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FEASIBILITY ANALYSIS OF REGIONAL TIMING AND POSITIONING SYSTEM FOR TURKEY

by

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Space-based global positioning systems are three-dimensional measurement systems that use radio signals from a constellation of satellites orbiting the Earth. They comprise a satellite navigation system designed to provide instantaneous position, velocity, and time information almost anywhere on the globe at any time. This technology is used in numerous areas such as unmanned systems, missiles, commercial and military aviation. The United States' NAVSTAR Global Positioning System and Russian Global Navigation Satellite System (GNSS) are fully operational and used by different nations. Because of the technology's essentiality, most countries aim for independence; however, this is a big problem for developing or non-space faring countries because of the cost of the systems. To decrease the cost of a position navigation and timing (PNT) constellation, some nations develop regional PNT systems. In this research, GNSS systems, regional navigation satellite systems and satellite-based augmentation systems are analyzed, and an independent regional timing and positioning system satellite constellation over Turkish territory is reviewed using the AGI Systems Tool Kit software.

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FEASIBILITY ANALYSIS OF REGIONAL TIMING AND POSITIONING SYSTEM FOR TURKEY

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ABSTRACT

Space-based global positioning systems are three-dimensional measurement systems that use radio signals from a constellation of satellites orbiting the Earth. They comprise a satellite navigation system designed to provide instantaneous position, velocity, and time information almost anywhere on the globe at any time. This technology is used in numerous areas such as unmanned systems, missiles, commercial and military aviation. The United States' NAVSTAR Global Positioning System and Russian Global Navigation Satellite System (GNSS) are fully operational and used by different nations. Because of the technology's essentiality, most countries aim for independence; however, this is a big problem for developing or non-space faring countries because of the cost of the systems. To decrease the cost of a position navigation and timing (PNT) constellation, some nations develop regional PNT systems. In this research, GNSS systems, regional navigation satellite systems and satellite-based augmentation systems are analyzed, and an independent regional timing and positioning system satellite constellation over Turkish territory is reviewed using the AGI Systems Tool Kit software.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFI	Africa-Indian
CDMA	Code Division Multiple Access
CS	Commercial Service
DGCA	Directorate General of Civil Aviation
DoD	Department of Defense
DTED	Digital Terrain Elevation Data
EGNOS	European Geostationary Overlay Service
EM	Electro Magnetic
ESA	European Space Agency
EU	European Union
FAA	Federal Aviation Administration
FDMA	Frequency Division Multiple Access
FOC	Full Operational Capability
GAGAN	GPS Aided Geostationary Earth Orbit (GEO) Augmented Navigation
GBAS	Ground Based Augmentation System
GEO	Geo Stationary Orbit
GIOVE	Galileo In-Orbit Validation Element
GLONASS	Russian Global Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSO	Geo Synchronous Orbit
GTSB	Galileo System Test Bed
HEO	Highly Elliptical Orbit
IGSO	Inclined Geo Synchronous Orbit
ILRS	Laser Ranging Stations
INC	ISRO Navigation Centre
IOV	In-Orbit Validation
IRCDR	IRNSS CDMA Ranging Stations

IRDCN	IRNSS Data Communication Network
IRIMS	IRNSS Range and Integrity Monitoring Stations
IRNSS	Indian Regional Navigation Satellite System
IRNWT	IRNSS Network Timing Centre
IRO	Indian Research Organization
JAXA	Japanese Space Agency
JPO	Joint Program Office
MCC	Master Control Station
MEO	Medium Earth Orbit
MTSAT	Multifunctional Transport Satellite
NAVIC	Navigation Indian Constellation
NAVSTAR	Navigation System with Timing and Ranging
NLES	Navigation Land Earth Stations
NTS	Navigation Technology Satellites
OS	Open Service
PNT	Position Navigation and Timing
PPS	Precise Positioning Service
PRS	Public Regulated Service
QZO	Quasi-Zenith Orbit
QZSS	Quasi-Zenith Satellite System
RDSS	Regional Radio Determination Satellite Service
RIM	Ranging and Integrity Monitoring Stations
RNSS	Regional Navigation Satellite System
RS	Restricted Service
SA	Selective Availability
SACCSA	South/Central America and the Caribbean SBAS Initiative
SAR	Search and Rescue
SBAS	Satellite Based Augmentation System
SCF	Spacecraft Control Facility
SDCM	System of Differential Correction and Monitoring
SNAS	Satellite Navigation Augmentation System
SOL	Safety of Life

SPS	Standard Positioning Service
STK	Satellite Tool Kit
TOA	Time of Arrival
UHF	Ultra High Frequency
VHF	Very High Frequency
WAAS	Wide Area Augmentation System

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I. INTRODUCTION

A. BACKGROUND

Global Navigation Satellite Systems (GNSS) are space-based three-dimensional measurement systems that use radio signals from a constellation of satellites orbiting the earth. They are designed to provide instantenaous position, velocitiy, and time information almost anywhere on the globe at any time, and in any weather. Applications of this technology serve not only military systems, but also offer lots of opportunity for civilian users [1].

The Global Positioning System (GPS) is one of the GNSS projects conducted by the U.S. Department of Defense (DoD) to support accurate navigation information for warfighters. The DoD decided to commence the GPS program in the early 1970s and the first Navigation System with Timing and Ranging (NAVSTAR) satellite was launched in 1978. In 1993, GPS became fully operational with 24 sattellites in orbit [2], [3].

The Russian Global Navigation Satellite System (GLONASS) is another GNSS program that provides all potential users with constant and accurate position information. The GLONASS program began in 1972 and the first satellite launched in 1982. The GLONASS constellation was completed in 1995 with 24 satellites [4].

Similarly, GALILEO is a European GNSS project conducted by the European Space Agency (ESA) and European Union (EU) for global coverage and civil purposes. GALILEO aims to supply global, highly accurate position information and interoperability between GPS and GLONASS. The GALILEO program uses a phased approach, and an "In-Orbit Validation (IOV) Phase" was completed in 2011. The "Deployment Phase" is currently ongoing and Fully Operational Capability (FOC) is planned for the end of this decade. Four satellites launched on 12 December 2017 and another four on 25 July 2018 increased the number of satellites in the constellation to 26 [5], [6].

Like GALILEO, China's BEIDOU Navigation Satellite System is another ongoing GNSS project. The development strategy of the BEIDOU project has three steps

(Experimental, Regional, Global) that aim to provide regional to global coverage. Like GALILEO, full deployment of the system is planned by the end of this decade [7].

GPS, GLONASS, GALILEO, and BEIDOU GNSS systems are aimed to provide global coverage at all times. To provide global coverage, a large number of satellites is needed. By adding spares and renewal satelllites, the life cycle cost of this kind of system can be very high. For of that reason, some regional solutions are available in the world.

For example, the Indian Regional Navigation Satellite System (IRNSS) is a regional Position Navigation and Timing (PNT) system developed by the Indian Research Organization (IRO). The IRNSS constellation consists of seven satellites, three of which are in geostationary orbits and four are in geosynchronous orbits; all are designed to provide PNT information accurately over India and its vicinity [8]. The last IRNSS satellite launched in March 2016 and the system became operational in June 2016. After completing the IRNSS constellation, India’s Prime Minister Narendra Modi renamed the system as Navigation Indian Constellation (NAVIC) [9].

Another regional satellite-based system is the Quasi-Zenith Satellite System (QZSS), which is interoperable with GPS signals. QZSS serves East Asia including Japan and Oceania. The first satellite of the QZSS constellation, named MICHIBIKI, launched on 11 September 2010, and by April 2018 the number of satellites in the QZSS constellation had reached four [10].

Besides global and regional navigation satellite systems, Satellite Based Augmentation Systems (SBAS) offer an opportunity to improve GNSS accuracy over a specific area at low cost [11]. Currently operational and under-development SBAS systems are the following:

- Wide Area Augmentation System (WAAS)
- European Geostationary Overlay Service (EGNOS)
- Multifunctional Transport Satellite (MTSAT) Satellite Based Augmentation System (MSAS)

- GPS Aided Geostationary Earth Orbit (GEO) Augmented Navigation (GAGAN)
- System of Differential Correction and Monitoring (SDCM)
- Satellite Navigation Augmentation System (SNAS)
- South/Central America and the Caribbean SBAS Initiative (SACCSA)
- Malaysia: a future SBAS System is under study
- Africa-European Union Strategic partnership' EGNOS extension to Africa-Indian Ocean (AFI) [12]

B. PURPOSE

This research presents the first investigation into a regional PNT system for Turkey. Additionally, it provides preliminary analysis results for well-known local positioning and timing systems.

The purpose of this research is to analyze Global/Regional GNSS and SBAS systems' constellation features and positioning performance. This research also aims not only to analyze current systems, but also to propose a Regional PNT System Constellation over Turkey to provide highly accurate and stable navigation information.

C. THE RESEARCH QUESTION

The following questions will be answered in the course of this research:

- What Regional/Global Navigation Satellite Systems and Space Based Augmentation Systems are operational or under development all around the world?
- What is the performance of Regional/Global Navigation Satellite Systems and Space Based Augmentation Systems over their operational area?

- Which constellation can be a good model for providing independent, highly accurate, and stable position information over the land of Turkey?
- What is the predicted accuracy of the proposed system?

D. SCOPE, LIMITATIONS, AND ASSUMPTIONS

The scope of this study is limited to determining and analyzing orbital constellation characteristics and positioning performance for the proposed system.

E. METHODOLOGY

Based on a review of the relevant literature, this thesis is developed according to the following methodology:

1. Conduct an open source review of Global/Regional Navigation Satellite Systems and SBAS Systems and programs.
2. Conduct a literature review for sources of error in GNSS Systems and Dilution of Precision values to determine the accuracy of GNSS Systems.
3. Propose a Regional and Independent PNT System Constellation for operation over the land of Turkey.
4. Analyze the proposed constellation to answer the question, “How accurate is the system?”

F. ORGANIZATION OF THE STUDY

The stated research questions are discussed chapter by chapter. This thesis begins with a literature review and the collection of data about current GNNS, Regional PNT, and SBAS Systems, and tries to show their accuracy over their respective operational areas. After gathering information from the literature review, a unique system to Turkey is proposed, and is analyzed with STK software. The results of analysis are discussed at the end of the thesis.

II. LITERATURE REVIEW ON NAVIGATION SATELLITE SYSTEMS

Space has attracted the attention of human beings for centuries. It was not until the 20th century, however, that space studies went beyond the examination of the celestial bodies and the introduction of a number of hypotheses by astronomers. The field of rocketry gained momentum in the 20th century as German scientists developed rockets with the goal of attacking enemies over longer distances during the Second World War. This technological development became a milestone in their dreams about space.

In the beginning, space activities, which often confer prestige on the sponsor nation and can serve as a deterrent, were confined to the superpowers. Over time, though, remote sensing and communication satellites have gained vital importance for the economic and military systems of many other countries. The military satellite systems deployed today have many unobtrusive applications, from identification and diagnosis of strategic/tactical targets to safe and fast data communication, as well as for navigation and early-warning in the use of force from a distance.

