ΠΑΝΕΠΙΣΤΗΜΙΟ ΔΥΤΙΚΗΣ ΑΤΤΙΚΗΣ
Τμήμα Μηχανικών Βιομηχανικής Σχεδίασης και Παραγωγής

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΙΓΑΙΟΥ
Τμήμα Ναυτιλίας και Επιχειρηματικών Υπηρεσιών

ΔΙΙΔΡΥΜΑΤΙΚΟ
ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ
«ΝΕΕΣ ΤΕΧΝΟΛΟΓΙΕΣ ΣΤΗ ΝΑΥΤΙΛΙΑ ΚΑΙ ΤΙΣ ΜΕΤΑΦΟΡΕΣ»

ΤΙΤΛΟΣ

Σχεδιαστική Επιλογή Αστερισμού Μικροδορυφόρων σε Τροχιά LEO με σκοπό την παγκόσμια κάλυψη Υπηρεσιών Επικοινωνίας και AIS στην Εμπορική Ναυτιλία

ΤΙΤΛΟΣ ΑΓΓΛΙΚΑ

Design Selection of Micro-Satellites Constellation in LEO Orbits on Purpose of Global Coverage for Communication and AIS Services in Shipping

Ονοματεπώνυμο Σπουδαστή:

Δημήτριος Νικολαΐδης

Ονοματεπώνυμο Υπεύθυνου Καθηγητή:

Ν. Νικητάκος

Γ. Μαντζούρης

Δ. Παπαχρήστος

ΔΙΑΤΡΙΒΗ

ΑΘΗΝΑ-ΟΚΤΩΒΡΙΟΣ 2020

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ΟΝΟΜΑ ΦΟΙΤΗΤΗ:

Δημήτριος Νικολαΐδης

Μεταπτυχιακή Διατριβή που υποβάλλεται στο καθηγητικό σώμα για την μερική εκπλήρωση των υποχρεώσεων απόκτησης του μεταπτυχιακού τίτλου του Διϊδρυματικού Προγράμματος Μεταπτυχιακών Σπουδών «Νέες Τεχνολογίες στη Ναυτιλία και τις Μεταφορές» του Τμήματος Ναυτιλίας και Επιχειρηματικών Υπηρεσιών του Πανεπιστημίου Αιγαίου και του Τμήματος Μηχανικών Βιομηχανικής Σχεδίασης και Παραγωγής του Πανεπιστημίου Δυτικής Αττικής.

Δήλωση συγγραφέα διπλωματικής διατριβής

Ο κάτωθι υπογεγραμμένος, **Δημήτριος Νικολαΐδης** του **Γεωργίου**, με αριθμό μητρώου **108,** φοιτητής του Διϊδρυματικού Προγράμματος Μεταπτυχιακών Σπουδών Τμήματος «Νέες Τεχνολογίες στη Ναυτιλία και τις Μεταφορές» του Τμήματος Ναυτιλίας και Επιχειρηματικών Υπηρεσιών του Πανεπιστημίου Αιγαίου και του Τμήματος Μηχανικών Βιομηχανικής Σχεδίασης και Παραγωγής του Πανεπιστημίου Δυτικής Αττικής, δηλώνω ότι: *«Είμαι συγγραφέας αυτής της μεταπτυχιακής διπλωματικής διατριβής και ότι κάθε βοήθεια την οποία είχα για την προετοιμασία της είναι πλήρως αναγνωρισμένη και αναφέρεται στην διατριβή. Επίσης έχω αναφέρει τις όποιες πηγές από τις οποίες έκανα χρήση δεδομένων, ιδεών ή λέξεων, είτε αυτές αναφέρονται ακριβώς είτε παραφρασμένες. Επίσης βεβαιώνω ότι αυτή η διατριβή προετοιμάστηκε από εμένα προσωπικά ειδικά για τη συγκεκριμένη μεταπτυχιακή διπλωματική διατριβή».*

Ο δηλών Ημερομηνία: 2020/10/26

ΣΥΝΟΨΗ

Τις δυο τελευταίες δεκαετίες, παρατηρείται μια αυξανόμενη τάση στην ανάπτυξη αστερισμών μικροδορυφόρων, ειδικά σε χαμηλές τροχιές, τις επονομαζόμενες LEO (Low Earth Orbit), μεταξύ 400 και 2.000 χιλιομέτρων. Το χαμηλό κόστος κατασκευής τους και η υψηλή αξιοπιστία των ηλεκτρονικών συστημάτων τους, τους κάνει ιδιαίτερα δημοφιλείς στην υποστήριξη πολλών εφαρμογών σε ποικίλα πεδία της οικονομίας και της άμυνας.

Σε αυτό το πλαίσιο, η παρούσα διπλωματική εργασία, αποσκοπεί στη σχεδιαστική επιλογή ενός αστερισμού μικροδορυφόρων, με στόχο την παγκόσμια κάλυψη του συστήματος AIS (Automatic Identification System) των πλοίων της εμπορικής ναυτιλίας και των επικοινωνιών αυτών. Επίσης, αναλύεται η κάλυψη (coverage) μιας περιοχής Ελληνικού ενδιαφέροντος, η οποία περιλαμβάνει την ευρύτερη περιοχή της Μεσογείου.

Αρχικά, αναγνωρίζονται οι παράγοντες προσδιορισμού της τροχιάς ενός δορυφόρου και παρουσιάζεται μια επισκόπηση των αστερισμών δορυφόρων, με έμφαση σε εφαρμογές στη ναυτιλία. Έπειτα αναλύονται οι παράγοντες που συμβάλλουν στο σχεδιασμό ενός αστερισμού μικροδορυφόρων. Στη συνέχεια εντοπίζονται τα διαδικαστικά βήματα στο σχεδιασμού ενός αστερισμού δορυφόρων, με τη δημιουργία σεναρίων των οκτώ (8), δώδεκα (12) και είκοσι τεσσάρων (24) δορυφόρων. Στην ανάπτυξη των σεναρίων των αστερισμών, χρησιμοποιήθηκε η μέθοδος Walker-delta, η οποία υπολογίζει τη μεγαλύτερη κάλυψη με τον μικρότερο αριθμό δορυφόρων. Η εξομοίωση των υποπεριπτώσεων συντελέστηκε με τη βοήθεια του προγράμματος STK (Systems Tool Kit). Τα αποτελέσματα συσχετίστηκαν μεταξύ τους, με στόχο την επιλογή του βέλτιστου συνδυασμού δορυφόρων, για την μεγαλύτερη κάλυψη και το μικρότερο revisit time.

Η σύγκριση των αποτελεσμάτων επιβεβαιώνει τη δυνατότητα επιλογής βέλτιστης απόδοσης, στο συνδυασμό των είκοσι τεσσάρων (24) δορυφόρων, αλλά και την πολύ ικανοποιητική απόδοση των σεναρίων των δώδεκα (12) και των οκτώ (8) δορυφόρων, στο ύψος των 1350 χλμ., με inclination 45°, αναλόγως των

απαιτήσεων της αποστολής. Τέλος, επισημαίνεται η στρατηγική αξία ενός αστερισμού μικροδορυφόρων, τόσο στο εμπορικό όσο και στον αμυντικό πεδίο, για μικρές χώρες όπως η Ελλάδα.

SYNOPSIS

Last two decades, the trend for microsatellite constellations has been growing, especially in LEO orbits, to support a plethora of applications in various domains. At the same time, the increasing reliability and the use of low-cost (COTS-commercial off-the-shelf) of electronic equipment, in conjunction with the commercialization of space exploration, give an unprecedented momentum to the deployment of mega-constellations.

In this ambit, the scope of this dissertation is to identify a design selection of satellite constellation, to support the AIS system for global and specific (Hellenic) region coverage, including the Mediterranean, mainly of commercial vessels. Initially, it has been detected the factors of orbit definition and its characteristics. Then, it is presented a review of satellite constellations, with an emphasis on shipping applications. Steps of design constellation have been identified, to design and simulate the scenarios of eight (8), twelve (12), and twenty-four (24) satellites. Walker-delta method has been used, as the most symmetric and optimum algorithm, for maximum coverage and the minimum number of satellites. Then, with the help of the STK program, simulations of subclasses have been analyzed and the results are related between themselves, to isolate the best performance of the scenarios.

The comparison of the results confirmed that the scenario of twenty-four satellites can support the best performance for coverage, from 1350 km and inclination of 45°. At the same time, the scenario of twelve satellites, gives satisfactory results, for both, global and specific regions (Hellenic).

Finally, the strategic value of microsatellite constellations, especially for small countries like Greece, has been detected.

Keywords: LEO Orbits-Space based AIS - Satellite constellation - Earth Coverage - Revisit time.

Dedication…

To my lovely wife Panagiota, who supported me in all my efforts and inspired me to the journey of our life.

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ACRONYMS

AAR - Area Access Rate

ACR - Area Coverage Rate

AIS - Automatic Identification System

COE - Classical Orbital Elements

CNES - Centre National d'Etudes Spatiales

DoD – Department of Defense

EMSA - European Maritime Safety Agency

ESA – European Space Agency

FA - Footprint Area

FOV – Field of View

GHG - Greenhouse Gas

GLONASS - Global Navigation Satellite System

GPS - Global Positioning System

GT - Gross Tonnage

IAA - Instantaneous Access Area

IMO - International Maritime Organization

IoT - Internet of Things

ISS - International Space Station

LEO - Low Earth Orbit

LDR Low Data Rate

M3MSat - Maritime Monitoring and Messaging Microsatellite

PNT – Position Navigation Timing

RAAN - Right Ascension of the Ascending Node

RLV - Reusable Launch Vehicles

RMT - Review of Maritime Transport

SAC-C - Satelite de Aplicanciones Cientificas-C

SAR – Synthetic Aperture Radar

SOLAS - Safety of Life at Sea

STK – Systems Tool Kit

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Chapter 1

SATELLITES' APPLICATIONS

1.1 Wide Range of Satellites' Applications

Since the dawn of the space era, October 1957, when the first artificial satellite – Sputnik – was placed into orbit, thousands of satellites have been launched into Earth's orbit, accomplishing various applications, supporting various domains of the global economy. Depending on their missions, satellites orbiting between 300 and 42.000 kilometers around Earth in combined planes, provide services like communication and TV programs between distant places, helping navigation of cars, ships and planes on Earth, observing the surface and sea, monitoring the atmosphere and predicting the weather on Earth.

Most of the realized satellites' unique attributes over the years, indicated four general areas of the most common space missions. These areas are Communications, Remote sensing, Science and exploration, and Navigation.

Communication is one of the most important factors in our life. The contribution of communication systems in international relations plays a fundamental role in economic growth and global security. Live TV broadcasts by satellite to distant areas of the globe, workers around the world can stay in constant contact with their home offices and military commanders rely on space probes to communicate with forces deployed worldwide (Sellers, 2005).

The mission of Remote-sensing satellites is to collect information about the nature and condition of Earth's land, sea and, atmosphere. Equipped with modern instruments, like sensitive and state-of-the-art sensors, they can "see" a wide area on the earth's surface, and report very fine details about the weather, the terrain, the underground and, the environment. Using the specific spectrum of electromagnetic radiation can show what objects are visible, such as clouds, hills, lakes, ships, vehicles, and people. Besides, military remote-sensing technology, offer great capabilities to detect forces, movements, troops, missiles launches, and strategic nuclear forces. Moreover, with the help of remote-satellites, we can identify and spot the best places for drilling oil or water and to better manage the earth’s scarce resources. As well as, weather forecasts by using satellites, contribute to the full for agriculture, transportation and to mitigate the consequences of natural disasters.

Another important domain, in which satellites contribute is Navigation. The American GPS (Global Positioning System) system and the similar Russian GLONASS (Global Navigation Satellite System), can determine where you are and where you are going, affecting all human activities. Although GPS has been developed for military use, today the system offers incredible civilian applications, decreasing the cost of transportation and increasing safety. Aviation, shipping, and driving are more efficient and safer than before. Everyone can now have any information needed to travel to a strange new city or hike a mountain or navigate by boat (Sellers, 2005).

The fourth domain, Science and Exploration, reveals the ardent passion of humans to explore not only our planet but also other planets, with the purpose to answer various scientific questions. Dozens of satellites have been launched for purely scientific purposes since the 70s. In the 1960s and 1970s, during superpowers competition, many space probes have orbited planets and some of them have also landed, to explore them. Scientific advances in exploration, material processing and, environmental observation, have proved the unique contribution of satellites to the global economy.

At present, more than two and a half thousand application satellites are in low, medium, or geosynchronous orbits, providing one or more types of commercial and military services.

1.2 Burgeoning Space Economy

The wide range of satellite applications, covers a great spectrum of the global economy, providing crucial services to society. Most of those applications have been driven by national and military utility, such as communication, position, navigation, and timing (PNT) systems. Opportunities for economic growth, have emerged through new business models and technological advancements due to the development of satellites.

So far, more than 8.950 satellites are placed in orbit, and more than 16.000 small satellites are expected to be launched by 2030, underling the importance of them in the global economy (Schingler, 2020). Since the 1980s, GPS satellites have helped generate benefits in the economy, nearly $1.4 trillion. Nowadays, two major trends lead to the tremendous development of satellites. The first one is the reducing cost to reach space, by offering launch capacity as low as $5000 per kilo, a 75% reduction in price as it was 10 years ago. The second trend considers the way we are building satellites. Today satellites are smaller, cheaper, and take a shorter time to be placed in orbit. The older satellites have been launched in space for so many years that their technology has become obsolete (Schingler, 2020).

At the same time, the commercialization of space exploration gives a large momentum to the space race and creates newcomers to be enabled to international efforts for investment in the space business. Commercial companies can do quicker and easier things than governments can. They have a better quicker decision making cycle, to plan, design, and work on projects (Cabana, 2020). Both, governments and private companies, have started to invest a huge amount of money in the space economy. Recently, Space X private company in collaboration with NASA launched and docked the first commercial spaceship to ISS (International Space Station).

Space launches and payloads are expensive because design, development, fabrication, testing, and operation are very labor-intensive. Also, labor cost is a dominant factor in space design and implementation (James R. Wertz, 2015). The high cost can be reduced by developing a viable strategy of using reusable launch vehicles (RLV) that would permit achieving low-cost flights to LEO (Low Earth Orbit).

The plethora of satellite applications, perceived as a multiplier to the growth of interdependence economies, to every domain of our life and especially to international transportations on land, air, and sea. The demands and needs of the placeholders, drive the progress of the systems and services.

The space economy has topped 415 $ billion and within the next 20 years, is expected to fund 1-3 $ trillion. Public and private companies are producing services and products, ranging from communications to manned spaceflight to Mars (Center for Innovation and Education, 2019).

1.3 Satellites for Maritime Applications

Placeholders, such as shipowners and insurance brokers, invested in applications of space technology, to alleviate the problems of distress alerting, search and rescue, and losses due to collisions, groundings and, heavy weather damage. Communications, navigation, distress alerting, search and rescue, were the four functional areas, in which satellite services support to the full. Primarily, communication and navigation satellites satisfied the requirements and alleviated the deficiencies (Baker, 1973). By the end of 1980, almost 14.000 large ships (greater than 10000 tons) were in service, of which 70% were at sea at any given time. Those ships carried about 80% of that time world ocean-going trade, playing a significant role in the global economy.

The use of satellite facilities reduced delay times of communications systems of that time and examined the limitations of ground navigation systems, while at the same time increased the accuracy of shipping.

Nowadays, more than 92.295 ships are traveling around the world, increasing the need for communication, navigation, and monitoring. Contemporary satellites offer many services to ships. The GPS supports safer navigation and at the same time, the Inmarsat system supports communication demands and search and rescue services. Inmarsat’s Fleet Data platform extracts the data from onboard sensors and uploads it to a secure central cloud-based database for easy access with no additional airtime cost (Anon., 2020). METEO satellites help ships to avoid bad weather conditions, reducing damages and insurance rates.

Further, digitalization and automation are transforming the shipping sector and requiring new skills. The latest technologies provide new opportunities to achieve greater sustainability in shipping and ports, as well as enhanced performance and efficiency. Digitalization and joint collaborative platforms and solutions enabled by new technologies and innovations, including block-chain, are being increasingly used by the shipping industry, transforming business and partnership models.

The aim is to promote efficient and secure trade, including by offering greater supply-chain visibility and the use of electronic documents, ultimately benefitting customers who rely on shipping industry services. Importantly, autonomous ships, also known as maritime autonomous surface ships, may soon become a reality, holding out the promise of enhanced safety and cost savings by removing the human element from certain operations (Development, 2020).

Moreover, global maritime security is challenged. The protection of critical maritime infrastructure, the counter of piracy, the cross-border illegal activities, are some of the domains that need to be addressed. Satellites can provide communication, traffic monitoring, and imagery services, to support activities and safety in the operational and tactical field of the maritime environment. At the same time, a satellite constellation of microsatellites or pico-satellites could improve the ability to exchanging information, create better situational awareness, ship owners, and friendly forces to support their operations (Georgios Mantzouris, 2015).

The upcoming IoT (Internet of Things), in close future, will incorporate new technologies, including onboard sensors, to facilitate the demand of shipping companies to monitor, control, and leading their fleets for safer operations. Transmitting information, from ships entering ports and managing flows of vessels, will be relaying via satellites at the same time at operations centers of shipping companies.

As the shipping industry embraces digitalization and automation, new and higher skills will be required from seafarers, according to the new redefined roles they will need to assume, both onboard and ashore, to ensure the safety of vessels and efficiency of operations (Development, 2020). The integration of countless onboard sensors will demand a mega-constellation of satellites, to cover the globe entirely.

1.4 Role of Shipping in the Global Economy

Generally, shipping plays an important role in the world trade and development process. Over the last fifty years, seaborne trade carries the vast majority of international trade. Especially, in developing countries this volume trade ranging between 80 and 90 percent, while in terms of global trade value, the shipping shares lower with various estimates around 60% to 70%. Although air transport is on the rise, regional and world trade leave limited space for air and land transport, as a matter of much chipper transport rates (Development, 2018).

In the last 30 years, globalization grew world trade faster than its wealth-creating capabilities. Manufacturers have been deconstructing the global value chain for goods to optimize profitability through labor cost reductions and technology-driven productivity gains. The key has been to retain high-value activities for educated, high-cost labor in developed countries, moving low-value activities to countries where labor costs are low. This takes advantage of economies of scale in maritime transportation, deregulation in landside transport, financial services and telecommunications, and the informational advantages granted by the Internet to generate wealth for shareholders and owners (Development, 2018, pg 56).

At the same time, technological developments of the past 50 years in shipping, are reflected in fleet development trends. Different ways in operations, changes in ship size, and transformation in dry bulk and tanker shipping are some of the distinct trends. Also, state-of-the-art technologies, contributes to low shipping cost rate, the safety of navigation, and more efficient services, such as speed and cargo damage, lowering the risk of uncertainties. Moreover, alternative fuels to substitute traditional fossil fuels on purpose to alleviate the environment from devastating air pollution, autonomous vessel technology to decrease human factor of creating accidents, 3-D printing application to reduce the need for transport of basic manufacturing parts, better management of port traffic using the Internet of Things, are some of the benefits which new technology already affecting international shipping (Development, 2018, pg 58).

The rapid growth in digitalization will impact complex maritime businesses, where multiple players from various countries participate in. Efforts will focus on strong maritime transports, built climate resilience by minimizing GHG emissions and, also focus on technological developments, such as cargo tracking and artificial intelligence. Moreover, monitoring, reporting, and analyzing data for shipping, are all essential in the globalized business environment. A high concern must be given by policymakers in sustainability, supply chain security, climate change mitigation, and adaptation, to cope with challenges in global markets (Development, 2018, pg 75-78).

Urbanization, growth of population, and rising income will continue to drive growth in demand for transport, and demand for shipping. As the shipping industry embraces digitalization and automation, new and higher skills will be required from seafarers, according to the new redefined roles they will need to assume, both onboard and ashore, to ensure the safety of vessels and efficiency of operations (Development, 2020). Geopolitical changes and ongoing political global realignment will reshape our world, rapidly. Decisions to be taken are more crucial than ever, especially to the development of the shipping industry in the new era.

1.5 The Function of the AIS System

In 2002 IMO Convention for the Safety Of Life At Sea (SOLAS), went global the mandate that, commercial vessels and passenger ships over 300 GT should equip with Class-A AIS transceivers onboard. Since then, more than 100.000 ships affected by the time, taking into account that the cost of transceivers has fallen and both compulsory and voluntary adoption has increased (Bhattacharjee, 2019). The system was designed for terrestrial maritime navigation and safety at sea and provides automatic scheduling of transmissions on the VHF frequency bands, between many AIS stations within a nominal range of 40 nautical miles of each other.

The Automatic Identification System (AIS) is a worldwide automatic positioning system, relying on fitting small transponders to vessels that transmit signals. This informs other vessels and shore stations, in the proximity of 20-40 miles with the AIS system, to the presence of other vessels. In its early years, the primary use of AIS was as a ship-to-ship anti-collision system, for use in poor visibility and at night, in support of radar and conventional watch keeping. Over time the amount of information that could be transmitted in the VHF signal grew and its usefulness increased (Anon., n.d.).

The position information is supplemented with additional information about the vessel. The signals and accompanying information can then be received by any vessel, land station, or satellite fitted with an AIS receiver and is then typically displayed on a screen, using interactive chart-plotting software (Bhattacharjee, 2019).

There is no perfect vessel tracking system, but AIS is becoming increasingly effective as accuracy and refresh rates get even better. Its ability to interface with other detection sources makes it an important component of integrated navigation and warning systems, and the addition of supplementary environmental and situational data makes it yet more versatile. It is worth saying that, the AIS is one of the most valuable information sources, available for anyone involved in the maritime sector (Anon., 2020).

There are two classes of AIS transponders: A and B. Broadly speaking, the higher specification class A is mandated for commercial vessels, while the lower specification class B, is intended for smaller, mostly leisure, vessels. Capabilities and prices vary greatly between the two classes.

