Horizontal component of geomagnetic field
I	: Inclination
IAS	: Indicated Air Speed
K	: Index of global geomagnetic activity
kg	: Kilogram
kHz	: Kilohertz
km	: Kilometer
MH	: Magnetic heading
MHz	: Megahertz
MN	: Magnetic north
N	: North
NM	: Nautical mile
nT	: Nanotesla, the unit of field strength
P_n^m	: Schmidt quasi-normalized associated Legendre functions of degree n , order m
r	: Spherical coordinate radius
R_E	: Radius of the Earth

S	: South
TAS	: True Air Speed
TH	: True heading
TN	: True north
UT	: Universal time
VAR	: Variation
V_i	: The potential of the magnetic field originating inside the Earth
W	: West
X	: The component of horizontal magnetic field in the true north direction
Y	: The component of horizontal magnetic field in the east direction
Z	: Vertical component of geomagnetic field
λ	: Lamda, spherical coordinate longitude
γ	: Gamma, the unit of the field strength
θ	: Spherical coordinate colatitudes
$^{\circ}$: Degree
\$: U.S. dollar

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INVESTIGATION ON THE EFFECT OF GEOMAGNETIC FIELD ON SAFE AIR NAVIGATION

SUMMARY

Geodesy is mainly concerned with the determination of the shape of the Earth surface, digital surface model, parameters of gravity and geomagnetic field and their changes through a certain period of time. Since the year 400 B.C., with the discovery of geomagnetism, investigations and studies on the parameters of geomagnetic field have been carrying on. Nowadays, with developing technology, not only terrestrial measurements at observatories, but satellite – based measurements of total intensity of geomagnetic field and its components are also used to derive geomagnetic field model. Throughout the Earth, there are plenty numbers of observatories which reveals the data used to create the global model of magnetic field. Since the last decade of 20th century, satellite missions have been launched to observe and measure the changes of not only magnetic field and its components, but also the effects of solar activities at both Earth's surface and space by time.

The Earth's magnetic field is called geomagnetic field. The main source of the geomagnetic field is conducting fluid and lava containing magnetized ingredients from outer core. This part of the field is known as main field. Magnetized rocks in the Earth's crust, fields generated outside the Earth by electric current in the ionosphere and magnetosphere as well as in the Earth's crust are other sources which play the role in generating geomagnetic field. The angle between horizontal component of magnetic field and the true north is called magnetic declination or magnetic variation. The angle between magnetic field and the horizontal plane is called magnetic inclination or magnetic dip. The units of magnetic declination and magnetic inclination are degrees, positive for declination in direction of east, positive for inclination in direction of down. Total field is composed of horizontal component and vertical component.

The geomagnetic field is similar to the field that would be generated if there were a huge bar magnet centered in the Earth, called a dipole field. It has an axis of symmetry parallel to that huge bar magnet and intersects the Earth's surface at both geomagnetic north and south poles. The dipole axis is not parallel to the Earth's rotation axis but is inclined approximately 10 degrees away. Thus, geomagnetic poles and geographic poles are not coincident. But, the position of the geomagnetic poles changes slowly as time goes by. So, this 10 degrees away position of geomagnetic pole is not fixed and will continue to change by time. The positional change of geomagnetic poles causes the annual change of the declination. That annual change can be observed by the study of paleomagnetism, which is the science of observing the properties of magnetized sediments, rocks or formations in terms of geology. Iron – rich rock materials show similar alignment behavior with those formed in the same geological epoch. Ferrous particles of rocks, which had been magnetized in different geological era, aligned in different directions. This fact

proves that the location of geomagnetic pole, or magnetic north direction, changes by time.

In 1903, the Wright brothers designed an airplane and attempted to fly it. The Wright brothers, as we all know, are written in the history as the people succeeded first time ever to fly an airplane. Developing technology and taking the milestone in aviation industry have led the aviation to be the essential part of human need in such a short period of time.

Not only producing airplanes, but to fly it is also important. Therefore, navigation aids which help pilots to fly the airplane on desired route were integrated to avionics part of the airplane. The major threat on safe air navigation is caused by the fact that navigation aids use magnetic values of degrees which are referenced to the magnetic north, whereas geodetic computations use true values of degrees that are originated from the true north. The difference between true north and magnetic north is called magnetic variation (declination), in degree. The scope of this study is to exhibit the effects of geomagnetic field, especially magnetic variation, on safe air navigation.

Navigation is the science of planning a voyage safely based on given time and conditions i.e. meteorological and aircraft conditions. For a classical navigation flight, some parameters which are remaining distance to destination, ground speed, traveling direction, wind correction, time to destination, current fuel consumption, and remaining fuel have to be calculated. The essential parameter which has to be taken into account for directional computations to destination is traveling direction. Navigation methods recently used are Dead Reckoning, terrestrial, astronomic and radio – navigation. The most frequently used navigation methods in commercial flights are radio – navigation method and RNAV.

As known in geodesy science, the north is mainly divided into three types which are true, magnetic and grid. The most geodetic calculations are made by referencing true north. For radio – navigation methods, the angle between magnetic north and the direction of desired route to destination in zero wind condition is used, called as magnetic course. If wind correction is applied on magnetic course, then that angle is called as magnetic heading. In case of applying compass deviation to magnetic heading, compass heading is obtained.

Position of the north magnetic pole is deviated approximately 1300 NM (nautical mile) from the position of geographic (true) north. This deviation results in difference between magnetic and geographical meridians. The Earth does not have a uniform distribution of magnetism. Therefore, it is not possible to measure the magnetic variation at any single meridian.

Magnetic compasses are integrated into navigation part of aircraft as standby instrument in case of unavailable radio navigation aids. A pilot has to be capable of controlling the aircraft and navigating through desired route even there is no electronic navigation aid. The principles of radio navigation aids have to be understood clearly to emphasize the effect of magnetic variation on safe air navigation.

A Non Directional Beacon (NDB) is a radio station placed in an identified location on the ground and it is used as an aviation or maritime navigation aid. These beacons are mostly located near airports since they provide the simplest navigation information to reach an airport.

Magnetic signals from NDB are received by an onboard instrument which is called Automatic Direction Finder (ADF). The NDB signal is received by the ADF which automatically and continuously displays the relative bearing from the aircraft to the selected NDB.

VOR (VHF Omnidirectional Radio Range) is a navigation aid that provides magnetic bearing information to and from the station. The prefix “omni-” means “all”, and an omnidirectional range is a VHF radio transmitting ground station that projects straight line courses (radials) from the station in all directions. These radials are referenced to magnetic north (MN).

The Instrument Landing System (ILS) is the most precise navigation system used in IFR flight. It is composed of at least two elements which are localizer and glide slope. Localizer directs aircraft in horizontal plane with respect to center of the runway axis, while glide slope provides vertical guidance to the aircraft based on approach slope.

RNAV is a method of navigation which permits aircraft operation on any desired flight path within the coverage of ground – based or space – based navigation aids or within the limits of self – contained aids, or a combination of these. Area navigation can be applied by using various sensors: GNSS (satellite – based), DME/DME (ground – based), VOR/DME (ground – based), or more rarely INS/IRS (self – contained).

If a pilot has travelled sixty miles then an error in track of one mile is approximately a 1° error in heading, and proportionately more for larger errors. The rule states that one degree deviation along 60 NM will result in 1 NM displacement from the course. This result proves that the 1 in 60 rule is %4.7 inaccurate. It means that if a pilot flies an aircraft over a distance of 600 NM with 1° displacement, it will result in approximately 10.5 NM off the course.

It can be clearly seen that it is important to apply magnetic variation or declination, caused by geomagnetic field, to navigation calculations for precise and safe navigation flights. In Europe, magnetic variation values vary between -2° (2° W) and $+8^\circ$ (8° E), total of 10 degrees. 10 degrees off the course might result in excessive displacement of distance which threatens safe air navigation.

So, the purpose of this thesis is investigating the effect of the geomagnetic field to the flight routes by means of error in heading via the numerical results along the selected routes. In the analyses, the economical aspects of this error on the flight expenses are mentioned and discussed as well.



JEOMANYETİK ALANIN GÜVENLİ HAVA NAVİGASYONU ÜZERİNE ETKİLERİNİN ARAŞTIRILMASI

ÖZET

Jeodezi bilim dalı yeryuvarının şeklinin, sayısal arazi modelinin, gravite ve jeomanyetik alanın, yeryuvarına ilişkin fenomenlerin incelenmesi ve modellenmesi konuları ile ilgilidir. Jeomanyetizmanın keşfedilmesi ile birlikte, M.Ö. 400 yılından bu yana, jeomanyetik alanın parametreleri üzerine araştırmalar ve çalışmalar devam etmektedir. Günümüzde, gelişen teknolojiyle, sadece gözlemlerinde yersel ölçümler değil, aynı zamanda jeomanyetik alan ve bileşenlerinin toplam yoğunluğunun uydu temelli ölçümleri de jeomanyetik alan modelini türetmek için kullanılmaktadır. Dünya çapında, küresel manyetik alan modelini oluşturmak için kullanılan verileri ortaya koyan çok sayıda gözlemleri bulunmaktadır. Yirminci yüzyılın son on yılından bu yana, hem manyetik alanın ve bileşenlerinin değişimini, hem de güneş aktivitelerinin Dünya'nın yüzeyinde ve uzaydaki etkisini gözlemlemek ve ölçmek amacıyla uydu görevleri başlatıldı.

Dünya'nın manyetik alanına jeomanyetik alan denir. Jeomanyetik alanın ana kaynağı, dış çekirdekteki manyetizma özelliği gösteren bileşenler içeren iletken sıvı ve lavdır. Alanın bu kısmı temel alan olarak bilinir. Yerkabuğundaki manyetize edilmiş kayalar, yerkabuğunda olduğu kadar iyonosfer ve manyetosferdeki elektrik akımları tarafından Dünya dışında oluşan alan da jeomanyetik alan oluşmasında rol oynayan diğer kaynaklardır. Manyetik alanın (B) yatay bileşeni (H) ile gerçek kuzey arasındaki açı manyetik sapma (D) veya manyetik varyasyon olarak adlandırılır. B ve yatay düzlem arasındaki açı manyetik eğim (I) veya manyetik daldırma olarak adlandırılır. D ve I birimleri derece; doğu yönünde D için pozitif, aşağı yönde I için pozitifdir. Toplam alanın (F) yatay bileşeni H , dikey bileşeni Z olarak gösterilir.

Jeomanyetik alan, Dünya'nın merkezinde büyük bir çubuk mıknatıs olduğu varsayıldığında üretilecek olan manyetik alana (dipol alanı olarak adlandırılır) benzer bir alandır. Bu alan, büyük çubuk mıknatısa paralel bir simetri eksenine sahiptir ve dünyanın yüzeyini hem jeomanyetik kuzey hem de jeomanyetik güney kutuplarında keser. Dipol ekseni, Dünya'nın dönme eksenine paralel değildir, ancak yaklaşık 10 derece eğimlidir. Böylece, jeomanyetik kutuplar ve coğrafi kutuplar çakışmaz. Ancak, zaman geçtikçe jeomanyetik kutupların konumu yavaşça değişir. Böylece, jeomanyetik kutup konumunun 10 derecelik farklılığı sabit değildir ve zamanla değişmeye devam edecektir. Jeomanyetik kutupların konumsal değişimi, sapmanın yıllık değişmesine neden olur. Bu yıllık değişim, manyetizma etkisinde oluşmuş sedimanların, kayaların veya formasyonların özelliklerini jeoloji açısından gözleme bilimi olan paleomanyetizma çalışmasıyla gözlemlenebilir. Demir açısından zengin kayaç bileşenleri, aynı jeolojik dönemde oluşanlarla benzer yönelim davranışları gösterir. Farklı jeolojik çağda manyetize edilmiş olan kayaç parçacıkları,

farklı yönelimlerde hizalanmıştır. Bu gerçek, jeomanyetik kutup konumunun veya manyetik kuzey doğrultusunun zamana göre değiştiğini kanıtlamaktadır.

1903'te, Wright kardeşler bir uçak tasarlamış ve uçmayı denemişlerdir. Wright kardeşler, hepimizin bildiği gibi, ilk kez bir uçağı uçurmayı başaran insanlar olarak tarihteki yerlerini almışlardır. Gelişen teknoloji ve havacılık endüstrisinde gerçekleşen kilometre taşları, havacılığın çok kısa bir sürede insan ihtiyacının vazgeçilmez bir parçası olmasını sağlamıştır.

Sadece uçak üretmek değil, onu uçurmak da önemlidir. Dolayısıyla, pilotların uçağı istenen rotada uçurmasına yardımcı olan seyrüsefer yardımcıları, uçağın aviyonik kısmına entegre edilmiştir. Güvenli hava seyrüseferine yönelik en büyük tehdit, navigasyon yardımcılarının manyetik kuzeye referanslanan değerleri kullanmasından kaynaklanırken, jeodezik hesaplamalar gerçek kuzeyden gelen değerleri kullanmaktadır. Gerçek kuzey ve manyetik kuzey arasındaki fark, derece olarak manyetik varyasyon (sapma) olarak adlandırılır. Bu çalışmanın amacı, jeomanyetik alanın, özellikle manyetik varyasyonun, güvenli hava seyrüseferine etkisini ortaya koymaktır.

Navigasyon, belirli bir zaman ve şartlara, örneğin meteorolojik şartlar ve uçak koşullarına, dayanarak bir yolculuk planlaması bilimidir. Klasik bir seyrüsefer uçuşu için, hedefe olan mesafe, yer hızı, seyir yönü, rüzgâr düzeltme, hedefe varış zamanı, mevcut yakıt tüketimi ve kalan yakıt gibi bazı parametreler hesaplanmalıdır. Destinasyona ulaşmak amacıyla yapılan yön hesaplamaları için dikkate alınan temel parametre, seyrüsefer doğrultusudur. Son zamanlarda kullanılan navigasyon yöntemleri arasında "Dead Reckoning", karasal, astronomik ve radyo – navigasyon metotları sayılabilir. Ticari uçuşlarda en sık kullanılan navigasyon yöntemleri radyo – navigasyon metodu ve RNAV'dir.

Jeodezi biliminde kuzey, esas olarak manyetik, grid ve gerçek kuzey olarak üç çeşide ayrılır. Çoğu jeodezik hesaplamalar gerçek kuzey referans alınarak yapılır. Radyo – navigasyon metotları için, sıfır rüzgâr koşulunda, manyetik kuzey ile hedef için istenen rotanın doğrultusu arasındaki açı manyetik iz olarak adlandırılır. Manyetik ize rüzgâr düzeltmesi uygulandığında ise bu açı manyetik baş olarak adlandırılır. Pusula sapmasının manyetik başa uygulanması durumunda ise pusula başı elde edilir.