The launching of Sputnik-1 by the Soviet Union in 1957 revealed the need to follow the orbit of a satellite. The assumption was that it was possible to determine the location of the satellite by following the radio signals sent by Sputnik-1. Then came the thought that the converse could also be possible. The position of a radio receiver could be calculated if the orbit of the satellite was known in advance. Even more satellites could be designed for this work and sent into space. The concept of the navigation satellite system was born in this thought [13].

Countries that want to secure their access to navigation satellite systems, which nowadays are considered an undeniable point of military and economic importance, are developing new programs with national and international initiatives. As satellite systems of regional and global navigation systems increase, these artificial stars are becoming an alternative to the polar star in the earthly journey of mankind.

A. APPLICATION OF NAVIGATION SATELLITES

Today, navigation satellite receivers are involved in many civilian and military applications. Navigation satellite systems are the most common system used in the aviation and maritime communities. Especially for air and sea vehicles, they are used for route and target information. Support systems that increase positioning sensitivity, such as the U.S.-run WAAS or the European EGNOS, have gained widespread use in aviation. In fact, many of these support systems can be used as an approach and landing system in air vehicles by certifying them within the framework of flight rules.

The use of navigation satellite systems is not limited to air and sea vehicles. One of the main uses of navigation satellite systems in the military area is cartography. As is discussed in the following sections, the coordinate measurement errors that are essential to the map drawing task can be reduced to submeter and millimeter levels by using differential satellite receivers [2].

Besides these applications, navigation satellite systems are widely used as a reference time source, especially in the management of communication networks and the banking sector. Solutions based on navigation satellite systems also find use in the meteorology, marketing, and transportation sectors. The applications for the use of navigation satellite systems are limited only by the imagination, but some areas of use can be listed as follows [14]:

- Earthquake investigations
- Agriculture
- Fishing
- Farming
- Emergency Services and Natural Disaster Management
- Scientific Research
- Traffic Management and Prevention of Accidents

- Landscaping
- Precision Guided Ammunition and Cruise Missiles
- Mine Clearing

B. PRINCIPLES OF NAVIGATION SATELLITE SYSTEMS

The Navigation Satellite System is a general term used for satellite-based systems that can provide location and time information. In general, navigational satellite systems consist of three parts [15]:

- Space Segment
- Control Segment
- User Segment

The Space Segment consists of satellites that broadcast navigation signals. The Control Segment generally forms the ground stations and centers where the system and navigational signals are managed. The User Segment can be defined as any type of customer, including military and civilian users, who receives navigation signals.

The GNSS receiver has to receive a signal in order to detect the position (latitude, longitude, and height) of at least three navigation satellites. Furthermore, a fourth satellite signal is needed to resolve time synchronization and locate the receiver more accurately. Within the signal sent by the navigation satellite, there is the position information of the satellite that sent the signal as well as the time it sent the signal. Based on this signal, the receiver uses the arrival time method to calculate the distance to each satellite from which it received the signal. In order to use the time of arrival (TOA) method, the receiver must have the following information [16]:

- Time the signal was sent
- Signal delivery speed
- Time the signal was received

Establishing a satellite's location based on the time information in the signal, which is delivered at the speed of light, requires precision. The time the signal was sent is already in the satellite signal. Despite the fact that atomic clocks on the satellites are very precise and stable among the specimens, the transmitted time information is not as precise as the receiver needs. Yet, the correction information for the satellite time error may also be included in the satellite signal. The time to receive the signal is recorded by quartz watches, which are less stable than the clocks on the satellites. Nevertheless, the time error on the receiver is not a big problem, and this error can easily be corrected by the signal from the fourth satellite. That is why a navigation satellite receiver needs signals from at least four satellites to predict its location. Otherwise, when a signal transmission speed is considered, a small time error causes a large distance error [2], [14]–[17].

C. NAVIGATION SATELLITE SYSTEMS

Navigational satellite system architectures vary according to the expectations of the satellites owners' countries, their aims, economic possibilities, and technological sub-structures. First of all, it is necessary to mention Global Navigation Satellite Systems can provide speed, time, and positioning information all over the world. There are four global navigation systems already known to be operational or in development.

- USA NAVSTAR Global Positioning System (GPS)
- RUSSIA Global Navigation Satellite System (GLObal'naya Navigatsionnaya Sputnikova Sistema-GLONASS)
- CHİNA COMPASS Navigation Satellite System
- European Union Global Navigation Satellite System (GALILEO) [18]

By 2018, NAVSTAR, owned by the United States, and GLONASS, owned by Russia, were globally available sources of accurate speed, time, and location information. In addition to Global Navigation Satellite Systems, Regional Navigation Satellite Systems, which can provide location and time information locally, are also being operated or developed. These are;

- China BEIDOU-1/2
- Indian Regional Navigation Satellite System (IRNSS)
- Japan Quasi-Zenith Satellite System (QZSS) [18]

Finally, the support systems used to improve the data of existing global navigation satellites have also been operationally applied. These are:

- Wide Area Augmentation System (WAAS)
- European Geostationary Overlay Service (EGNOS)
- Multifunctional Transport Satellite (MTSAT) Satellite Based Augmentation System (MSAS)
- GPS Aided Geostationary Earth Orbit Augmented Navigation (GAGAN)
- System of Differential Correction and Monitoring (SDCM)
- Satellite Navigation Augmentation System (SNAS)
- South/Central America and the Caribbean SBAS Initiative (SACCSA)
- Malaysia: a future SBAS System is under study
- Africa-European Union Strategic partnership EGNOS extension to Africa-Indian Ocean (AFI) [11], [12]

1. Global Navigation Satellite Systems

As previously mentioned, two countries currently have GNSS, and the European Union has a program to have such a system to be independent. GPS and GLONASS programs are conducted by United States of America and Russia, respectively, and became operational after long development processes. The GALILEO program, which belongs to the European Union, is making steady progress to join the other GNSS. This section discusses the current and future GNSS programs.

a. NAVSTAR GPS

It would be useful to talk about the evolution of navigational satellite systems from which GPS emerged. As is known, the U.S. TRANSIT system, which was the predecessor of modern satellite navigation systems, operated according to the principle of measuring the doppler shift of satellites in polar orbits. Only two-dimensional location information was obtained from this system. Therefore, it was not a suitable positioning system for aircraft, because altitude information could not be obtained from it. Instead, the TRANSIT system could generally be used in slow moving vehicles or on sea vehicles. In the meantime, the Soviet Union developed two nearly identical systems. These were the "Parus" developed for the Soviet Navy and the "Tsikada" developed for commercial ships [19].

The success of the TRANSIT system encouraged the U.S. Air Force and the U.S. Navy to develop even better systems. First, the U.S. Air Force Project 621B started obtaining three-dimensional positioning information. In 1973, the GPS Joint Program Office (JPO) was established and the NAVSTAR GPS concept was born [14], [20]. The versions of NAVSTAR GPS satellites are as follows [21]:

- Navigation Technology Satellites (NTS)
- Navigation Development Satellites (Block-I)
- Block-II and Block-IIA (First Operational Satellites)
- Block-IIR and Block-IIR-M (Replenishment Satellites)
- Block-IIF (Modernization Satellites)
- Block-III (The first satellite will be launched in December 2018)

The space segment of the GPS consists of 24 active satellites nominally located at about 20,000 kilometers altitude and in 12-hour periodic orbits. Besides these 24 operational satellites, additional ones are active spares. These satellites are located in six orbital planes with a 55-degree inclination angle (that is, four satellites per orbit). This constellation ensures that a receiver anywhere in the world can continuously receive signals from at least four satellites. Nevertheless, in order to provide better performance for users, the number of satellites today is 31 [22].

To control GPS satellites, the U.S. DoD is running one master control station located in Schriever Air Force Base (AFB), Colorado, and one alternate master control station located in Vandenberg AFB, California. There are 12 command and control antennas and 16 monitor stations generally all around the world [2]. The task of these stations is to monitor system performance and make measurements to accurately determine satellites' orbits.An illustration of the control segment is given in Figure 1.

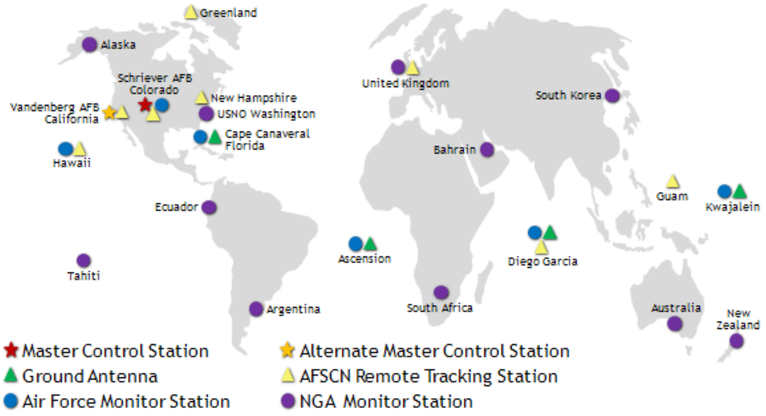

Figure 1. GPS Control Segment. Source: [23].

The GPS has two kinds of services. One of them is Standard Positioning Service (SPS), which is available to all users, and the other one is Precise Positioning Service (PPS), which is available only for authorized users [24]. For reasons of security, in earlier decades the accuracy of the system was intentionally reduced through the deliberate addition of errors to their GPS signals. This process was known as Selective Availability (SA), and it was discontinued on 1 May 2000 due to economic reasons and is no longer used [25].

The three different signals sent by the GPS to the receiver are:

- L1 (1575.42 MHz)

- L2 (1227.6 MHZ)
- L5 (1176 MHz) [26], [27]. The L5 is a new signal. Initially an experimental signal, GPS-IIR satellites, GPS-IIF, and Block-III satellites have the capability to transmit it.

Furthermore, there are three different types of coding on these three different signals.

- Coarse Acquisiton (C/A Code): The C/A Code is the unencrypted code that is introduced to the system to capture the GPS signal. It is included in the L1 signal.
- Precise (P/Y) Code: It is a code found in L1 and L2 signals and used for better performance and sensitivity. Initially, the receiver is locked onto the C/A code because the P-code is more difficult to lock. The satellite does not normally send a P-Code, but the encrypted P (Y) -code is sent instead. Unauthorized receivers can not lock directly onto this code.
- Military Code (M-Code): The M-Code signal will broadcast with Block-III satellites when they are at FOC phase. This signal is more powerful and harder to jam, as well as more flexible, secure, and interoprable than other signals [26].

When it comes to the stability and correctness of the GPS signals, differences depend on the situation. GPS error size for civilian users when SA was enabled was 100 meters. With the shutdown of SA the error size was reduced to 10 meters.

b. GLONASS

While the United States was developing the NAVSTAR GPS, the Soviet Union was developing a navigation system called GLONASS with similar features. GLONASS, which started development in 1976, was aimed at providing global coverage with full capacity in 1991. This aim was met with only 21 operational satellites after four years. But the financial troubles of the Russian Federation following the breakup of the Soviet Union left only 16 satellites operational in 1998 [28]. Until 2010, the constellation consisted of 24 satellites [18]. Now, GLONASS is currently operational with 26 satellites; one of them is under flight test and one is under maintenance [29]. A picture of the GLONASS constellation is given in Figure 2.

Figure 2. GLONASS Constellation Overview. Source: [30].