Class A provides three types of information: Fixed information which must be only changed if the ship changes its name or the type of it. This fixed or static information includes data such as:

- MMSI (Maritime Mobile Service Identity)
- Call sign and name of the vessel
- IMO Number
- Length and beam
- Type of Ship
- Location of Position-fixing antennal

The second type of information is the Dynamic, which, apart from navigational status information, is automatically updated from the ship sensors connected to AIS. This type includes:

- Ship’s position with accuracy indication and integrity status
- Position time stamp in UTC
- Course over ground (COG)
- Speed over ground (SOG)
- Heading
- Navigational status (e.g. underway by engines, at anchor, engaged in fishing, etc.)
- Rate of turn (ROT)

The third type of information is Voyage-related information, which might need to be manually entered and updated. This type includes:

- Ship’s draught
- Hazardous cargo (type) (e.g. DG (Dangerous goods), HS (Harmful substances) or MP (Marine pollutants)
- Destination and ETA
- Route plan (waypoints) (at the discretion of the master)

The Class B transponders transmit only static information every six minutes. This type includes:

- MMSI (Maritime Mobile Service Identity)
- Call sign and name of the vessel
- Length and beam
- Type of vessel

Although, the initial purpose of AIS was to reduce the risk of vessels colliding with each other in poor visibility, the combination of space-based AIS system, allowing near-global coverage, to monitor individuals or groups of vessels, or volumes of traffic in certain areas, like ports or congested straits. In that way, ship owners and operators can manage and monitor their fleets, as well as port managers and service providers, government agencies, maritime security providers, and other maritime professionals.

Over the years, AIS evolution from a simple collision-avoidance system is truly remarkable. AIS today provides anyone who wants to see it with the most complete view available of the activity that takes place 24/7/365 on the world’s oceans, seas, and inland waterways, together with a treasure trove of information on the size, type, and often cargoes of the vessels themselves (Anon., n.d.).

However, AIS data can be used for many applications; it can be used to examine global, regional, or local trade patterns, traffic patterns between port pairs, within a port, and the like for port managers. It can be used for evaluating trade lanes against other uses (like fishing vessels) or overlaid on other ‘big data’ sources (like marine mammal migratory and feeding patterns for the designation of traffic lanes and marine protected areas). While the availability of AIS and the use of predictive analytics on ‘big data’ are technologies, they will also change the way that the shipping industry, ports, and governments assess the impact of other trends, like sea-level rise, Arctic transit, and climate change, and make policies for the future that will affect all RMT readers.

AIS technologies in conjunction with the use of predictive analytics have enabled many countries to contemplate new shipping service opportunities and make strategic investments in trade-serving infrastructure. Since the mid-2000s suitably equipped low earth orbit (LEO) satellites have been able to pick up and decode the signals directly from the vessels themselves, and re-transmit the data back to receiving earth stations connected to the internet. The coverage offered by space-based AIS providers is continually improving and data accuracy is already very good. However, orbit patterns and the need to download and process the data before it can be made available to service providers, means that there is a latency between the time of the collection of a position report and its availability via AIS services (Anon., n.d.).

In the same ambit, ESA is promoting a European-based SAT-AIS system-named telecom Artes 4 program- in collaboration with the European Maritime Safety Agency (EMSA). The system will increase the coverage and effectiveness of programs such as SafeSeaNet. The system incorporates the capability to track vessels beyond coastal areas that are equipped with AIS tracking devices, giving the capability to overcome terrestrial coverage limitations, providing AIS services at any given area on earth. Many users of such a system have been identified, among them are maritime security services for vessel traffic management and support of safety (Agency, 2020).

The great challenge for satellite operators is to develop a constellation of satellites, on purpose to build a maximum coverage volume monitoring thousands of square kilometers of ocean. Building any constellation of satellites is a very demanding process. Combinations of specific planes, inclinations, and altitudes, must be traded, to identify the best coverage for specific areas or global coverage. There isn't only one solution, to fulfill the demands and needs of placeholders. The most efficient and the cheapest of all will prevail in the end.

1.6 Satellite Constellation Necessity

The fundamental advantage of a single satellite is the reduced cost due to minimized design demands. A single satellite has one power system, one attitude control system, and requires a single launch vehicle to be put into orbit. On the other hand, a system of satellites does not necessarily communicate between them or a constellation of satellites may provide better coverage, higher reliability if a satellite is lost and finally greater survivability. Continues coverage of the earth for communication or observation, varying with geometries for navigation, altitude, and inclination of the orbit. To meet budget limits, placeholders trade-off between a single large and expensive satellite versus a constellation of smaller and simpler satellites (James R. Wertz, 2015.).

Taking into account that, today small satellites have become more capable via miniaturized electronics and on-board processors, manufacturing small low-cost satellites, frequently called SmallSats, is the trend of future space systems evolution. The integration of the upcoming IoT (Internet of Things) is still needed much more work to be done, on purpose to prevail on the Planet. A mega constellation of satellites is necessary to support the function of IoT covering entirely the Earth.

A great example of a satellite constellation structure is GPS (Global Positioning System). The GPS consists of several satellites orbiting approximately 20.000 Km height, providing navigation services around the world to countless users, such as cars, planes, ships, individuals, etc. These satellites can support global coverage, between latitudes 70° to -70° were taking place the vast majority of human activities. Similar to GPS is the Russian GLONASS, Chinese DEIDU, European GALILEO, Globalstar, Iridium, etc.

The problem of designing a constellation exhibits a lot of parameters with many possible combinations: total number of satellites, orbital parameters of each satellite, number of orbital planes, number of satellites in each plane, spacings between satellites of each plane, spacings between orbital planes, and relative phasings between consecutive orbital planes. (ERICK LANSARD, 1998).

The notion of coverage is strictly connected with satellite constellation, on purpose to offer services for continuous communication or observation of a specific point or area on the earth, or between different points at the same time.

1.7 Aim and Objectives

Having mentioned the vital role of shipping in the global economy in conjunction with burgeoning space development, a wide range of maritime applications using satellite services contribute to the global maritime industry. In this context, taking into account the fundamental function of the AIS for ships, we proposed to create a constellation of satellites in LEO orbits, to support AIS services to cover as much as the possible area around the globe. To achieve this goal, we proposed three (3) case studies using eight (8), twelve (12), and twenty-four (24) satellites in various combinations of altitude, planes, and inclinations. By using the program STK of AGI company, we will calculate the volume of coverage of each constellation for the designated area of interest. Then we will calculate the revisit time of any grid point of the geographical area. In the end, we will compare the results on purpose to decide which constellation fulfills our needs for better coverage, and revisit time, to support the AIS system.

Also, to support our main scope, we will review existing constellations and will identify, which factors and how affecting constellation. Next, we will define parameters to the trade-off between scenario options, to build constellations for our case studies. We will also review different types of orbits and fundamental elements of orbit. Then, we will define the design process of a constellation and which of the fundamental elements of orbits affect the design.

Finally, we will compare the results to relate the operational options, to support communications and the function of the AIS system in the maritime economy. In the end, we will designate some strategic options of using constellations in LEO orbits, as well as in shipping and defense, in particular for the Hellenic Region.

Chapter 2

ORBITAL PRINCIPLES AND ORBIT ELEMENTS AND GEOMETRY

2.1. Different Types of Orbits

The satellite revolves around the center of the earth in either a nominal circle or a nominal ellipse. The nominal shape is characterized by the eccentricity, which is zero for a circle and positive for an ellipse. The circle or ellipse is only nominally the motion because it is perturbed by the non-spherical shape of the earth, local variations in the earth's density, the gravitational pull of other heavenly bodies, and other effects. The satellite's path lies in a plane that contains the center of the earth. This plane makes an angle with the earth's equatorial plane, called the inclination angle, which stays nominally constant. The highest latitude that the satellite reaches in its orbit is equal to the inclination angle. Another aspect of the orbit is its period, which along with eccentricity determines its altitude profile. Yet another aspect, although dependent on the others, is the speed variation over the orbit, and a satellite in elliptical orbit will move faster while it is near the earth and more slowly while it is far away (Braun, 2012).

The choice of an orbit depends on the nature of the mission, the acceptable interference, and the performance of the launchers. The most favorable orbits are as follows:

➢ Geostationary Orbit (GEO): The GEO or GSO (Ground Stationary Orbit) is by far the most popular orbit for communications satellites. The satellite revolves in a circle in the equatorial plane at a nominal distance of 36.000 Km, at a stable point that maintains the satellite at a fixed position in the sky. The communications' coverage area of a GEO satellite is in the mid-latitudes (Braun, 2012).

➢ Low-Earth Orbit (LEO): The altitude of the orbit is between 600 km and 1500 km, and its orbital period is a little over an hour and a half. The orbit is circular.

The altitude of the satellite is constant and equal to several hundreds of kilometers. With near 90° inclination, this type of orbit guarantees worldwide long term coverage as a result of the combined motion of the satellite and earth rotation, A constellation of several tens of satellites in low altitude (e.g. IRIDIUM with 66 satellites at 780 km) circular orbits can provide worldwide real-time communication. Non-polar orbits with less than 90° inclination, can also be envisaged. For instance, the GLOBALSTAR constellation incorporates 48 satellites at 1414 km with a 52° inclination.

- Highly Elliptical Orbit (HEO): HEO in which the apogee’s altitude is much higher than the perigee’s. The satellite moves very fast near perigee and relatively slowly near apogee. HEOs generally incline 63.4° because there the orbit is the most stable for the least station-keeping fuel. One type of HEO is the Molniya orbit, which has a period of about 12 h. The exact altitudes of apogee and perigee are not defined but for the original Molniya orbit of the former USSR, the altitudes were about 39.000 and 1.000 km, respectively. Another type of HEO is the tundra orbit, which has a period of about 24 h. For both these orbits, when the satellite is near apogee it seems to hang high in the sky in about the same place for 2/3 of the orbital period (Gerard Maral, 2009).

- Circular medium earth orbits (MEO), also called intermediate circular orbits (ICO), has an altitude between 5.000 and 12.000 km and an inclination of about 50°. The period is 6 hours. With constellations of about 10 to 15 satellites, continuous coverage of the world is guaranteed, allowing worldwide real-time communications. A planned system of this kind was the ICO system (which emerged from Project 21 of INMARSAT but was not implemented) with a constellation of 10 satellites in two planes at 45° inclination (Gerard Maral, 2009).

- Circular orbits with zero inclination (equatorial orbits). The most popular is the geostationary satellite orbit; the satellite orbits around the earth in the equatorial plane according to the earth rotation at an altitude of 35.786 km. The period is equal to that of the rotation of the earth. The satellite thus appears as a point fixed in the sky and ensures continuous operation as a radio relay in real-time for the area of visibility of the satellite (43% of the earth’s surface). — Hybrid systems.

Some systems may include combinations of orbits with circular and elliptical orbits. Such a design was envisaged for the ELLIPSO system (Braun, 2012).

- Polar Orbits are orbits with an inclination of 90° which would pass over the Earth’s poles each orbit. Many orbits with inclinations near 90° which pass over earth’s higher latitudes are also called polar orbits. The benefit of such orbit, besides being able to view the higher latitudes, comes from the fact that the orbital plane is fixed and the earth rotates continuously beneath this plane. This type of orbit is used by satellites gathering information about the earth's surface and environment and resources (Bruce A. Campbell and Samuel Walter McCandless, 1996). Figure 3 depicts most types of orbits by Inclination, shape, and altitude.

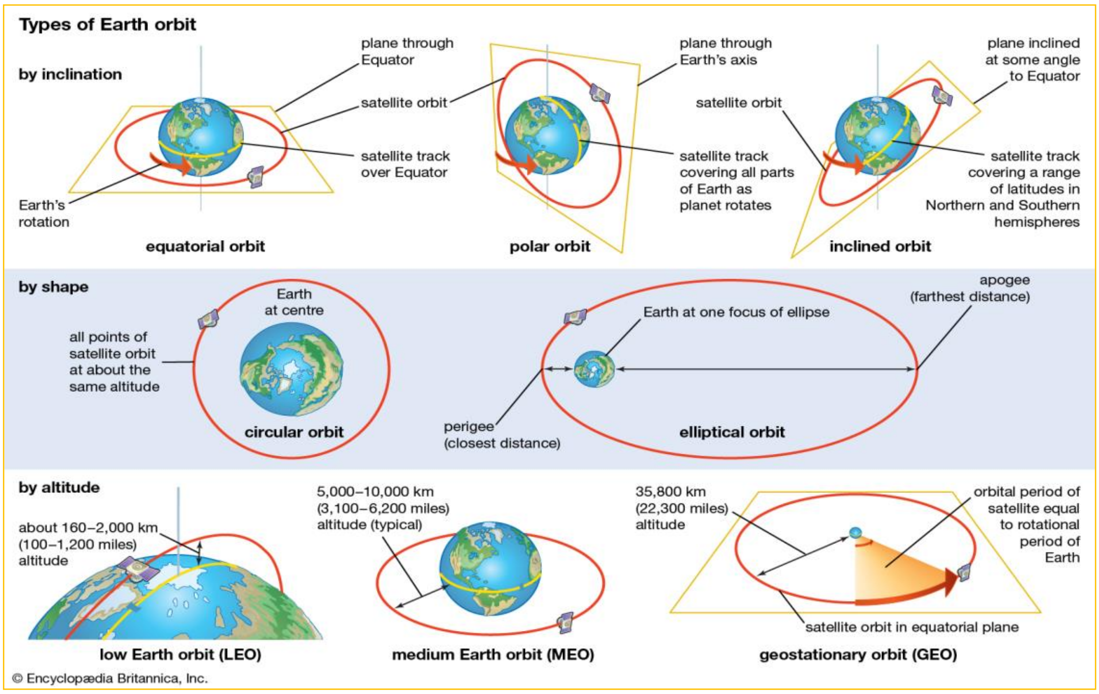


Figure 1: Different Types of Orbits by Inclination, Shape, and Altitude (source: https://www.britannica.com/science/space-exploration/Space-applications

2.2. Fundamental Elements of a Satellite Orbit

Having described various types of orbits in the previous paragraph, it is necessary to define and analyze orbits and their properties, to better understand the geometry of orbits. Predicting the motion of satellites orbiting Earth can be counted on Keplerian Laws.

The characteristics of satellite orbits vary to the shape, altitude, and plane of the orbit. The orbit is the trajectory followed by the satellite. The trajectory is within a plane and shaped like an ellipse with a maximum extension at the apogee and a minimum at the perigee. The satellite moves more slowly in its trajectory as the distance from the earth increases (Gerard Maral, 2009).

Using gravitational theory and his laws of mechanics, Newton was able to derive Kepler's three laws of planetary motion. These laws apply to any two-point masses moving under their mutual gravitational attraction. These three laws derive by Newton are (Sellers, Understanding Space-An introduction to Astronautics, 2005):

First Law: If two objects in space interact gravitationally, each will describe an orbit that is a conic section with the center of mass at one focus. If the bodies are permanently associated, their orbits will be ellipses; if not, their orbits will be hyperbolas.

Second Law: If two objects in space interact gravitationally, a line joining those sweeps out equal areas in equal intervals of time.

Third law: If two objects in space revolve around each other due to their mutual gravitational attraction, the sum of their masses multiplied by the square of their period of mutual revolution is proportional to the cube of the mean distance between them.

These three laws in conjunction with conservation laws of energy and momentum, arrange satellite orbit in different shapes and sizes, depending on each mission requirement. Space operators use radars at tracking sites to measure the current position (R) and velocity (V) of satellites. This information helps them to predict the spacecraft's future position and velocity by integrating the equations of motion.

Johannes Kepler, hundreds of years ago, developed a method for describing orbits that allows us to visualize the size, shape, and orientation of satellites. Since then, we still need six quantities to describe an orbit. According to Kepler's method, we need three components of the position and three components of velocity at any instant. These six elements are called Classical Orbital Elements (COE) (Sellers, Understanding Space-An introduction to Astronautics, 2005).

Keplerian or COE’s elements are (Figure 2):

- The semimajor axis (a), which specifies the size of an orbit.
- Eccentricity (e) which specifies the shape of an orbit.
- The inclination (i) which orientate the orbital plane in space.
- The right Ascension or longitude of the ascending node (Ω) orientates the orbital plane in space together with inclination.
- The argument of perigee or periapsis (ω) orientates the orbit within the plane.
- The true anomaly (v), which specifies spacecraft location in the orbit.

These parameters uniquely define the absolute coordinates (inertial) of the satellite at any time. They are used to determine the satellite track and provide a prediction of the satellite location for extended periods beyond the current time (Louis J. Ippolito, 2017).

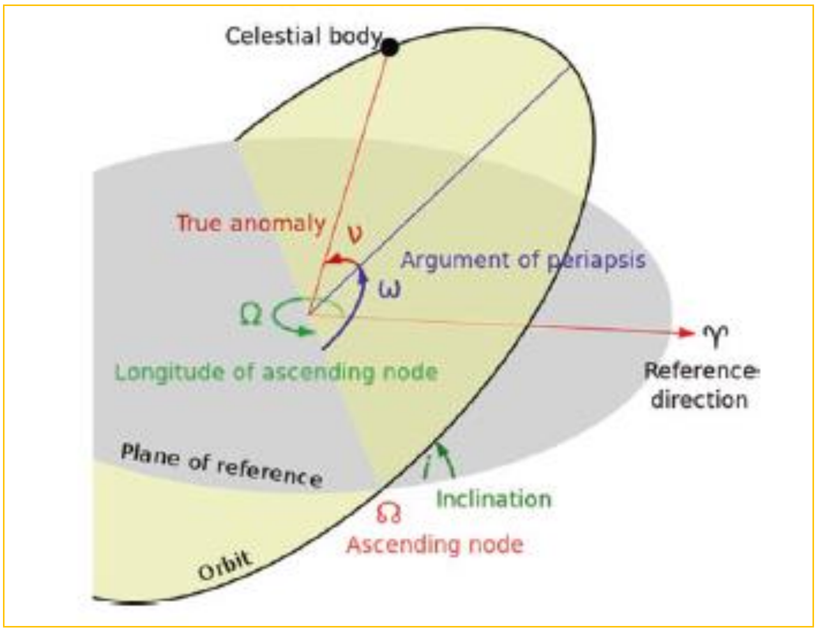


Figure 2: Elements of Orbit/source: (George Sebestyen, page 6, 2018)

2.2.1 Semimajor Axis (a)

The semimajor axis (a), is defined as the half distance across the orbit's major axis, as shown in figure 3. The semimajor axis is accounted for the size of the orbit (Sellers, Understanding Space-An introduction to Astronautics).

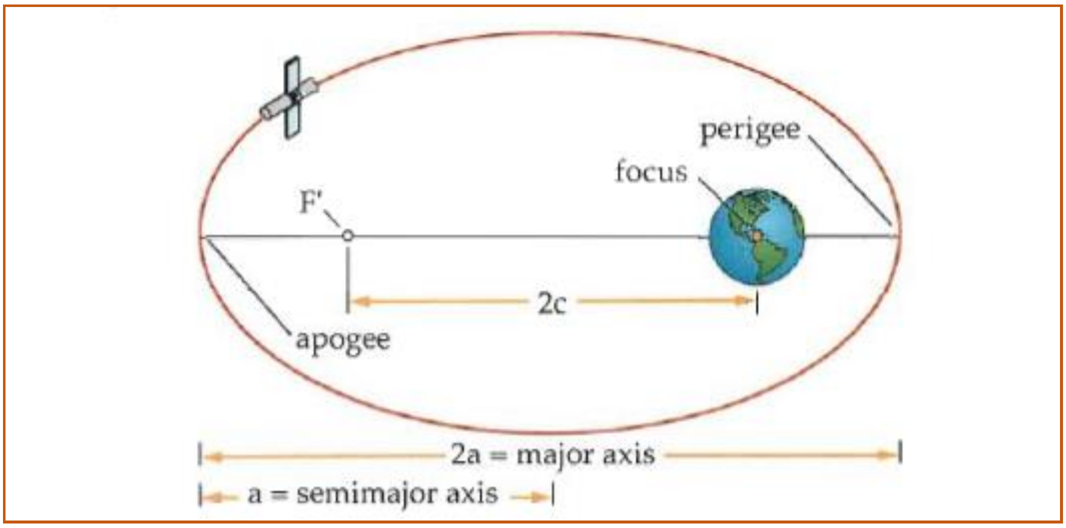


Figure 3: Semimajor Axis of an ellipses/source:

2.2.2 Eccentricity (e)

The eccentricity specifies the shape of an orbit by looking at the ratio of the distance between the two foci and the length of the major axis (figure 5). The notion is described by the next formula:

$$e = \frac{2c}{2a}$$

Formula 1

Eccentricity is a medieval term representing a conic's degree of non circularity. Any deviation from circular motion, which is perceived as perfect, is abnormal or eccentric. The distance between the foci in an ellipse is always less than the length of the ellipse, its eccentricity is between 0 and 1(figure 6). Figure 4 summarizes the relationship between the conic section and the eccentricity.

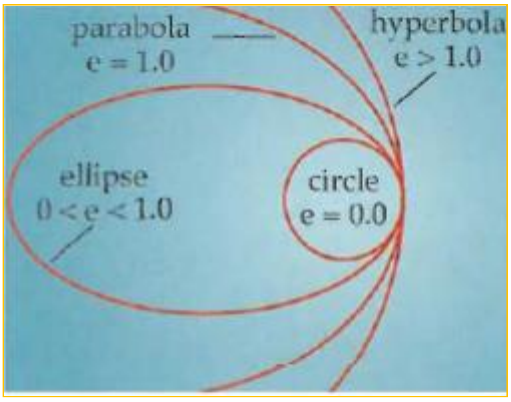


Figure 5: Eccentricity defines an orbit’s shape

Conic Section	Eccentricity
Circle	e = 0
Ellipse	0 < e < 1
Parabola	e = 1
Hyperbola	e > 1

Figure 4: Conic section and eccentricity

2.2.3 Inclination (i)

This element is the first angle that describes the tilt of the orbital plane concerning the fundamental plane (the equatorial plane). We use inclination to define several kinds of orbits. An earth’s plane with an inclination of 0° or 180° is an equatorial orbit. If the orbit is 90° it is a polar orbit. There are two major classes’ orbits: direct or prograde when the inclination is between 0° and 90° (the satellite is moving with earth’s rotation), and the retrograde or indirect orbit when the inclination is between 90° and 180° (the spacecraft is moving opposite from earth’s rotation) (Sellers, Understanding Space-An introduction to Astronautics, 2005).