Manyetik kuzey kutbun yeri yaklaşık olarak 1300 NM (deniz mili) coğrafi (gerçek) kuzey kutbun konumundan farklıdır. Bu sapma manyetik ve coğrafi meridyenler arasındaki farkla sonuçlanır. Dünyada tek bir tip manyetizma dağılımı yoktur. Bu nedenle, herhangi bir meridyendeki manyetik varyasyonu ölçmek mümkün değildir.

Radyo navigasyon yardımcılarının arızalanması veya kullanılmaması durumunda, manyetik pusulalar uçakların navigasyon kısmına yedek navigasyon aleti olarak entegre edilmiştir. Bir pilotun, elektronik radyo navigasyon yardımcısı olmasa bile, uçağı kontrol etme ve istenen rotada seyre devam ettirme kabiliyetine sahip olması gerekir. Radyo seyrüsefer yardımcılarının prensipleri, manyetik varyasyonun güvenli hava seyrüseferine etkisini vurgulamak için açıkça anlaşılmalıdır.

NDB (Non Directional Beacon), yerdeki belirli bir yere yerleştirilmiş bir radyo istasyonudur. Hava veya deniz seyrüsefer yardımcısı olarak kullanılır. Bunlar çoğunlukla havalimanlarına yakın konumdadır, çünkü bir havalimanına ulaşmak için en temel navigasyon bilgilerini sağlarlar. NDB'den gelen elektromanyetik sinyaller, ADF (Automatic Direction Finder) adı verilen hava aracına yerleştirilmiş bir cihaz tarafından otomatik ve sürekli olarak alınır.

VOR (VHF Omnidirectional Radio Range), hava aracının istasyondan ve istasyona olan rölatif manyetik açı değerini belirten seyrüsefer cihazıdır. İçindeki “omni – ” ön eki, “tüm” anlamına gelir. Her 1 dereceye karşılık gelecek şekilde düz çizgiler yansıtır, bunların her birine radyal denir. Radyaller, manyetik kuzey referans alınarak belirlenir.

Aletli İniş Sistemi (ILS – Instrument Landing System), IFR uçuşunda kullanılan en hassas navigasyon sistemidir. Lokalizer ve alçalış hattı olmak üzere en az iki elemandan oluşur. Lokalizer, pist ekseninin merkezine göre yatay düzlemde uçağı yönlendirirken, alçalış hattı yaklaşma eğimine dayalı olarak uçağı dikey yönlendirme sağlar.

RNAV, yer bazlı olarak, uzay bazlı olarak, hali hazırda uçakta bulunan sistemler yardımı veya bunların kombinasyonu ile herhangi bir uçuş güzergahı boyunca uçabilmesini sağlayan bir navigasyon metodudur. Bu metod, GNSS (uydu bazlı), DME/DME (yer bazlı), VOR/DME (yer bazlı) veya daha nadir olarak INS/IRS (kendi kendine yeten) gibi farklı sensörler kullanılarak uygulanabilir.

Bir pilotun altmış mil kat etmesi halinde, rotadaki bir millik bir hata yaklaşık 1°'lik bir sapmaya sebep olur. Daha büyük hatalar orantılı olarak daha fazla sapmaya sebep olur. Kural, 60 NM boyunca bir derece sapmanın, rotanın 1 NM yer değiştirmesi ile sonuçlanacağını belirtir. 60'a 1 kuralı, %4.7'lik bir yanılma payıyla sonuçlanacağını kanıtlamaktadır. Bir pilotun 600 NM boyunca 1°'lik sapma ile uçması, rotadan yaklaşık 10.5 NM sapması ile sonuçlanacağı anlamına gelmektedir.

Jeomanyetik alanın neden olduğu manyetik varyasyon veya sapmanın, hassas ve güvenli navigasyon uçuşları için navigasyon hesaplamalarına uygulanmasının önemli olduğu açıkça görülmektedir. Avrupa'da, manyetik varyasyon değerleri -2° (2°W) ve + 8° (8°E), toplam 10 derece arasında değişiklik göstermektedir. Rotada yapılacak olası 10 derecelik bir yanlılık, güvenli hava seyrüseferini tehdit eden çok büyük sapmaya neden olabilir.

Bu tez çalışmasının amacı, belirlenen örnek uçuş rotalarında gerçekleştirilecek hesaplamalar ile jeomanyetik alanın neden olduğu sapmanın hava navigasyonuna etkisini detaylı bir biçimde incelemektir. Ayrıca, bu etkinin uçuş maliyeti açısından da bir değerlendirmesini yapmaktır.



1. INTRODUCTION

The problem of geodesy is defined as the study of determining the figure and external gravity field of the Earth and of other celestial bodies as a function of time, from observations on and exterior to the surfaces of these bodies (Torge, 2001). Physical geodesy, which is one of the sub-divisions of geodesy science, is mainly concerned with the determination of the shape of the Earth surface, parameters of gravity field and their changes through a certain period of time. To define the parameters as we are dealing with the search of geomagnetism as much as gravity field of the Earth are essential in addition to terrestrial observations, which are obtained from declinometer, magnetic compass and satellite measurements.

1.1 History of Geomagnetism

The period of the improvement of the meaning of geomagnetism had been taken a very long time. It is originated from the year of 400 B.C. as Plato emphasized the attraction, due to the magnetism, of certain rocks known to Greeks. The year of 300 – 200 B.C., the Chinese compass spoon, Si Nan (Figure 1.1), was used to align constructions with the natural Earth forces.



Figure 1.1: Magnetic compass spoon called Si Nan (Iron and Steel Research Institute, China, n.d.).

The spoon – shaped magnetite indicator, balancing on its heavy rounded bottom, allows the narrow handle to direct southward, to align with the directions carved symmetrically on a non-magnetic base plate.

Arabic or European merchant caravans brought this design of the magnetic compass to eastern Mediterranean region as they had traveled from China to Turkey along the Silk Road. The name for the natural magnet used for compasses by the late 1100's was loadstone (or known as leading stone). That loadstone is nowadays called as magnetite by geologists (Campbell, 2000). Magnetite is a rock mineral and one of the main iron ores, with the chemical formula Fe_3O_4 . It is one of the oxides of iron, and is ferromagnetic; it is attracted to a magnet and can be magnetized to become a permanent magnet itself. It is the most magnetic of all the naturally occurring minerals on Earth. Naturally magnetized pieces of magnetite, called lodestone, will attract small pieces of iron, which is how ancient peoples first discovered the property of magnetism (Wikipedia, n.d.).

1.2 Literature Review

The first textbook about geomagnetism was published by Gilbert (1590). He is recognized as the pioneer of magnetism science. *De Magnete*, which is Gilbert's book published in 1600, contains the general view of the knowledge of his time and of his own magnetic experiments. He was the first scientist to state that the Earth itself behaves as a great magnet (Gilbert, 1590) with a horizontal field at the Earth's equator and with two oppositely directed vertical fields at the Earth's poles. Thus, the Earth has the configuration that is expected from a magnetized iron bar which has a pair of magnetic poles distant to each other.

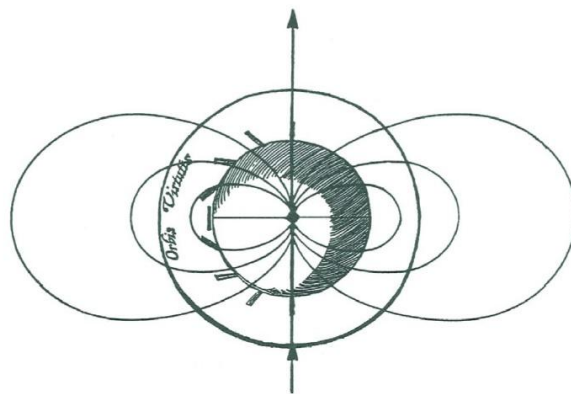


Figure 1.2: The Earth as a great magnet (Gilbert, 1590).

Figure 1.2 made by Gilbert illustrates that how the Earth behaves as great magnet. Tilted bars indicate that the field directions of a dip – needle compass.

Edmund Halley, between 1697 and 1701, was the captain of the ship Paramour for two voyages across the Atlantic Ocean. He was in charge of mapping the magnetic field direction for navigational purposes and produced the very first chart of magnetic direction pattern for a major region of the Earth. Figure 1.3 shows that the map of magnetic direction pattern produced by Halley in 1701 (Glaßmeier et al, 2009). The plotted declinations are inaccurate due to difficulties in obtaining longitude at sea during those years.

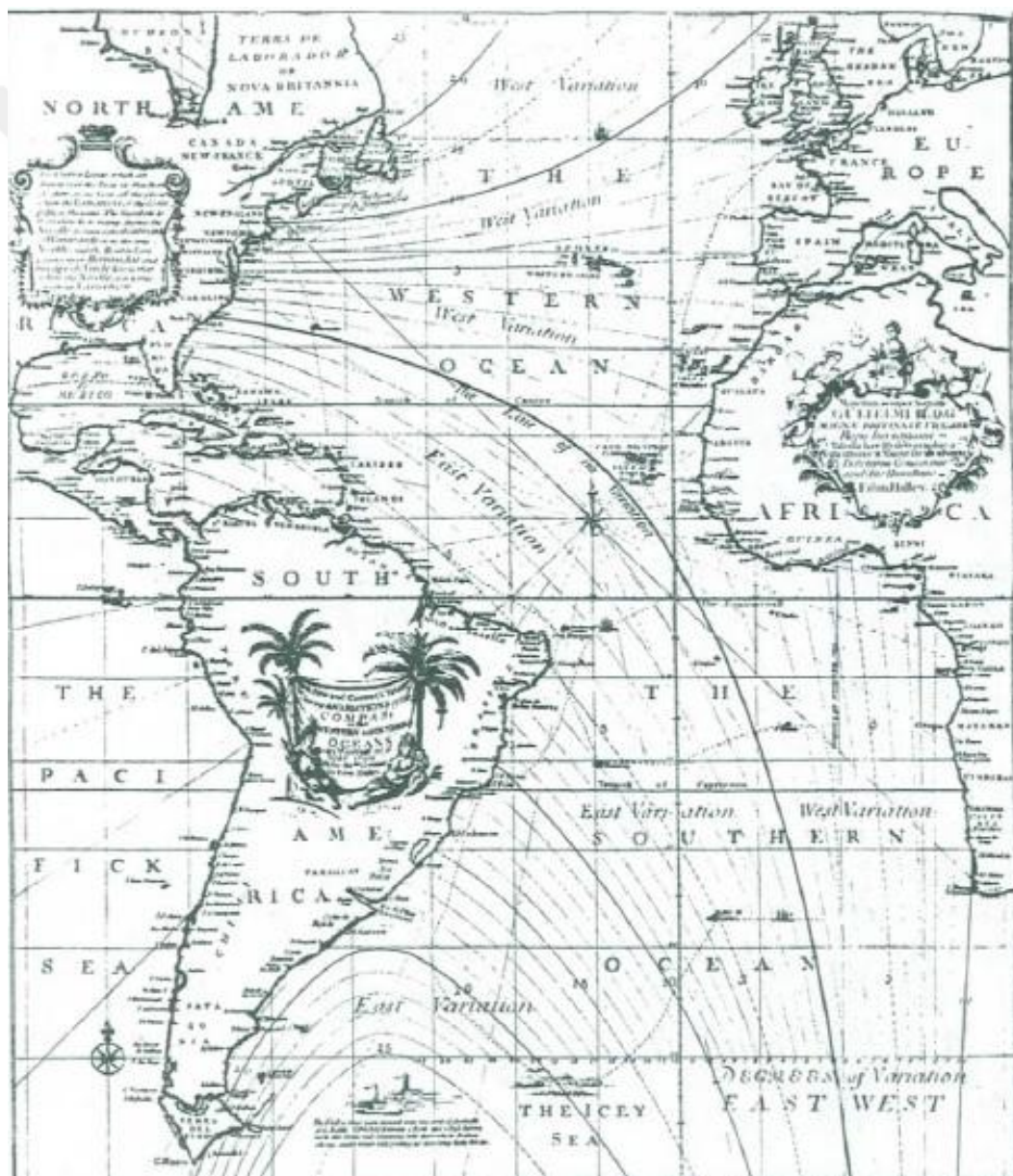


Figure 1.3: Map of magnetic declination contours produced by Halley (Glaßmeier et al, 2009).

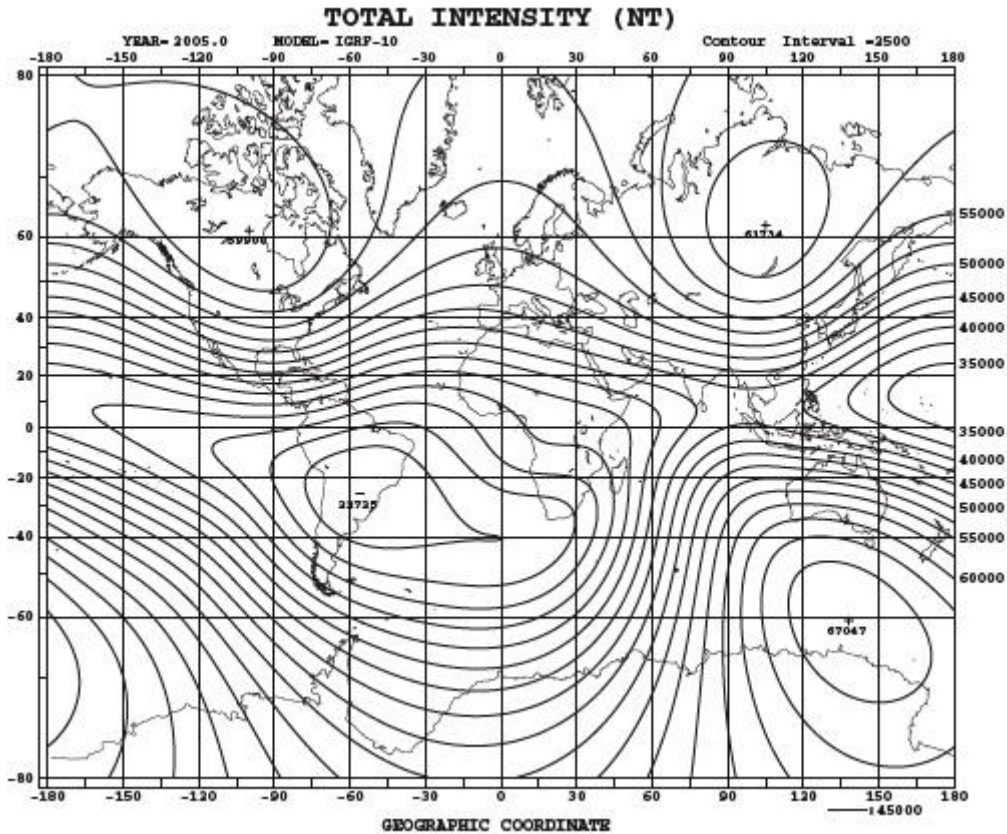


Figure 1.4: The global map of total intensity, International Geomagnetic Reference Field (IGRF) for the year of 2005 (Glaßmeier et al, 2009).