The space segment of GLONASS consists of about 24 active satellites nominally located at about 19,100 km altitude and in 11 hour-15 minute-45 second periodic orbits. These satellites are in three orbital planes with a 64.8-degree inclination angle (eight satellites per orbit). This constellation ensures that a receiver anywhere in the world can continuously receive signals from at least four satellites [18]. The satellites used in the GLONASS constellation are depicted in Figure 3 chronologically.

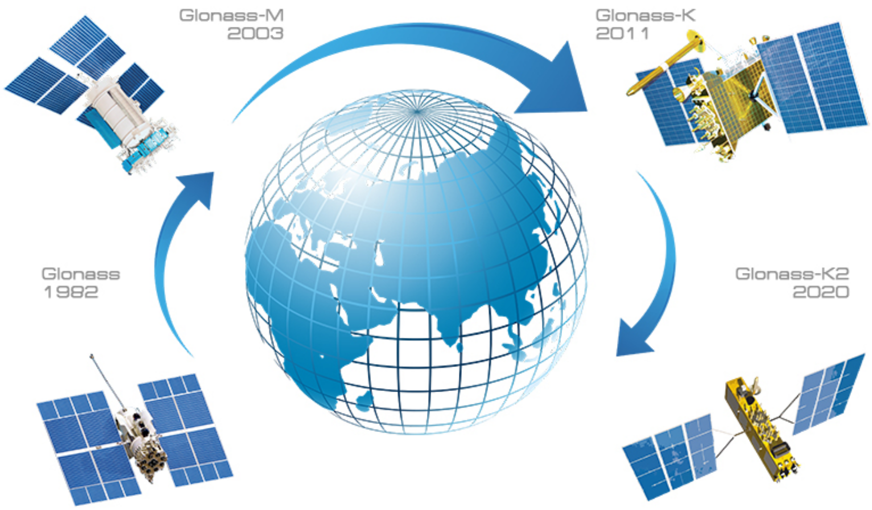

Figure 3. History of GLONASS Satellites. Source: [31].

The ground segment includes: a system control center; a network of five telemetry, tracking, and command centers; the central clock; three upload stations; two satellite laser ranging stations; and a network of four monitoring and measuring stations. As shown in Figure 4, different from the GPS ground segment, all stations are distributed over Russian territory. It is known, however, that there are also efforts to establish ground stations outside of Russia to improve the reliability and correctness of GLONASS [18].

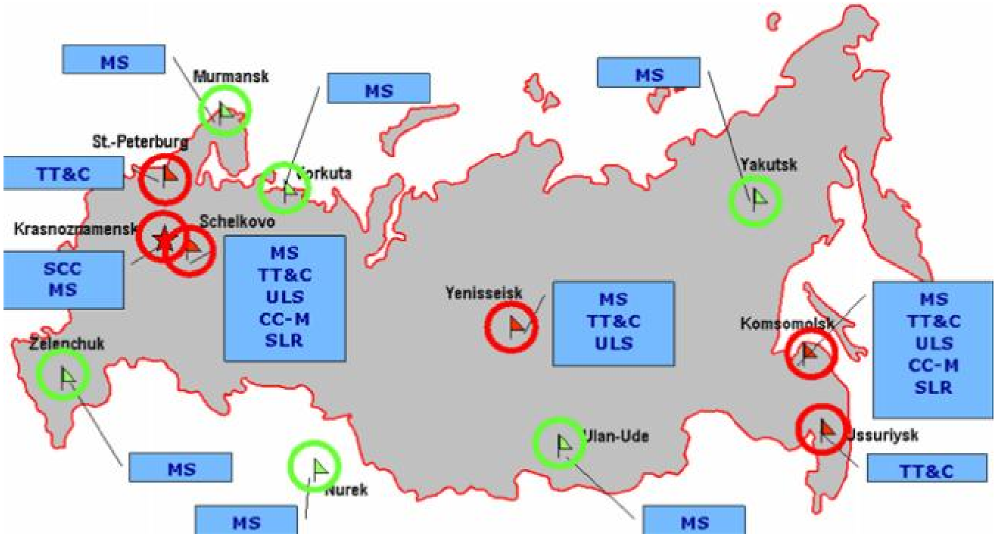

Figure 4. GLONASS Ground Segment. Source: [32].

As in GPS, GLONASS satellites also send signals by using three main carrier frequencies to provide two services: an open service with open access, and a secured service with authorized access. GLONASS uses Frequency Division Multiple Access (FDMA) while GPS and GALILEO, which is described later, use Code Division Multiple Access (CDMA). Because of this, a GPS receiver cannot receive the GLONASS signal although it can receive a GALILEO signal. During a GPS-GLONASS Interoperability and Qualification Workshop held in 2006, work on resolving this issue was announced. As a consequence of these efforts, modernized GLONASS-K satellites contain CDMA with the L3 signal. This way GLONASS and other GNSS systems are targeted to be mutually operable [34]. A summary of the characteristics of GLONASS signals is given in Table 1.

Table 1. Summary of GLONASS Signals and Service Types

Signal	**Carrier Frequency (MHz)**	**Modulation**	**Data Rate (bps)**	**Service Type**
L1	1,600.995	FDMA	125	Open
				Authorized
L2	1,248.06	FDMA	250	Open
				Authorized
L3	1,202.025	CDMA (with modernized GLONASS-K satellites)	100	Open

c. GALILEO

GALILEO is a cooperative project of the ESA and the EU to provide position information with high sensitivity from GPS and GLONASS. The main goal of the GALILEO project is that ensure Europe be independent from the United States and Russia in terms of navigation. Other motivating issues are to create dominance in satellite-based navigation systems and to encourage EU industry for the satellite navigation market [35].

For the GALILEO program, a phased approached is applied. ESA launched the Galileo System Test Bed (GSTB-V1) in 2002 to develop the ground segment by using raw

GPS data [35]. After this step, ESA implemented the GSTB-V2 program that aimed to design and launch two test satellites. The first satellite of the GSTB-V2 program, Galileo In-Orbit Validation Element-A (GIOVE-A), launched in December 2005. After that, GIOVE-B launched in April 2008. This phase concluded successfully with the reception of GALILEO-like signals from these experimental satellites. GIOVE-A and GIOVE-B satellites were retired in 2012 [5], [18], [35].

After an early technology demonstration with the GSTB-1 and GTSB-2 programs, the IOV Phase started. The IOV phase began with the launching of experimental satellites on 21 October 2011 and concluded successfully at the end of 2013. The Full Operational Phase will be completed with the deployment of the whole constellation and is still ongoing. Currently there are 18 operational satellites in orbit and four satellites under flight test [35].

The space segment of the GALILEO constellation consists of about 30 active satellites, including six spares, located at about 23,222 kilometers altitude and in approximately 14-hour periodic orbits. These satellites are in three orbital planes with a 56-degree inclination angle. This constellation ensures good coverage over polar regions as well [18].

The ground infrastructure of GALILEO includes: two Control Stations, five Mission Uplink Stations, six Tracking and Command Stations, and 16 Sensor Stations worldwide, as shown in Figure 5.

Figure 5. GALILEO Ground Segment Overview. Source: [36].

GALILEO will provide five different kinds of service: Open Service (OS), providing PNT information for all users at no charge; Public-Regulated Service (PRS), which provides PNT information for users who have receivers equipped with a PRS security module; Commercial Service (CS), which will be capable of transmitting external data to all users; Search-and-Rescue Service (SAR), which is designed to support the COSPAS-SARSAT Program; and Safety-of-Life (SOL) Service, which is for aviation applications [37]. Current and planned signals and the corresponding services are given in Table 2:

Table 2. GALILEO Signals and Service Types

	Signal	**Frequency**	**Service Type**
1.	GALILEO E1	1559-1594 MHz	OS, PRS
2.	GALILEO E5a	1164-1188 MHz	OS
3.	GALILEO E5b	1195-1219 MHz	OS
4.	GALILEO E6	1260-1300 MHz	PRS, CS
5.	SAR Downlink	1544-1545 MHz	SAR
6.	Improves the OS performance and uses the same frequencies as the OS		SOL

2. Regional Navigation Satellite Systems

Besides the GNSS, there are a few RNSS programs that offer independent PNT services over a specific area at a low cost. The prominent feature of such systems is low deployment and life cycle cost due to the limited number of satellites. The Indian Regional Navigation Satellite System, which is owned by India, the Quasi-Zenith Satellite System, which is owned by Japan, and BEIDOU-1/COMPASS, which is owned by China, are examples of RNSS programs. This section discusses the current and future GNSS programs.

a. Indian Regional Navigation Satellite System (IRNSS)

The IRNSS is a regional positioning system that covers the entire 1,500–2,000 kilometer area surrounding India, which is owned by the Indian government [38]. The project was launched in 2006 by the Government of India, which aimed to finish the project in 2012. The last IRNSS satellite was launched in 2016, and became operational in June 2016. After the IRNSS constellation reached completion, India’s Prime Minister Narendra Modi renamed the system the Navigation Indian Constellation, or NAVIC [9].

The IRNSS architecture consists of three primary segments, like others: space, ground, and user segments [8]. The space segment of IRNSS consists of seven satellites placed at geostationary and geosynchronous orbits. The geosynchronous satellites have 29-degree inclination angles. This inclination provides coverage around lower and higher latitudes [8], [18], [38]. Detailed information about IRNSS satellites is given in Table 3.

Table 3. IRNSS Satellites

Satellites	**Orbit type**	**Launch Date**	**Degree**	**Inclination**
IRNSS-1A	GSO	01 Jul 2013	55	29
IRNSS-1B	GSO	04 Apr 2014	55	29
IRNSS-1C	GEO	15 Oct 2014	83	0
IRNSS-1D	GSO	28 Mar 2015	111	29
IRNSS-1E	GSO	20 Jan 2016	111	29

Satellites	**Orbit type**	**Launch Date**	**Degree**	**Inclination**
IRNSS-1F	GEO	10 Mar 2016	32	0
IRNSS-1G	GEO	28 Apr 2016	132	0
IRNSS-1H	Launch Failure			
IRNSS 1I	GSO	12 Apr 2018	55	28.8

The IRNSS architecture is depicted in Figure 6. Note that the ground segment of IRNSS consists of different kinds of stations and facilities to support the maintenance and operation of IRNSS satellites. These ground segment elements are:

- IRNSS Spacecraft Control Facility (SCF)
- ISRO Navigation Centre (INC)
- IRNSS Range and Integrity Monitoring Stations (IRIMS)
- IRNSS Network Timing Centre (IRNWT)
- IRNSS CDMA Ranging Station (IRCDR)
- Laser Ranging Stations (ILRS)
- IRNSS Data Communication Network (IRDCN) [8], [39]