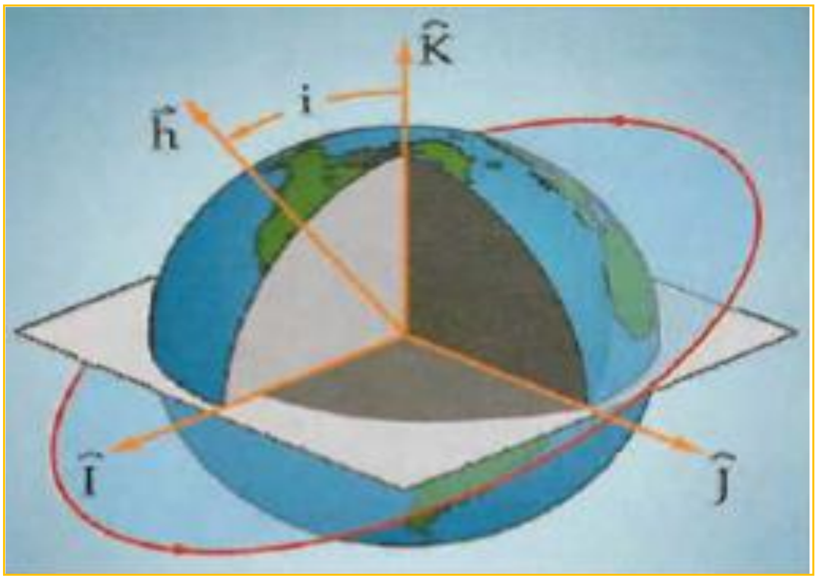


Figure 6: Inclination/ source: (Sellers, Understanding Space-An introduction to Astronautics, 2005)

2.2.4 Right Ascension of the Ascending Node (Ω)

The right ascension of the ascending node (Ω) is the angle in the equatorial plane (Figure 7) measured eastward from the vernal equinox to the ascending node of the orbit (James R. Wertz, 2015.).

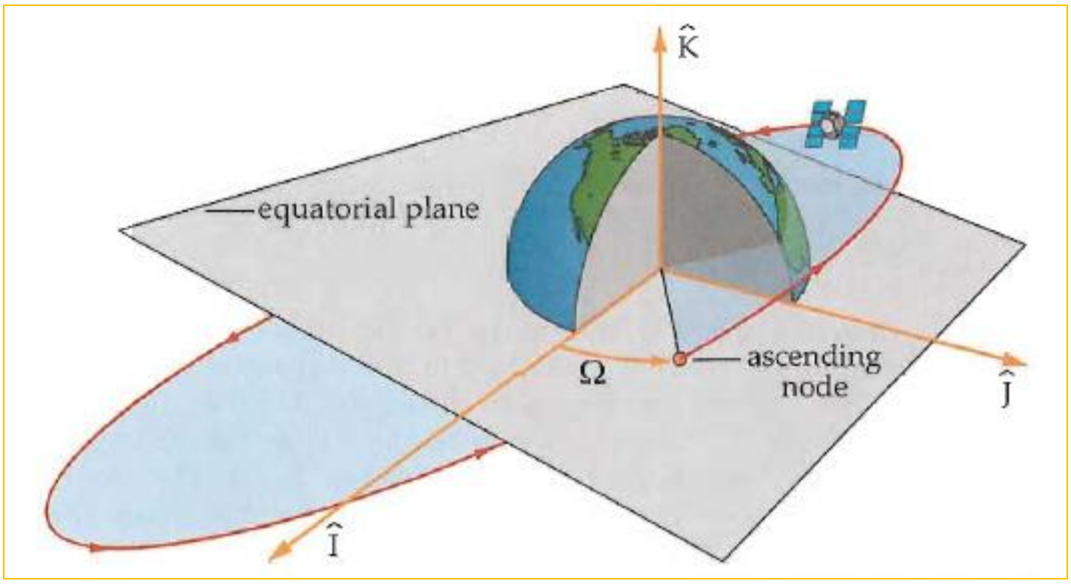


Figure 7: RAAN right ascension of the ascending node/
source: (Sellers, Understanding Space-An introduction to Astronautics, 2005)

2.2.5 Argument of Perigee (ω)

To be specified the rotational orientation of the major axis within the orbit plane, introduced an angle at the center of the mass of earth measured in the orbit plane in the direction of the satellite’s motion from the ascending node to perigee or periapsis (James R. Wertz, 2015.). This angle is called the argument of perigee.

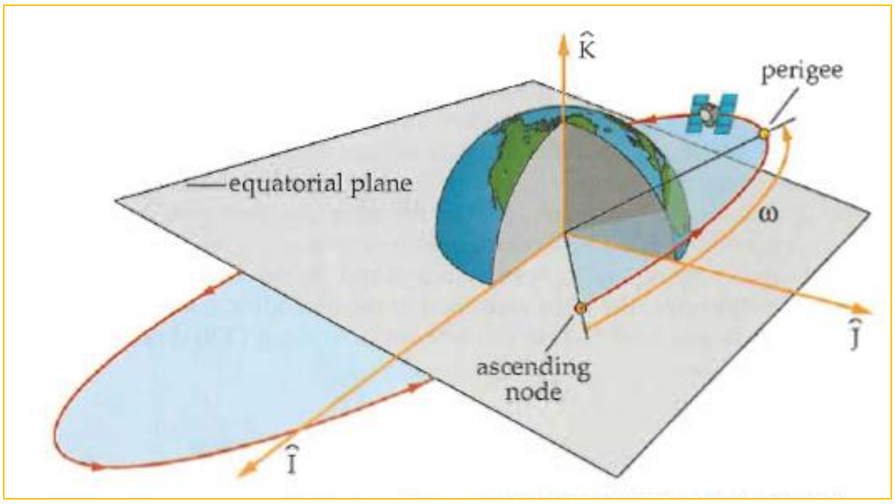


Figure 8: Argument of perigee/
source: (Sellers, Understanding Space-An introduction to Astronautics, 2005)

2.2.6 True Anomaly (v)

Finally, it required a mechanism to specify where the satellite is in its orbit. The true anomaly (v), is the angle measured at the center of mass between the perigee and the satellite. Unfortunately, the true anomaly is difficult to calculate. For this reason, introduced a new notion of the mean anomaly as 360° (Δt/P), where P is the orbital period and Δt is the time since the perigee passage.

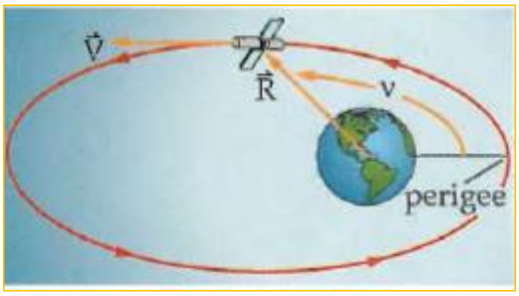


Figure 9: True Anomaly/source:

2.3. Perturbations of Orbits

The six classical orbit elements would behave constantly for a given orbit unless additional forces implied on satellites in orbit. These forces consist mainly of the non-spherical components of terrestrial attraction; the attraction of the sun and the moon, the solar radiation pressure, the aerodynamic drag, and the motor thrust (Gerard Maral, 2009).

The movement of a satellite in its orbit is determined by the forces on the center of a mass. Taking into account the assumptions of Keplerian Hypotheses, the only attraction of a central, spherical, and homogeneous body defines a conservative field of forces. The orbit obtained is plane, fixed in space, and characterized by a set of constant orbital parameters. Perturbations of the orbit are the result of the action of the forces (previous paragraph), which are exerted on the satellite.

One of the assumptions that have been made is that the earth is a symmetry sphere. But in reality, the earth is not spherical. If we look closer at the actual mass distribution, we find that earth is kind of squashed. This squashed shape is called oblateness (Sellers, Understanding Space-An introduction to Astronautics, 2005). Earth is fatter at the equator than at the poles. This bulge is often modeled by complex mathematics and is very frequently referred to as the J2 effect. J2 is a constant describing the size of the bulge in the mathematical formulas used to model the oblate Earth.J2 affects the right ascension of the ascending node (Ω) and the argument of perigee (ν).

Another gravitational force is created by the sun and moon, affecting satellites around earth, especially at high altitudes. Besides, the sun creates solar radiation pressure, which causes long term orbital perturbations and unwanted satellite rotation. The solar radiation pressure affects the solar panels of satellites, due to exposed big surfaces of them. Sometimes satellites can perturb their orbits due to unexpected thrusting caused by either outgassing or malfunctioned thrusters.

Aerodynamic drag is a very significant non-conservative force that is acting at satellites, especially in low altitudes (200-400 Km). This force is getting negligible only above 3000 km. The aerodynamic force is exerted on the satellite in the opposite direction to its velocity axis. The form of calculation this force is:

$$\boxed{F_{\mathrm{AD}} = -0.5_{\rho\mathrm{A}} C_{\mathrm{D}} A_e V^2}$$

Equation 1

Where ρ_A is the density of the atmosphere, Cd is the coefficient of aerodynamic drag, Ae is the equivalent surface area of the satellite perpendicular to the velocity and V is the velocity of the satellite concerning the atmosphere.

The main effect of the atmospheric friction is a decrease of the semimajor axis of the orbit due to a reduction of the energy of the orbit. For an elliptical orbit, the braking occurs at the perigee. The altitude of the apogee decreases, while the altitude of the perigee remains almost constant, the eccentricity decreases and the orbit tends to become circular (Gerard Maral, 2009).

Aerodynamic Drag is very difficult to model because of the many factors affecting the earth's upper atmosphere and the satellite's altitude.

2.4. Characteristics of the Satellite Orbit

The six classical orbital elements of an orbit, contain some characteristics and notions, necessary to use each orbit. These characteristics are (Louis J. Ippolito, 2017):

- Orbital period: Time is taken by a satellite to complete one revolution in its orbit around the earth. It varies from around 100 minutes for near-polar earth observing satellite to 24 hours for a geostationary satellite.

- Apogee and Perigee: Apogee is the point in the orbit where the satellite is at maximum distance from the earth. Perigee is the point in the orbit where the satellite is nearest to the earth (fig. 10).

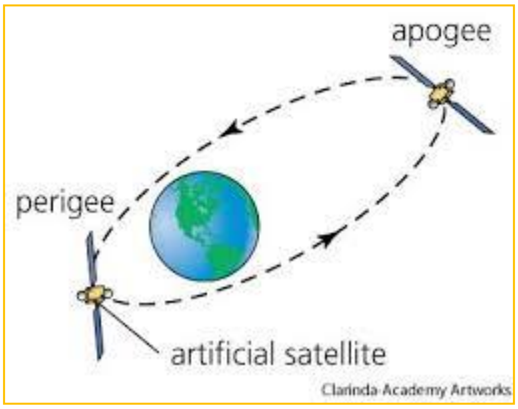


Figure 10: Apogee & Perigee

- Altitude: it is the height of a satellite concerning the surface of the earth immediately below it. Depending on the mission of the satellite, the orbit varies between 160 to 40.000 Km.

- Orbital Cycle: is completed when the satellite retraces its path when the nadir point of the satellite passes over the same point on the earth's surface for a second time.

- Revisit time: is the time elapsed between two successive views of the same area by a satellite. Onboard the satellite there is an instrument that can view off-nadir areas before and after the orbit passes over a target. Because of this off-nadir viewing capability of the satellite, revisit time can be less than the orbital cycle. The revisit time is important especially when frequent imaging is required.

- Nadir &Zenith: is the point of interception on the surface of the earth of the radial line between the center of the earth and the satellite. This is the shortest point from the satellite to the earth's surface. Any point opposite to the nadir, above the satellite, is called the zenith.

- Swath (fig.11): is the width of an area on the surface of the earth, which is imaged by the sensor of a satellite, during a single pass.

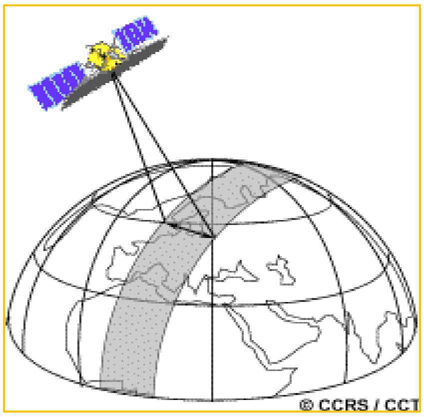


Figure 11: Swath image

- Ground track: The circle on the earth's surface is described by the nadir point as the satellite revolves. It is the projection of the satellite's orbit on the ground surface.

2.5. The problem of space debris

Despite the infinity of space, the space around the earth is not empty. In fact, except for thousands of satellites, it contains millions of objects which are revolving around the earth. These objects are called space junk or space debris. For astronauts or spacecraft in orbit, the risk of getting hit by a meteoroid or micrometeoroid is remote. However, since the dawn of the space era, debris has begun to accumulate from each launch payload, rocket bodies, and mission-related debris. Most orbital debris comprises human-generated objects, such as pieces of spacecraft, tiny flecks of paint, parts of rockets, satellites no longer working (James R. Wertz, 2015).

According to the latest data (February 2020) published by ESA (European Space Agency), since 1957 has been launched 5.560 rockets, over 9.600 satellites have been put into orbit, which 5.500 of them are still in orbit. Only 2.300 of these satellites are still functioning. Detectable and tracking objects monitoring from the earth are 22.300, while statistical models have shown that revolving the earth over 34.000 objects greater than 10cm, over 900.000 objects between 1 and 10 cm, and 128 million objects between 1 and 10 mm (Space debris by the numbers, 2020).

NASA has officially begun in 1979 the orbital debris program in the space sciences branch. The program looks for ways to create less orbital debris and design equipment to track and remove the debris already in space. The problem of managing space debris is both an international challenge and an opportunity to preserve the space environment for future space exploration missions (Kitter, 2016).

Nevertheless, national and international scientific and space operations organizations, such as NASA, ESA, Air Force, the Russian space agency, and more others, have been collecting statistical data on untrackable objects since the 1990's on purpose to create a model of the debris environment and the sources of debris (James R. Wertz, 2015.).

The debris objects are moving very fast and can reach speeds of 18.000 miles per hour. Due to the rate of speed especially at low altitudes (LEO) where take place most of the manned space missions like ISS (International Space Station) and space operations, pose a safety risk to people and property in space and on earth.

The possibility for a spacecraft of getting hit by an object larger than a baseball during one year in orbit is about one in 100.000 or less. The chance of getting hit by something only 1mm or less in diameter is about one hundred times more likely, or about one in a thousand during one year in orbit (Sellers, Understanding Space-An introduction to Astronautics, 2005).

2.6. Space Debris in LEO Orbits

Most orbital debris resides within an altitude of 2.000 Km of the earth’s surface. Within this volume, the amount of debris varies significantly with altitude (fig. 12-13). The greatest concentrations of debris are found near 750-850 Km (Press, 2020).

It is shown that the probability of a collision affecting satellite constellations in LEO orbits, if one main collision occurs at an altitude of 800 km, becomes greater than 2% by 2035, putting in danger satellite constellations at all. At higher altitudes close to 1200 km, satellites have to execute avoidance maneuvers to survive (R. Luckena, 2019).

LEO is indeed becoming a congested area for satellites and space flights, making orbital debris a major concern for space operations. This congestion was highlighted by the collision of the Iridium 33 and Cosmos 2251 satellites in 2009 and the deliberate destruction of the Chinese Fengyun-1C spacecraft in 2009, which alone has increased the large orbital debris population in LEO by approximately 70% (Thomas K. Percy, 2014).

So far, there are no international space laws to remove debris in our LEO orbits. Besides, it is too expensive to clean up these debris objects from LEO due to huge dimensions of them. Space junk is certainly no one countries responsibility but the responsibility of every spacefaring country (James R. Wertz, 2015).

Spacecraft designers handle the orbital debris environment in various ways. For the very small objects which are untrackable, the building of sufficient shielding on spacecraft may help them to survive an impact. At the other end of the size of the spectrum. Large objects are tracked using two ways: radar and optical sensors.

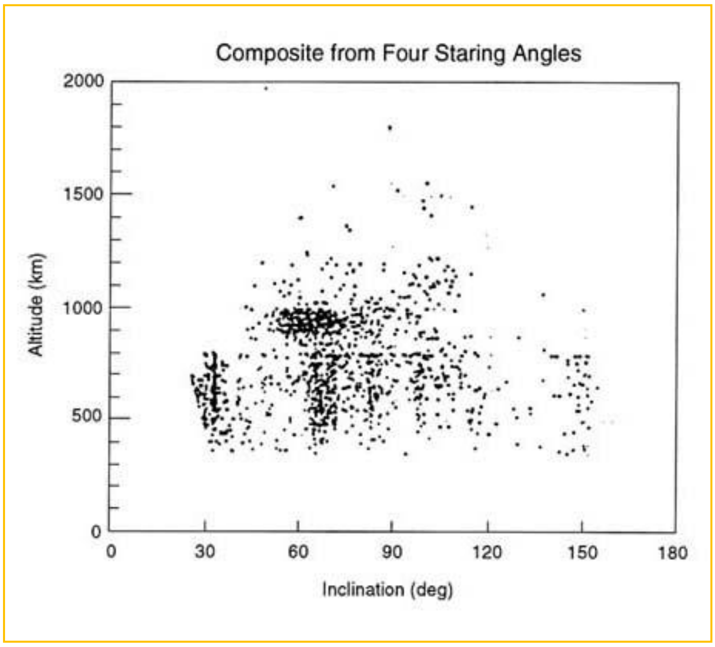


Figure 12: Concentrations of Debris in a relation to altitude and inclination/
source: https://www.nap.edu/read/4765/chapter/6

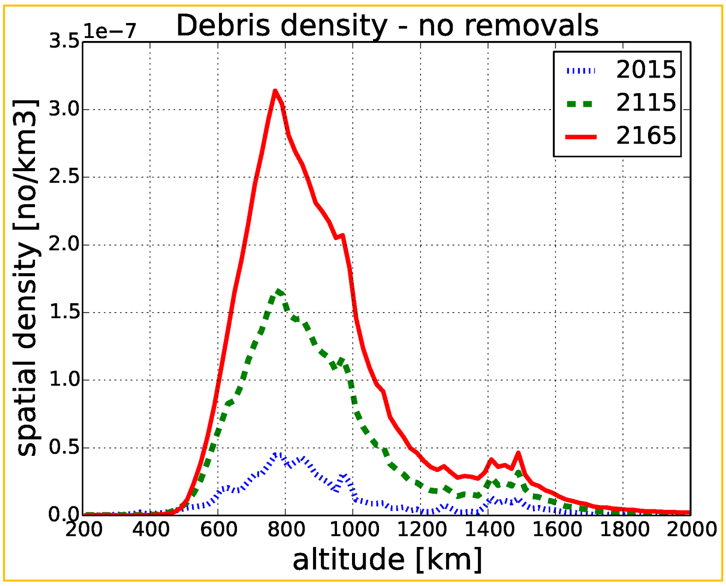


Figure 13: Debris density by altitude/
Source NASA https://www.orbitaldebris.jsc.nasa.gov/measurements/

Moreover, complex mathematical models are building to identify the risk to a relation potential collision with debris. In LEO orbits, has been spotted the majority of debris at specific altitudes, so designers depended on the mission to avoid using these altitudes.

Chapter 3

SATELLITES CONSTELLATIONS

3.1 Satellite Constellations Review

In the 1990s, engineers were exploring new satellite architectures that might allow the successful deployment of satellite communication systems using unutilized Ka-band frequencies. They were seeking a satellite system design that was optimized to provide Internet-based broadband services and simultaneously overcome the problem that rain attenuation posed in particular for very high frequencies. This new satellite system was first called the Calling Satellite system and then renamed Teledesic represented a radical departure from geosynchronous satellite networks. The new system would deploy a massive amount of satellites in LEO. The total network plus spares would have involved the launching of 920 satellites (Joseph N. Pelton • Scott Madry, 2017).

Advantages of the new idea were: the satellites would be designed and qualified on a largely automated production line reducing significantly the unit cost, the system would be orbiting 30 times closer to the ground than a GEO satellite, offering a better continuity and data quality and finally would consuming 900 times less power loss for transmission.

The use of low earth satellite constellations primarily for mobile services appears on the verge of significant change. The trend for satellite constellations has been growing since their first establishment about 20 years ago, in May 1997 for Iridium and February 1998 for Globalstar. More recently, new constellations comprising a tremendous number of small satellites (i.e., mega-constellations) have been considered to respond to the explosive demand for telecommunication services. For example, OneWeb is setting up a 900-satellite constellation in a low Earth orbit (LEO) to provide broadband services, whereas SpaceX is planning a mega-constellation of nearly 12,000 interlinked broadband Internet satellites (Pauline Jakob, 2019).

Further, a great number of store and forward satellite networks have been launched over the years. These have included among others, the commercial Orbcomm system, the Surrey space center, and Utah state university satellites, and the Oscar (Amateur Radio) small satellites that have been launched (Joseph N. Pelton • Scott Madry, 2017).

A constellation is several satellites placed into orbit at height, planes, and inclinations to function collaboratively to achieve common and specific objectives. When satellites are close together, such as a flying interferometer, they are called a cluster or formation (James R. Wertz, 2015.).