In 1838, Carl Friedrich Gauss published a mathematical method to analyze the natural field observations and determine how much of the magnetic field measured at the Earth's surface comes from sources within the Earth (Campbell, 2000).

All the relationships between the laws of behaviors of electrical charges, currents, and fields were taken together to create a unique representation by James Clerk Maxwell in 1893. His mathematical equations to analyze and predict them are recently in use as the best physical description of the interaction magnetism and electricity (Campbell, 2000; Glaßmeier et al, 2009).

The term geomagnetism has ended up its recent concept with the help of extensive publications by Sydney Chapman, who is known as the scientist introducing space magnetism originating from solar activities. He produced in 1940 his first textbook called Geomagnetism (Campbell, 2003).

Since the beginning of 20th century, geomagnetic field are regularly analyzed by applying the dataset obtained from over hundred stations where magnetic field observations are made. For the last 5 decades, standardized methods have been

applied to dataset for the purpose of analysis, concluding in International Geomagnetic Reference Field (IAGA, 2005) for a certain period of time. By the end of the 20th century, with developing technology, missions of satellite integrated with magnetometer have been carrying on to get the geomagnetic field data (Glaßmeier et al, 2009).

These magnetic field data are gathered from satellites in use such as Swarm, CHAMP and Ørsted. For instance, German satellite CHAMP, launched in 2000, is orbiting around the Earth at an altitude of 450 km. Two magnetometers are on board of CHAMP. Thus, with an orbit, it is possible to get the magnetic field dataset which has 500 km spatial resolution by using spherical harmonic equations up to 80 degrees and orders (Glaßmeier et al, 2009). Sample geomagnetic field models are derived from observed terrestrial and satellite data. Figure 1.4 is one of the models that are created by using magnetic field data obtained from both terrestrial method and satellite, as well.

1.3 The Aim of the Thesis

The need of new approach to transportation is born due to the requirement of safe and rapid transportation of goods and people over prolonged distances, also military and research purposes. Thus, it forced people to create a new technology to fulfill the requirement of transportation. In 1903, the Wright brothers designed an airplane and attempted to fly it. The Wright brothers, as we all know, are written in the history as the people succeeded first time ever to fly an airplane. Developing technology and taking the milestone in aviation industry have led the aviation to be the essential part of human need in such a short period of time.

Not only producing airplanes, but to fly it is also important. Therefore, navigation aids which help pilots to fly the airplane on desired route were integrated to avionic part of the airplane. The major threat on safe air navigation is caused by the fact that navigation aids use magnetic values of degrees which are referenced to the magnetic north, whereas the geodetic computations use true values of degrees that are originated from the true north. True values of degrees represent the angle between geographic north and the direction of desired route in the clockwise direction, while magnetic values of degrees signify the angle between magnetic north and the direction of desired route in the clockwise direction. The difference between true

north and magnetic north is called magnetic variation (declination), in degree. Therefore, to emphasize the main source of geomagnetic field and factors that affect the magnetic field and variation, hence safe air navigation, is mainly discussed in this thesis.

Introduction part of the thesis gives brief information of history of geomagnetism, literature review of studies contributed to geomagnetism science and the aim of the thesis.

In the second chapter, geomagnetic field is introduced with a proper definition and the parameters that affect it. Basic mathematical equations between main geomagnetic field and its parameters are also given in the text.

The third chapter is about the introduction to air navigation, navigation aids and the effect of magnetic variation on safe air transportation. Case studies are provided to emphasize the importance of usage magnetic variation in air navigation.

The fourth chapter is about the case study about the effect of magnetic variation on safe air navigation. Finally, the last chapter gives the brief summary of the thesis with the found results and their discussions.

2. GEOMAGNETIC FIELD

After an introduction to magnetism basically and literature review, to go further, geomagnetic field should be reviewed as the main physical phenomena with its definition and components in detail.

2.1 Definition

To describe the potential electrical and magnetic effects even in case of no charge is available, auxiliary quantities such as electrical field E and magnetic field B , independent of charge and velocity of particle, can be used. The magnetic field is a vector field as electrical field, because it also has both magnitude and direction.

At any point of space, the tangent to the field line represents the direction of magnetic field at that point, where the spacing of the field lines represents the magnitude of magnetic field. The closer field lines, the stronger magnetic field.

The Earth's magnetic field is called geomagnetic field. The main source of the geomagnetic field is conducting fluid and lava containing magnetized ingredients from outer core. This part of the field is known as main field. Magnetized rocks in the Earth's crust, fields generated outside the Earth by electric current in the ionosphere and magnetosphere as well as in the Earth's crust are other sources which play the role in generating geomagnetic field.

The geomagnetic field is similar to the field that would be generated if there were a huge bar magnet centered in the Earth, called a dipole field. It has an axis of symmetry parallel to that huge bar magnet and intersects the Earth's surface at both geomagnetic north and south poles. The dipole axis is not parallel to the Earth's rotation axis but is inclined approximately 10 degrees away. Thus, geomagnetic poles and geographic poles are not coincident. But, the position of the geomagnetic poles changes slowly as time goes by. So, this 10 degrees away position of geomagnetic pole is not fixed and will continue to change by time.

The positional change of geomagnetic poles causes the annual change of the declination. That annual change can be observed by the study of paleomagnetism,

which is the science of observing the properties of magnetized sediments, rocks or formations in terms of geology. Iron – rich rock materials show similar alignment behavior with those formed in the same geological epoch. Ferrous particles of rocks, which had been magnetized in different geological era, aligned in different directions. This fact proves that the location of geomagnetic pole, or magnetic north direction, changes by time. Figure 2.1 shows the alignment of ferrous particles in non – magnetized and magnetized form of the same rock sample. Such rocks reveal about the paleo – ages of the Earth. Arrows in Figure 2.1 shows magnetic field alignment.

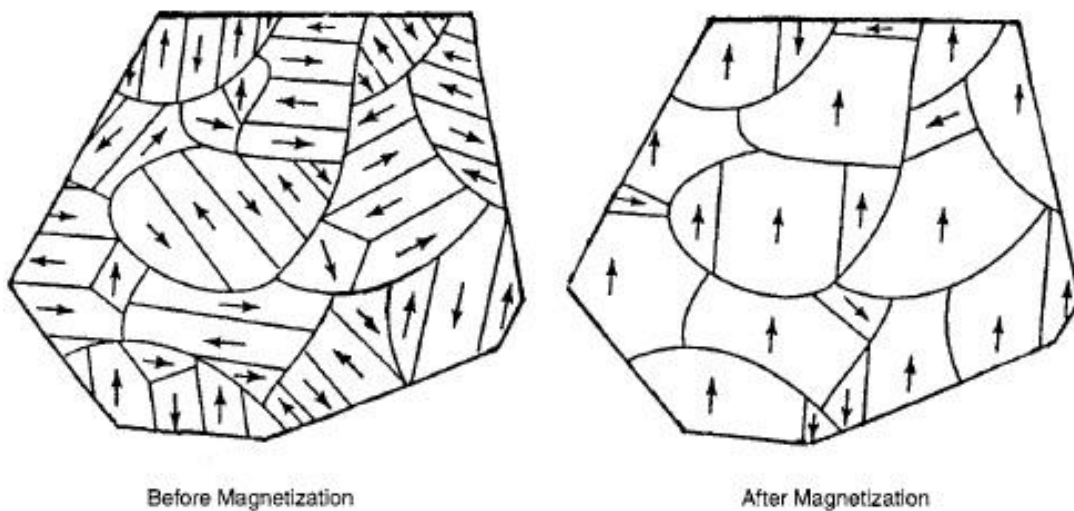


Figure 2.1: Microscopic view of a rock before and after magnetization (Campbell, 2000).

Magma has the plasma – like form due to its higher temperature than the Curie temperature that is the temperature above which certain materials lose their permanent magnetic properties, to be replaced by induced magnetism. Thus, magnetic particles included in magma are randomly oriented. The orientation of these ferrous particles aligns with the similar direction of the geomagnetic poles or magnetic north at the cooling period. This reveals the local magnetic field direction at this geological period

The particles need time to align their ferrous particles with the Earth’s local magnetic direction of that formation period for the sedimentary (formed by settling) rock. A paleomagnetician can identify the paleo – magnetic field direction of the Earth at the time when sedimentary rock was formed (Campbell, 2000).

2.2 Components of Geomagnetic Field

It is important to emphasize the components of geomagnetic field. First of all, local reference system can be stated as x axis refers to geographic north (true north), z axis refers to nadir (local direction of gravity), and y axis is a part of right – hand rule. One can use, alternatively, geodetic reference system and appropriate reference ellipsoid.

The angle between horizontal component (H) of magnetic field (B) and the true north is called magnetic declination (D) or magnetic variation. The angle between B and the horizontal plane is called magnetic inclination (I) or magnetic dip. The units of D and I are degrees, positive for D in direction of east, positive for I in direction of down. The horizontal component of total field (F) is shown as H , where Z indicates vertical component. In general, the units of the components of total magnetic field are nanotesla (nT). Figure 2.2 shows all parameters of geomagnetic field in one illustration.

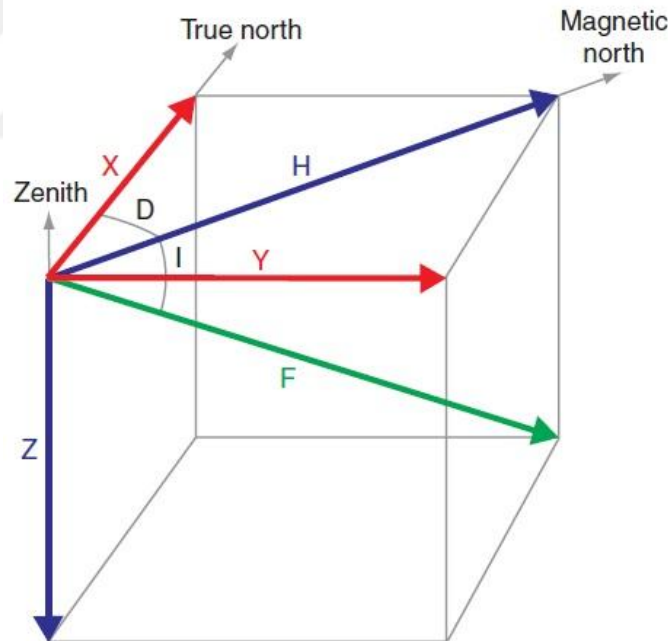


Figure 2.2: The illustration of the parameters of geomagnetic field (Langley, 2003). Intensity of total field (F), horizontal field (H), vertical field (Z), north (X) and east (Y) field components, declination (D) and inclination (I).

Mathematical relations and equations of the components of geomagnetic field are as follows

$$X = H \cos(D), Y = H \sin(D). \quad (2.1)$$

Total field strength, F , is given as

$$F = \sqrt{X^2 + Y^2 + Z^2} = \sqrt{H^2 + Z^2}. \quad (2.2)$$

The angle between total field strength and horizontal plane is inclination, I , or dip angle:

$$Z/H = \tan(I). \quad (2.3)$$

It is important to make a mathematical equation to get the value of declination, D , using the angular relationship in Figure 2.2 and basic trigonometry rules. Finally, following mathematical equations are obtained as

$$H = \sqrt{X^2 + Y^2}. \quad (2.4)$$

$$D = \tan^{-1}(Y/X). \quad (2.5)$$

Commonly used SI units for the field strength are gamma (γ), nanotesla (nT) and Gauss. The conversion between units is as follow

$$T = 10^9 \gamma = 10^9 nT = 10^4 \text{ Gauss}. \quad (2.6)$$

The main field varies based on the region of the Earth. For instance, it is 6×10^4 gammas near the poles, where it is half this amount, 3×10^4 gammas, near the equator. Some sources affect the size of magnetic field and their values are as follows. This scale is not linear, but logarithmic.

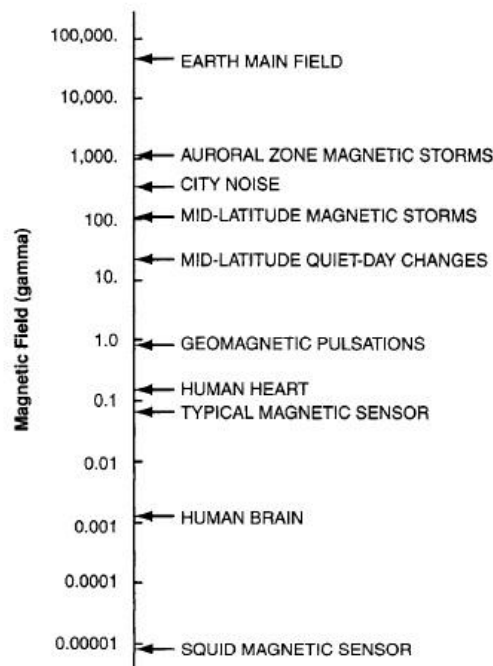


Figure 2.3: The magnetic field originating from various sources (Campbell, 2003).

Table 2.1: Ranges of magnetic elements at the Earth's surface (Chulliat et al, 2015).

Element	Name	Alternative Name	Min.	Max.	Unit	Positive Sense
<i>X</i>	North Component	Northerly Intensity	-17000	42000	nT	North
<i>Y</i>	East Component	Easterly intensity	-18000	17000	nT	East
<i>Z</i>	Down Component	Vertical Intensity	-67000	61000	nT	Down
<i>H</i>	Horizontal Intensity		0	42000	nT	
<i>F</i>	Total Intensity	Total Field	22000	67000	nT	
<i>I</i>	Inclination	Dip	-90	90	Degree	Down
<i>D</i>	Declination	Magnetic Variation	-180	180	Degree	East / Clockwise

Table 2.1 shows the minimum and maximum values of total intensity of main geomagnetic field and its components at the Earth's surface.

One can figure out the logarithmic change in the power of the Earth magnetic field (by means of change in spherical harmonic expansion degree) and domination of Earth's core and lithosphere in the power of the magnetic field. (eq. 2.7). Spherical harmonic equation is expanded up to more than 50 degrees from Figure 2.4 below. The circumference of the Earth, approximately taken as 4×10^4 km, is divided by spherical harmonic degree for the computation of spatial wavelength in kilometer (Lühr et al, 2009).

V_i is the potential of the magnetic field originating inside the Earth. R_E stands for the radius of the Earth, where r , θ , λ are the radius of the spherical coordinates, colatitudes and longitude, respectively, and P_m^n is the Schmidt quasi – normalized

associated Legendre functions of degree n and order m . Gauss coefficients in this spherical harmonic expansion equation are g and h (Lühr et al, 2009).

$$V_i(r, \theta, \lambda) = \sum_{n=1}^{n_{max}} \sum_{m=1}^n R_E \left(\frac{R_E}{r}\right)^{n+1} [g_n^m \cos m\lambda + h_n^m \sin m\lambda] P_n^m(\theta) \quad (2.7)$$

As seen in Figure 2.4, graphic indicates a logarithmic decrease of power up to 13 – 14 degrees and almost steady behavior, with slightly increase, from 16 – 17 degrees until 60 degrees in spherical harmonic expansion. Core dominates the power up to approximately 15 degrees, where lithosphere does from 15 degrees until 60 degrees.