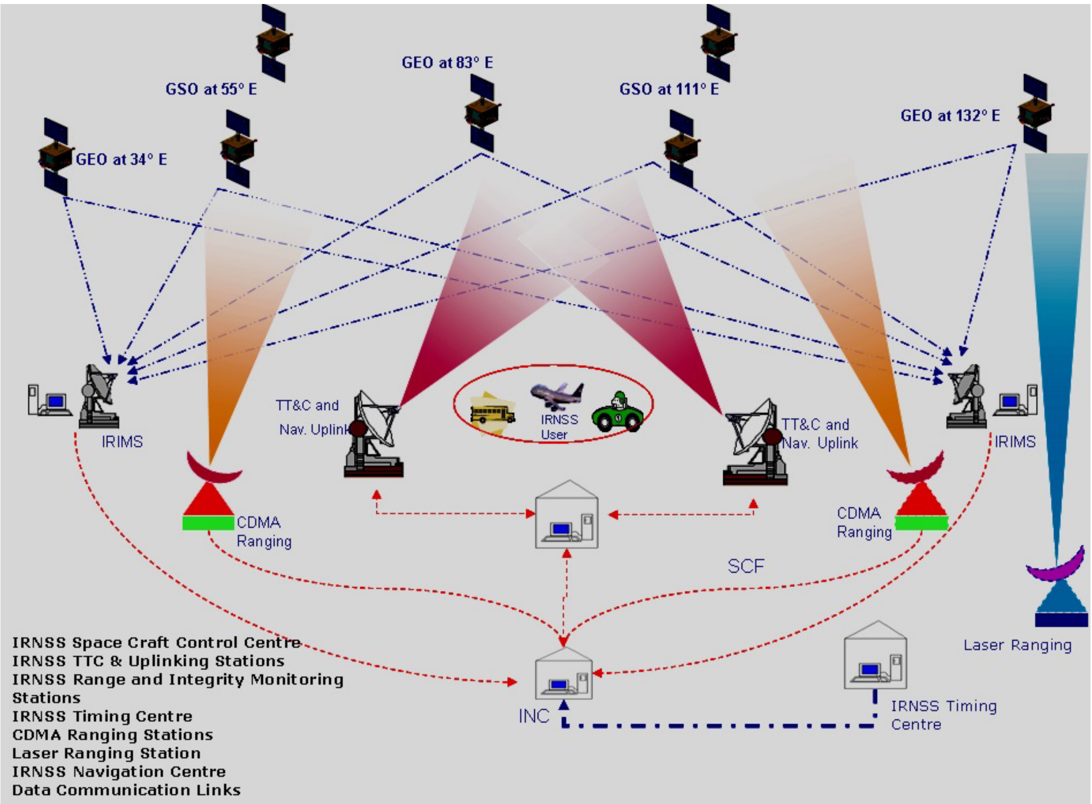

Figure 6. IRNSS Architecture. Source: [39].

The IRNSS constellation transmits two signals in the L5 and S bands for two operational services, which are Standard Positioning Service (SPS) and Authorized/Restricted Service (RS) [18]. The Restricted Service uses encryption technology and is only available for authorized users. Detailed information about transmission frequencies and related services is given in Table 4.

Table 4. IRNSS Signals and Service Types

	Signal	**Frequency (MHz)**	**Bandwith (MHz)**	**Service Type**
1.	L5	1,176.45	24	SPS
2.				RS
3.	S	2,492.028	A6.5	SPS
4.				RS

b. Quasi-Zenith Satellite System (QZSS)

QZSS, developed by the Japanese Space Agency (JAXA), is a PNT system as well as an SBAS system that is planned to operate in full compliance with GPS. The main objectives of QZSS are to broadcast GPS-interoperable and augmentation signals for users around Japan and Oceania/Australia [18], [40].

Established in June 2002, this program is the coordinated effort of four different ministries of the Government of Japan [41]. The first satellite Michibiki, which means “guiding” or “showing the way,” was launched on 11 September 2010. At that time, full operational capability was aimed to be completed by 2013. The last satellite launched, however, on 09 October 2017, and in April 2018 the four-satellite constellation finally became operational [42].

Because Japan is located at a high latitude, GNSS signals generally come with a relatively low elevation angle. These signals are often obstructed in areas with narrow streets and elevations surrounded by buildings, and their strength weakens. Moreover, for uninterrupted signals in countries like Japan, where high buildings are numerous, satellites must be on top of Japan. These two motivating elements dictate the use of a quasi-zenith trajectory for this system [43].

Quasi-Zenith Orbit (QZO), which is used in QZSS, is typical geo-synchronus orbit (GSO) that has eccentricity and inclination. These two orbital parameters provide at least one satellite above Japan during seven to nine hours constantly. On the other hand, the satellite will not always propogate signals directly overhead (zenith), so the system is called "quasi-zenith" [44].

After the first satellite launched in 2011, the three other satellites followed beginning in 2017. Three of the four satellites have QZO orbits and one of them is in GEO. The satellite that has a GEO orbit is located at 127 E longitude. The three satellites located in QZO are 130 degrees apart from each other in terms of their planes [18]. The nominal parameters of QZO are given in Table 5.

Table 5. QZSS Satellites Nominal Orbital Parameters

Orbit Parameter	**Nominal Allocation**	**Tracking Range**
Semimajor Axis (A)	42,164 km	-
Eccentricity	0.075	0.075 ± 0.015
Inclination	40 degree	36~45 degree
Argument of Perigee	270 degree	270 ± 2.5 degree
RAAN	117 ± 130 degree	-
Central Longitude	136 degree	130~140 degree

The ground segment of QZSS includes: two master control stations, which are located in Hitachi-Ota (main) and Kobe (redundant); seven satellite control stations, which are mostly located at the southern part of Japan and were set up at the end of 2016; and more than 30 monitor stations all around the world [10], [18].

Considering QZSS services, QZSS has three main functional capabilities [10]:

- **GPS Complementary:** Navigation signals L1-C/A, L1C, L2C, and L5 sent from high elevation to improve the time percentage of positioning availability.

- **GNSS Augmentation:** Navigation Signal L1S has sub-meter augmentation data and L6 has centimeter class augmentation data.

- **Messaging Service:** This service is available on L1S receivers. This service is planned for transmitting disaster and crisis related information to the users, for example, in earthquakes and tsunamis, terrorist attacks, and evacuation orders. For these services, seven different signals are used in four different main carrier frequencies [18], as given in Table 6.

Table 6. QZSS Signals and Service Types

	Signal	**Frequency (MHz)**	**Bandwith (MHz)**	**Service Type**
1.	L1 C/A	1575.42	30.69	Navigation
2.	L1S			Augmentation (sub-meter) and Messaging
3.	L1C			Navigation
4.	L2C	1227.6	30.69	Navigation
5.	L5	1176.45	24.9	Navigation
6.	L5S			Navigation
7.	L6	1278.75	42	Augmentation (cm class)

c. ***BEIDOU-1/COMPASS***

This program was established by the Chinese government to contruct GNSS for PNT and short message services for users anywhere and anytime in the world. As seen in Figure 7, the development of the whole system is divided into two main steps and planned in three phases [45].

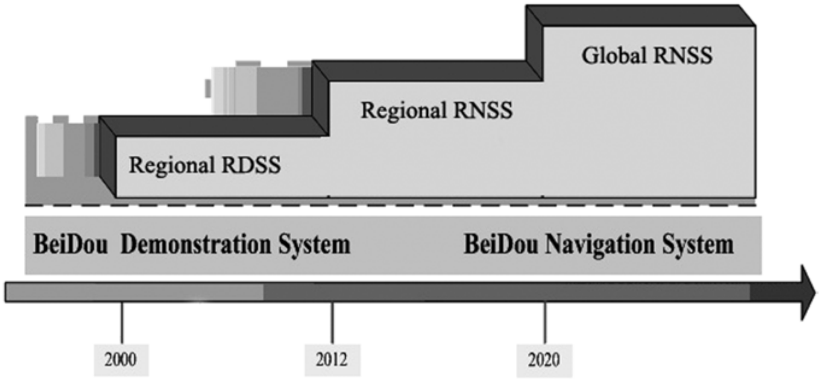

Figure 7. BEIDOU/COMPASS Timetable. Source: [45].

Regional Radio Determination Satellite Service (RDSS) is an experimental regional PNT system consisting of three satellites at GEO (80E, 110.5E, 140E), designed to be the basis for the COMPASS Navigation System. Another name for Regional RDSS is BEIDOU-1, with three satellites launched between 2000 and 2003. This system's operational area is between 70E-140E and 5N-55N. With this constellation, the system has better than 20-meter positioning accuracy [45].

In the second phase (BEIDOU-2), Radio Navigation Satellite Service (RNSS) was established at the end of 2012 by using 14 satellites. Five of the satellites are located at GEO (80E, 58.75E, 110.5E, 140E, 60E); another five of them have inclined geosynchronous orbits (IGSO), locating them at 118E and 98E with a 55-degree inclination angle. This system covers an area extending 55°S-55°N and 55°E-180°E. Regarding the system's performance, RNSS is more accurate than the previous one, with positioning accuracy of less than 10 meters, velocity measurement accuracy less than 0.2 meters per second, and timing accuracy of less than 50 nanoseconds [18].

The Global RNSS phase (COMPASS) is under construction and its expected completion is by the end of 2020. At the end of 2020, the system will have five GEO, three IGSO, and 27 MEO satellites in three types of orbits for global coverage [7], [18].

The COMPASS/BEIDOU System has two different services at the global or regional level [18]:

- **Open Service:** This service provides free positioning, velocity, and timing services for all users at anytime.
- **Authorized Service:** This service is also divided into two kinds of services, which are wide area differential service and short-message communication service. Overall, Authorized Service provides safer PNT and velocity information. For these services, signals that are used by the COMPASS/BEIDOU system are given in Table 7.

Table 7. BEIDOU Signals and Service Types

Signal	Carrier Frequency (MHz)	Bandwith (MHz)	Service Type
B1	1,575.42	1.023	Open
		2.046	Authorized
B2	1,191.795	10.23	Open
B3	1,268.52	10.23	Authorized

The ground segment of the COMPASS/BEIDOU System is planned to have control, upload, and monitor stations.

D. GNSS SYSTEMS MEASUREMENTS ERRORS

All GNSS systems have space, ground, and control segments, and these segments communicate with each other by using electromagnetic waves. Among the GNSS segments, electromagnetic (EM) waves travel millions of kilometers and pass through different mediums. This travel causes some measurement errors, but this is not the only source for the errors. There are three main sources for GNSS errors:

1. Clock-Related Errors

Precise time information is very important for measuring position in GNSS ystems. Thus, there are very precise and expensive atomic clocks on satellites. On the other hand, clocks on both the satellite and user segment drift from system time. These drifts cause measurement errors, and they can be grouped as follows [17]:

- Satellite Clock Error
- Receiver Clock Error
- Intersystem Biases
- Signal Propagation Errors
- Sagnac Effect: This is an error caused by Earth's rotation during the travel of EM waves among the satellites and the ground segment.
- Ionospheric Errors: The effect of ionosphere density on the GPS signal is not known in advance because of its regional and temporal changes.
- Troposphere Errors: These errors are a fault that is a function of air temperature, air pressure, and humidity in the air.
- Multipath Errors: These are the mistakes caused by signals from Earth, such as those from water deposits or signals reflected from buildings.

2. System Errors

- Satellite Orbital Errors (Ephemeris Errors): These are mistakes that originate from different gravitational forces on the GNSS satellites.
- Receiver Noise: This is the typical noise that can be found in all RF receiver sides and caused by antennas and cables (generally considered as white noise).