The purpose of using a constellation is twofold: first, to increase geographic coverage on Earth's surface and second, to reduce revisit time of the same point. Today, there are plenty of satellite constellations, such a GPS and Globalstar at MEO (Medium Earth Orbit), and many are planned for the future covering various fields, such as communications, observation, navigation, and monitoring scientific parameters. Most present constellations are for navigation by use of satellites at MEO orbit, or for communications with satellites at LEO orbits (George Sebestyen, 2018). The US Department of Defense (DoD) launched the initial defense satellite communications system. This was a series of LEO satellites in random orbit constellation that allowed for more or less global communications, although there were some periodic service interruptions because of gaps in the satellite coverage. The system was designed to test the feasibility of having a dedicated satellite system for defense and security. (Joseph N. Pelton • Scott Madry, 2017).

As the trend for satellite mega-constellations grows, a large number of satellite failures can be expected from future mega-constellations, and a steady replacement strategy has to be established to maintain the service level. The race is on for satellite broadband as companies surge ahead with plans to blanket LEO orbit in satellites. The goal is to provide global coverage while avoiding the pitfalls that led to similar ventures in the 1990s to fail (Hoafacker, 2020).

The major orbital characteristics of several constellations are listed in table 1. Figures of the orbits of Galileo and GPS are shown in fig. 1 & 2 respectively.

Name	Purpose	Country	SC	Planes	SC/Plane	Alt(Km)
GPS	Navigation	USA	24	6	4	20180
GLOSSNAS	Navigation	Russia	24	3	8	19100
Iridium	Phone Communication	USA	66	6	11	781
Orbcomm	Store-Forward Comms	USA	30	4	6-8	825
Globalstar	Communication	EU	24	8	3	1400
Galileo	Navigation	EU	30	3	8+spares	23222
Bei Dou	Regional Navigation	China	4	N/A	N/A	GEO
Quasi-Zenith	Regional Navigation	Japan	4	N/A	N/A	42164
Regional Nav	Indian Regional Nav System	India	4	N/A	N/A	36000

Table 1: Several Satellite Constellations/
Source (George Sebestyen, 2018), page 31

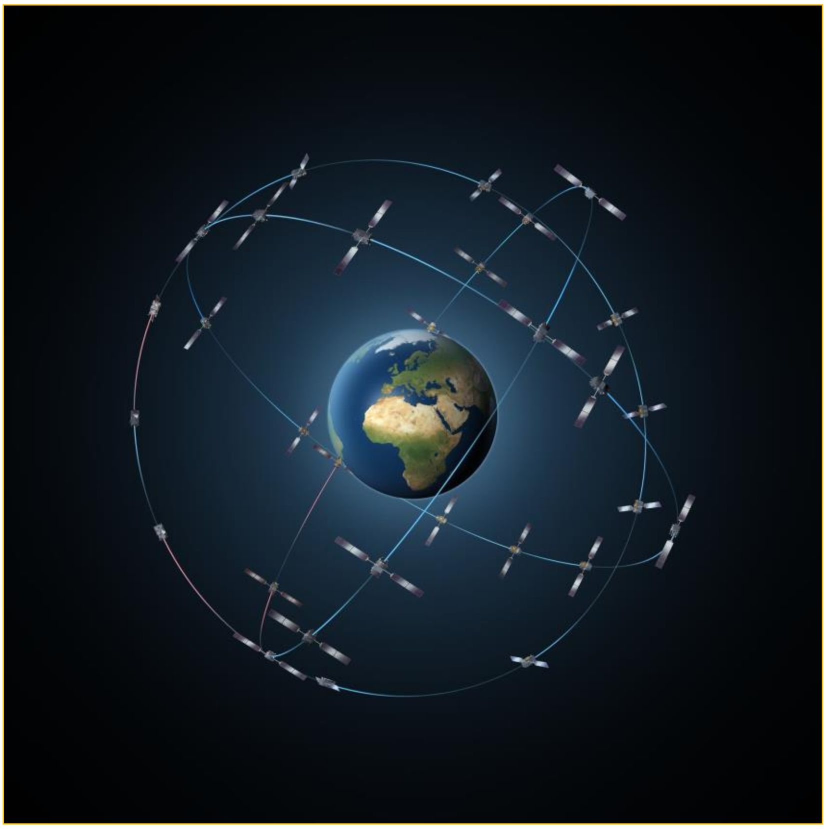


Figure 14: Galileo Constellation

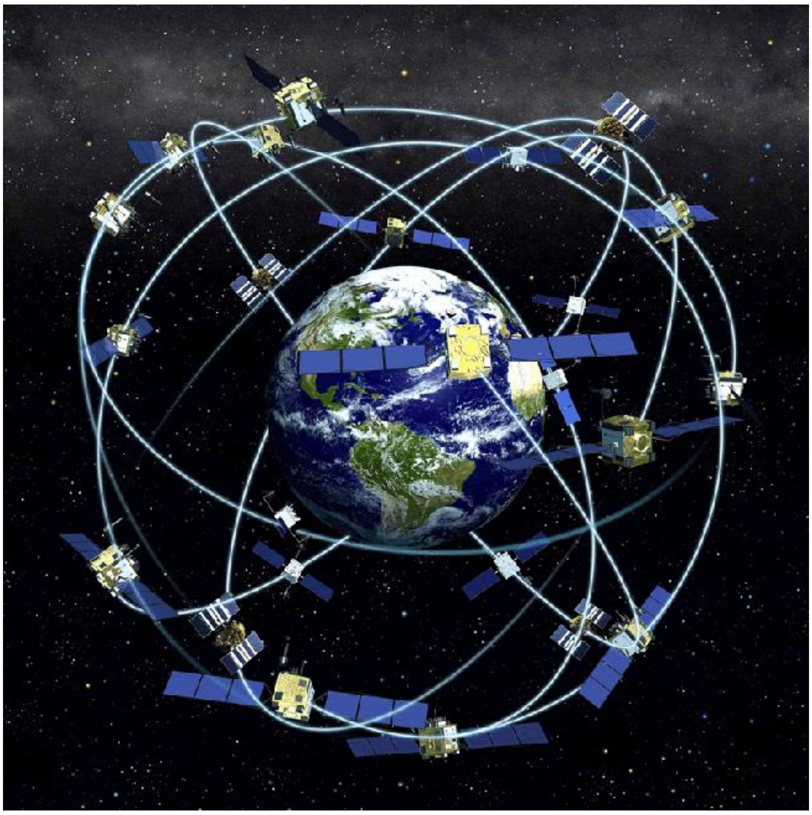


Figure 15: GPS Constellation

A joint venture of Airbus and Communications Company OneWeb is competing among other companies, like SpaceX, to bring satellite broadband to rural populations. Both ventures, are to put in LEO orbit hundreds of thousands of satellites to make their goals visible. While OneWeb is planning to launch into orbit 648 satellites, SpaceX had launched 300 of its planned initial constellation of 12000 of the StarLink satellites net (Thompson, n.d.).

The necessity to communicate simultaneously with every point of the earth or the continuous coverage of a point on Earth, dictates the using of a fleet of identical satellites in different orbits, to accomplish each mission - communication, navigation, remote sensing - requirements (Sellers, Understanding Space-An introduction to Astronautics, 2005).

These systems of satellite constellations, create new challenges to avoid collision with orbital debris. It is vital and paramount to maintain the orbital positions of satellites in their constellation with precision and accuracy, as assigned by ITU in the United Nations (UN). The deployment of a great number of satellites in LEO orbit, to support a new type of fixed satellite services (FSS) for Internet networking, reveals the plans for the future. Besides, the new so-called MegaConstelllation LEO of small satellites, to support Internet services, promise a time of major change in the satellite industry over the next few years (Joseph N. Pelton • Scott Madry, 2017).

The economies of scale driven by the consumer electronics industry have reduced the cost of surface-mounted processors, sensors, and radios to a tiny fraction of what they were just a decade ago. Besides, this technological evolution, reduced and the timeframe for building and assembly of printed circuit boards. The Monarch spacecraft, which was built through entirely automated processes, started to be developed at Cornell University in 2007, although earlier work at The Aerospace Corporation in 1999. The spacecraft weighs 2.5 grams and can be built for less than 50 $ a piece and launched and deployed by the hundredths or thousands in LEO constellations orbits and do things that conventional satellites cannot. Academic community research into swarm satellites constellation for different missions not only on Earth orbit but also at the exploration of another planet such as Saturn's rings, around Enceladus or a comet, Mars, and Lunar (V. Hunter Adams, 2020).

Taking into account that the last decade has increased the number of launched satellites by the international community, it appeared as a new approach to forming constellations of heterogeneous satellites. This formation of satellites driven mainly by science requirements. The first constellation of earth-observing was the Terra satellite and the United States Geological Survey's (USGS‟s) Landsat-7 satellite in 1999 into a 705-kilometer altitude, sun-synchronous orbit. The next year, this constellation was joined by NASA‟s Earth Observing-1 (EO-1) satellite and the Satelite de Aplicanciones Cientificas-C (SAC-C) from the Argentine Commission on Space Activities (CONAE). This group of four satellites was named 'Morning Constellation' (Fig. 16). A second constellation ('Afternoon Constellation') began forming in 2002, with the launch of NASA‟s Aqua satellite, followed 2 years later by Aura. A third satellite, Polarization, and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from Lidar (PARASOL), managed by the French Space Agency, Centre National d'Etudes Spatiales (CNES), joined the A-Train in 2004 and 2006 The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite

Observations (CALIPSO) satellite (a joint U.S./French mission) and CloudSat (a joint NASA/Canadian Space Agency (CSA)/U.S. Air Force mission) joined in the same constellation. The sixth satellite, the Orbiting Carbon Observatory, was unsuccessfully launched in February 2009 (Johnson, 2010).

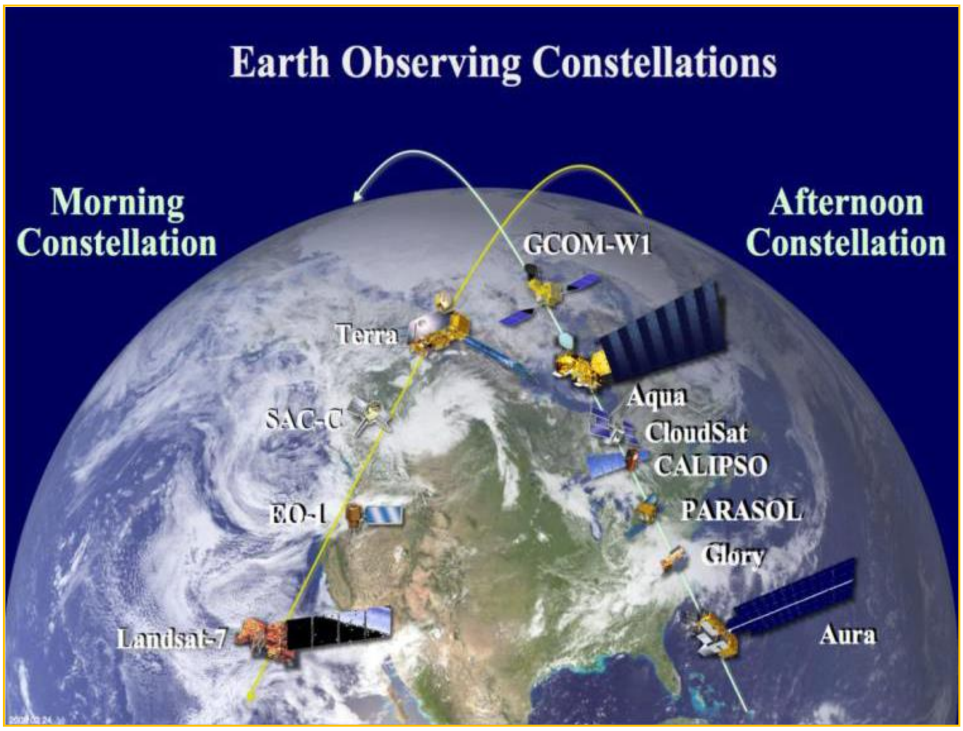


Figure 16: Earth Observing Constellations/ source

3.2 Space-based AIS Satellites Review

The concept of satellite-based AIS has been continuously developed by the USA, Norway, and Canada, etc. Moreover, some military units, commercial companies, and research institutions have increasingly and successfully conducted satellite-based AIS activities, providing ship's AIS monitoring service.

In 2007 the US Air Force Research Laboratory (AFL) launched the AIS satellite of TacSat-2 to verify the concept of satellite-based AIS for one year. The next year Space Flight Laboratory (SFL) of Toronto University under the sponsorship of Canadian COM DEV Company, has successfully launched the AIS satellite of NTS (Nano-satellite Tracking Ships). It was the first commercial unit for providing the service of satellite-based AIS data in the world.

The same year US ORBCOMM Company and the US Coast Guard jointly launched the AIS satellite M2M (Machine-to-Machine). Initially, ORBCOMM had planned to launch 17 AIS satellites by the end of 2014, to complete the satellite AIS management system, together with the existent 16 ground stations (Chen, 2014). On December 21, 2015, ORBOCOMM Company has announced the launch of 11 satellites OG2 with a SpaceX Falcon 9 rocket, to provide services for M2M messaging and AIS. The 11 satellites constellation is spaced within three separate drift cycling orbit planes at an altitude of 750 Km and inclination of 47° (GUNTER'S SPACE PAGE, 2020). The satellite constellation works in conjunction with the terrestrial AIS receivers, to create the most comprehensive and cost-effective global AIS coverage, drawing data from both satellite and terrestrial AIS receivers. ORBCOMM is now processing 30 million messages daily, from over 240.000 unique vessels surpassing all other AIS networks in service quality (Rochelle Park, 2016).

In 2009 the US SpaceQuest Company launched the two AIS satellites, but both of them were incorporated into the exactEarth Company system. The same year an AIS satellite named PathFinder2 manufactured by the LuxSpace Company was launched, which enabled this company to become the first commercial unit for providing the service of satellite-based AIS data in Europe. In September 2009, the AIS satellite of SumbandilaSat jointly developed by the University of Stellenbosch South Africa, Council for Scientific and Industrial Research (CSIR), and Kenya SunSpace Company (Chen, 2014).

In October 2010, under the guidance of Norway, the AISSat-1 satellite designed and manufactured jointly by Norwegian Defense Research Establishment (FFI) and Canadian Space Flight Laboratory has been launched. In May 2012, the Japan Aerospace Exploration Agency (JAXA) has successfully launched the SDS-4 AIS satellite to show the research outcome in the aspect of the Satellite-based AIS. In July 2012, the Canadian exact Earth Company has successfully launched the EV-1 AIS satellite, which enabled its satellite-based AIS system of exactView™ to become the largest system for providing the service of satellite-based AIS data in the world. In February 2013, the AIS satellite of AAUSAT3 funded by the Danish Maritime Authority (DMA) but designed by the Aalborg University has been successfully put into service (Chen, 2014).

Also, China has launched its first AIS satellite ‘Tian Tuo-1’ which saw developed by the National University of Defense Technology (NUDT) on the 10th of May 2012. On the 20th of September 2015 ‘Tian Tuo-3’, a microsatellite constellation, has been launched into a sun-synchronous orbit of inclination 97.5° at 496 Km altitude. The constellation consisted of the main satellite weighed 23 Kg, one mobile satellite 1 Kg, and four Femto-satellite-each weigh 0.1 Kg (Shiyou Li, 2017).

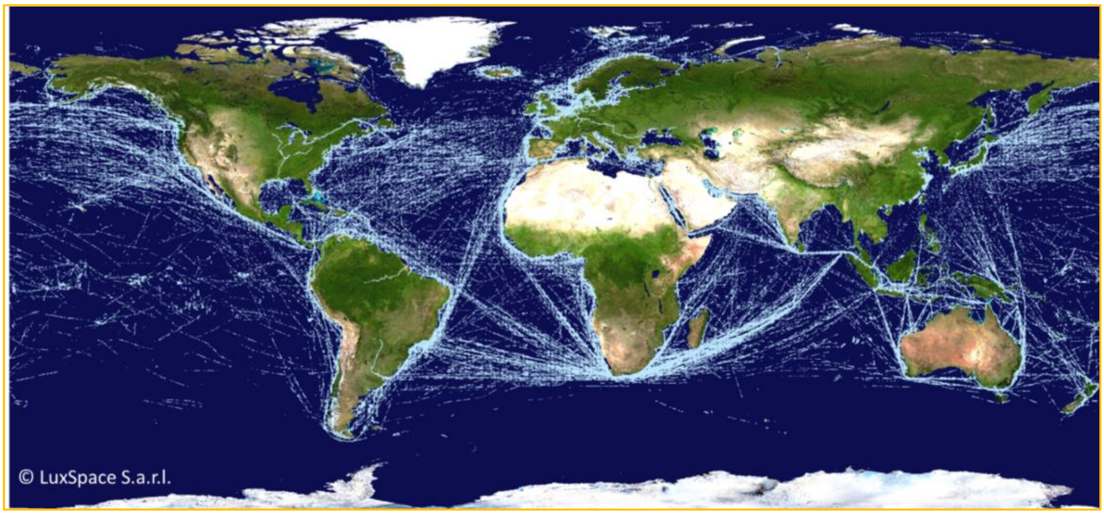
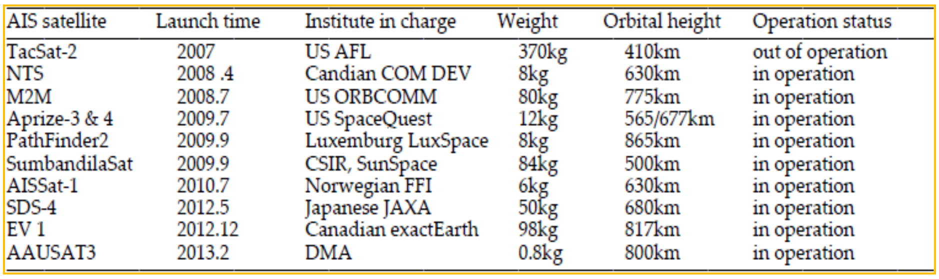


Figure 17: Satellite-AIS-based map of global ship traffic pillars/Source: ESA

Another significant effort to recognize and confirm the viability of the Space-based AIS receiver had been accomplished by ESA in June 2010. The ISS was used as a hosted spaceship for the NORAIS receiver, on purpose to receive AIS messages from the vessels. The receiver is operated by FFI/Norway, sending by telemetry the data collected via ESA’s Columbus Control Centre in Germany. On a fruitful day (Figure 17), almost 400.000 ship position reports were received from more than 22.000 different ship identification numbers (ESA, 2012).



AIS satellite	Launch time	Institute in charge	Weight	Orbital height	Operation status
TacSat-2	2007	US AFL	370kg	410km	out of operation
NTS	2008 .4	Candian COM DEV	8kg	630km	in operation
M2M	2008.7	US ORBCOMM	80kg	775km	in operation
Aprize-3 & 4	2009.7	US SpaceQuest	12kg	565/677km	in operation
PathFinder2	2009.9	Luxemburg LuxSpace	8kg	865km	in operation
SumbandilaSat	2009.9	CSIR, SunSpace	84kg	500km	in operation
AISSat-1	2010.7	Norwegian FFI	6kg	630km	in operation
SDS-4	2012.5	Japanese JAXA	50kg	680km	in operation
EV 1	2012.12	Canadian exactEarth	98kg	817km	in operation
AAUSAT3	2013.2	DMA	0.8kg	800km	in operation

Table 2: Detailed Information regarding AIS Satellites till 2014/source: (Chen, 2014)

Some detailed information about space-based AIS system, regarding international efforts till 2014, are presented in table 2(Chen, 2014).

On the 21st of July 2016, a microsatellite named M3MSat (Maritime Monitoring and Messaging Microsatellite) was launched successfully for the Canadian Department of Defence (DND) and operated by the Canadian Space Agency. M3MSat was a microsatellite built by Honeywell, carrying among another payload an AIS receiver. For the Canadian government, it is crucial to control traffic vessels by space-based assets covering large coastal regions. Space-Based AIS allows users to get a global picture of ship location and headings (Christian Carrié, 2018).

3.3 Space-based AIS system

The potential to use space-probes to support the function of the AIS system especially on open seas was first introduced by Norwegian FFI at the 4th IAA Symposium on small satellites for earth observation in 2003. Since then, many studies and researches have been contacted, to confirm the feasibility of the scope. AIS reception in space can be achieved by the use of a space-based AIS receiver and a small omnidirectional antenna. A constellation of micro or nano-satellites could be used for global maritime traffic monitoring (Gudrun K. HZye, Space-basedAIS for global maritime traffic monitoring, 2008).

3.4 Advantages and disadvantages of LEO constellations

The contemporary trend to design satellite constellations in LEO, reveals the appetite for the rapid development of communications globally. This trend is enforced by the technological advances in satellite manufacturing and the present commercialization of space. Moreover, the increased reliability of systems, in conjunction with the decrease of satellite building time and the reduced cost of them, accelerated investments in space evolution. To design the optimized constellation, there are several key questions that a satellite system operator has to address. The selection of a particular parameter to be optimized in an LEO constellation system dictates the number of satellites and the planes of orbits (Joseph N. Pelton • Scott Madry, 2017).

The construction of the LEO satellite constellation, especially for communications services, has some advantages. First of all, LEO satellites are up to 40 times closer to the earth’s surface and thus there is 1.600 times less transmission path loss. Also, there is up to 40 times less latency or transmission delay than GEO orbits. This is happening because LEO satellite orbits are 20-40 times closer to the surface of the earth (Joseph N. Pelton • Scott Madry, 2017).

Secondly, LEO satellites cover the lower and higher latitudes more effectively than GEO satellites, because they fly more directly overhead. As a sequence, LEO satellites have lower masking angles to user receivers, and particularly provide more effective coverage at upper latitudes and can support service to Polar Regions. Moreover, due to lower path loss and lower masking angles, concentrated beam coverage and modest transmission delay can provide designers a desire with lightweight, compact, and low-cost antennas (Gerard Maral, 2009).