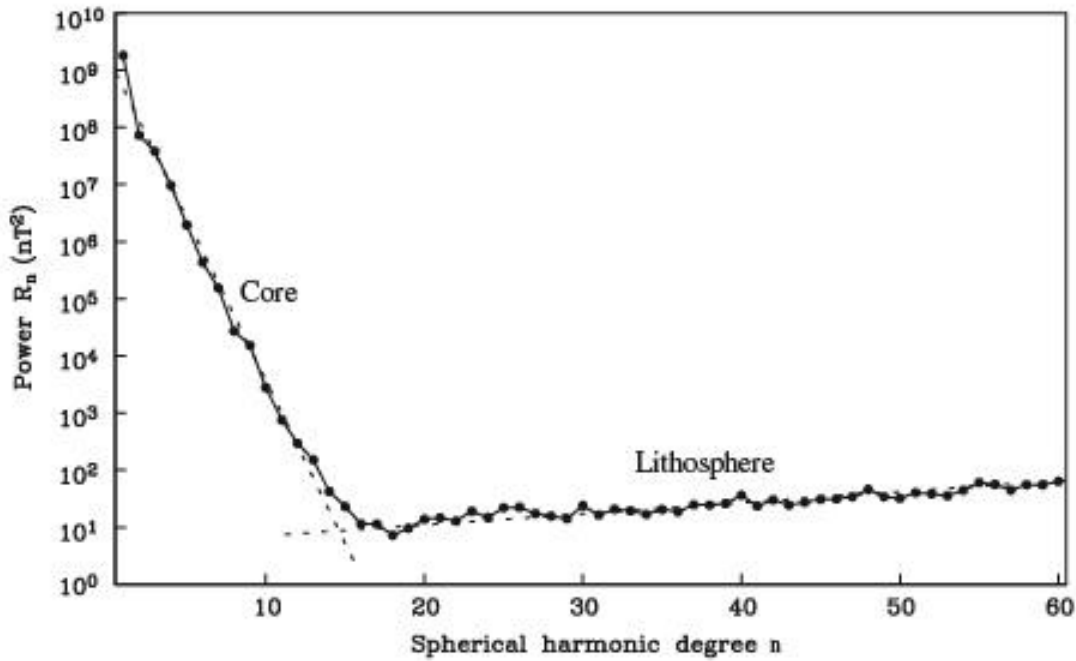


Figure 2.4: The illustration of main and lithospheric field spectrum at the surface of the Earth (Lühr et al, 2009).

Not only the sources at the Earth’s surface, but also sources at the space also affect the geomagnetic field and its variation. Main source at the space is solar activities. K variations are all irregular disturbances of the geomagnetic field caused by solar particle radiation within the 3 hours interval concerned. All other regular and irregular disturbances are non K variations. Geomagnetic activity is the occurrence of K variations (Matzka, J., n.d.; Siebert, M., 1971). A_p is defined as the earliest occurring maximum 24 – hour value obtained by computing an 8 – point running average of successive 3 – hour a_p indices during a geomagnetic storm event without regard to the starting and ending times of the UT – day. It is uniquely associated with the storm event (Allen, 2004). Hence, the Sun plays the major role among space –

based sources. Figure 2.5 illustrates the internal structure and main magnetic activities of the Sun.

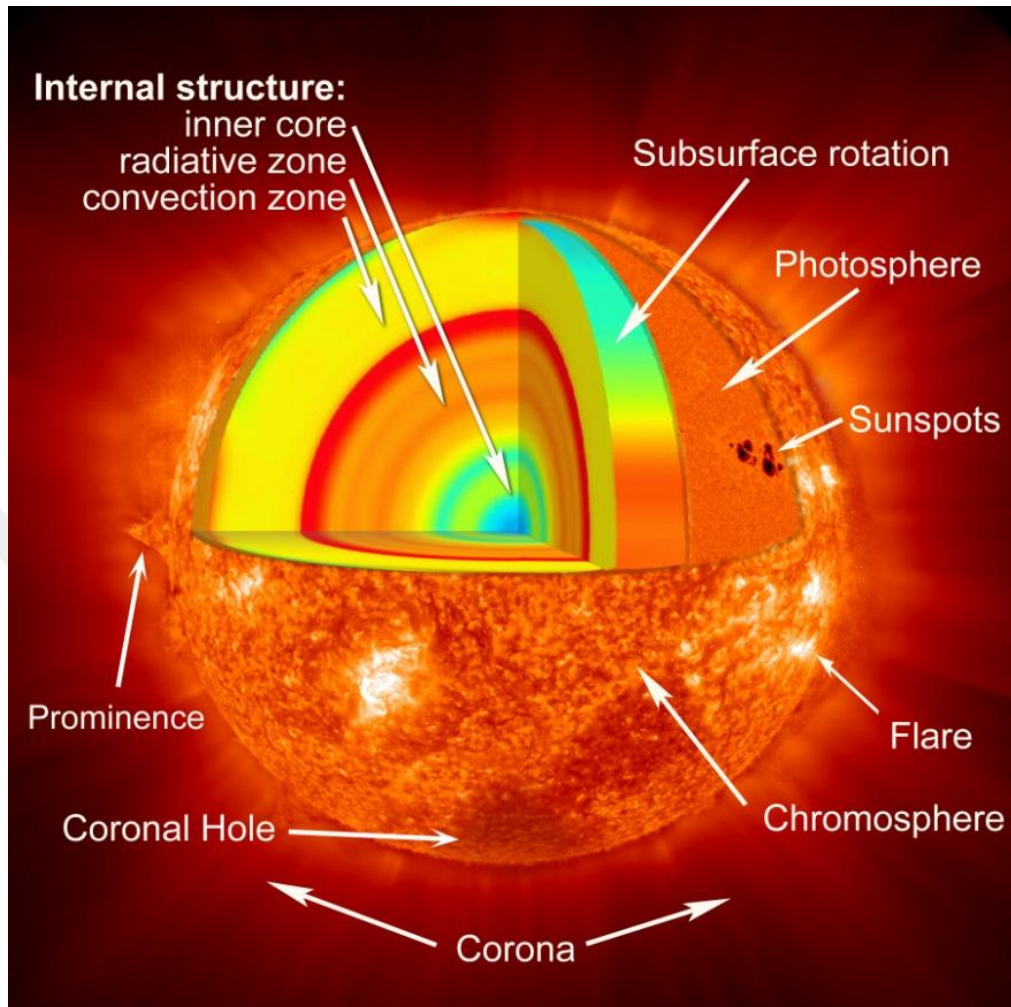


Figure 2.5: The structure and main magnetic activities of the Sun (NASA).

2.3 Modeling of the Geomagnetic Field

Magnetic field of the Earth is not a constant or steady phenomenon, but alters with space and time. Various sources contribute to this phenomenon as it is measured at or above the Earth's surface. These observations are carried on either terrestrial or satellite – based missions.

Stations for the terrestrial – based observations are widely distributed throughout the Earth to cover as large area as possible for derivation of a global magnetic field model (Figure 2.6). In Turkey, there are two stations that magnetic field observations have been carrying on, which are located at Iznik (IZN, N 40°.50 E 29°.72) and Kandilli (ISK, N 41.06 E 29.06). Iznik geomagnetism observation center contributed

477 (Maus et al, 2009) and 1,243 data (Chulliat et al, 2015) to the project of production of the global magnetic field model, WMM 2010 and WMM2015, respectively.

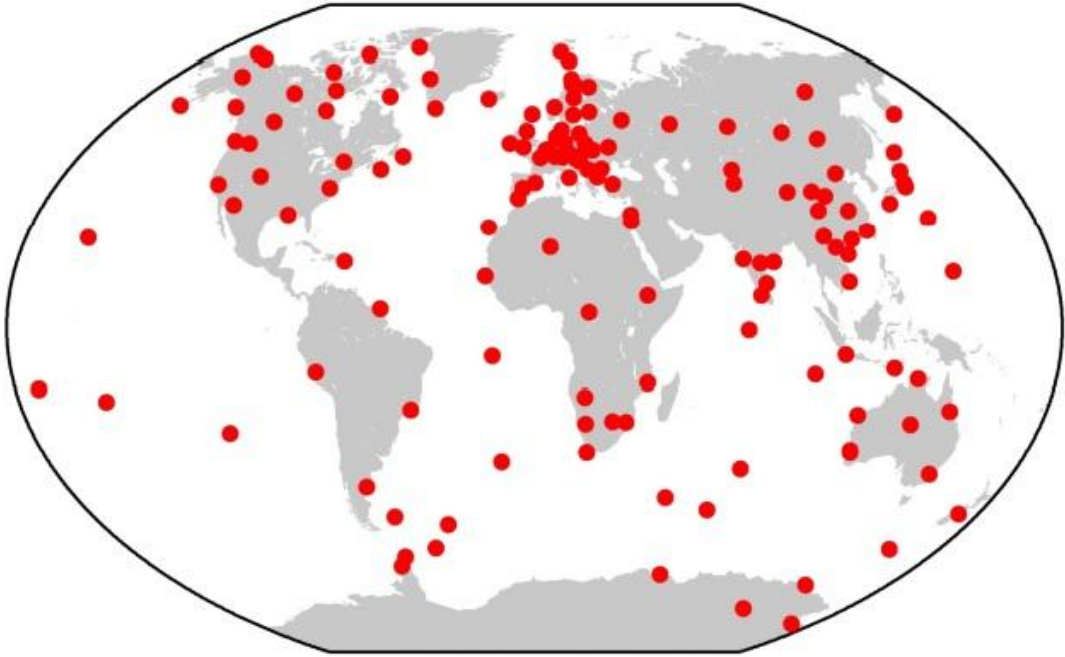


Figure 2.6: Observatories whose data was used in WMM2015 (Chulliat et al, 2015).



Figure 2.7: Gyro theodolite (left), DI fluxgate magnetometer (right) (Duma et al, 2012).

In Figure 2.7, gyro theodolite serves to determine the direction of true north, as DI fluxgate magnetometer is used to measure magnetic declination and inclination.

Although some terrestrial observations are poor in the basis of acquiring spatially accurate data, this spatially inaccurate data contributes to enhance the magnetic model locally in terms of time. Satellite – based observations are mainly in progress to derive the global geomagnetic field model due to good global coverage and low noise level.

Vector component measurements from the German satellite, CHAMP, were integrated into the data used for global geomagnetic field model derivation until the last quarter of 2010. Until the middle of the year 2013, the Danish satellite, Ørsted, provided the data of total intensity of the geomagnetic field. In recent years, three satellites of the European Swarm mission, launched in November 2013, are in progress for global geomagnetic field observations (Chulliat et al, 2015). GPS is used to provide an absolute time frame. Moreover, it also enables the instruments on the board to be synchronized.

CHAMP (CHALLENGING Minisatellite Payload) under GFZ (Deutsche Geo Forschungs Zentrum Potsdam) leadership for geoscientific and atmospheric research was launched on July 15, 2000. Magnetometer, accelerometer, star – sensor, GPS receiver, laser retro – reflector and ion drift meter were integrated into the structure of the CHAMP satellite. With its high – precision, multi – functional and complementary instrumentation and its orbital properties enabled CHAMP to be the first satellite measured gravimetric and magnetic field generated simultaneously over a period of 10 years. Its mission was completed on September 19, 2010, burning after 10 years (Stolle, n.d.).

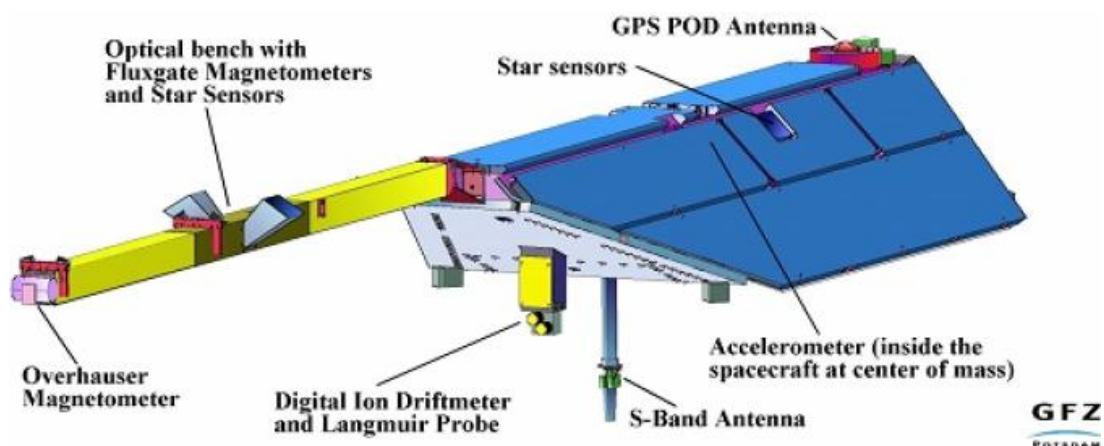


Figure 2.8: Structure of the CHAMP satellite (Maus et al, 2009).

The Danish satellite Ørsted was launched to contribute satellite – based data to the derivation of magnetic field model on February 23, 1999. In spite of the fact that it was launched initially for 14 months, it was delivering high quality data in mid – 2013, for approximately 14 years after its launch (Chulliat et al, 2015).

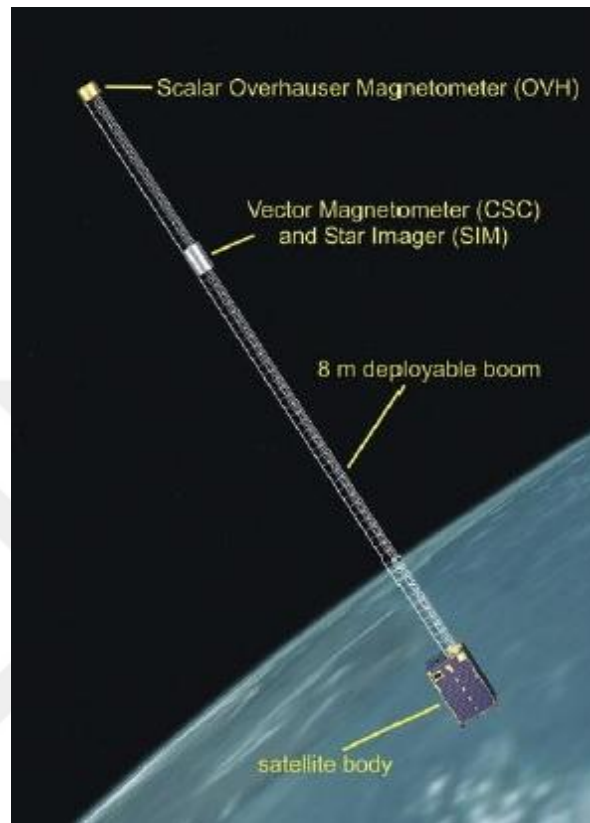


Figure 2.9: Ørsted satellite (Chulliat et al, 2015).