3. Intentional Error Sources

- Selective Availability: These are the errors introduced to the system in order to prevent the effectiveness of the Navigation Satellite System from being at the same level for each receiver.

- Signal Jamming: This is inntentional signal interference for GNSS signal degradation.
- Signal Spoofing: This is sending a fake signal to a receiver for spoofing. Signal Jamming and Signal Spoofing terms are related to Electronic Warfare.

E. DIFFERENTIAL NAVIGATION SATELLITE SYSTEM

Differential Navigation Satellite Systems are systems that operate with the principle of correlating errors between similar receivers. Sources of error in two receivers close to each other are almost identical. If the position of one of the receivers is fully known, error correction of the navigation satellite system can be calculated. These calculated corrections can then be applied to the other receiver to improve the performance of the measurements made. With this type of satellite system, it is possible to achieve centimeter-level accuracy [46].

Two similar receivers close to each other have the same Satellite Time Error and Controlled Access error, Ephemeris error, Ionospheric error, and Tropospheric error. The same Satellite Clock fault and Controlled Access fault through the Differential Navigation Satellite System are completely recovered while similar errors are reduced. On the other hand, different receiver noise and signal reflections are being added and increased. While the receiver noise can be reduced with a better design, the error caused by the signal reflection can be reduced by the antenna-based approach, which centers on designing antennas more sensitive to the Right-Hand Circular Polarization Signals (referred to as GNSS Polarization) than Left Hand Circular Polarization Signals. Conversely, signal reflection error can also be reduced by a receiver-based approach that increases the resolution of the receivers' code discriminator.

F. AUGMENTATION SYSTEMS

Applications of the studies on Global Navigation Satellite Systems to national and international programs are generally concentrated on the regional improvement of the satellite signal. There are three points to be considered when the desire is to improve the satellite signal.

- Reliability
- Accuracy
- Availability

Reliability is the timely notification of faulty navigation solutions to the user. Accuracy is the difference between actual values and measured navigational values. Availability means that navigation solutions can be reached whenever the user desires.

Terrestrial networks are being constructed from receiving stations in the context of studies to improve the navigation satellite signal regionally. In these stations, where geographical locations are known precisely, the error values of the signals from the satellites are calculated and a reference signal is transmitted to the region of interest to be used to increase the reliability and availability of the data.

Different solutions are used at the point of publication of the reference signals. The most important of these is the Ground Based Augmentation Systems (GBAS). These systems broadcast the reference signal to the region of interest via radio stations. These radio stations can broadcast in the Very High Frequency (VHF) or Ultra High Frequency (UHF) band. The disadvantage of these systems is that they are limited to the area where they can broadcast.

In addition to terrestrial lines and relays, SBAS, such as satellites that are orbiting at GEO or HEO, are used to provide a wider coverage area. SBAS signals are sent via special communication equipment placed on general purpose public and commercial communications satellites.

There are many completed and ongoing SBAS studies all around the world due to the low cost and faster deployment of these systems. Areas of interest for current and planned SBAS systems are highlighted in Figure 8.

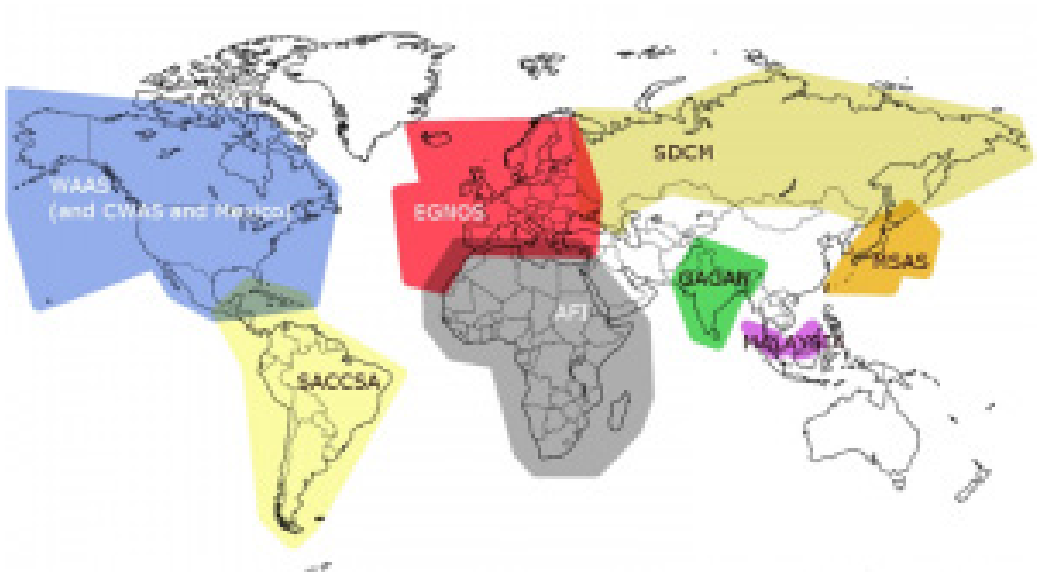

Figure 8. Current and Planned SBAS Systems. Source: [11].

1. Wide Area Augmentation System (WAAS)

The Wide Area Augmentation System (WAAS) is a system that ensures the correctness, reliability, and accessibility of location information by improving GPS performance. The most important advantage of WAAS is its low cost. Prior to WAAS, the U.S. Federal Aviation Administration (FAA) had undertaken several ground-based navigation systems.

The FAA has been maintaining many different ground-based navigation systems. It was concluded that a single system was needed to replace this collection of ground-based navigation systems and be used more cost effectively. GPS alone, however, cannot provide Category-I (CAT-I) accurate approach information to aircraft in terms of accuracy, reliability, and accessibility. Thus, WAAS was considered as a solution [47].

In WAAS implementation, reference receivers with specific distances between them are located within U.S. borders. GPS information is collected by these reference receivers and sent to a center where system faults are calculated. Through this center, the correction information is sent to two satellites in GEO, and to all users via these satellites. WAAS was fully deployed in July 2003 and put into service in December 2003 [48].

2. European Geostationary Navigation Overlay Service (EGNOS)

EGNOS, which is similar to WAAS of the United States, is a project launched by the European Space Agency, the European Union, and EUROCONTROL to provide GPS service with increased accuracy and validity. On 01 January 2009, the European Commission declared that EGNOS officially went live. The system consists of 40 Ranging and Integrity Monitoring stations (RIM), four Mission Control Centers (MCC), six Navigation Land Earth Stations (NLES), and three satellites located at GEO. Within EGNOS, Open Service was put implemented on 01 October 2009, and Safety of Life Service was activated on 02 March 2011 [18], [49].

3. GPS-Aided GEO-Augmented Navigation System (GAGAN)

As mentioned earlier, GAGAN is a satellite-based augmentation system intended to improve the performance of the NAVSTAR GPS system by sending reference signals. The GAGN project is run by the Government of India and the estimated budget is $170 million. The aim of the project is to provide navigation services at every stage of the flight in the Indian and adjacent airspace. The system consists of three geostationary satellites, 15 reference stations installed throughout India, three uplink stations, and two control centers. GAGAN is compatible with other GPS-based SBAS systems, such as WAAS, EGNOS, and MSAS as well. GAGAN was certified in December 2013 by the Directorate General of Civil Aviation (DGCA) in India [18], [50].

4. The Multi-Functional Transport Satellite (MTSAT) Satellite-Based Augmentation System (MSAS)

MSAS NAVSTAR is a satellite-based support system designed to improve positioning accuracy derived from GPS. The purpose of the system developed by Japan is to provide positioning information in the vertical and horizontal direction with a precision of 1.5 to 2 meters. The system consists of two GEO satellites whose names are MTSAT-1 (140E) and MTSAT 2 (145E), two master control stations (one at Kobe and one at Hitachioota), two monitoring and ranging stations (one in Australia and one in Hawaii), and four ground monitoring stations (at Sapporo, Tokyo, Fukuoka, and Naha). The system has been used in the aviation industry since September 2007 [18].

5. The System For Differential Corrections and Monitoring (SDCM)

SDCM, which is planned to be Russia's satellite-based augmentation system, will provide real-time differential corrections for GLONASS and GPS signals. The system consists of three GEO satellites, which are the Luch-5A (launched in 2011 at 167E), Luch-5B (launched in 2012 at 16W), and Luch-5V (launched in 2014 and placed at 95E), along with 24 reference stations in Russia and eight reference stations abroad. By the end of 2018, Russia's plan is to cover all Russian territory with L1/L5 and precise positioning service [18].

6. Other SBAS Systems

According to [11] and other public resources, there are a few SBAS studies including the Chinese Satellite Navigation Augmentation System (SNAS), and the South/Central America and the Caribbean SBAS initiative (SACCSA). In Malaysia a future SBAS system is planned, and there is an Africa-European Union strategic partnership, as well as an EGNOS extension to the Africa-Indian Ocean (AFI) Region. It is difficult, however, to find reliable information sources about these planned project during this compilation.

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III. NEED FOR A REGIONAL NAVIGATION AND TIMING SYSTEM IN TURKEY AND CURRENT CAPABILITIES

Space technologies have an important role in accelerating the development of countries and in increasing the quality of people's lives. Therefore, in the field of space sciences and space technologies, studies are rapidly increasing all over the world. Ever since the launch of the Sputnik-1 satellite, space exploration has become a world-class competition. Moreover, space science and techology has become a shining industry that provides a number of benefits to countries, especially in the area of defense. Developments in space technologies have enabled people to get to know others who inhabit the planet and the atmosphere that surrounds it. For this reason, space technology has fostered socio-economic development, new business opportunities, and fields of expertise, and ithas opened new global markets. As countries have gained political and military advantages in space, they have also gained greater prestige in the international arena.

With the use of satellites, countries have also taken great steps in the acquisition of scientific data and in matters directly related to human life. The desire to monitor the physical changes that take place on the Earth and, in particular, to overcome the difficulties in obtaining data from regions beyond the borders of one's own country, are addressed by satellite technology. In this context, earthquakes and floods, forest fires, and landslides can be monitored by satellites by developed countries. Research during space studies also contributes to the creation of many innovations that facilitate the daily life of asociety, and the findings are transformed into consumer technologies that provide additional comfort and convenience in everyday life. In this chapter, information about Turkey's space assets and space studies are introduced, and areas in which it can be developed, particularly in terms of regional navigation and timing satellite technology, are considered..

A. CURRENT CAPABILITIES

From the beginning of the Space Era, Turkey has aimed to accomplish a goal in space science and technology. As a result of this, several satellites have been owned by Turkey for years. In this section, satellites owned by Turkey are discussed.

1. Communication Satellites

As countries worldwide have been rapidly developing their space science and technology, Turkey began by using Iranian and Yugoslavian stations in 1968 to meet its communication needs from space. Subsequently, Turkey met its communications needs by renting transponders from INTELSAT satellites. TURKSAT-1B became the first Turkish-owned satellite in 1994, and its second satellite, TURKSAT-1C, went into orbit in 1996. In this section of the thesis, Turkish-owned communication satellites are introduced chronologically in three parts, which are Endof-Life Satellites, In-Orbit Satellites, and Ongoing Projects.

a. End of Life Satellites

The following paragraphs describe the earliest satellites launched by Turkey.