Thirdly, orbital designs for LEO constellations have to concentrate coverage at lower latitudes (0°-70° North & South), including unfortunately all longitudes provide coverage of the Atlantic, Pacific, and Indian Oceans, where there are limited customers. Elaborated computer programs can be designed to make LEO orbits smarter and dynamically flexible. For instance, decrease or increase the performance in specific locations, by modifying parameters of orbits and transmissions, could reduce the cost and increase the reliability of the constellation system.

On the other hand, there are some disadvantages to using LEO satellite constellations. To complete a global constellation network are needed a large number of satellites, which increases the cost due to more launches and complex networks for system control.

A satellite in LEO orbit has relatively limited coverage footprints on the surface of the earth by comparison with satellites in higher altitude orbits. Another drawback is the increased attraction of satellites by earth gravitational field, due to low altitude, which entails more fuel to keel orbit. Normally, the operational lifetime of the satellite is approximately 7 years, comparing with GEO satellites' lifetime which can be 12-18 years (James R. Wertz, 2015.).

There is a higher probability of LEO satellites being hit by space debris, especially at specific altitudes, with a high concentration of space junk.

3.5 Small Satellites

The miniaturization and advances in microelectronics have engaged small spacecraft to maintain the performance features of modern spacecraft in extremely small packages. These spacecraft are inexpensive to build and launch to create large constellations of satellites. These constellations are being used to provide daily imagery enabling new uses in defense, agriculture, business intelligence, forestry, and disaster recovery. Competitors are entering the small satellite market at a staggering rate providing new ideas and innovations. Governments are taking a new look at small satellites, as commercial customers use them for their flexibility, speed of development, resiliency, low cost, and tolerance of risk in cutting edge technology. A new era of small satellites has emerged augmenting larger systems and, in some cases, replacing them (Joseph R. Kopacza, 2020).

Smallsats are broadly defined as satellites weighing less than about 1000 lbs. of 500 Kg. In recent years with the advent of Cubesats and very small satellites, a variety of terms have come into use. Then, emerged the need for more well-defined terminology. The most widely adopted terminology for small satellites is the following:

➢ MiniSat	100-500 Kg
➢ MicroSat	10-100 Kg
➢ NanoSat	1-10 Kg
➢ PicoSat	0.1-1 Kg

Moreover, Cubesat dimensions are 10 cm X 10 cm X 10cmcube and weigh at most 1 Kg. Smallsats have been flown since the dawn of the space program, largely because of limitations of size and mass capability of launch systems. Generally, Smallsats are simpler than larger satellites but they have fewer capabilities.

Normally, Smallsats are built in 1 to 3 years, which is a big advantage of incorporating the new technology much faster than traditional satellite programs. The dramatic increase of the Smallsats capabilities due to technological developments contributes to maintaining low cost for any space program. Also, there is less complexity to build Smallsats than larger ones. Oh the other hand, Smallsats have a single payload, dedicated to specific jobs (James R. Wertz, 2015.).

Christopher Baker, NASA’s Small Spacecraft Technology program executive, observes that CubeSats also offer frequent, flexible, low-cost access to space, while the schedule from conception to launch of these diminutive spacecraft can be fast-paced. They allow you to do things that previously would not have been possible with a large, monolithic spacecraft. Recently, NASA announced on 25th of February 2020, that innovative spacecraft called CubeSats are poised to play a role in NASA’s ‘Artemis’ program, in Lunar exploration (Hall, 2020).

Generally, there are significant advantages of using small satellites or CubeSats, to support a variety of applications such as navigation, communication, exploration, or remote sensing. The most profitable advantage is the overall cost. With much less budget and in a shorter time, engineers can build satellites, with less consumption of power, and put them in orbit with much less money (cost per kilo to put it in orbit). Also, small satellites have fewer parts than the larger, which entails a lower probability of failure. Moreover, the testing process of smaller satellites is much easier and chipper than the big one (James R. Wertz, 2015.).

Using a large number of small, low-cost satellites, can provide better support to missions for remote sensing and communications, in a mega satellite constellation in LEO. In recent years, amongst space organizations, universities laboratories, and private companies, there is a trend for manufacturing SmallSats or CubeSats to accomplish various missions and applications. The space industry has accommodated the new trend, investing a great amount of money, projecting the increasing promised future in space exploration.

3.6 Process of Satellites Constellation Design

A constellation is a combination of satellites distributed in orbits on purpose to work together to achieve common tasks. The selection of a specific orbit and the design of any satellite constellation is a process rather than a set of specific calculations or equations. There is a variety of missions’ types, each of which will be unique in any selection process. The design process is inclined to be complex with no agreed solution by the community (James R. Wertz, 2015.).

The most significant result of constellation studies, along the years, is that no absolute rules exist for constellation design. The vital key in the process is to fully recognize the mission objectives, particularly concerning coverage. Normally, the goal of creating a satellite constellation is to provide needed Earth coverage with a minimum number of satellites. The principal factors to be defined during the constellation design are listed in table 3.

Generally, trying to specify a constellation by the definition of all of the orbit elements for each satellite is a complex, inconvenient, and overwhelming procedure. A factual way to start with is by looking at constellations with all satellites at a common altitude and inclination and in circular orbits. We should bear in mind that the number of satellites is not representing the cost of a system. For example, when you increase the altitude to get better coverage, reduces the number of satellites needed and as a sequence reduces the cost, but the launch cost increases and exposes the system in the Van Allen belts. Then you have to protect satellites from the radiation of the Van Allen belts, so the cost increases again. On the other hand, reducing the number of satellites may not minimize the system cost (James R. Wertz, 2015.).

The Constellation Design Process		
	STEP	**SUBSTEP**
1	Establish constellation-related mission requirements	Latitude-dependent coverage
		Goals for growth and degradation plateaus
		Requirements for different modes of sensors
		Limits on system cost or number of satellites
2	Establish Orbit types	
3	Determine Orbit-related Mission requirements	
4	Evaluate Orbit performance	Earth coverage
		Specialized Orbits
		Single satellite Vs constellation
		Other ways the orbit impacts performance
		Do mission orbit design trades
5	Evaluate Orbit cost	Evaluate launch options and launch cost
		Look at low-cost options if possible
		Add disposal options
		Create a delta-V budget
		Evaluate the orbit cost-function-launch cost Vs available on-orbit mass
6	Document selection criteria, key orbit trades, selected orbit parameters, and allowed ranges	
7	Do trades between swath width, coverage, and number of satellites	Evaluate candidate constellations for:
		Coverage Figures of Merit Vs Latitude and mission mode
		Coverage excess
		Growth and degradation
		Altitude plateaus
		End of life options
		Consider the following orbit types:
		Walker Delta pattern
		Polar constellation with seam
		Equatorial
		Equatorial supplement
		Elliptical
8	Evaluate ground track plots for potential coverage holes or methods to reduce the number of satellites	
9	Adjust inclination and in-plane phasing to maximize the inter-satellite distances at plane crossings for collision avoidance	
10	Review the Rules of constellation design	
11	Document reasons for choices and iterate	

Table 3: Steps of Constellation design process/ (James R. Wertz, 2015.)

3.7 Coverage and Constellation Structure

The design and existence of the satellite constellation is the earth coverage, which is the key parameter using multiple satellites. Providing services such as observations and communications, the main objective of satellite constellations are the earth coverage as a measure of performance versus the number of satellites as a measure of cost.

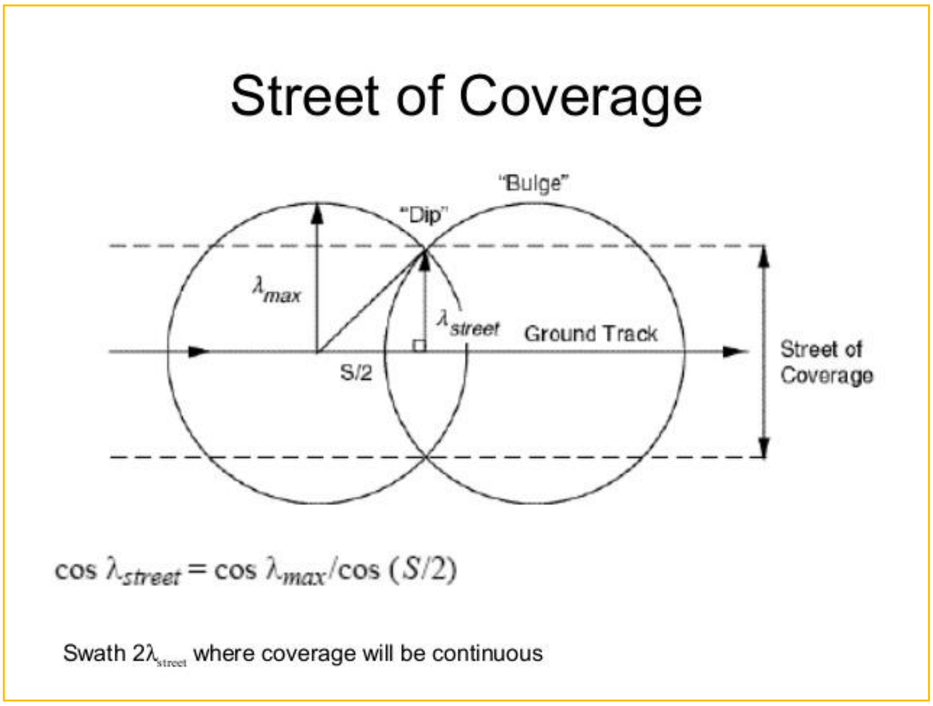
A fundamental characteristic of any satellite constellation is the number of planes, in which the satellites reside. Symmetry in the constellation structure requires an equal number of satellites per orbit plane. The number of satellites relates strongly to a coverage issue. Constellations with a small number of orbit planes have a distinct advantage over many plane ones. Communications constellations are normally thought of as having a very rigid requirement of continuous global coverage. Also, a smaller number of orbit planes leads to more graceful degradation (James R. Wertz, 2015.).

One more significant characteristic is the orbit inclination. Seemingly, one could design satellite constellations with many different inclinations to get the best coverage. This is very difficult due to the rate of nodal regression for a satellite orbit is a function of both altitude and inclination. Thus, we usually design constellations to have all the satellites at the same inclination.

As depicted in figure 17, the spacing between satellites in a single orbit plane determines whether coverage is continuous in this plane and the width of the continuous coverage region. We consider λ_{max} as a maximum earth central angle and **N** satellites equally spaced at $S=360°/N$ deg in the same orbit plane. There is intermittent coverage throughout a swath of half-width λ_{max}.

If $S > 2\lambda_{max}$. The coverage is intermittent throughout the entire swath.

If $S < 2\lambda_{max}$. There is a narrower swath, often called a street of coverage, centered on the ground trace and the width $2\lambda_{street}$, in which there is continuous coverage. This width is given by $\cos\lambda_{street} = \cos\lambda_{max}/\cos(S/2)$ (James R. Wertz, 2015.)


Street of Coverage

$$\cos \lambda_{street} = \cos \lambda_{max} / \cos (S/2)$$

Swath $2\lambda_{street}$ where coverage will be continuous

Figure 18: Swath width centered on the Ground track

3.8 Polar Constellation

There is another pattern of satellite constellation to alleviate deficiencies at earth coverage continuity. The Polar constellation is often called Streets of Coverage illustrated in figure 18.

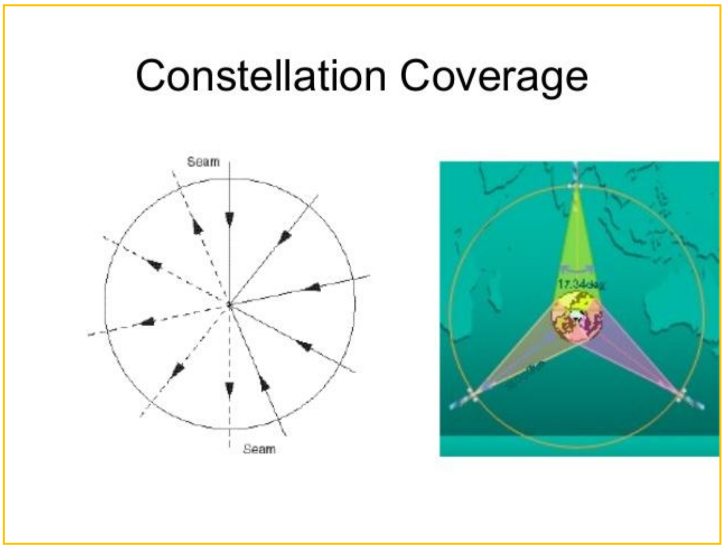

Constellation Coverage

Figure 19: Streets of Coverage Constellation Pattern

In this case, M planes of N satellites are used to provide continuous global coverage. At any given time, satellites over half the world are going northward a=nd satellites over the other half are going southward. Within both regions, the orbit planes are separated by $\mathbf{D_{max}}\ s = \lambda_{street} + \lambda_{max}$. Between the two halves, there is a seam in which the satellites are going in opposite directions. This pattern shows another critical characteristic of constellations. There are discrete jumps in coverage that depend primarily on λ_{max}, which in turn depends on the minimum elevation angle (ε_{min}) and the altitude. In case we keep the elevation angle fixed and lower altitude then we will reach an altitude plateau at which we will need to add another orbit plane and N more satellites to cover the earth (James R. Wertz, 2015.).

As the altitude changes, the constellation design changes by altering the number of satellites and coverage characteristics required for continuous coverage.

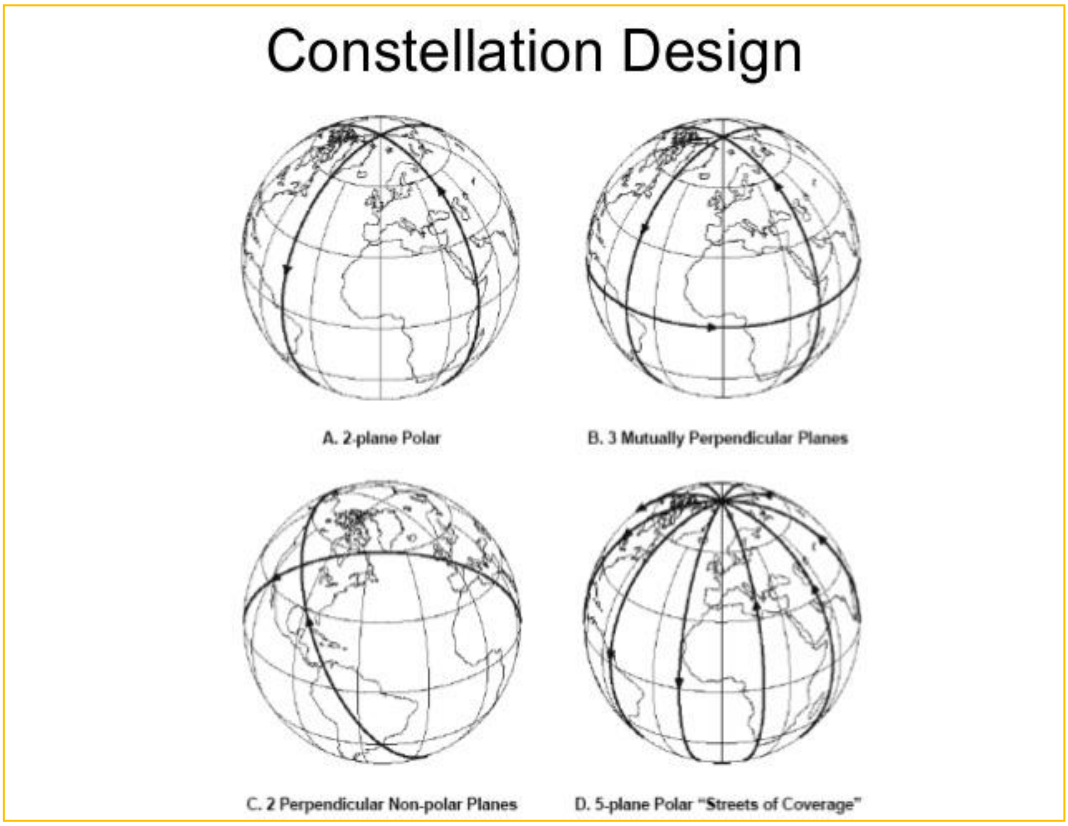
3.9 Walker Delta Pattern

The simplest constellation design question is: what is the minimum satellite number required to provide continuous coverage of the earth? In the late 1960s, Easton and Brescia of the Naval Research Laboratory in the USA analyzed coverage by satellites in two mutually perpendicular orbit planes and concluded we would need at least 6 satellites to provide complete earth coverage. In the 1970s Walker at the British Royal Aircraft Establishment expanded the types of constellations considered to include additional circular orbits at a common altitude and inclination. He founded that continuous coverage of the earth would require 5 satellites. Due to his extensive work, Walker constellations are a common set of constellations to evaluate for overall coverage. In the 1980s, John Draim found and patented a constellation of 4 satellites in elliptical orbits which would provide continuous earth coverage. A minimum of 4 satellites is required at any one instant to provide full coverage of the earth (James R. Wertz, 2015.).

Walker in 1984 developed a notation for labeling orbits that are commonly used in the orbit design community and frequently used as a starting point for constellation design. More specifically, the Walker Delta Pattern contains a total of **t** satellites with **s** satellites evenly distributed in each of **p** planes. All the orbits planes are assumed to be at the same inclination (i), relative to a reference plane-typically the earth's equator. In a Walker pattern, the ascending nodes of the p planes are uniformly distributed around the equator at intervals of 360°/p. In the same plane, the s satellites are uniformly distributed at intervals of 360°/s (James R. Wertz, 2015.).

The next issue which we have to define is the relative phase between the satellites in adjacent orbit planes. To do this we define the phase difference (Δφ). It represents the angle in the direction of motion from the ascending node to the nearest satellite, in a constellation, at a time, when a satellite in the next most westerly plane is at its ascending node. For all of the orbit planes to have the same relationship to each other, Δφ, must be an integral multiple, f, of 360°/t, where f can be any integer from 0 to p-1. The pattern is fully specified by giving the inclination and the tree parameters, t, p, and f. For example, a walker constellation of 15/5/1 at i=65°. That means, 15 satellites in 5 orbit planes (t=15, p= 50), 3 satellites per plane (s=t/p=3). Pattern Unit (PU) is equally 360°/15=24°. In the same plane then, the spacing between satellites will be PUxp=24°x5=120°. Then node spacing is equal with PUxs=72°. Finally, the phase difference between adjacent planes is PUxf= 21x1 =24° (James R. Wertz, 2015.).

Walker constellation is important to design constellations but maybe not the only option for better coverage for a given mission. We may wish to support the best coverage to the poles, mid-latitudes regions, or the equator. In these cases, we may want constellation types other than Walker. Some of these designs are depicted in figure 19. The two-planes polar at right angles to each other, are perpendicular to the equator. The two planes can also be tipped to the equator to achieve any inclination from 90° to 45° to create perpendicular non-polar planes. Finally, an example of a non-walker constellation is the Molniya orbits used for Russian communications satellites, to cover Northern latitudes while requiring less energy than circular high altitude orbits (James R. Wertz, 2015.). At table 3 we have identified principal factors and design variables that must be defined for each constellation design.



Constellation Design

A. 2-plane Polar

B. 3 Mutually Perpendicular Planes

C. 2 Perpendicular Non-polar Planes

D. 5-plane Polar "Streets of Coverage"

Figure 20: Different types of design constellation other than Walker

Principal Factors to be Defined During Constellation Design		
Principle Design Variables:		
Factor	Effect	Selection Criteria
Number of Satellites	The principal determinant of cost and coverage	Minimize number consistent with meeting other criteria
Constellation Pattern	Determines coverage Vs Latitude, plateaus	Select the best coverage
Minimum Elevation Angle	The principal determinant of single satellite coverage	Minimum value consistent with payload performance and constellation pattern
Altitude	Coverage, environment, launch and transfer orbit	System-level trade of cost Vs performance
Number of Orbits Planes	Determines coverage plateaus, growth, and degradation	Minimize consistent with coverage needs
Collision Avoidance Parameters	Key to preventing constellation self-destruction	Maximize the inter-satellite distances at plane crossings
Secondary Design Variables:		
Inclination	Determines latitude distribution of coverage	Compare latitude coverage Vs launch costs
Between Plane Phasing	Determines coverage uniformity	Select best coverage among discrete phasing options
Eccentricity	Mission complexity and coverage Vs cost	Normally zero; non-zero may reduce the number of satellites needed
Station keeping Box Size	Coverage needed; cross-track pointing	Minimize consistent with low-cost maintenance approach
End of Life Strategy	Elimination of orbital debris	Any mechanism that allows you to clean up after yourself

Table 4: Principal Factors to be defined During Constellation Design

3.10 Principal Issues Dominate Constellation Design

Without a doubt, constellations are expensive Thus, all of our system trades should be based on cost Vs. performance. The principal issues that dominate constellation design are depicted in table 4. There are four criteria we can evaluate for each constellation design.

Principal Issues Dominate Constellation Design			
Issue	Why Important	What Determines It	Principal Issues or Options
Coverage	Principal performance parameter	Altitude, minimum elevation angle, inclination, constellation pattern	Gap times for discontinuous coverage; the number of satellites simultaneously in view for continuous coverage
Number of Satellites	Principal cost driver	Altitude, minimum elevation angle, inclination, constellation pattern	Altitude, minimum elevation angle, inclination, constellation pattern
Launch Options	Major cost driver	Altitude, inclination, spacecraft mass	Low altitude, low inclination costs less
Environment	Radiation level and therefore lifetime and hardness requirements	Altitude	Options are below, In, or above Van Allen radiation belts
Orbit Perturbations	Causes Constellations to disassociate over time	Altitude, inclination, eccentricity	Keep satellites at common altitude and inclination to avoid drifting apart
Collision Avoidance	The Snowball effect can destroy an entire constellation	Constellation pattern, orbit control	No option-must design the entire system for collision avoidance
Constellation Built-up End of Life	Determines level of service over time and impact of outages	Altitude, constellation pattern, built-up and sparing philosophy	Sparing: on-orbit spares Vs launch on-demand; end of life: deorbit Vs raise to a higher orbit
Number of Orbit Planes	Determines performance plateaus	Altitude, inclination	Fewer planes mean more growth plateaus and more graceful degradation
Legal or Political Constraints	Limits options, locations in GEO, frequency use	Law, policy, international treaties and agreements	Need to be sure all needed permissions can be secured and time needed to do so
Viewing and Lighting Conditions	Determines visibility of targets and objects of interest	Distance, surface propertied, Sun angle	May drive orbit selection viewing direction or observation timing

Table 5: Principal Issues that Dominate Constellation Design

3.11 Rules for Constellation Design

We should keep in mind that there are no absolute rules for any design of satellite constellation. The key to the design is to look at the fundamental mission objectives and determine how these objectives can best be met at minimum cost and risk. Our purpose must be to minimize the number of satellites which achieving the appropriate volume of coverage. While there are no absolute rules, there are guidelines that can assist in the process of constellation design. These rules are summarized in table 5(James R. Wertz, 2015.).