To better understand the Earth’s interior and the region around the Earth that affects geomagnetic field, the Swarm mission was selected to provide the most accurate measurements of strength, direction and variation of the magnetic field to derive global total magnetic field model. Swarm was launched on November 22, 2013 in Russia. It has three satellites; two of them orbit at lower altitude, 450 km, as the other one orbits at relatively higher altitude, 530 km (Christensen et al, 2006). Its magnetometers have an accuracy of less than 1 nT (Chulliat et al, 2015). The duration of the mission was initially planned as four years.

SAC – C was developed through the partnership of its senior partners, CONAE and NASA with contributions from Brazil, Denmark, France, and Italy. Even it was launched on November 21, 2000, initially for four years, the satellite was still operating in 2011 with some limitations. SAC – C provided multispectral imaging of terrestrial and coastal environments. The spacecraft investigated on the structure and

dynamics of the Earth's atmosphere, ionosphere and geomagnetic field. Its mission was completed in August, 2013.

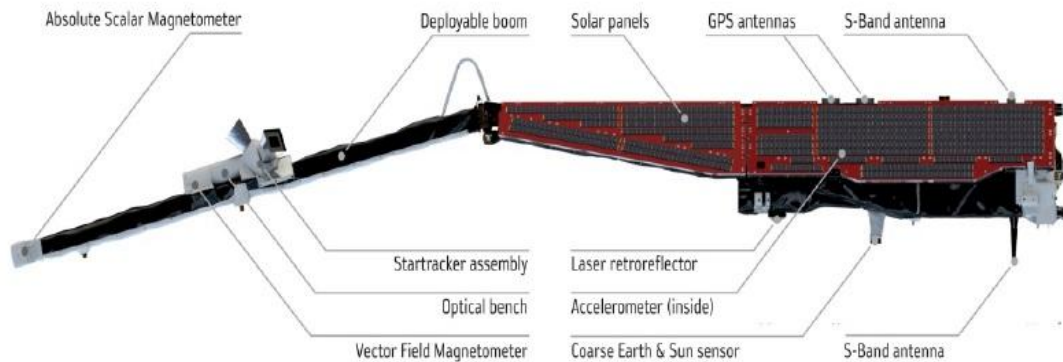


Figure 2.10: Structure of the Swarm satellite (Chulliat et al, 2015).

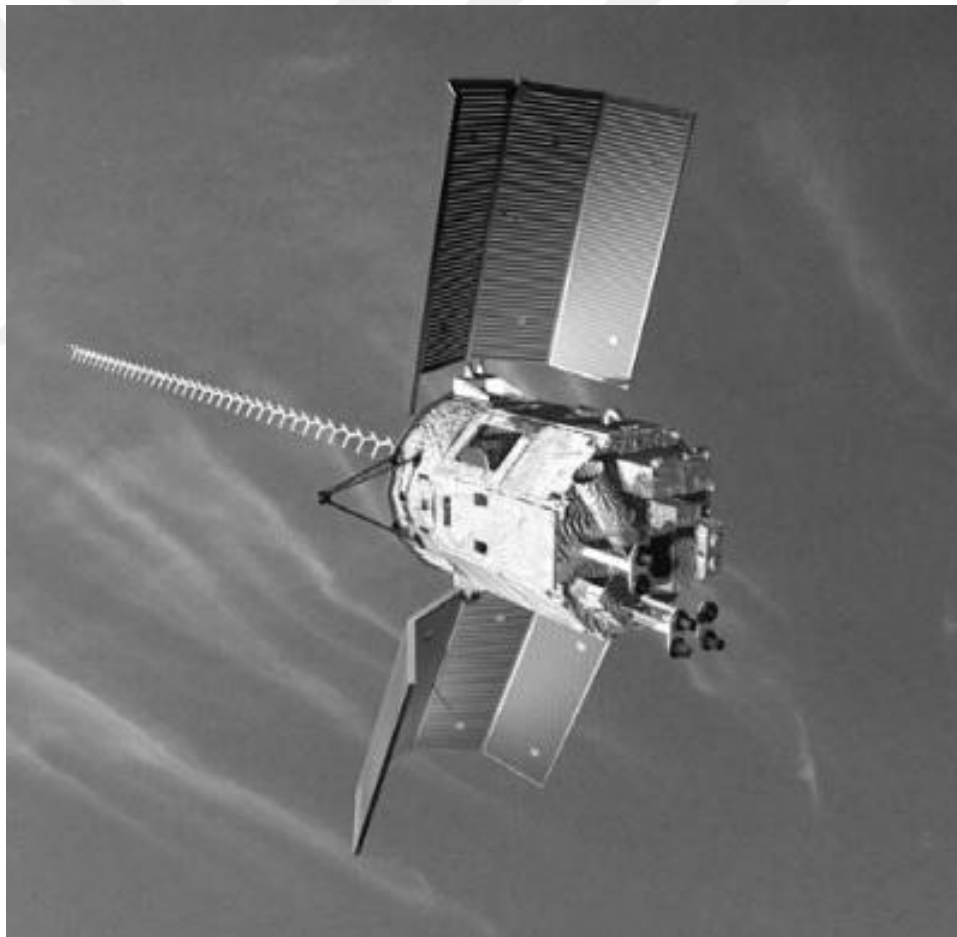


Figure 2.11: An image of SAC – C satellite (NASA).

Modeling the geomagnetic field with temporal changes has been serving to scientists from various departments. Since late 20th century, the investigation and determination of the geomagnetic field, and its temporal changes, especially of core and lithosphere, have been enabled by launching the satellite missions. The core field

changes by time. This effect is known as secular variation which is participated in the derivation of geomagnetic model as a factor changing linearly. But the coefficients of that model have to be updated every five – year period due to unpredictable non – linear changes in the core.

The scalar and vector data are used for derivation of both WMM2010 and WMM2015, whose total main fields are represented in Figure 2.12 and Figure 2.13, respectively.

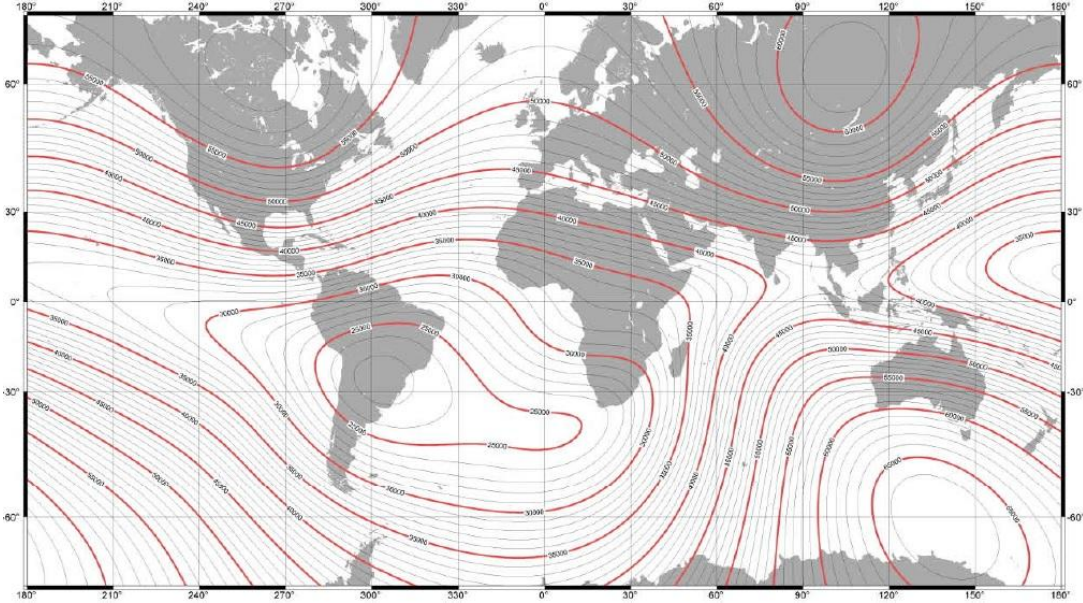


Figure 2.12: Total main field represented in WMM2010 (Maus et al, 2009). Contour interval is 1,000 nT.

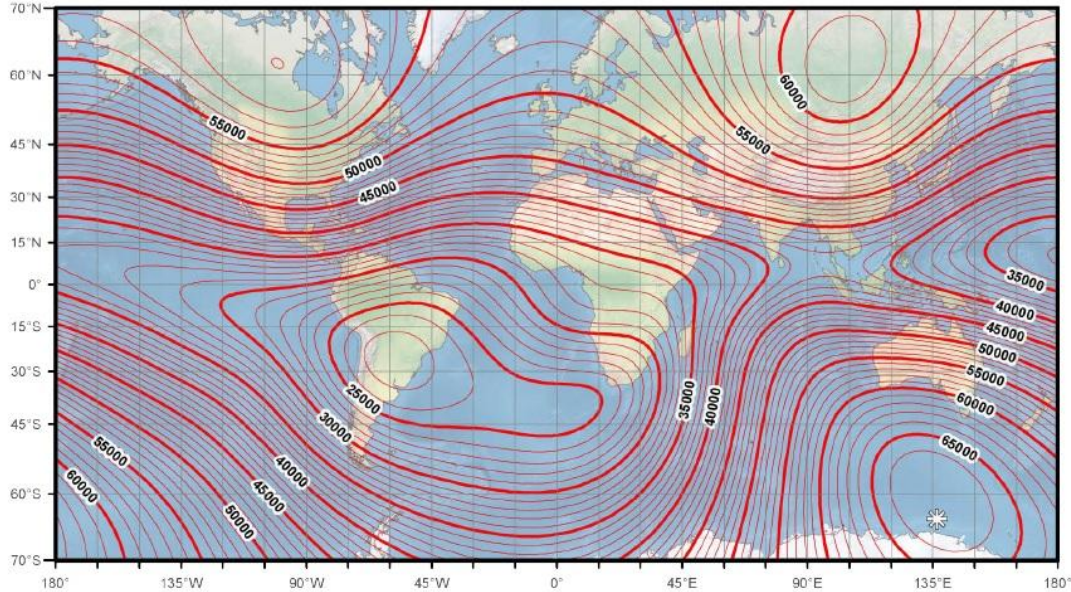


Figure 2.13: Total main field represented in WMM2015 (Chulliat et al, 2015). Contour interval is 1,000 nT.

In addition, declination maps of total main field in WMM2010 and WMM2015 are given in Figure 2.14 and Figure 2.15, respectively. The effect of magnetic variation, or declination, on safe air navigation is reviewed in Chapter 3 in detail. Periodic changes of total geomagnetic field and its components can be revised in related articles (Maus et al, 2009; Chulliat et al, 2015).

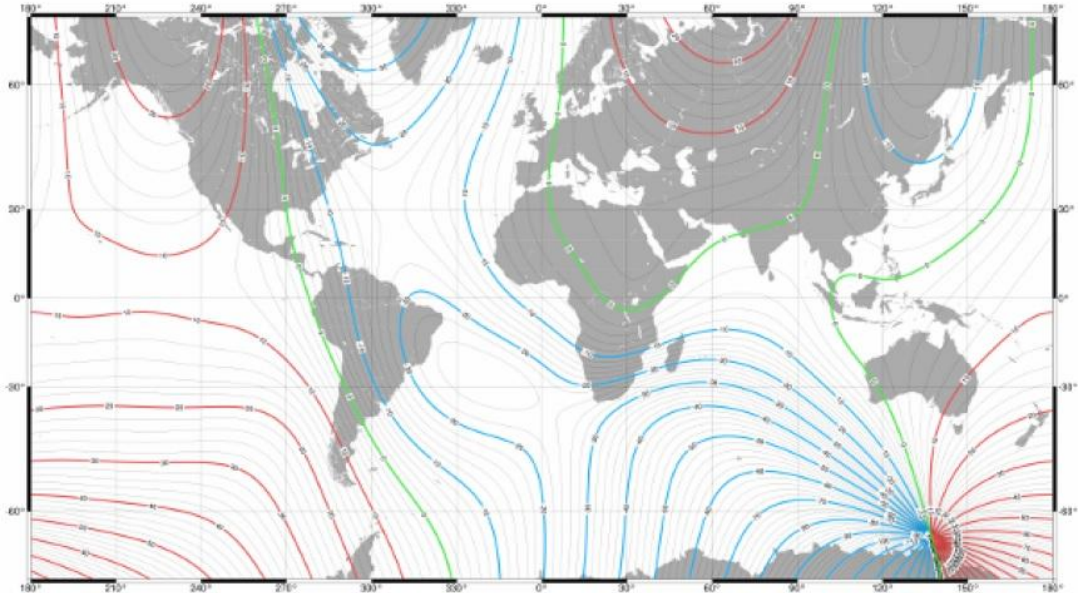


Figure 2.14: Declination map represented in WMM2010 (Maus et al, 2009). Contour interval is 2 degrees. Red contours positive (east), blue contours negative (west), green zero (agonic) line.

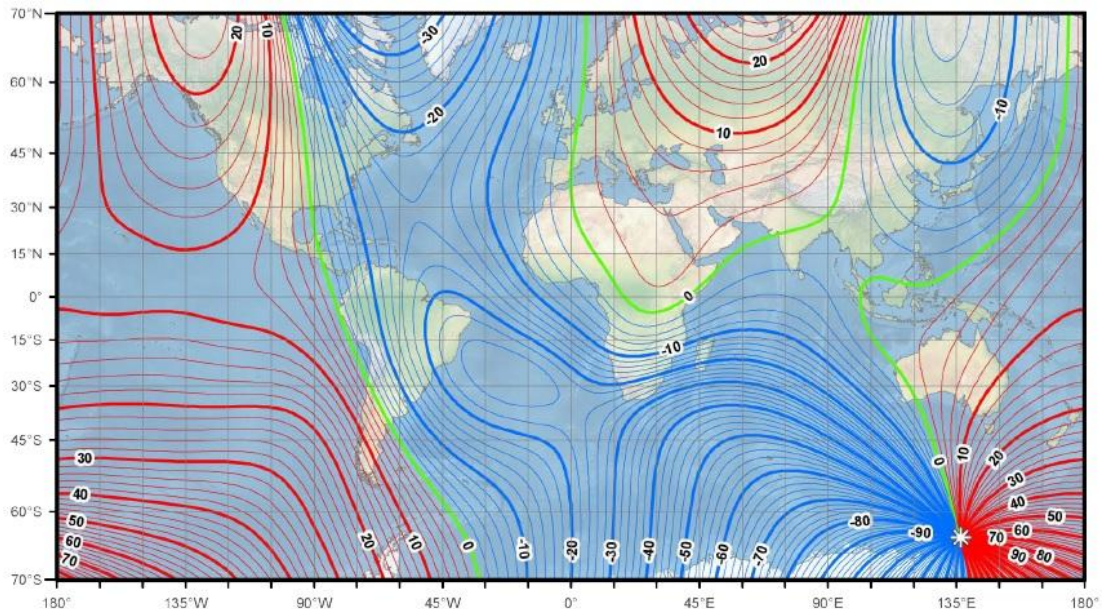


Figure 2.15: Declination map represented in WMM2015 (Chulliat et al, 2015). Contour interval is 2 degrees. Red contours positive (east), blue contours negative (west), green zero (agonic) line.