(1) TURKSAT 1B

Turkey's first satellite to reach orbit was TURKSAT 1B, which was launched on an Ariane 4 rocket in 1994, successfully served for 12 years between 1994 and 2006. (Its predecessor, the Turksat 1A, failed to reach orbit due to a fault in the launch vehicle.) The TURKSAT 1B satellite was developed by the French company Alcatel Alenia Space Industries and covered Turkey, Europe, and the Middle East. The location of its orbit was 31 degrees East Longitude [51].

(2) TURKSAT 1C

To serve Turkey, Europe, and the Middle East simultaneously, TURKSAT 1C launched in 10 July 1996 on an Ariane 4 rocket. Like TURKSAT 1B, TURKSAT 1C was also developed by France's Alcatel Alenia Space Industries. This satellite's orbital location was 31 degrees East Longitude during the orbital tests and shifted to 42 East Longitude. After taking over all broadcast traffic on TURKSAT 1B completely, it returned to 31 degrees East Longitude for its mission. The TURKSAT 1C satellite completed its mission on 23 September 2010 [51].

(3) TURKSAT 2A

The TURKSAT 2A Satellite was placed in the same position with the TURKSAT 1C satellite, which serves 42 degrees East Longitude. The TURKSAT 2A satellite was developed by EURASIASAT, a consortium established between Turk Telekom and French Aerospatiale. TURKSAT 2A was launched in 10 January 2001 and served for 15 years until 27 September 2016 [51].

b. On-Orbit Satellites

In the following paragraphs, the Turkish satellites currently in service are described.

(1) TURKSAT 3A

TURKSAT 3A was launched on an Ariane 5 rocket at Kourou Guyana Space Center on 13 June 2008. This satellite, which serves at 42 degrees East, has a bandwidth of 1296 MHz. Its operational life is designed as 20 years. Therefore, TURKSAT 3A has a 25 percent longer service life than previous satellites. TURKSAT 3A is currently on active duty, and it serves not only for communication but also TV broadcasting [52].

(2) TURKSAT 4A

On 7 March 2011 a contract was signed with Japanese company Mitsubishi Electric Corporation (MELCO) for the supply of TURKSAT 4A and TURKSAT 4B communication satellites. The TURKSAT 4A communication satellite was launched on 14 February 2014 on a Proton rocket from the Baykonur Space Base in Kazakhstan. The TURKSAT 4A Ku-band channel covers Turkey, North Africa, Europe, the Middle East, Asia, and sub-Saharan Africa regions. The Ka frequency band is also used on the satellite. Launching of the TURKSAT 4A satellite to replace TURKSAT 2A resulted in increased communication capacity [52].

(3) TURKSAT 4B

The TURKSAT 4B communication satellite was successfully launched on 16 October 2015 from the Baykonur Space Base in Kazakhstan. TURKSAT 4B has a bandwidth of 3400 MHz, and the satellite’s location marked the first time that Turkey used the position of 50 degrees East. TURKSAT 4B covers Turkey, Africa, Europe, the Middle East, and the west of China. In addition to TV broadcasting in the Ku frequency band, the TURKSAT 4B communication satellite is designed to provide high speed and low cost Internet access services with spot coverage in the Ka frequency band [52].

c. On-Going Projects

The TURKSAT 5A satellite is planned to be put into service in 2020 and TURKSAT 5B satellite will be put into service in 2021. It is foreseen that the TURKSAT 6A communication satellite, which will be manufactured in Turkey at the Satellite Systems Integration and Test Center (USET), will be launched into space in 2020 [53].

2. Remote Sensing Satellites

Remote sensing is a way of gathering information about location by using special detectors according to the features of the target. Remote sensing satellites are useful detectors for intelligence services to get data from contested or access denied areas. In this section, Turkey’s current and ongoing remote sensing capabilities from space are discussed.

a. BILSAT

BILSAT 1, jointly produced by TUBITAK UZAY and British Surrey Satellite Technology Limited (SSTL), was launched on 27 September 2003. The cost of the satellite is $ 13.3 million and its task life is planned as 15 years. The BILSAT project was conducted for starting, developing, and supporting small satellite technology. In 2006, the BILSAT satellite was shut down due to a malfunction in the battery cells [54].

b. RASAT

RASAT is the second remote sensing satellite owned by Turkey after BILSAT. RASAT was the first satellite designed and manufactured in Turkey. RASAT has a high-resolution optical imaging system and new modules designed and developed by Turkish engineers.

RASAT, launched from Russia on 17 August 2011, is located in a sun-synchronous circular orbit at an altitude of 700 kilometers. RASAT can take images from all over the world. It has 5-meter panchromatic and 15-meter multi-band spatial resolution using a pushbroom camera. RASAT, which has a design life of three years, completed its seventh year in orbit [55].

c. GOKTURK-1

The aim of the GOKTURK-1 program is to provide high-resolution images for military intelligence from any region in the world without a geographical restriction. At the same time, another objective of this satellite system is to support many civilian activities, such as control of forest areas, follow-up of illegal construction, damage detection as soon as possible after natural disaster, annual product detection, and production of geographical map data. In addition to these objectives, a satellite installation, integration, and test center will be established according to the international standards whereby the integration and testing of all satellites up to five tons can be carried out in Turkey.

The contract for the GOKTURK-1 project was signed on 13 July 2009 between the Turkish Ministry of Defense, the Undersecretariat for Defense Industries, and TELESPAZIO and entered into force on 19 July 2009. In the project, TELESPAZIO was the main contractor and TUSAS participated directly in the work packages for which it was responsible to TELESPAZIO. Apart from direct participation, some components of the GOKTURK-1 satellite were produced by TAI.

The GOKTURK-1 satellite was launched from the Korou Space Base on 26 December 2016 on a Vega rocket. The program cost was 250 million Euro. GOKTURK-1 is located in a sun-synchronous circular orbit at an altitude of 700 kilometers [56].

d. GOKTURK-2

The GOKTURK-2 satellite is intended to be the first national ground observation satellite designed and manufactured using TUBITAK resources. The Project Support Agreement of the GOKTURK-2 project was signed on 13 April 2007 by the Turkish

Ministry of National Defense, TUBITAK, and TUBITAK UZAY-TUSAS Joint Venture. The objectives of the GOKTURK-2 project are to develop technologically specialized manpower and infrastructure for space and satellite systems, and to meet the observation and research needs of public institutions and organizations with national capabilities.

The GOKTURK-2 satellite pre-shipment tests were completed at the TAI facilities, and the satellite was then sent to the Jiuquan Launch Center of the People's Republic of China. GOKTURK-2 was launched into space on 18 December 2012. The first signal from the satellite, which was placed into mission orbit after 12 minutes, was received after 86 minutes. The commissioning process was completed and the images taken by GOKTURK-2 satellite were then downloaded to the ground station in Ankara [57].

GOKTURK-2 is located in a sun-synchronous circular orbit at an altitude of 686 kilometers. The sensor on the satellite has 2.5-meter resolution [58].

e. GOKTURK-3

The goal of the GOKTURK-3 project is to develop an observation satellite with a Synthtetic Aperture Radar (SAR) payload that can operate continuously. This is an ongoing project carried out by the Undersecretariat for Defense Industries, and the project contract has not yet been signed.

B. NEED FOR A REGIONAL NAVIGATION AND TIMING SYSTEM IN TURKEY

Precise position information, which is the product of GNSS systems, is being used in many fields with the development of technology. Enabled by GNSS, precision-guided munitions and cruise missiles can hit their targets. In addition, unmanned aerial vehicles need GNSS systems as a key navigation aid.

Not only is its navigation feature important, but the timing function also provides critical information for military communication and link systems such as frequency hopping systems, Link-16 and Link-22. Nowadays, timing information is crucial for secure communication.

Furthermore, since the SA feature was discontinued in 2001, the error margin that could be added to these systems can cause irreparable results. All countries that do not have GNSS systems should always consider the existence of spoofing.

Currently the satellite systems owned by Turkey serve only two areas: communication and remote sensing. After achieving independence in communication and remote-sensing missions, the next critical self-sufficient mission area is PNT**.**

Because of the inherent impact on national security, most countries try to be independent in this technology. Yet, is the high cost of space-based systems pose a challenge for developing or non-space faring countries. To decrease the cost of a PNT constellation, some nations have developed regional (RNSS) rather than globally based systems. Thus, in the next chapter, a proposed RNSS aimed to provide precise PNT information for Turkey continuously is simulated.

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IV. MODELING AND SIMULATION FOR TURKEY

This chapter of the thesis applies similar architectures of the GNSS constellations presented in the literature review chapter, and evaluates their performance as a possible solution for a Turkey GNSS system. The method uses STK simulation and Dilution of Precision (DOP) as a parameter for evaluating the accuracy of the system.

A. DILUTION OF PRECISION

As mentioned in Chapter II, the performance of a GNSS is based on three factors: reliablity, accuracy, and availability. DOP gives insight to GNSS users about the accuracy of GNSS systems by showing the impact of distributed visible satellite geometry.

For accurate GNSS calculations, visible satellites should be distributed in the sky with wide angular separation. This angular separation results in low DOP value, which means the receiver can calculate its position more accurately. On the other hand, visible satellites distributed with low angular separation in the sky causes high DOP values, which means weak geometry for accurate GNSS calculations.

Mathematically, the DOP value is a ratio between two calculated standard deviations: pseudorange and a specific parameter of calculation, such as vertical, horizontal, time, and position. For example, horizontal DOP (HDOP) is the ratio between the standard deviation of pseudorange and the standard deviation of the horizontal position component of the receiver. Also there is a Geometric DOP, which includes all of the specific parameters in its calculation. According to the components of the position/time solution, there are five different kinds of DOP: Position Dilution of Precision (PDOP), Horizontal Dilution of Precision (HDOP), Vertical Dilution of Precision (VDOP), Time Dilution of Precision (TDOP), and Geometric Dilution of Precision (GDOP).

For this analysis, the descriptions of the DOP values are given in Table 8, which is taken from [59].

Table 8. DOP Value Taxonomy. Source: [59].

DOP Value	Rating	Description
1	Ideal	This is the highest confidence level to be used for applications demanding the highest possible precision at all times.
2–3	Excellent	At this confidence level, positional measurements are considered accurate enough to meet all but the most sensitive applications.
4–6	Good	This represents a level that marks the minimum appropriate for making business decisions. Positional measurements could be used to make reliable in-route navigation suggestions to the user.
7–8	Moderate	Positional measurements could be used for calculations, but the fix quality could still be improved. A more open view of the sky is recommended.
9–20	Fair	This represents a low confidence level. Positional measurements should be discarded or used only to indicate a very rough estimate of the current position.
21–50	Poor	At this level, measurements are inaccurate by as much as 300 meters with a 6-meter accurate device and should be discarded.

B. CONSTELLATION PROPOSAL

In order to obtain location information from navigation satellite systems, at least three signals must be received at the same time. Due to the fact that the user's clock is not sufficiently sensitive, in order to obtain the required time information at least four signals must be gathered from satellites at the same time. When the existing systems mentioned in the literature review section are examined, we find it is necessary to have a satellite constellation of 24 satellites in orbit in order to provide continuous coverage in the world. It is also understood that the installation and maintenance costs of such a system can be quite high.