Rules for Constellation Design	
	Rule
1	To avoid differential node rotation, all satellites should be at the same inclination, except that an equatorial orbit can be added
2	To avoid perigee rotation, all eccentric satellites should be at the critical inclination of 63.4°
3	Collision avoidance is critical, even for dead satellites, and maybe a driving characteristic for constellation design
4	Symmetry is an important but not critical element of constellation design
5	Altitude is typically the most important of the orbit elements, followed by inclination. 0 eccentricity is the most common, although eccentric orbits can improve dome coverage and sampling characteristics
6	The minimum working elevation angle is as important as the altitude in determine coverage
7	Two satellites can see each other if and only if they can see the same point on the ground
8	Principal coverage Figures of Merit for constellations:
	Percentage of time coverage goal is met,
	Number of satellites required to achieve the needed coverage
	Mean and maximum response times
	Excess coverage percent
	Excess coverage Vs Latitude
9	The size of the stationkeeping box is determined by the mission objectives, the perturbations selected to be overcome, and the method of control
10	For long-term constellations, absolute stationkeeping provides significant advantages and no disadvantages compared to relative stationkeeping
11	Orbits perturbations can be treated in 3 ways:
	Negate the perturbing force
	Control the perturbing force
	Leave perturbation uncompensated
12	Performance plateaus and the number of orbits planes required are a function of altitude
13	Changing position within the orbit plane is easy; changing orbit planes is hard; implies that a smaller number of orbits planes is better
14	Constellation built-up, graceful degradation, filling in for dead satellites, and end of life disposal are critical and should be addressed as part of constellation design
15	Taking satellites out of the constellation at end of life is critical for long-term success and risk avoidance. This is done by:
	Deorbiting satellites in LEO
	Raising them above the constellation above LEO

Table 6: Rules for Constellation Design

Key answers in the design of a satellite constellation are mission-imposed requirements, degree of coverage, number of planes and launches, and orbital altitude and cost (George Sebestyen, 2018). Depending on the number of satellites orbiting in a plane at a given altitude, their coverage might have gaps between satellites or overlapped their coverage.

3.12 Earth Coverage

Coverage is a cornerstone requirement for any referenced mission on earth or another planet. Coverage is not uniform either a random variable. Thus, statistical data that are often used can prove very misleading. In the process of constellation design, we must first determine if a specialized orbit applies to the requirements of the mission. Some examples of specialized orbits are; Sun-synchronous, Molniya, and Lagrange point. We should examine if each of these orbits is feasible for the mission. And worth its cost. As we mentioned earlier in this chapter, small satellites have become more capable due to miniaturized electronics and on-board processing. So that, we can design constellations consistent by small satellites, low-cost, often called SmallSats of LightSats (James R. Wertz, 2015.).

Most typically, the calculation of coverage of a constellation is done by computer simulation and statistical analysis of the results. However, the most important characteristic of the coverage is that earth coverage is not a Gaussian parameter and statistical data can give very misleading results (James R. Wertz, 2015.).

3.13 Evaluating Earth Coverage

To evaluate the earth coverage, we should describe the reference of it. The earth coverage is the part of the earth's surface that is viewed when a spacecraft instrument or antenna can see at one instant or over an extended period. There is also a notion of instantaneous field of view, normally called the FOV or footprint, which is the actual area the instrument or antenna of a spacecraft can see at any moment. On contrary, the access area is the total area on the ground that potentially can be seen at that moment by turning the spacecraft or the instrument (James R. Wertz, 2015).

The FOV or Footprint is defined by the characteristics of the antenna onboard of microsatellite, which is kept small, to be compliant with the size of the spaceship.

Performed studies by Telecommunication Union in 2006, Cervera and Ginesi) in 2008, Scorzolini in 2010, have limited the FOV and the corresponding instantaneous ground swath, on the probability of ship detection at least 99%, in ranges between 800 nm in areas of dense maritime traffic and 1900 nm in remote oceans (Maria Daniela Graziano, 2012).

Studies in Spaceborne AIS system, have shown that there is no need for continuous global coverage. In reality, continuous update of ship position is required only in congested areas, nearby the shores in port, where normally satisfied AIS service is guaranteed by on-ground facilities. This aspect has an important impact on constellation design since it manipulates one to reduce the number of satellites. In particular, the update period is estimated in TU (2006) at 1 hour for ships hundred miles from the coats, which can be increased to 4 hours or 12 hours for further distances. Finally, Cervera and Ginesi (2008) proposed an update time of 3 hours, no matter the coast distance of a ship, as mandatory and 1 hour as desirable (Maria Daniela Graziano, 2012).

Four parameters characterize the Earth coverage:

- Footprint Area (FA, FOV) area-is the area that a specific instrument or antenna is viewing at any instant.
- Instantaneous Access Area (IAA)- is all the area that the instrument or antenna could potentially see at any instant.
- Area Coverage Rate (ACR)- is the rate at which the instrument or antenna is sensing or accessing new land.
- Area Access Rate (AAR)- is the rate at which new land is coming into the spacecraft’s access area.

The coverage rate and access rate will be the same when the instrument covers all the area available to it as the spacecraft moving. Generally, the access area and access rate depend only on the orbit and limiting geometry of the system (James R. Wertz, 2015.).

Chapter 4

STK ANALYSIS-CALCULATE COVERAGE IN CASE STUDIES

4.1 STK program as a tool of Calculations and Simulations

The calculation of earth coverage for a single spacecraft is a very demanding process. In a complex environment such as a satellite constellation, the analysis and calculation of the earth coverage are much more puzzled. In our calculations, we are going to use an analytical operational tool, the STK (System Tool Kit) program, of the AGI Company[1], which is already used by many placeholders.

The STK is a platform for analyzing and visualizing complex systems in the context of your mission. Interact with data from platforms across the aerospace, defense, telecommunications, and other industries. Simulate your intended missions and communicate the results with reports, graphs, and stunning 3D animations. The STK is an important tool to design, built, and test various parameters, for many different missions, in aerospace, communications, geospatial analysis, and space. The program has many capabilities such as importing precise models of ground, sea, air, and space assets and combine them to represent existing or proposed systems. Building on the capabilities that serve as STK's foundation, STK introduces advanced access constraints, flexible sensor shapes, complex visibility links, more object tracks, and digital terrain data. At the end of the design process, you can simulate the entire system in action, at any time to gain a clear understanding of the system behavior and performance[2].

4.2 General Assumptions of Creating the Constellation

Our goal is to calculate and compare earth coverage for three different scenarios of 8, 12, and 24 satellite constellations, on purpose to support AIS global

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[1] https://www.agi.com/

[2] Ibis 1

coverage. As we mentioned in chapter 3, the constellation design process is an accurate demanding procedure. To achieve our main objective, we have to make some assumptions about each satellite sensors (receivers and transmitters) and the weight of each satellite (needed for lifetime calculations). Some other detailed parameters such as the power system of each satellite, the on-board processing capabilities, and other technical details of each satellite subsystem, are not necessary to be taken in all design processes. Also, the estimation of the cost of each satellite or the constellation is out of the scope of this master's dissertation. The main objective is to evaluate the earth coverage for three different cases of 8, 12, and 24 satellites, trading-off with altitude, inclination, and method of constructing the LEO satellite constellation.

4.3 AIS Receiver of each Satellite

Two factors that impact constellation design are the spaceborne receiver of AIS and its relative FOV. The function of the AIS system is achieved by the use of a dedicated receiver with specific characteristics, to fulfill the feasibility of such a space-based AIS system. Spaceborne AIS must have complied with standard terrestrial AIS transmitters. Thus, the orbit selection is strongly affected by the requirement to receive o low power signal of 12 watts for AIS A, taking into account atmospheric loss and path loss (Maria Daniela Graziano, 2012).

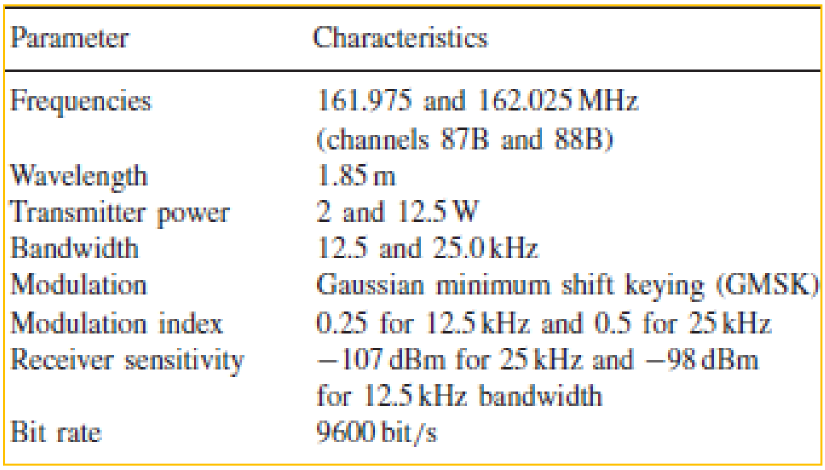
The second element of FOV is down-limited by antenna dimensions, which we should keep small to compliant with a small satellite option, and up-limited by the number of ships expected to be in the FOV. Various studies (Telecommunication Union, 2006; Cervera and Ginesi, 2008; Scorzolini et al., 2010; Eriksen et al., 2006), have limited the FOV and the corresponding instantaneous ground swath on the probability of ship detection, in case of too many ships. These studies have shown that to achieve a ship detection probability of 99% instantaneous ground swath must be limited from 800nm in areas of high maritime traffic areas to 1900 nm in remote ocean regions (Maria Daniela Graziano, 2012).

Analyses of ship density in European waters have shown that an AIS sensor at an altitude of 1.000 km with a field of view-FOV-to the horizon (width swath of

3.630nm) may see up to 6200 ships carrying AIS at the same time (Gudrun K. HZye, 2007).

By default, an AIS station broadcasts alternately on channels 87B and 88B. Other channels can be applied in some regions. The transmitter power of 12.5W and bandwidth of 25 kHz are default settings for the open oceans (Torkild Eriksen∗, 2006). A space-based AIS receiver is depended on the performance and characteristics of the physical layer and the link-layer on the AIS system.

Conference 2015, allocated world radio-communication frequencies for the terrestrial segment of VDES (VHS Data Exchange System) and released considerations of regulatory provisions and spectrum allocations to enable the satellite component of VDES. The VDES satellite component operates in the relevant part of the VHF maritime frequency bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz. The growing demand for maritime data services has led to the development of the VDES system, which integrates the AIS messages (Laura M. Bradburya, 2012). In figure 20 is depicted the AIS link layer requirements.



Parameter	Characteristics
Frequencies	161.975 and 162.025 MHz (channels 87B and 88B)
Wavelength	1.85 m
Transmitter power	2 and 12.5 W
Bandwidth	12.5 and 25.0 kHz
Modulation	Gaussian minimum shift keying (GMSK)
Modulation index	0.25 for 12.5 kHz and 0.5 for 25 kHz
Receiver sensitivity	−107 dBm for 25 kHz and −98 dBm for 12.5 kHz bandwidth
Bit rate	9600 bit/s

Figure 21: AIS link layer requirements

The nominal AIS channels are 161.975 MHz and 162.025 MHz. The two nanosatellites, AISSat-1 and AISSat-2, which had been launched by the Norwegian Defense Research Establishment (FFI), on purpose to study space-based AIS system, have used two channels, 156,775 and 156,825 MHz, for long-range. The IMO to support space-borne AIS system, proposed in 2012 to add a mobile satellite service

(MSS) –Earth to Space- allocation to 156.775 MHz and 156.825 MHz (Channels 75 and 76) for the improved AIS satellite detection using solely type-27 AIS message as specified in recommendation ITU-RM.1371. The proposal has been approved by the 15th World Radio Conference (WRC-15) in 2015 (Shiyou Li, 2017).

These long-range frequencies are referred to as the space AIS channels. Accordingly, the antenna patterns were approximated omnidirectional and the corresponding FOV extends to the horizon in all directions. The antenna was monopole and had a null point along the axis (Skauen, 2015).

Analytical numerical calculations simulations will be executed to define the characteristics of coverage and its quality. Duration of all cases computations will be 24 hours (1 day), to avoid complicated calculations and increased required time to simulate any scenario with an existing computer system (home version).

4.4 Requirements of the Sensor-receiver and Orbit Type

Our satellite receiver will be equipped with similar characteristics to those close to the AIS receiver which had been used in the ‘Tian Tuo-3’ satellite. These parameters are set up on the onboard receiver of each satellite constellation. Due to the lack of detailed parameters to model the receiver, we are going to use the Simple Receiver model, which doesn’t contain all the necessary information. The basis for the FOV approach is the orbit and antenna configuration of the space AIS system (Andreas Nordmo Skauen, 2015). In our satellite constellation, the antenna of the VHF AIS system will be a monopole omnidirectional using two channels (156,775MHz -156,825 MHz). Besides, we will exclude from computations restrictions of the antenna manufacture, weather interference to the received signals through the atmosphere, and any restriction of VHF frequency characteristics. All these, are out of the scope of this dissertation.

4.5 The Orientation of Latitude Coverage

Taking into account the fact that the vast majority of ships traffic, is between latitudes 70° to -60°, it is vital for our constellation design, to restrict the required coverage by excluding the area of global poles, North and South. In figure 22, we can see that the area between latitudes 70° and -60°, can include all the traffic paths of ships. In figure 23, we can observe the global traffic of vessels around the globe.

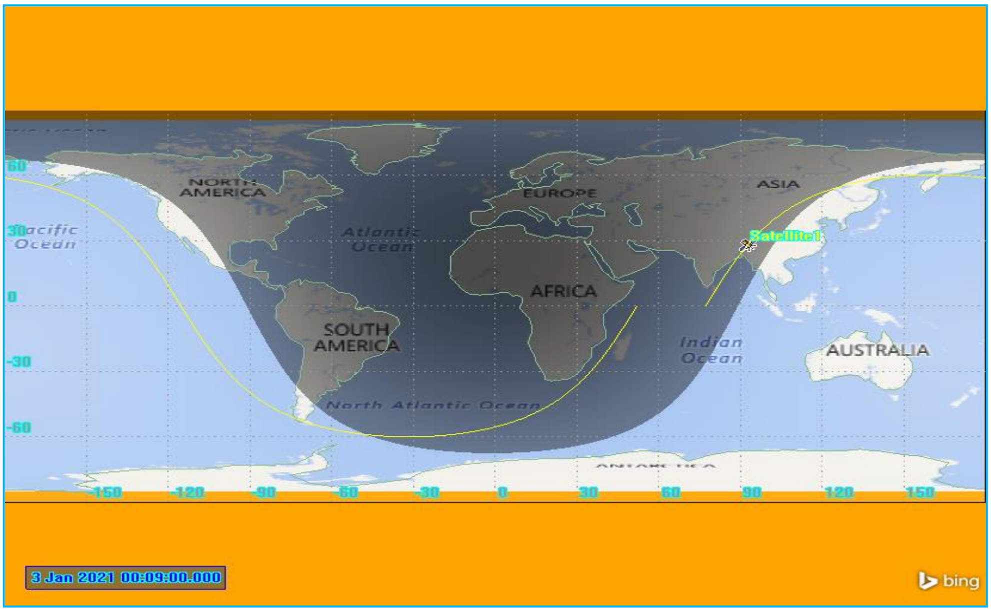


Figure 22: Latitude-dependent coverage/STK 11.2 Version

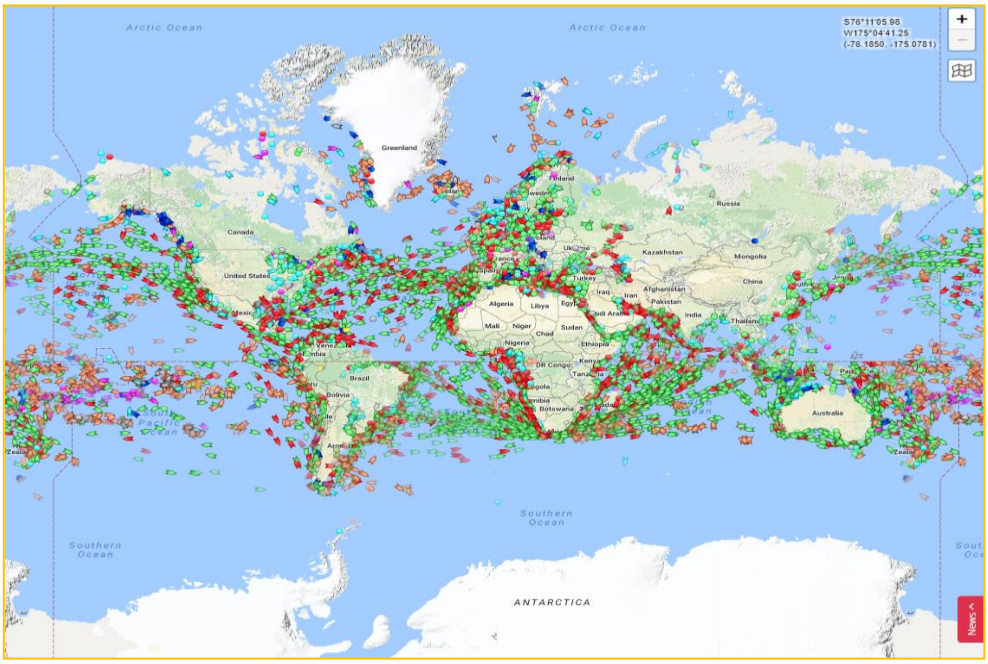


Figure 23: Map of Real-Time of global AIS marine traffic map/
https://blog.adafruit.com/2017/08/29/heres-a-real-time-map-of-global-ais-marine-traffic/

4.6 Weight of Microsatellite, type orbit, and Inclination

The weight of our microsatellite will be 50 Kg. Our microsatellites will not be equipped with the propulsion system, so the lifetime of each will be dependent mainly on altitude, aerodynamic drag, and inclination. For purpose of simplifying parameters and make computations more eligible, we are going to use circular LEO orbits, at the same altitude and inclination, each time.

As concerning the inclination, we are going to use the same inclination for each constellation, at specific values of 30°, 45°, and 60°. Inclination smaller than 30° is most eligible for areas close to the equator, while inclination greater than 60° is not fruitful. Finally, the orientation of the minimum elevation angle will be at 0°. In table 7 is summarized all the setting parameters, which have been described, to calculate and evaluate the global coverage.

4.7 Altitude Determination

The selection of the altitude of the LEO constellation is needed as an important parameter to optimization the design. We should avoid altitude between 1.500 km and 5.000 km because in this area there are erosion irradiation and Val Allen radiation belt, which leads to reduce the lifetime of the satellite. Moreover, below 650 km there are erosive attacks of oxygen atoms and atmospheric drag, which reduces also the lifetime (Saeid Kohani, 2018). Also, we should avoid altitude near 800 km, due to the high concentration of debris at this altitude (figure 13). Given the problems and damage mentioned in LEO orbits, we will examine the three different scenarios of 8, 12 and, 24 satellites, at 650 km and 1350 km.

The selection of the altitude defines the period of each satellite. Period (Appendix C), the time needed to complete one revolves around the earth, is 97.7 minutes for 650 km and 112.6 minutes or 1350 km. So, in 24 hours each satellite makes 15 and 13 revolves around the earth.

Fundamental Characteristics of Satellites Constellation				
Method	**Type Orbit**	**Antenna**	**Modulation**	**Sensor-Detector**
Walker Delta	Circular-LEO	Monopole	GMSK	156.775-156.825
Latitude	**Weight**	**Min Elev Angle**	**Inclination**	
From 70° to -60°	50 Kg	0°	30°-45°-60°	

Table 7: Summarized fundamental Characteristics of Design Constellation

4.8 Parameters to Evaluate Coverage

To assess our scenarios to identify the proper satellite constellation for the best coverage, firstly we will calculate **the mean coverage** of the selected area between latitudes -60° to 70° in twenty-four (24) hours, and secondly**, the revisit time** of each grid point of our analysis.

Coverage analyses are based on the accessibility of assets (objects that provide coverage) and geographical areas. For analysis purposes, the geographical areas of interest are further refined using regions and points. Points have specific geographical locations and are used in the computation of asset availability. Regions are closed boundaries that contain points. Accessibility to a region is computed based on accessibility to the points within that region. The combination of the geographical area, the regions within that area, and the points within each region is called the coverage grid.

Revisit Time measures the intervals during which coverage is not provided (also known as “the gaps”). The dynamic definition of Revisit Time computes the duration of the current gap in coverage for each grid point. If a grid point is accessible at the current time, the gap duration is computed as zero. The computed value is the average of the duration of all the gaps in coverage over the entire coverage interval. If there are N number of gaps, then the average is:

$$\frac{\sum_{i=0}^{N} GapDuration_i}{N}$$

Equation 2

Taking into account previous explanations about coverage and revisit time, we present a table with the simulations results for hundred and eight (108) different options for the scenario of eight (8), twelve (12), and twenty-four (24) satellites making trade-offs between altitude, inclination, and the number of planes options.