One can refer to International Geomagnetic Reference Field 12th generation (Thébault et al., 2015) for IGRF – 12. A list of different magnetic field models, which are derived from various sources or combined of them, can be found in Magnetic Field Model (Willer, n.d.). Calculators of magnetic field and declination can be used from Magnetic Field Calculators (NOAA, n.d.) and Magnetic Declination Calculator (Natural Resources Canada, 2018). One can also refer to World Magnetic Model 2015 Calculator (British Geological Survey, 2018) for magnetic field and secular variation calculation. For further information about modeling of geomagnetic field, one can refer to Geomagnetic Observations and Models (Mandea & Korte, 2011).



3. AIR NAVIGATION

Navigation is the science of planning a voyage safely based on given time and conditions i.e. meteorological and aircraft conditions. For a classical navigation flight, some parameters which are remaining distance to destination, ground speed, traveling direction, wind correction, time to destination, current fuel consumption, and remaining fuel have to be calculated. The essential parameter that has to be taken into account for directional computations to destination is traveling direction. Navigation methods recently used are Dead Reckoning, terrestrial, astronomic and radio – navigation. The most frequently used navigation method in commercial flights is radio – navigation method (Rasson & Delipetrov, 2006).

As known in geodesy science, the north is mainly divided into three types which are true, magnetic and grid. The most of geodetic calculations are made by referencing true north. For radio – navigation methods, the angle between magnetic north and the direction of desired route to destination in zero wind condition is used, called as magnetic course. If wind correction is applied on magnetic course, then that angle is called as magnetic heading. In case of applying compass deviation to magnetic heading, compass heading is obtained. TN and TH are true north and true heading, MN and MH are magnetic north and magnetic heading, CN and CH are compass north and compass heading, VAR and DEV stand for variation and deviation.

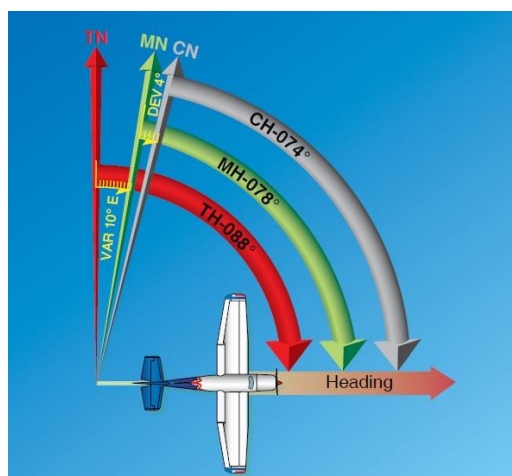


Figure 3.1: Relationships between true heading, magnetic heading and compass heading (Duncan, 2016).

Position of the north magnetic pole is deviated approximately 1,300 NM (nautical mile, the unit of length which corresponds to one minute of latitude and 1 NM is equal to 1,852 meters) from the position of geographic (true) north as seen in Figure 3.2. This deviation results in difference between magnetic (red in Figure 3.2) and geographical meridians (blue in Figure 3.2). The Earth does not have a uniform distribution of magnetism (Duncan, 2016). Therefore, it is not possible to measure the magnetic variation at any single meridian.

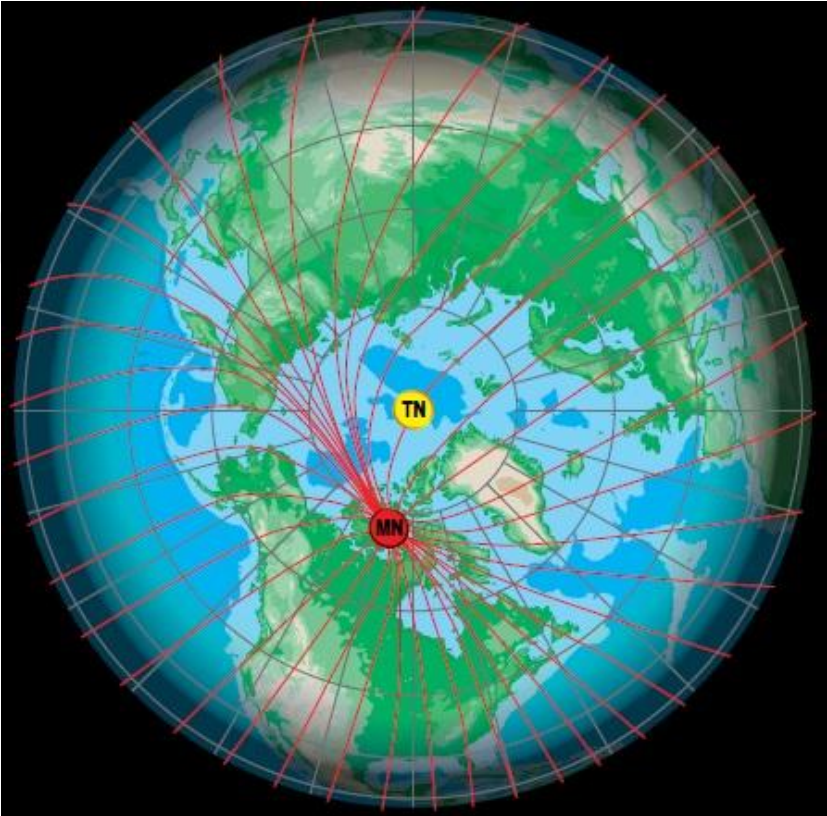


Figure 3.2: The positions of true north (TN) and magnetic north (MN) (Duncan, 2016).

The needle of magnetic compass is affected by the variation, and points towards magnetic pole with a deviation which is equal to local variation value.

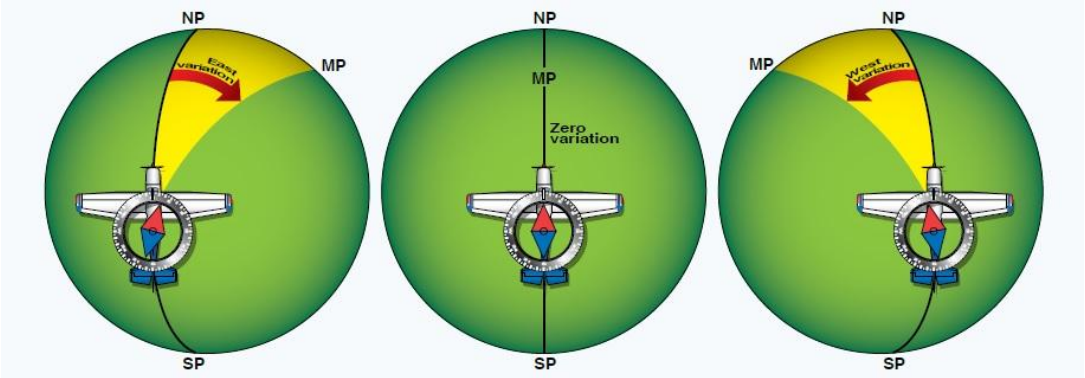


Figure 3.3: The effect of variation on the magnetic compass (Duncan, 2016).

Magnetic compasses are integrated into navigation part of aircraft as standby instrument in case of unavailable radio navigation aids. A pilot has to be capable of controlling the aircraft and navigating through desired route even there is no electronic navigation aid. As explained in Figure 3.1 above, the pilot can make all necessary calculations for navigation with standby, non – electronic, instruments by applying the deviation to the heading value which is read from standby magnetic compass on flight deck.



Figure 3.4: Standby magnetic compass onboard.

Also Inertial Navigation System (INS) can align itself with True North without the need of variation. INS provides this alignment with the help of three accelerometers which measures the acceleration in vertical, lateral and longitudinal axes. The only thing that has to be made for INS alignment is to set INS in align mode to insert a reference initial position. With the attitude of aircraft, accelerometers measure accelerations and the double integration of these accelerations gives the displacements in three different axes. As a result, instant position can be obtained by updating reference initial position using these displacements. INS is effectively used between 70°N and 70°S, including equator. Outside of this region, magnetic variation varies so steeply due to extreme change of geomagnetic field over polar region. Therefore, magnetic variation over polar region is stored in database to obtain magnetic heading using true heading derived from INS.

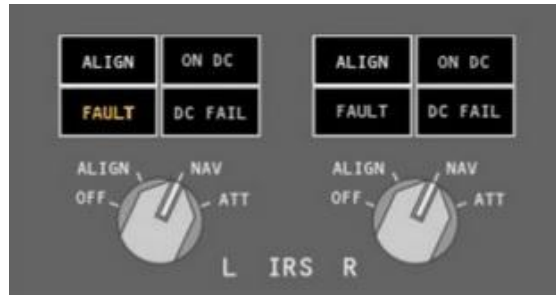


Figure 3.5: Onboard control panel of INS at aircraft.

3.1 Navigation Aids

The principles of radio navigation aids have to be understood clearly to emphasize the effect of magnetic variation on safe air navigation. Therefore, main radio navigation aids that are used for flights are reviewed briefly.

3.1.1 Non directional beacon (NDB)

A Non Directional Beacon (NDB) is a radio station placed in an identified location on the ground and it is used as an aviation or maritime navigation aid. In the aviation, the NDB use is regulated by the Annex 10 of ICAO (International Civil Aviation Organization) which specifies that NDB are exploited over a frequency range between 190 and 1,750 kHz, in LF and MF bands. These beacons are mostly located near airports since they provide the simplest navigation information to reach an airport (IVAO, 2015).

Magnetic signals from NDB are received by an onboard instrument which is called Automatic Direction Finder (ADF). The NDB signal is received by the ADF which automatically and continuously displays the relative bearing from the aircraft to the selected NDB. The pair of NDB and ADF is not sufficiently precise for single use, especially in case of turning. But, it is still used at some airports in Europe.



Figure 3.6: ADF display screen and control panel.

3.1.2 VHF omnidirectional radio range (VOR)

VOR is a navigation aid that provides magnetic bearing information to and from the station. The prefix “omni-” means “all”, and an omnidirectional range is a VHF radio transmitting ground station that projects straight line courses (radials) from the station in all directions (Duncan, 2016). These radials are referenced to magnetic north (MN). Therefore, a radial is a hypothetical line of magnetic bearing projected outward from the VOR station. It completes a whole circle, begins 001° and ends in 360°. 001° indicates that 1 degree east of the magnetic north.

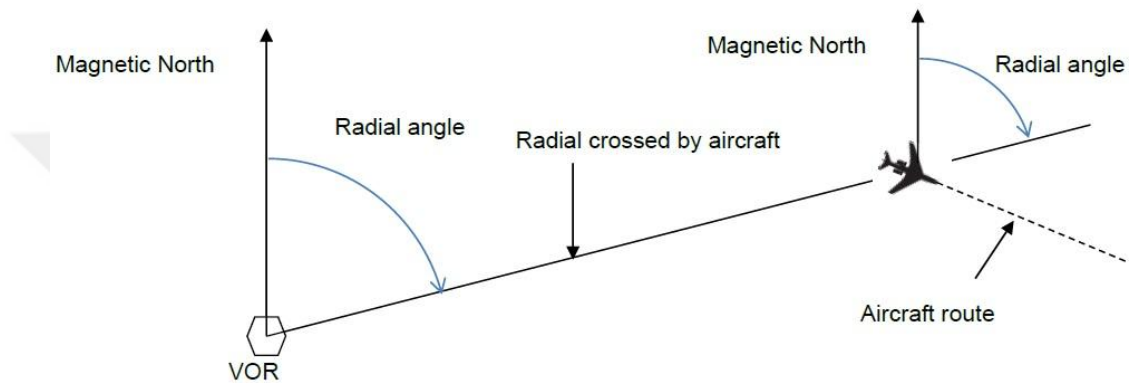


Figure 3.7: Radial extending outward from the VOR station (IVAO, 2016).

VOR ground stations transmit within a VHF frequency band of 108.0 – 117.950 MHz. Because of the fact that the equipment is VHF, the signals transmitted are subject to line – of – sight restrictions. So, its range depends on direct proportion to the altitude of receiving equipment.

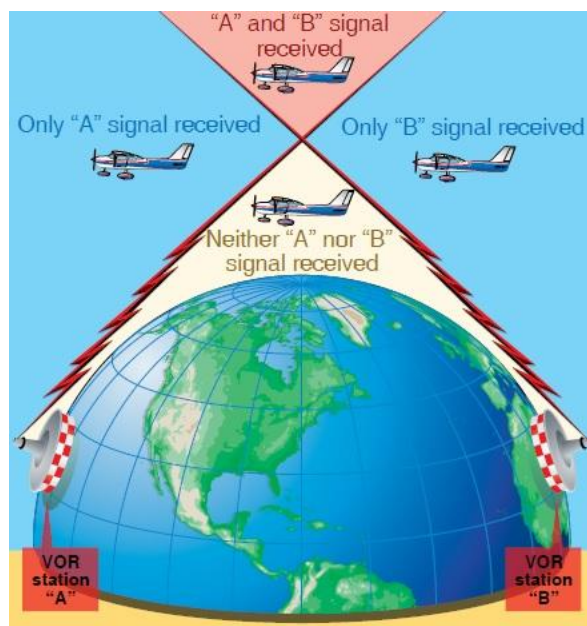


Figure 3.8: Line of sight restriction of VOR stations (Duncan, 2016).

3.1.3 Instrument landing system (ILS)

The Instrument Landing System (ILS) is the most precise navigation system used in IFR (Instrument Flight Rules) flight. It is composed of at least two elements which are localizer and glide slope (IVAO, 2015). Localizer, frequency between 108.10 MHz and 111.95 MHz, directs aircraft in horizontal plane with respect to center of the runway axis, while glide slope provides vertical guidance to the aircraft based on approach slope. Distance measuring equipment (DME) and marker beacons are generally coupled with ILS. But some airports, for instance Isparta Suleyman Demirel Airport in Turkey, execute only localizer part of full ILS approach procedure.

Its certified range is normally between 15 and 20 NM for localizer and slightly less for the glide slope. Glide slope signal is not reliable below 50 ft above ground level. For the pilots, to set only localizer frequency is enough to execute full ILS approach procedure which includes localizer, glide slope, DME and marker beacons.