A regional solution for Turkey can be addressed using different approaches. The first of these approaches is considered to be an independent system similar to the IRNSS architecture introduced by India.

When the number of satellites needed for an RNSS and the trajectories that can be used are taken from the technical point of view, a study conducted in 2008 designed a navigation satellite system that maximized accuracy and accessibility in a region defined in the world by using a genetic algorithm. According to this study, a four-satellite constellation is not a suitable solution for a region in the middle latitudes due to an average of three-hour unavailability periods over that region. As a result of the analysis, it was revealed that a regional positioning system that would cover a region located in the middle latitudes should have at least five satellites and at least two of these satellites should be located at GEO. This suggests that the architecture of our proposed systme should include at least five satellites in GEO and GSO orbits [16].

Although the constellation of the IRNSS satellite system is ideal for the latitudes that include India, it is not ideal for covering the latitudes of Turkey. This constellation is more suitable for the equator and areas near the equator. If the IRNSS system is applied to Turkey's geography, the inclination of the GSO orbit must be at least 40 degrees to cover middle latitudes. In this case, the satellites would spend less time over Turkey due to the symmetry of the orbiting satellite and hence more time in the Southern hemisphere. This effect can be somewhat mitigated by using an eccentric orbit (that is, QZO) with the apogee located over Turkey.

QZSS itself is not actually a fully independent regional navigation satellite system. Instead, QZSS has been proposed to strengthen and support the existing GPS system within the borders of Japan. Because GPS signals usually come with a low angle of inclination, these signals are often blocked in narrow streets and elevated spaces surrounded by buildings, and their strength is weakened. For uninterrupted signals, satellites must be more directly overhead in countries that have many tall buildings like Japan. With three satellites planned to be placed at the QZO with a special orientation, it is planned that the receivers will receive the signals more vertically and the GPS signals will be improved. Furthermore, because there is always one satellite at zenith, QZSS is very suitable in terms of GDOP efficiency for countries that are located at high latitudes like Japan and Turkey.

In satellite-based positioning systems, satellite layout is important in order to get full efficiency. When satellites are placed in the sky as wide as possible and spread out, the inefficiency due to geometric effects is also reduced. For Turkey that locatation is between 36 and 42 degrees North latitudes, and an IRNSS or QZSS architecture does not provide a favorable geometry in this case. By contrast, a more efficient geometry can be obtained by designing a constellation that accommodates the characteristics of both IRNSS and QZSS.

In order to calculate position, receivers must see at least four satellites scattered with good geometry. In this study, a combination of the IRNSS and QZSS solution and recommendations from [16] were analyzed. As a result of this, an eight satellite constellation is proposed. Constellations with various numbers of satellites can also be studied, but the solution is already known. For example, decreasing the number of satellites in the constellation will decrease the cost but increase the DOP value, which means poor accuracy. On the other hand, increasing the number of satellites in the constellation will increase the cost but decrease the DOP value. That is why an eight satellite constellation is proposed and studied as an indegeneous solution for RNSS over the land of Turkey.

For a deeper look, six of the satellites should be located at two separate QZO orbits (each of them has three satellites) so that a satellite is always located around zenith. The remaining two satellites shoud be located in GEO orbit. This satellite constellation has only one more satellite than India's IRNSS system. In addition, this constellation will be the best for a region at high latitudes such as Turkey. The proposed constellation is shown in Figure 9.

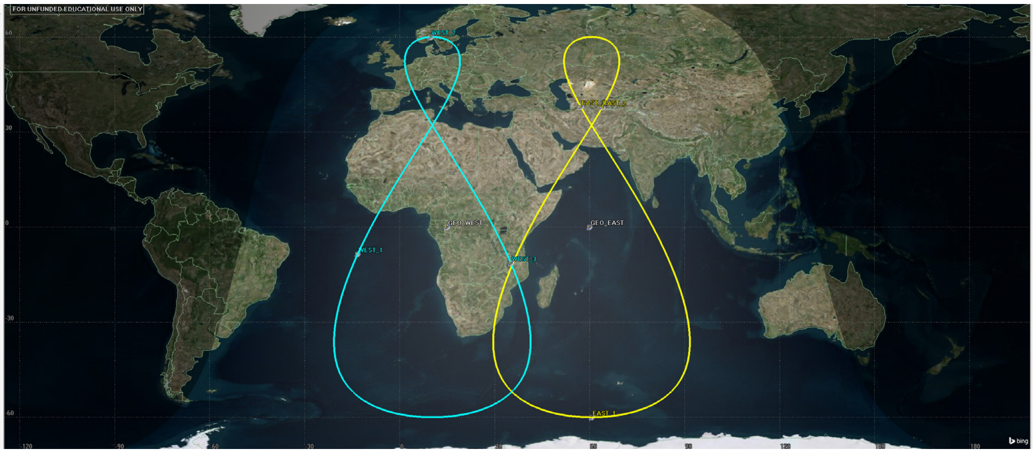

Figure 9. Proposed Constellation for Turkey

One of the critical points of the proposed architectural design is the positioning of two satellites in the GEO orbit. According to the international use of GEO orbits, Turkey can use 30, 42, and 45 degrees East longitude. The GEO satellites in the proposed constellation, however, have been deployed at 15 and 60 degrees East longitudes in order to place them as far as possible from each other and to obtain a better DOP efficiency.

The remaining six satellites are placed in QZO orbits. The important motivation for using QZO orbits is that Turkey is located at approximately the middle of the northern hemisphere. As mentioned previously, the QZO orbit is a good solution that ensures that one satellite is always at zenith. The use of two QZO orbits in this constellation ensures that two satellites are always at zenith. The eccentricity of the QZO orbit also provides slower movement when the satellites are at apogee, so access time over Turkey is increased. In addition, the three satellites have a 120-degree separation in Right Ascension of Ascending Node (RAAN) to get homogeneous separation in orbit. Technical parameters of the satellites used in the simulation are given in Table 9.

Table 9. Satellite Parameters

Satellites	**Semi-Major Axis (km)**	**Eccentricity (e)**	**Inclination (i)**	**Argument of Perigee (w)**	**Right Ascension of the Ascending Node (Ω)**	**True Anomaly (v)**
East-1	42164	0.17	60	270.067	321.255	0
East-2	42164	0.17	60	270.067	81.225	224.921
East-3	42164	0.17	60	270.067	201.225	135.082
West-1	42164	0.17	60	270.067	332.458	279.762
West-2	42164	0.17	60	270.067	92.458	178.912
West-3	42164	0.17	60	270.067	212.458	76.809
Geo_East_60	42166.3	0	0	0	230.673	0
Geo_West_15	42166.3	0	0	0	185.673	0

This constellation is proposed to provide PNT for the specific region covering Turkey. The service area is defined as shown in Figure 10. This service area extends from northwest of Iceland to northwest of Malaysia.

Figure 10. Selected Service Area for Proposed Constellation

C. STK PROGRAM

STK is a simulation program created by Analytical Graphics Inc. (AGI). Approximately 1,000 global governmental or commercial organizations and associations, such as NASA, JAXA, ESA, and Lockheed Martin use STK.

STK is an engineering software that can be used to solve complex problems related to space design and space operations, as well as muti-domain problems that include land, sea, air, space, aircraft, UAVs, and missle systems. In this thesis I used STK to model satellite constellations for space operations, to present 2D and 3D visualizations, to analyze the relationship between the area of interest and space assets, and to create graphs and reports [60].

D. RESULTS OF STK SIMULATION

The mission of this proposed constellation is to provide PNT service to public and private organizations ın Turkey and abroad, especially the Turkish Armed Forces, continuously in peace as well as in crisis and operational situations. The goal of the simulation is to model various constellations, determine whether four satellites always cover the area of interest, and estimate the resultant DOPs to predict the accuracy of position information from each constellation.

Initially I used N-Asset coverage analysis for the area of interest. N-Asset coverage analysis aims to define the number of satellites simultaneously over a region. In this analysis the average number of available assets over each grid point is calculated and analyzed. This analysis is very important for PNT systems because users always have to receive four signals from four different satellites to get accurate PNT information. I specifically used the N-Asset Coverage Figure of Merit function in STK. 2D visualization of the simulation is given in Figure 11, and graphs by latitude and longitude are given in Figure 12 and Figure 13, respectively. The number of satellites between four and eight is depicted in the Figure 11, where green indicates the maximum number of satellites available over the area of interest while yellow and red indicate the minimum number of satellites.