Walker Delta Parameters Design 8 Satellites								
Options 8.	Sats	Altitude	Inclination	Planes(p)	Sats per Plane(s)	Pattern Unit(PU)	Node Spacing	In-plane Spacing
Number	Number	Km	Degrees	Number	Number	Degrees	Degrees	Degrees
1	8	650	30°	1	8	45°	0°	45°
2	8	650	45°	1	8	45°	0°	45°
3	8	650	60°	1	8	45°	0°	45°
4	8	1350	30°	1	8	45°	0°	45°
5	8	1350	45°	1	8	45°	0°	45°
6	8	1350	60°	1	8	45°	0°	45°
7	8	650	30°	2	4	45°	180°	090°
8	8	650	45°	2	4	45°	180°	090°
9	8	650	60°	2	4	45°	180°	090°
10	8	1350	30°	2	4	45°	180°	090°
11	8	1350	45°	2	4	45°	180°	090°
12	8	1350	60°	2	4	45°	180°	090°
13	8	650	30°	4	2	45°	090°	180°
14	8	650	45°	4	2	45°	090°	180°
15	8	650	60°	4	2	45°	090°	180°
16	8	1350	30°	4	2	45°	090°	180°
17	8	1350	45°	4	2	45°	090°	180°
18	8	1350	60°	4	2	45°	090°	180°
19	8	650	30°	8	1	45°	45°	360°
20	8	650	45°	8	1	45°	45°	360°
21	8	650	60°	8	1	45°	45°	360°
22	8	1350	30°	8	1	45°	45°	360°
23	8	1350	45°	8	1	45°	45°	360°
24	8	1350	60°	8	1	45°	45°	360°

Table 8: Options of different combinations of 8 Satellites Walker-Delta Method

4.9 The scenario of 8 Satellites Options

The first scenario of the satellite constellation consists of 8 microsatellites. The walker-delta method will be used to determine all possible subclasses, according to various combinations of planes and the number of satellites in total. We will calculate the mean coverage (%) of the designated area between latitudes (70 North to 60 South), and the maximum revisit time for three specific values of inclination: 30°, 45°, and 60°, from two different altitudes of 650 km and 1350 km. The combinations for the walker-delta method (&3.8) are summarized in table 8, taking into account all the subclasses trading-off with altitude, inclination, and planes.

In table 9, summarized the results of all twenty-four (24) simulations of the scenario of eight (8) satellites. The data and the figures of the detailed simulations (STK program) are all collected in a folder, which is accompanied by this dissertation as an Appendix B. The data have shown the mean coverage, the maximum revisit time and the revisit time by latitude.

As we can see in table 9, the maximum mean coverage is achieved at option seventeen (17). At the same time, this option gives the minimum revisit time (21 minutes and 23 seconds). This time represents the average time of coverage gap for the geographical area between specific latitudes. In figure 24, we see the minimum and the maximum revisit time which lies between twelve (12) minutes and forty-two (42) minutes approximately.

In figure 26, we see the distribution of revisit time by latitude. We observe that there is a severe diverge of increased revisit time, for latitudes greater of 50° north and -50° south. Also, there is an increase of revisit time between the latitude of 20° and 5° on both sides of the equator.

Walker Delta Parameters Design 8 Sat Max Revisit Time Figure of Merit-FOM					
Option 8.	**Altitude Km**	**Inclination Degrees**	**Planes**	**Revisit Time (Hours)**	**Mean Coverage (%)**
1	650	30°	1	11.3	39.74
2	650	45°	1	9.98	39.22
3	650	60°	1	9.2	36.42
4	1350	30°	1	8.2	58.67
5	1350	45°	1	8.3	51.62
6	1350	60°	1	7.8	52.52
7	650	30°	2	4.5	35.34
8	650	45°	2	3.2	34.35
9	650	60°	2	4	35.04
10	1350	30°	2	1.7	68.05
11	1350	45°	2	1.1	65.80
12	1350	60°	2	2.44	58.91
13	650	30°	4	2.95	41.25
14	650	45°	4	0.7	40.78
15	650	60°	4	0.99	37.59
16	1350	30°	4	1.1	71.04
17	1350	45°	4	21.23 min	72.16
18	1350	60°	4	26.40 min	65.21
19	650	30°	8	2.93	36.15
20	650	45°	8	45.44 min	37.30
21	650	60°	8	51.18 min	35.14
22	1350	30°	8	60.08	62.90
23	1350	45°	8	29.48 min	65.67
24	1350	60°	8	39.20 min	62.10

Table 9: Results scenario options of 8 satellites/ STK Version 11.2

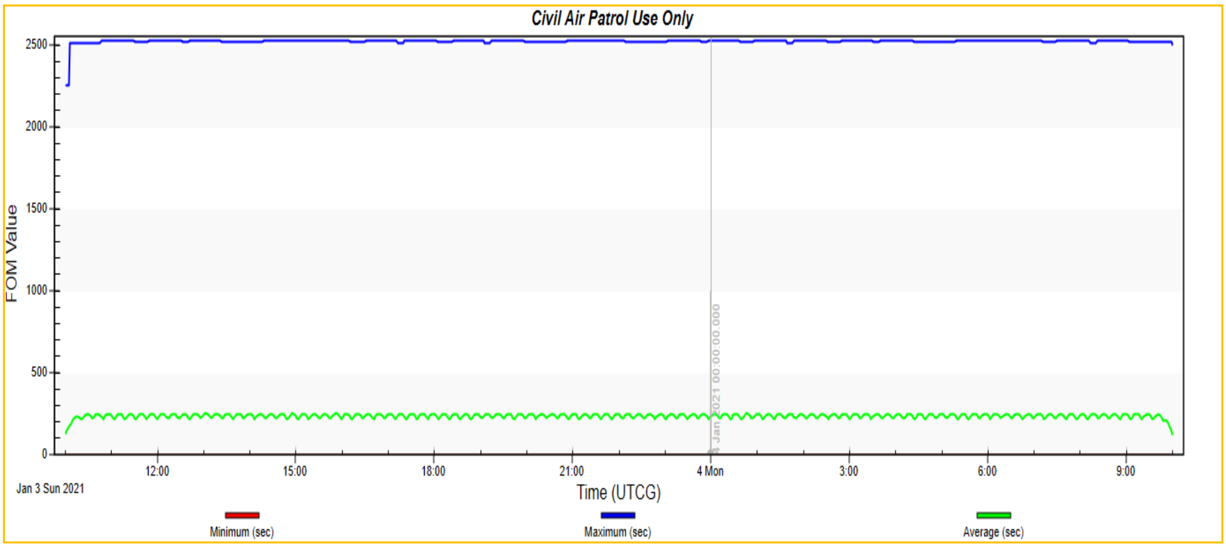
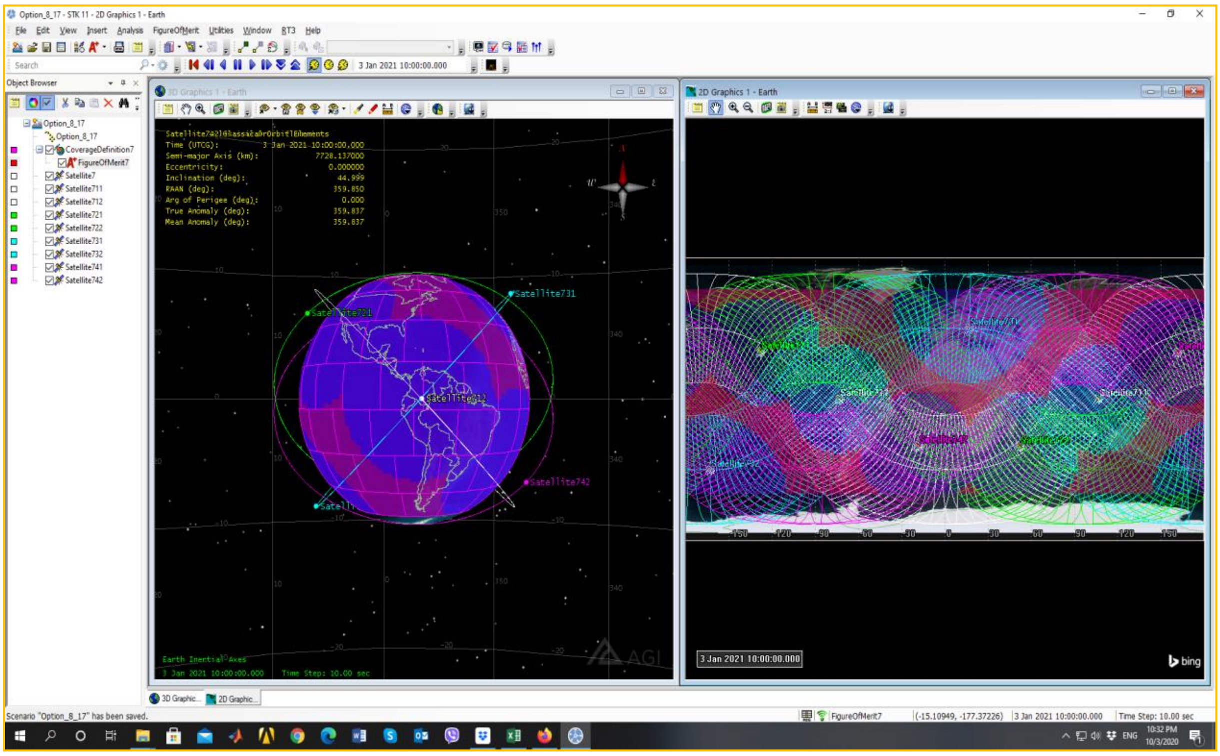


Figure 24: Diagram of maximum and minimum revisit time/scenario 8.17/STK 11.2 Version



```
Satellite742 ClassicalOrbitElements
Time (UTCG):              3 Jan 2021 10:00:00.000
Semi-major Axis (km):              7728.137000
Eccentricity:                         0.000000
Inclination (deg):                      44.999
RAAN (deg):                            359.850
Arg of Perigee (deg):                    0.000
True Anomaly (deg):                    359.837
Mean Anomaly (deg):                    359.837

Earth Inertial Axes
3 Jan 2021 10:00:00.000   Time Step: 10.00 sec
```

3 Jan 2021 10:00:00.000

Scenario "Option_8_17" has been saved. FigureOfMerit7 (-15.10949, -177.37226) 3 Jan 2021 10:00:00.000 Time Step: 10.00 sec

ENG 10:32 PM 10/3/2020

Figure 25: Calculation of coverage of option 8.17/STK 11.2 version

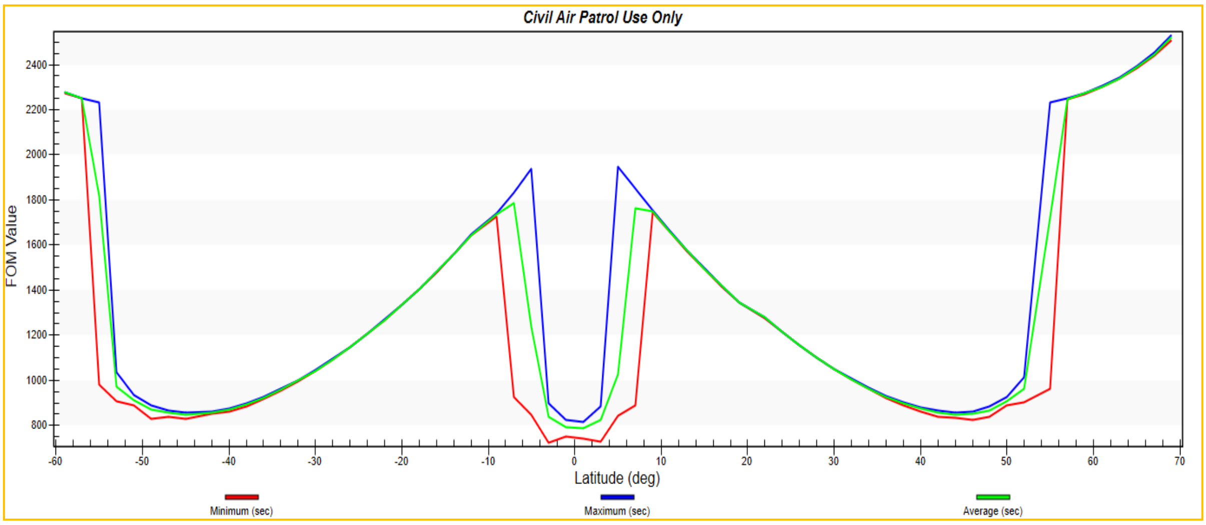


Figure 26: FOM of revisit time by latitude/8.17 Scenario/STK 11.2 version

4.10 The scenario of 12 Satellites

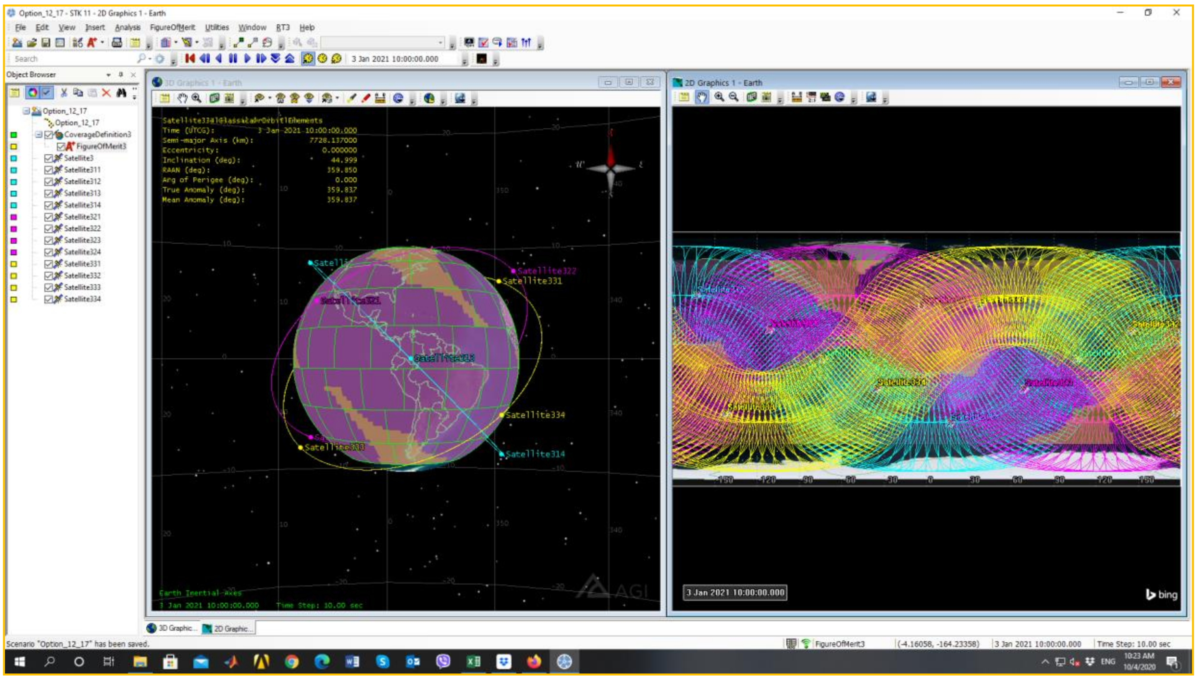
In the second scenario of twelve (12) satellites, we implement the same parameters as it was in the first one, concerning the altitude, planes, and inclination. In table 10, it is shown the thirty-six (36) different combinations, using the walker-delta method. The results of the simulations are summarized in table 11. We notice that the best mean coverage is achieved in option eleven (11). In the same option, the revisit time is not the best one. The best revisit time is achieved in option seventeen (17), with nine (9) minutes and four (4) seconds. Also, we see in table eleven (11) that there are similar results in option seventeen (17). Both options were designed from an altitude of 1350 km and have the same inclination of 45°. Moreover, there is another option-29th – with almost the same revisit time as option seventeen (17). In option 29, the mean coverage decreases a little bit (from 85.71% to 83.74%), but in option 29 the revisit time by latitude gives better results and smaller revisit time for latitudes between 20° and 50°, in both sides, North and South. Figures 27 and 28, display the two different option

Walker Delta Parameters Design 12 Satellites								
Options 12.	Sats	Altitude	Inclination	Planes(p)	Sats per Plane(s)	Pattern Unit(PU)	Node Spacing	In-plane Spacing
Number	Number	Km	Degrees	Number	Number	Degrees	Degrees	Degrees
1	12	650	30°	1	12	30°	0°	30°
2	12	650	45°	1	12	30°	0°	30°
3	12	650	60°	1	12	30°	0°	30°
4	12	1350	30°	1	12	30°	0°	30°
5	12	1350	45°	1	12	30°	0°	30°
6	12	1350	60°	1	12	30°	0°	30°
7	12	650	30°	2	6	30°	180°	60°
8	12	650	45°	2	6	30°	180°	60°
9	12	650	60°	2	6	30°	180°	60°
10	12	1350	30°	2	6	30°	180°	60°
11	12	1350	45°	2	6	30°	180°	60°
12	12	1350	60°	2	6	30°	180°	60°
13	12	650	30°	3	4	30°	120°	090°
14	12	650	45°	3	4	30°	120°	090°
15	12	650	60°	3	4	30°	120°	090°
16	12	1350	30°	3	4	30°	120°	090°
17	12	1350	45°	3	4	30°	120°	090°
18	12	1350	60°	3	4	30°	120°	090°
19	12	650	30°	4	3	30°	90°	120°
20	12	650	45°	4	3	30°	90°	120°
21	12	650	60°	4	3	30°	90°	120°
22	12	1350	30°	4	3	30°	90°	120°
23	12	1350	45°	4	3	30°	90°	120°
24	12	1350	60°	4	3	30°	90°	120°
25	12	650	30°	6	2	30°	180°	180°
26	12	650	45°	6	2	30°	180°	180°
27	12	650	60°	6	2	30°	180°	180°
28	12	1350	30°	6	2	30°	180°	180°
29	12	1350	45°	6	2	30°	180°	180°
30	12	1350	60°	6	2	30°	180°	180°
31	12	650	30°	1	6	30°	0°	360°
32	12	650	45°	1	6	30°	0°	360°
33	12	650	60°	1	6	30°	0°	360°
34	12	1350	30°	1	6	30°	0°	360°
35	12	1350	45°	1	6	30°	0°	360°
36	12	1350	60°	1	6	30°	0°	360°

Table 10: Options of different combinations of 12 Satellites Walker-Delta Method

Walker Delta Parameters Design 12 Sat Max Revisit Time Figure of Merit- FOM					
Option 12.	**Altitude Km**	**Inclination Degrees**	**Planes**	**Revisit Time (Hours)**	**Mean Coverage (%)**
1	650	30°	1	11.24	44.03
2	650	45°	1	9.89	43.28
3	650	60°	1	9.18	40.09
4	1350	30°	1	8.23	60.86
5	1350	45°	1	8.21	58.27
6	1350	60°	1	7.76	54.53
7	650	30°	2	4.1	55.77
8	650	45°	2	2.83	55.49
9	650	60°	2	3.85	50.26
10	1350	30°	2	1.54	85.95
11	1350	45°	2	55.33 min	86.74
12	1350	60°	2	2.3	75.71
13	650	30°	3	2.9	58.17
14	650	45°	3	41.30 min	56.91
15	650	60°	3	71 min	49.60
16	1350	30°	3	56.49 min	84.14
17	1350	45°	3	9.04 min	85.51
18	1350	60°	3	42.37 min	78.26
19	650	30°	4	2.8	36.79
20	650	45°	4	30.47 min	45.75
21	650	60°	4	49 min	48.72
22	1350	30°	4	62.48 min	58.04
23	1350	45°	4	16.09 min	69.38
24	1350	60°	4	20.18 min	73.83
25	650	30°	6	2.7	45.18
26	650	45°	6	21.55 min	52.21
27	650	60°	6	25.45 min	52.13
28	1350	30°	6	55.11 min	72.95
29	1350	45°	6	9.2 min	83.74
30	1350	60°	6	11.37 min	80.13
31	650	30°	12	2.8	54.23
32	650	45°	12	37.20 min	55.95
33	650	60°	12	43.55 min	51.57
34	1350	30°	12	58.18 min	83.83
35	1350	45°	12	19.42 min	82.60
36	1350	60°	12	30.08	72.86

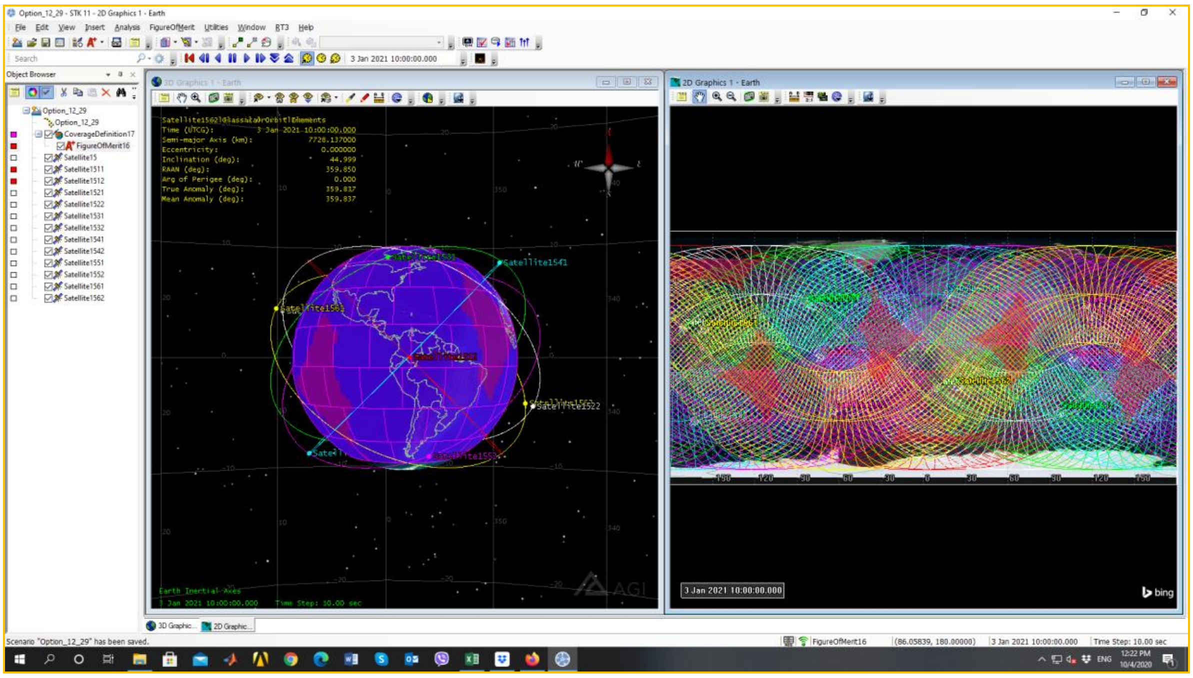
Table 11: Results scenario options of 12 satellites/ STK Version 11.2



```
Time (UTCG):                3 Jan 2021 10:00:00.000
Semi-major Axis (km):                  7728.137000
Eccentricity:                             0.000000
Inclination (deg):                          44.999
RAAN (deg):                                359.850
Arg of Perigee (deg):                        0.000
True Anomaly (deg):                        359.837
Mean Anomaly (deg):                        359.837
```

Scenario "Option_12_17" has been saved.