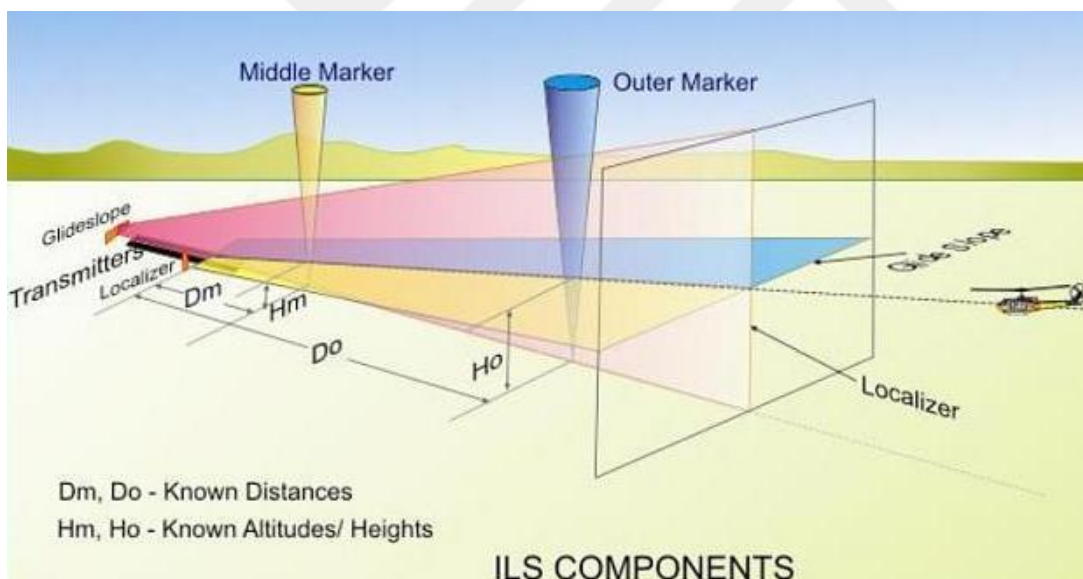


Figure 3.9: Components of ILS approach.

3.2 Area Navigation (RNAV)

RNAV is a method of navigation which permits aircraft operation on any desired flight path within the coverage of ground – based or space – based navigation aids or within the limits of self – contained aids, or a combination of these (IVAO, 2017). Area navigation can be applied by using various sensors: GNSS (satellite – based), DME/DME (ground – based), VOR/DME (ground – based), or more rarely INS/IRS

(self – contained) (IVAO, 2017). Fixes defined by means of geographical coordinates (in WGS84) can be used for RNAV. This lets the pilot to define any waypoint through the desired route and provides more flexible routes.

RNAV – X indication refers to the lateral navigation accuracy of which aircraft must be able to fly while being 95% of flight time within a precision of X nautical miles (IVAO, 2017).

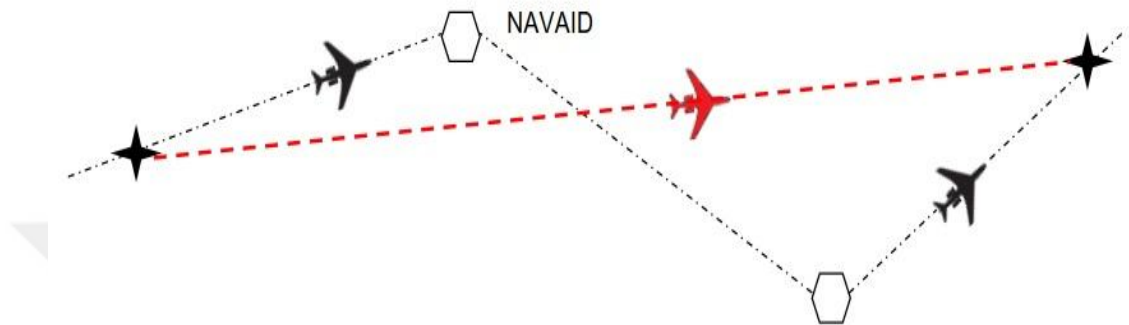


Figure 3.10: Red path is RNAV, black path is conventional navigation (IVAO, 2017).

ICAO (2014) and IVAO (2017) documents can be reviewed for more information about RNAV.

3.3 1/60 Rule in Air Navigation

If a pilot has travelled sixty miles then an error in track of one mile is approximately a 1° error in heading, and proportionately more for larger errors. For some basic aircrafts with no autopilot, pilots need to make some calculations in their heads.

The rule states that one degree deviation along 60 NM will result in 1 NM displacement from the course. For instance, this rule can be applied to en route navigation and approach.

Mathematical equations of this rule are as follows. If a circle has a radius of 60 NM, then its circumference is:

$$2 \times 60 \times \pi = 376.99 \text{ NM.} \quad (3.1)$$

Then, if we divide this circumference by 360, we get:

$$376.99 / 360 = 1.047 \text{ NM.} \quad (3.2)$$

This result proves that the 1 in 60 rule is %4.7 inaccurate. It means that if a pilot flies an aircraft over a distance of 600 NM with 1° displacement, it will result in approximately 10.5 NM off the course.

In Europe, magnetic variation values vary between -2° (2°W) and +8° (8°E), total of 10 degrees. 10 degrees off the course might result in excessive displacement of distance which threatens safe air navigation. The effect of magnetic field to the safe air navigation is emphasized numerically over the selected routes in following case study section.

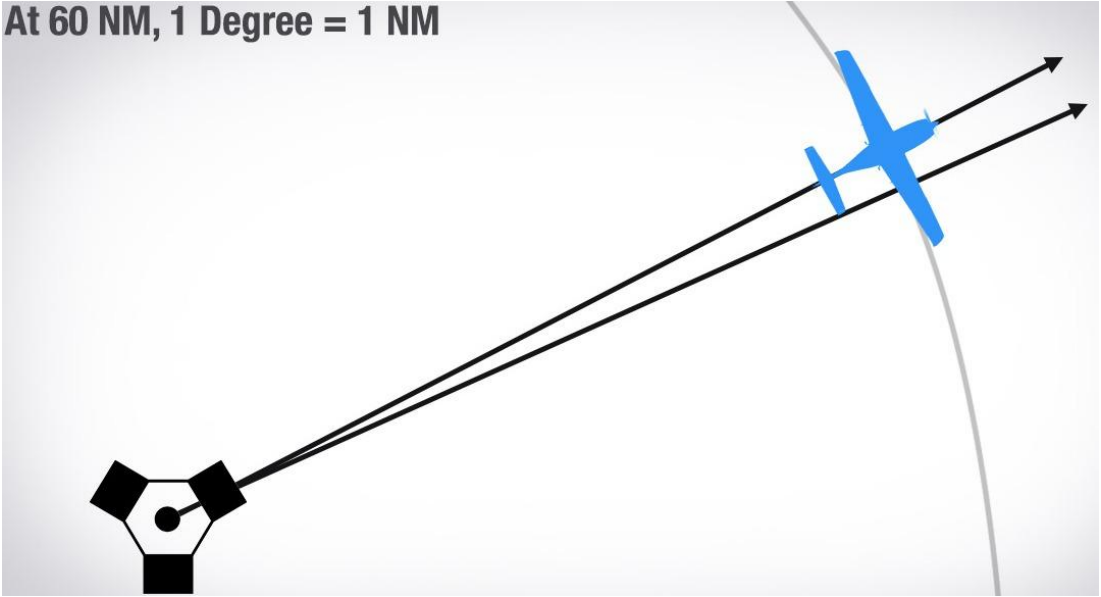


Figure 3.11: Basic illustration of 1 in 60 rule (Martin, 2017).

4. CASE STUDY

In this section, three case studies are analyzed by means of the effect of magnetic variation having the routes of Istanbul Ataturk International Airport (LTBA, N40°.98 E028°.81) – EuroAirport Basel Mulhouse Freiburg Airport (LFSB, N47°.59 E007°.55), Istanbul Ataturk International Airport (LTBA, N40°.98 E028°.81) – Brussels National Airport (EBBR, N50°.90 E004°.49), and Istanbul Ataturk International Airport (LTBA, N40°.98 E028°.81) – Porto Francisco Sa Carneiro Airport (LPPR, N41.24 W008.68). In addition to these airports, Lille Lesquin Airport (LFQQ, N50°.56 E003°.09) and Lisbon Airport (LPPT, N38°.78 W009°.14) are also taken into account for the case studies. These routes are considered based on direct navigation with no wind condition. They do not include any standard instrument departure (SID), standard terminal arrival (STAR), neither precision (ILS) nor non – precision (LOC only, VOR or NDB) approach procedures. These procedures are published, including selected waypoints and fixes. Table 4.1 shows that departure and destination airports, true courses with no variation correction and total distances. True course corresponds to the bearing measured from true north to the destination airport with no wind condition. Note that 1 NM is equal to approximately 1,852 m.

Table 4.1: Stations, established routes and parameters of case studies.

Departure Airport	Destination Airport	True Course (Degree)	Distance (NM)
LTBA N40°.98 E028°.81	LFSB N47°.59 E007°.55	298	995
LTBA N40°.98 E028°.81	EBBR N50°.90 E004°.49	308	1172
LTBA N40°.98 E028°.81	LPPR N41.24 W008.68	281	1687

Magnetic variation values at which each airport is based are essential to understand how magnetic variation affects safe air navigation and economical aspect of flights. Table 4.2 shows variation values of airports used for case studies.

Table 4.2: Variation values of airports used for case studies.

ICAO Code of Airport	City of Airport	Magnetic Variation (Degree)	Magnetic North Deviation
EBBR	Brussels	1	E
LFQQ	Lille	0	-
LFSB	Basel, Mulhouse	2	E
LPPR	Porto	3	W
LPPT	Lisbon	3	W
LTBA	Istanbul	4	E

Each route is separately analyzed to emphasize the effect of magnetic variation derived from WMM 2015 (Chulliat et al, 2015) on safe air navigation. Performance and fuel consumption of engines vary slightly with some factors such as outside air temperature, atmospheric pressure, level which the airplane flies, aircraft configuration, aircraft total weight, or company cost index value. However, for this study, an average quantity of fuel consumption is assumed and used for calculations. For example, a Boeing 737 – 800 airplane consumes of approximately 3,000 kg jet fuel for each one hour flight time. On the ground, fuel quantity which is required for taxi and APU (Auxiliary Power Unit) is approximately 500 kg, by the experiments of pilots. These are taken into account for the calculation of the flight cost.

4.1 LTBA – LFSB Route

LFSB EuroAirport Basel Mulhouse Freiburg Airport is located within France border line. In fact, this airport is recently in use for France and Switzerland, also for Germany, as well. Hence, its location is quite critical for the border violation.

As stated above at Table 4.1, this route has total distance of approximately 995 NM, and true course for this route is 298°. Navigation system integrated into airplane uses magnetic course value instead of true course (see Chapter 3). Hence, in case of take off from LTBA, magnetic variation value of 4°E has to be applied to the true course value. In the end, magnetic course is obtained as 294°.

Magnetic variation changes through the route. Magnetic course should be calculated with the magnetic variation value at the destination airport which is 2°E.

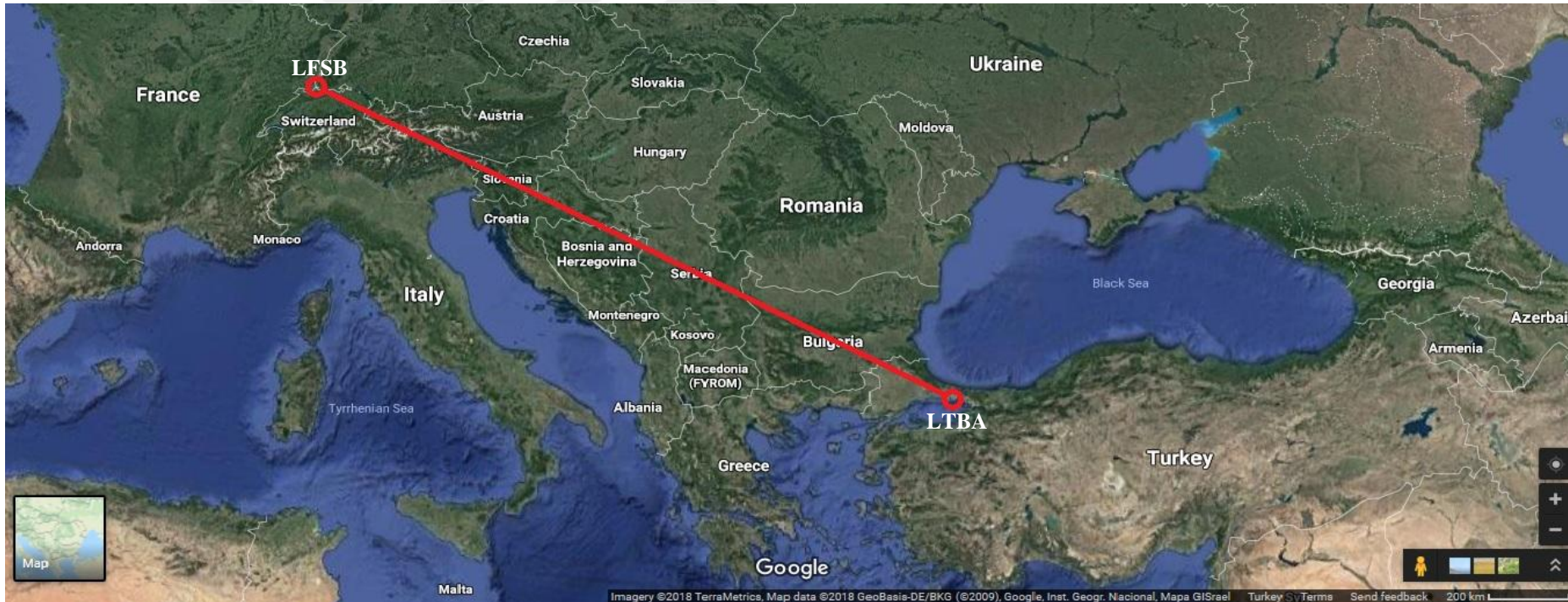


Figure 4.1: Istanbul Ataturk International Airport (LTBA) – EuroAirport Basel – Mulhouse – Freiburg Airport (LFSB) Route.

Therefore, magnetic course at final segment of the flight should be 296°. It is clear that there is a difference of 2° for approximately 995 NM.

In case of using magnetic variation at departure airport continuously, LTBA, there could be a difference of 2° for approximately 995 NM. This case leads to a deviation for each degree, using 1/60 rule:

$$(995 / 60) \times 2 = 33.2 \text{ NM.} \tag{4.1}$$

This result proves that there could be a significant deviation to the southwest of destination airport which threatens safe air navigation and could lead a hazard.

In case of applying magnetic variation at destination airport as 2°W instead of 2°E, with a difference of 6° for the same route, this case results in:

$$(995 / 60) \times 6 = 99.5 \text{ NM.} \tag{4.2}$$

This result also proves that there could be a significant deviation from the desired route to the northeast of destination airport which could lead border violation by crossing Germany country border line and threatens safe air navigation.

Table 4.3: Deviation for LTBA – LFSB route.

Departure Airport	LTBA
Destination Airport	LFSB
Magnetic Course for Desired Route	294°
Miscalculated Magnetic Course	300°
Deviation from Desired Route	99.5 NM

4.2 LTBA – EBBR Route

This route has total distance of 1,172 NM. True course for this route is 308°. In case of take off from LTBA, magnetic variation value of 4°E has to be applied to the true course value. As a result, magnetic course is obtained as 304°.