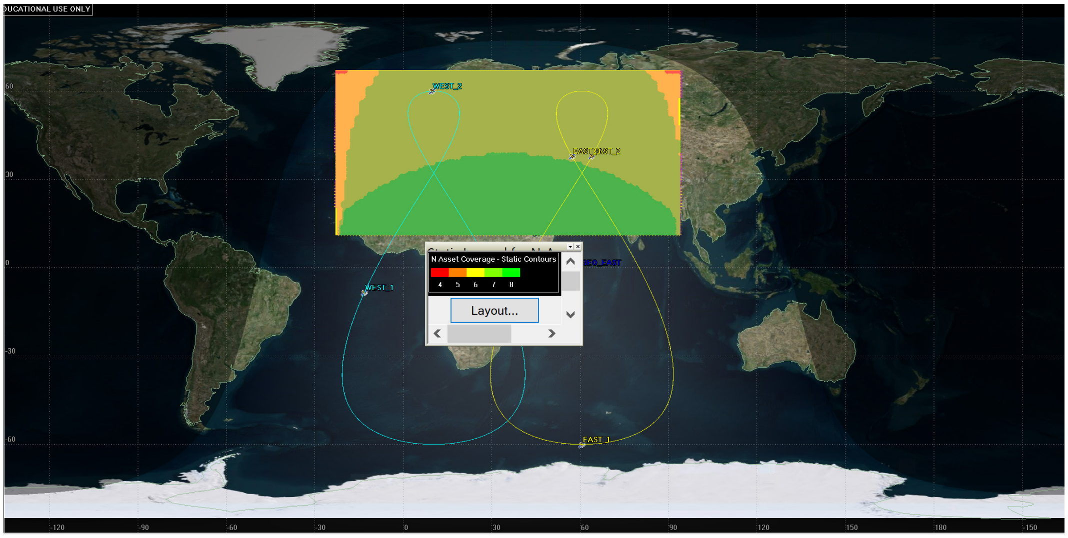

Figure 11. 2D Visualization of N-Asset Coverage Analysis

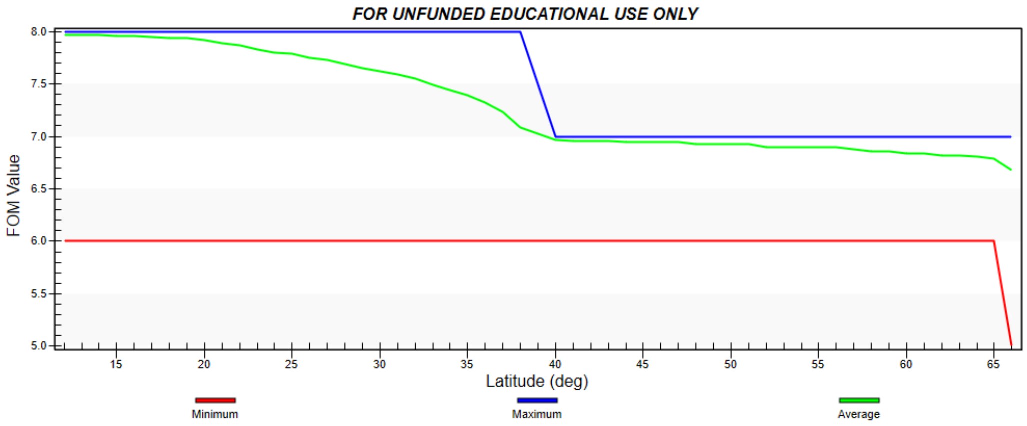

Figure 12. Value by Latitude

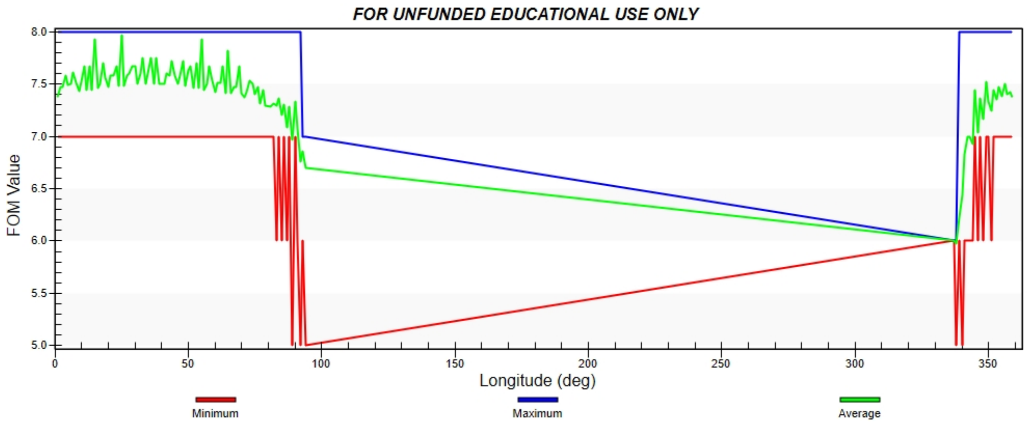

Figure 13. Value by Longitude

As seen from the preceding figures, for middle latitudes in the northern hemisphere, especially over the land of Turkey (36N-42N latitude and 26E-45E longitude), there are always at least six satellites in view. For a deeper look, seven satellites are always available for the southern part of Turkey while six satellites are always available in the northern part of Turkey. These results show that this constellation can provide four different PNT signals from four different satellites continuously; so, the first important requirement for position calculation is satisfied.

The second step is to calculate DOP values to determine the accuracy of the system. For this calculation GDOP value was calculated because it contains all of the components of individual DOPs. The program calculated the average value of GDOP over a selected period of time. The time step value selected for the simulation was 60 seconds. The 2D visualition of GDOP analysis is given in Figure 14, and the values by latitude and longitude are given in Figure 15 and Figure 16, respectively. According to the legend green areas have a lower DOP value, which gives high accuracy for navigation solutions. It is also seen that small yellow and red areas representing a higher DOP value (that is, greater than 20) are not suitable for navigation solutions.

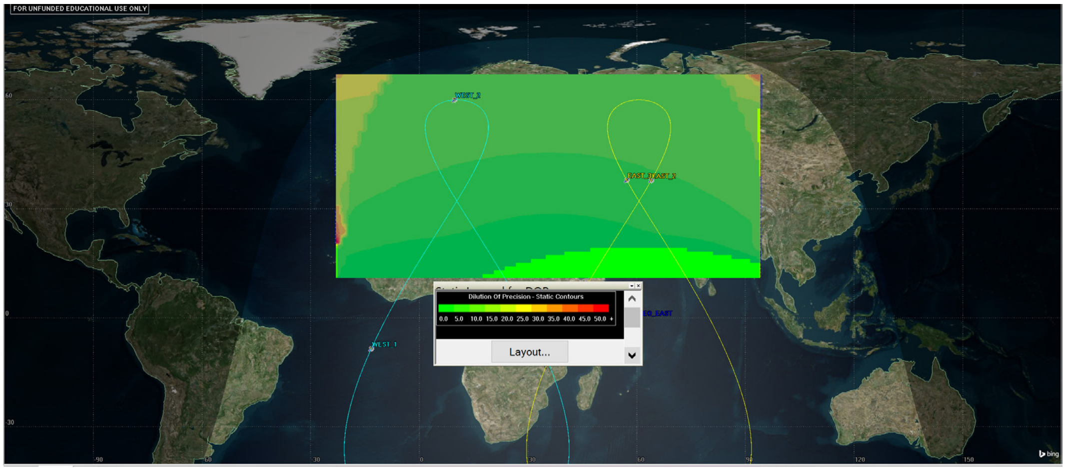

Figure 14. 2D Visualization of GDOP Analysis

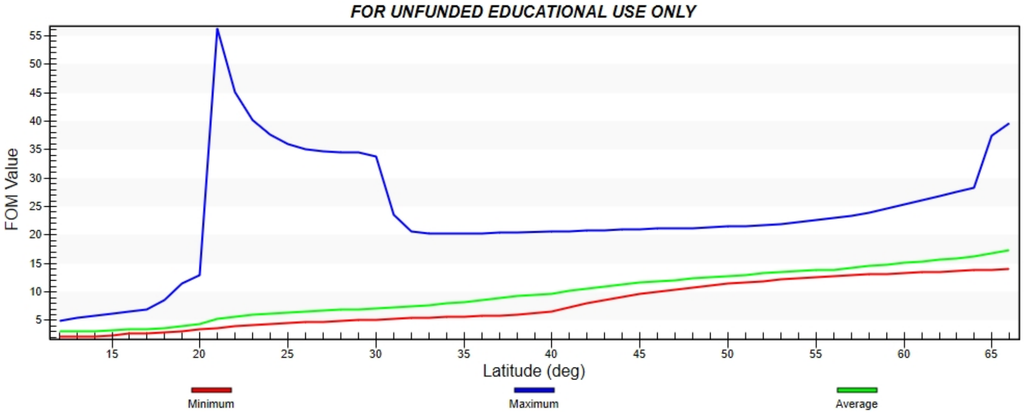

Figure 15. GDOP Values by Latitude

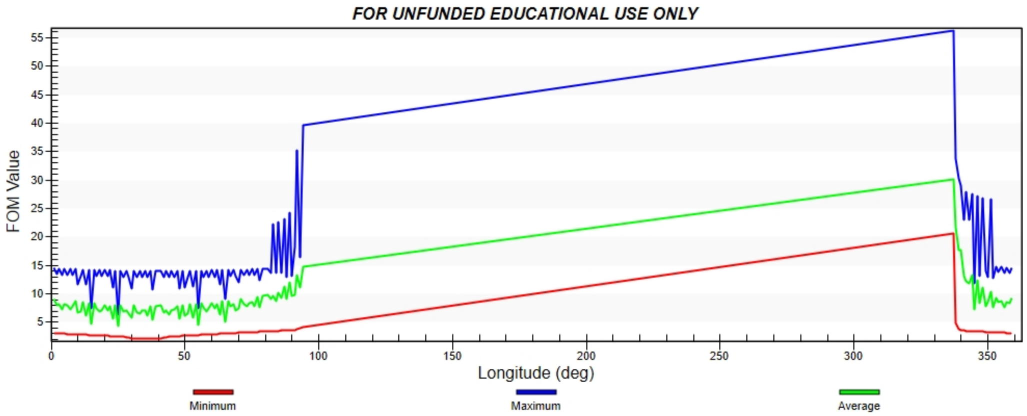

Figure 16. GDOP Values by Longitude

As seen from the preceding figures, the average GDOP values for Turkey (36N-42N latitude and 26E-45E longitude) are always around 10, which is depicted as green. Similar to the N-Asset coverage analysis, the southern part of Turkey gets lower DOP than the northern part of the country. But it is seen from these graphs that the value is never above 15. This result shows us this constellation can provide PNT service at the fair and moderate levels depending on the user's position. According to Table 8, the PNT information provided by the constellation is a rough estimate of current position. Moreover, as seen from Figure 14, the southern part of the service area gets more accurate information than the northern part.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS AND FUTURE WORK

In this study, global and regional navigation satellite systems and augmentation systems serving the Earth have been examined. Augmentation systems, which use GPS or GLONASS signals, were not evaluated or proposed since the goal of this thesis was to establish an independent PNT system for Turkey.

The result of this thesis proposes a constellation that is independent and cost effective. This constellation has eight satellites; three each in two QZO orbits and two in GEO orbits.

As detailed in the previous chapter, GDOP values ranging from 8 to 15 were obtained modeling this constellation over the land of Turkey. The confidence levels of these DOP values, however, are not sufficient to obtain precise position information. This constellation would not be appropriate for sensitive applications, such as aircraft precision approaches. Therefore, for future research, the issues discussed in this study can be improved in order to increase the DOP values and to move forward.

In the proposed model, QZO and GEO orbits are used to place eight satellites. In later studies, eight or more satellites can be analyzed by using the HEO orbit instead of QZO orbit to decrease DOP value. The effect of the increase in the number of satellites on the DOP value can also be examined. Furthermore, the use of QZO orbits in the proposed constellation allowed for the assumption that there will always be a satellite near zenith. The Digital Terrain Elevation Data (DTED) maps of Turkey and identified service areas can be gathered and used in simulation to analyze whether a satellite can be seen at zenith over mountainous areas.

It is also worth considering that in this study only the space segment of the RNSS system was investigated in the identified service area. Future work could include details of the payloads that can be used in such a system, as well as on the placement and architecture of the control stations, and features of the user segment.

B. RECOMMENDATIONS

Previous studies on RNSS and analysis done within the scope of this thesis concluded that a constellation containing a minimum of five satellites is required. To improve DOP accuracy from RNSS systems, it is necessary to increase the number of satellites. Considering the cost of a satellite is roughly estimated at $350 million, it is estimated that a cost of about $2 billion to $2.5 billion will be needed for the creation of an eight satellite RNSS architecture. This includes launch and ground segment costs and was estimated by comparing the cost of similar programs. The annual operating cost of such a system is expected to be around $150 million.

Establishing such an architecture is a time-consuming process and is not capable of responding immediately to our current needs. Instead, a more accurate strategy would be to progress gradually to this scale using a build-up approach. I propose that the following approach is more constructive:

- In the first stage, investigate interoperability conditions with an existing and operational differential satellite system.
- As a next step, develop an original satellite-based augmentation satellite system architecture.
- At the last stage, consider the experiences and changing needs to revise and define a regional navigation satellite system.

As a result, it is considered that the development of a support system that will include terrestrial stations and support satellites in the architecture, and the efforts to create a regional positioning system with the experience and infrastructure to be gained therein, will be the most appropriate approach.

Nevertheless, the most important step in the near future should be to reduce Turkey’s dependence on one source and increase our accessibility to global satellite navigation systems. For this purpose, cooperative opportunities with GLONASS and GALILEO should be investigated and navigation satellite receivers should be gradually adapted to these systems.

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   Naval Postgraduate School
   Monterey, California