Magnetic variation value at the destination airport is 1°E. Therefore, magnetic course at final segment of the flight should be 307°. In case of using magnetic variation at departure airport, which is LTBA, during whole flight, there could be a difference of 3° for approximately 1,172 NM. In this case, possible deviation could result in, using 1/60 rule:

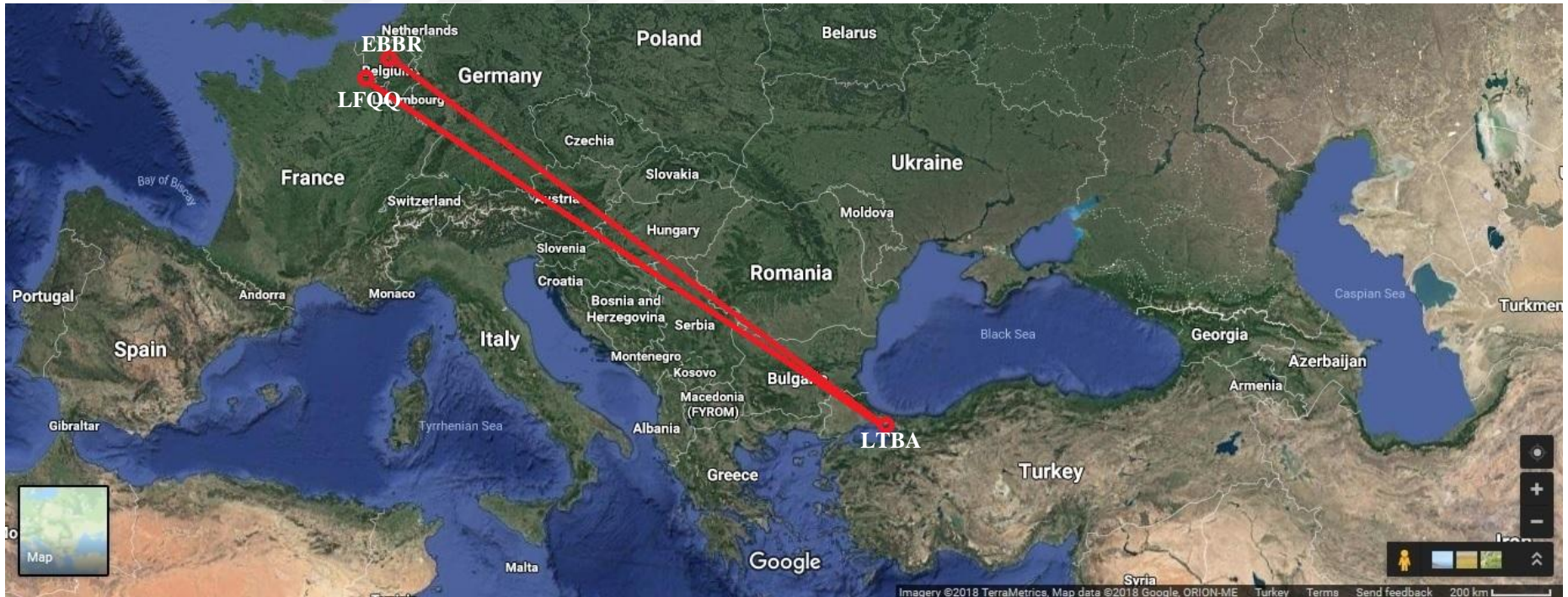


Figure 4.2: Istanbul Ataturk International Airport (LTBA) – Brussels National Airport (EBBR) Route.

$$(1,172 / 60) \times 3 = 58.6 \text{ NM.} \quad (4.3)$$

This result shows that there could be a significant deviation to the southwest of destination. Moreover, Lille Lesquin Airport is located at the southwest of Brussels National Airport with a distance of approximately 63 NM. This case also could lead a violation of France border line or a hazard. It obviously threatens safe air navigation.

Table 4.4: Deviation for LTBA – EBBR route.

Departure Airport	LTBA
Destination Airport	EBBR
Magnetic Course for Desired Route	307°
Miscalculated Magnetic Course	304°
Deviation from Desired Route	58.6 NM

4.3 LTBA – LPPR Route

LTBA – LPPR route has total distance of 1,687 NM, referred to Table 4.1. True course for this route is 281°. In case of take off from LTBA, magnetic variation value of 4°E has to be applied to the true course value. Finally, magnetic course is obtained as 277°.

The values of magnetic variation at departure and destination airport are 4°E and 3°W, respectively. In case of no change in magnetic variation value, there could be a difference of 7° for approximately 1,687 NM. That difference could lead a deviation of, using 1/60 rule:

$$(1,687 / 60) \times 7 = 196.8 \text{ NM.} \quad (4.4)$$

This result shows that there could be a significant deviation to the south of destination. Moreover, Lisbon Airport is located at the south of Porto Francisco Sa Carneiro Airport with a distance of approximately 172 NM. Pilot could unintentionally attempt to land the plane at Lisbon Airport when runway is insight as if it is the correct destination airport. Indeed, these two airports are located too far away from each other. It is definitely a hazardous situation which threatens safe air navigation.

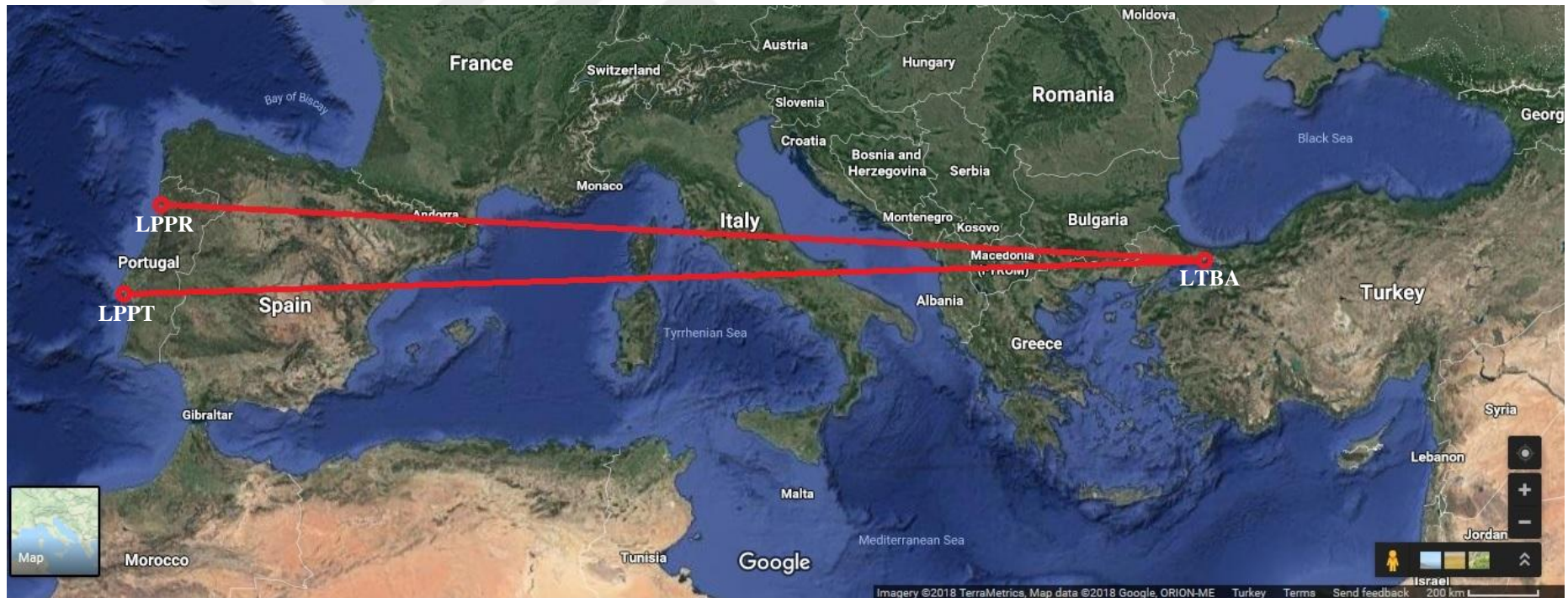


Figure 4.3: Istanbul Ataturk International Airport (LTBA) – Porto Francisco Sa Carneiro Airport (LPPR) Route.

Table 4.5: Deviation for LTBA –LPPR route.

Departure Airport	LTBA
Destination Airport	LPPR
Magnetic Course for Desired Route	284°
Miscalculated Magnetic Course	277°
Deviation from Desired Route	196.8 NM

4.4 Economical Aspect

There are many factors that affect the total cost of a flight such as slot and fuel price, maintenance cost, crew salary, and tax. One of the major factors is fuel price.

Average speed for the routes of case study is assumed as 280 knots IAS (Indicated Air Speed) which corresponds to approximately 450 knots TAS (True Air Speed) at FL300 (Flight Level, 30,000 feet in standard atmospheric pressure) in standard atmospheric conditions. As stated, average hourly fuel consumption is assumed approximately 3,000 kg of jet fuel. For taxi and APU, average fuel consumption for each sector is approximately 500 kg. Price of a jet fuel is 218.23 cts / gal (IATA, 2018), which is equal to approximately \$0.72 / kg.

For the route of LTBA – LFSB, there could be a possible deviation of 100 NM approximately. Airplane has to travel double of this deviation which results in 200 NM to return to and land safely at destination airport following an off – track. This takes approximately 27 minutes and there could be a need of 1,333 kg jet fuel. The extra need of jet fuel costs \$960 in addition to planned fuel consumption just for a single flight.

For LTBA – EBBR route, there could be a possible deviation of 59 NM approximately. Airplane has to travel extra 118 NM to land safely at destination airport. This takes approximately 16 minutes and there could be a need of 787 kg jet fuel. The extra need of jet fuel costs \$566 in addition to planned fuel consumption just for a single flight.

For the same reasons, in case of LTBA – LPPR route, airplane has to fly extra 394 NM and it takes approximately 53 minutes. There could be a need of 2,624 kg jet fuel. The extra need of jet fuel costs \$1,889 in addition to planned fuel consumption just for a single flight.

On the other hand, traffic data in the basis of a company, Turkish Airlines, for the period of January – August in 2018 was revealed. Turkish Airlines was awarded by Skytrax as the best airline in Europe for consecutive 6 years, the period of 2011 – 2016, and best airline in Southern Europe for the ninth consecutive time in 2017 (Anadolu Agency, 2018).

The fleet of Turkish Airlines consists of various airplane models (THY, n.d.) such as Boeing 737, Boeing 747, Boeing 777, Airbus A300, Airbus A310, Airbus A319, Airbus A320, Airbus A321, Airbus A330, Airbus A340. Although there are different types of airplane models which consume various quantity of fuel, average hourly fuel consumption of 3,000 kg jet fuel is assumed to have not an accurate result but a general idea of the quantity and cost of jet fuel that is needed for such a leader airline company of the Republic of Turkey. According to the report, 959,836 hours of flight time and 333,670 landings were performed by the crew and fleet (THY, 2018).

Table 4.6: Total cost of jet fuel for flight hours (IATA, 2018; THY, 2018).

Total flight hour for January – August 2018	Jet fuel cost for each flight hour (million \$)	Total jet fuel cost for January – August 2018 (million \$)
959,836	0.00216	2,073.2

Table 4.7: Total cost of jet fuel for taxi and APU (IATA, 2018; THY 2018).

Total landing for January – August 2018	Jet fuel cost for each sector (million \$)	Total jet fuel cost for January – August 2018 (million \$)
333,670	0.00036	120.1

The results show that the required amount jet fuel for trip costs more than roughly \$2,200,000,000. It can be clearly seen that the cost of fuel plays the major role amongst all expenses for a flight.



5. CONCLUSION

The Earth's magnetic field is called geomagnetic field. The main source of the geomagnetic field is conducting fluid and lava containing magnetized ingredients from outer core. The geomagnetic field is similar to the field that would be generated if there were a huge bar magnet centered in the Earth, called a dipole field. It has an axis of symmetry parallel to that huge bar magnet and intersects the Earth's surface at both geomagnetic north and south poles. The positional change of geomagnetic poles causes the annual change of the declination (magnetic variation).

Geomagnetic field is not a steady phenomenon, but changes with space and time. Various sources contribute to this phenomenon as it is measured at or above the Earth's surface. These observations are carried on either terrestrial or satellite – based missions. Stations for the terrestrial – based observations are widely distributed throughout the Earth to cover as large area as possible for derivation of a global magnetic field model. In Turkey, there are two stations that magnetic field observations have been carrying on, which are located at Iznik (IZN, N 40°.50 E 29°.72) and Kandilli (ISK, N 41.06 E 29.06). Since late 20th century, the investigation and determination of the geomagnetic field, and its temporal changes, especially of core and lithosphere, have been enabled by launching the satellite missions. These terrestrial and satellite – based observations are used to derive each parameters of geomagnetic field and world magnetic models.

The purpose of this study is to investigate the phenomena of geomagnetic field and its effect on safe air navigation. The principle of air navigation is emphasized to understand how pilots consider geomagnetic field variations in air navigation. Navigation aids are introduced as one of the tools in order to enable pilots to deal with the change of geomagnetic field variations. The 1/60 rule in air navigation contributes to see the importance of calculation by using correct magnetic variation.

Selected routes are analyzed to underline the essential role of using correct magnetic variation in navigation calculations for safe air navigation. These routes are Istanbul

Ataturk International Airport (LTBA, N40°.98 E028°.81) – EuroAirport Basel Mulhouse Freiburg Airport (LFSB, N47°.59 E007°.55), Istanbul Ataturk International Airport (LTBA, N40°.98 E028°.81) – Brussels National Airport (EBBR, N50°.90 E004°.49), and Istanbul Ataturk International Airport (LTBA, N40°.98 E028°.81) – Porto Francisco Sa Carneiro Airport (LPPR, N41.24 W008.68). The distances of these routes are 995 NM, 1172 NM, and 1687 NM, respectively. Note that 1 NM is equal to 1,852 m. The reason of selection of these routes is the difference in variation values at where the selected airports are located. Changes in magnetic variation values of the routes are 6°, 3°, and 7°. Analyzing these routes by using 1/60 rule is resulted in the deviation of a distance depending on the distance between departure and destination airports, approximately 100 NM, 59 NM, and 197 NM, respectively. On the other hand, every single flight which does not consider the magnetic variation change costs much more than planned costs. If magnetic variation values are incorrectly taken into account, an extra cost of \$960, \$566, and \$1,889 are resulted in the basis of each case study, respectively.

As a result, this study aims to emphasize the principle of geomagnetic field and its effect on safe air navigation. Change in magnetic variation has vital importance for safe air navigation. Especially in polar areas, the magnetic variation varies steeply and widely. Hence, a dynamic model of magnetic variation may be derived for pilot's usage.

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