Figure 27: Calculation of coverage of option 17/12 Satellites/STK 11.2 version



```
Time (UTCG):                3 Jan 2021 10:00:00.000
Semi-major Axis (km):                  7728.137000
Eccentricity:                             0.000000
Inclination (deg):                          44.999
RAAN (deg):                                359.850
Arg of Perigee (deg):                        0.000
True Anomaly (deg):                        359.837
Mean Anomaly (deg):                        359.837
```

Scenario "Option_12_29" has been saved.

Figure 28: Calculation of coverage of option 29/12 Satellites/STK 11.2 version

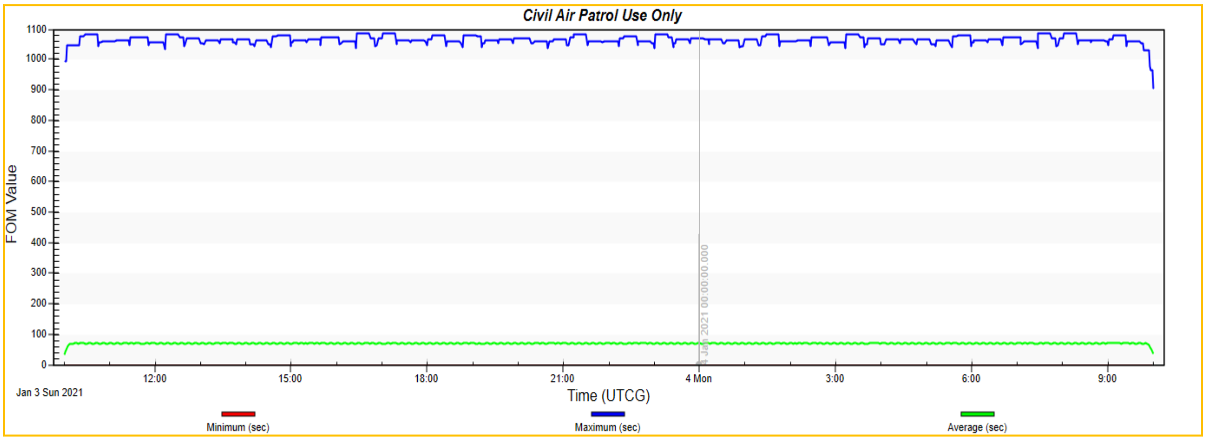


Figure 29: Diagram of maximum and minimum revisit time/scenario 12.17/STK

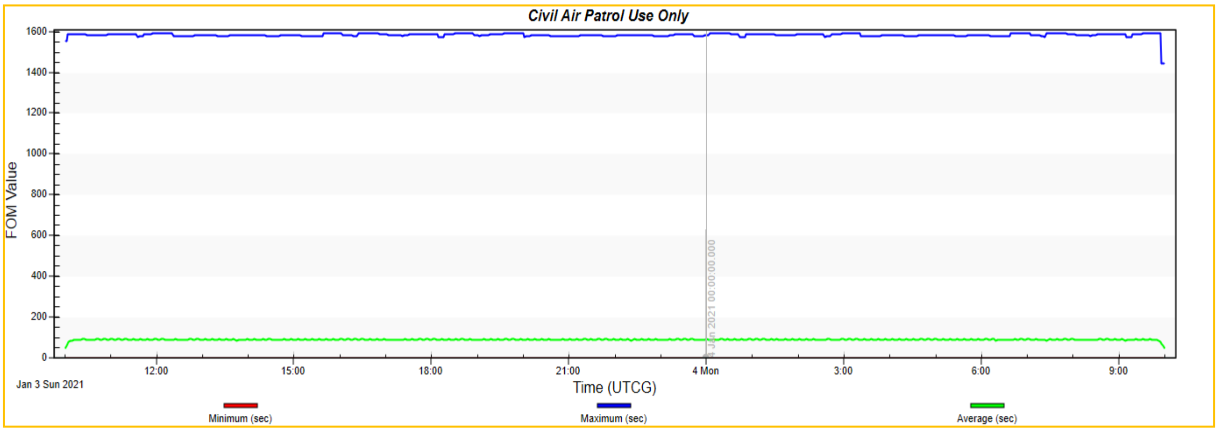


Figure 30: Diagram of maximum and minimum revisit time/scenario 12.29/STK

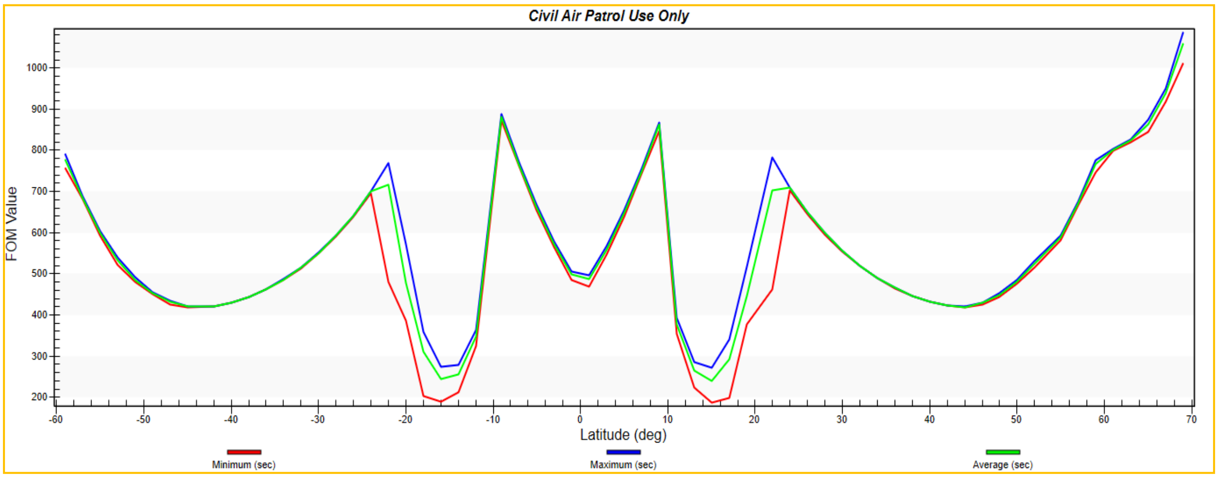


Figure 31: FOM of revisit time by latitude/option 12.17/STK 11.2 version

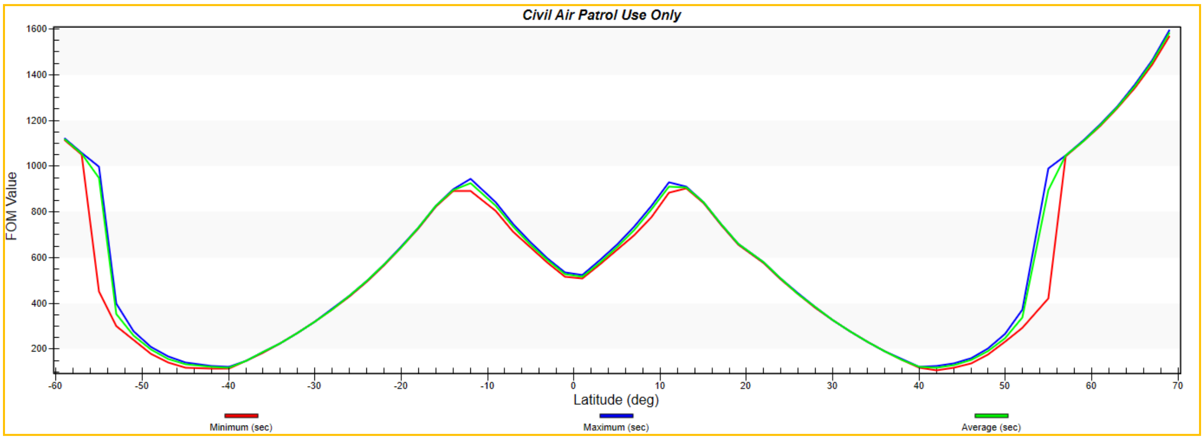
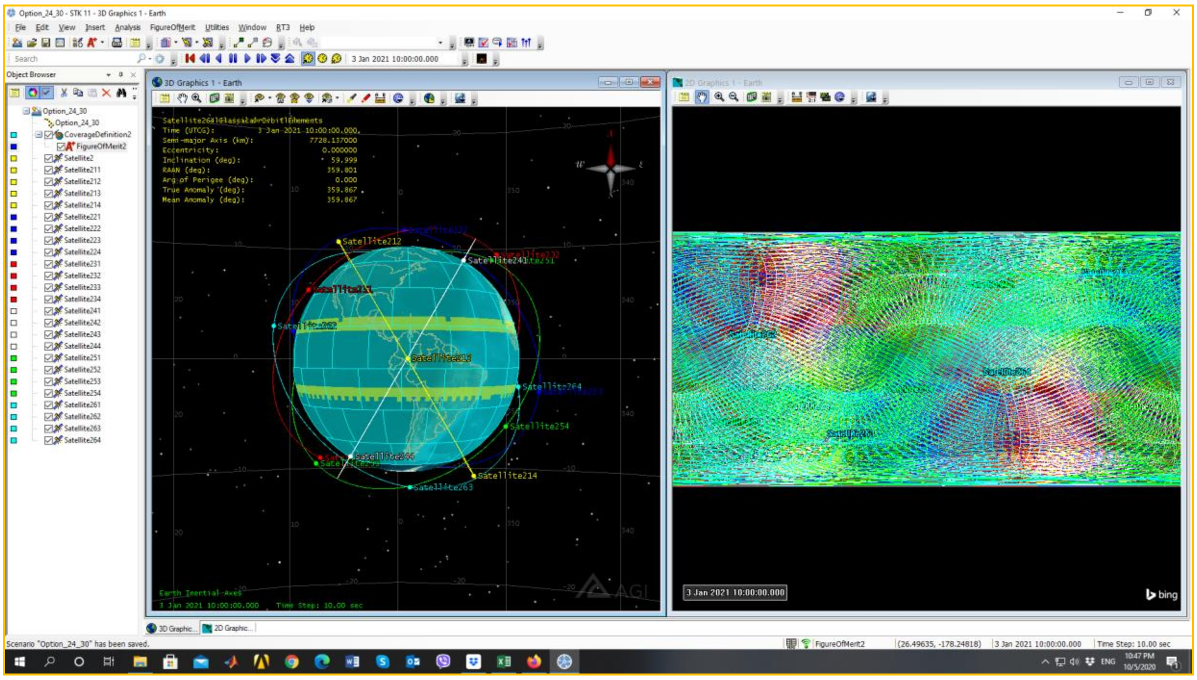


Figure 32: FOM of revisit time by latitude/option 12.29/STK 11.2 version

The selection between these two options depends on the requirements of the placeholders. For instance, if needed better revisit time near to the equator, we would prefer option seventeen (17).

4.11 The scenario of 24 Satellites

In the third scenario of twenty-four (24) satellites, we have explored forty-eight (48) different options. In tables 12 and 13, is summarized detailed parameters concerning altitude, number of planes, and inclination, which were traded-off to create total options. Results are depicted in tables 14 and 15. In these tables, we notice that the best mean coverage is at option seventeen (17) with approximately the same percentage at options 23, 29, 30, and 35. As regards the revisit time we observe that the minimum time is in options 17, 29, and 30. To support our decision for the best option we have to study the revisit time by latitude. Figures 32 to 37, display the minimum and maximum revisit time by latitude. We notice that there are variations on maximum revisit time near to equator till latitudes of 10° and 20°. In conclusion, option 30 entails the best mean coverage in coordination with the best revisit time. Figure 33 illustrates the simulation coverage for option 30 and figure 34 represents the diagram of maximum and minimum value of revisit time.



```
Satellite261 Classical Orbit Elements
Time (UTCG):                3 Jan 2021 10:00:00.000
Semi-major Axis (km):              7728.137000
Eccentricity:                         0.000000
Inclination (deg):                      59.999
RAAN (deg):                            359.801
Arg of Perigee (deg):                    0.000
True Anomaly (deg):                    359.867
Mean Anomaly (deg):                    359.867
```

Scenario "Option_24_30" has been saved.

Figure 33: Calculation of coverage of option 24.30/STK 11.2 version

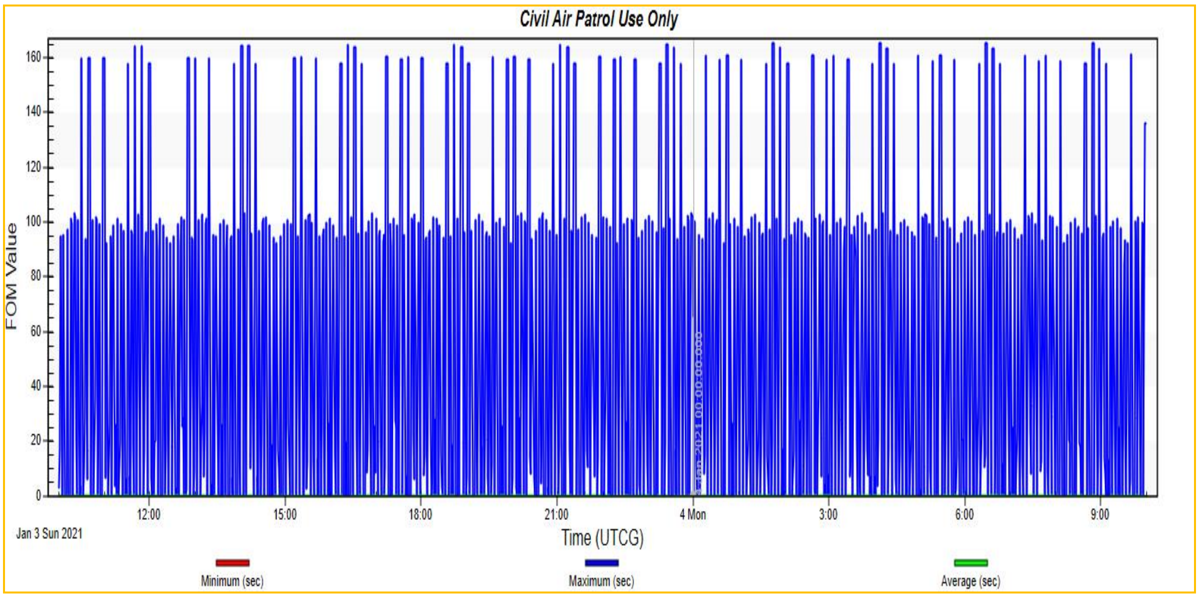


Figure 34: Diagram of maximum and minimum revisit time/scenario 24.30/STK 11.2 version

Walker Delta Parameters Design 24 Satellites

Options 24.	Sats	Altitude	Inclination	Planes(p)	Sats per Plane(s)	Pattern Unit(PU)	Node Spacing	In plane Spacing
Number	Number	Km	Degrees	Number	Number	Degrees	Degrees	Degrees
1	24	650	30°	1	24	15°	0°	15°
2	24	650	45°	1	24	15°	0°	15°
3	24	650	60°	1	24	15°	0°	15°
4	24	1350	30°	1	24	15°	0°	15°
5	24	1350	45°	1	24	15°	0°	15°
6	24	1350	60°	1	24	15°	0°	15°
7	24	650	30°	2	12	15°	180°	30°
8	24	650	45°	2	12	15°	180°	30°
9	24	650	60°	2	12	15°	180°	30°
10	24	1350	30°	2	12	15°	180°	30°
11	24	1350	45°	2	12	15°	180°	30°
12	24	1350	60°	2	12	15°	180°	30°
13	24	650	30°	3	8	15°	120°	45°
14	24	650	45°	3	8	15°	120°	45°
15	24	650	60°	3	8	15°	120°	45°
16	24	1350	30°	3	8	15°	120°	45°
17	24	1350	45°	3	8	15°	120°	45°
18	24	1350	60°	3	8	15°	120°	45°
19	24	650	30°	4	6	15°	90°	60°
20	24	650	45°	4	6	15°	90°	60°
21	24	650	60°	4	6	15°	90°	60°
22	24	1350	30°	4	6	15°	90°	60°
23	24	1350	45°	4	6	15°	90°	60°
24	24	1350	60°	4	6	15°	90°	60°
25	24	650	30°	6	4	15°	60°	90°
26	24	650	45°	6	4	15°	60°	90°
27	24	650	60°	6	4	15°	60°	90°
28	24	1350	30°	6	4	15°	60°	90°
29	24	1350	45°	6	4	15°	60°	90°
30	24	1350	60°	6	4	15°	60°	90°
31	24	650	30°	8	3	15°	45°	120°
32	24	650	45°	8	3	15°	45°	120°
33	24	650	60°	8	3	15°	45°	120°
34	24	1350	30°	8	3	15°	45°	120°
35	24	1350	45°	8	3	15°	45°	120°
36	24	1350	60°	8	3	15°	45°	120°

Table 12: Options of different combinations of 24 Satellites Walker-Delta Method

Walker Delta Parameters Design 24 Satellites (cont 2)								
Options 24.	Sats	Altitude	Inclination	Planes(p)	Sats per Plane(s)	Pattern Unit(PU)	Node Spacing	In-plane Spacing
Number	Number	Km	Degrees	Number	Number	Degrees	Degrees	Degrees
37	24	650	30°	12	2	15°	30°	180°
38	24	650	45°	12	2	15°	30°	180°
39	24	650	60°	12	2	15°	30°	180°
40	24	1350	30°	12	2	15°	30°	180°
41	24	1350	45°	12	2	15°	30°	180°
42	24	1350	60°	12	2	15°	30°	180°
43	24	650	30°	1	24	15°	0°	15°
44	24	650	45°	1	24	15°	0°	15°
45	24	650	60°	1	24	15°	0°	15°
46	24	1350	30°	1	24	15°	0°	15°
47	24	1350	45°	1	24	15°	0°	15°
48	24	1350	60°	1	24	15°	0°	15°

Table 13: Options of different combinations of 24 Satellites Walker-Delta Method (cont.2)

Walker Delta Parameters Design 24 Sat Max Revisit Time Figure of Merit- FOM					
Option 24.	**Altitude Km**	**Inclination Degrees**	**Planes**	**Revisit Time (Hours)**	**Mean Coverage (%)**
1	650	30°	1	11.2	46.08
2	650	45°	1	9.85	45.18
3	650	60°	1	9.14	41.84
4	1350	30°	1	8.18	61.99
5	1350	45°	1	8.16	59.30
6	1350	60°	1	7.71	55.46
7	650	30°	2	3.99	74.19
8	650	45°	2	2.7	74.80
9	650	60°	2	3.7	66.20
10	1350	30°	2	60.28 min	90.82
11	1350	45°	2	50.05 min	92.27
12	1350	60°	2	2.2	80.34
13	650	30°	3	2.7	81.09
14	650	45°	3	27.48 min	88.26
15	650	60°	3	56.51 min	81.42
16	1350	30°	3	51.20 min	94.38
17	1350	45°	3	2 sec	99.97
18	1350	60°	3	4.52 min	98.05
19	650	30°	4	2.3	80.57
20	650	45°	4	12.50 min	86.04
21	650	60°	4	32.45 min	78.81
22	1350	30°	4	45.52 min	93.82
23	1350	45°	4	14.5 sec	99.66
24	1350	60°	4	5.23 min	97.32
25	650	30°	6	2.42	79.88
26	650	45°	6	3.48 min	93.59
27	650	60°	6	7.28 min	85.74
28	1350	30°	6	44.38 min	94.34
29	1350	45°	6	2.2 sec	99.96
30	1350	60°	6	6.2 sec	99.96
31	650	30°	8	2.4	73.41
32	650	45°	8	6.51 min	85.67
33	650	60°	8	9.07 min	80.79
34	1350	30°	8	44.31 min	94.53
35	1350	45°	8	22 sec	99.46
36	1350	60°	8	1.56 min	97.26

Table 14: Results scenario options of 24 satellites/ STK Version 11.2

Walker Delta Parameters Design 24 Sat Max Revisit Time Figure of Merit- FOM (cont 2)					
Option 24.	**Altitude Km**	**Inclination Degrees**	**Planes**	**Revisit Time (Hours)**	**Mean Coverage (%)**
37	650	30°	12	2.44	80.04
38	650	45°	12	8.4 min	84.39
39	650	60°	12	12.45 min	75.03
40	1350	30°	12	45.45 min	93.41
41	1350	45°	12	1.15 min	98.7
42	1350	60°	12	4.37 min	92.5
43	650	30°	24	2.6	71.79
44	650	45°	24	29.40 min	69.46
45	650	60°	24	37 min	60.13
46	1350	30°	24	53.45 min	88.06
47	1350	45°	24	14.8 min	87.49
48	1350	60°	24	24.40 min	77.11

Table 15: Results scenario options of 24 satellites/ STK Version 11.2

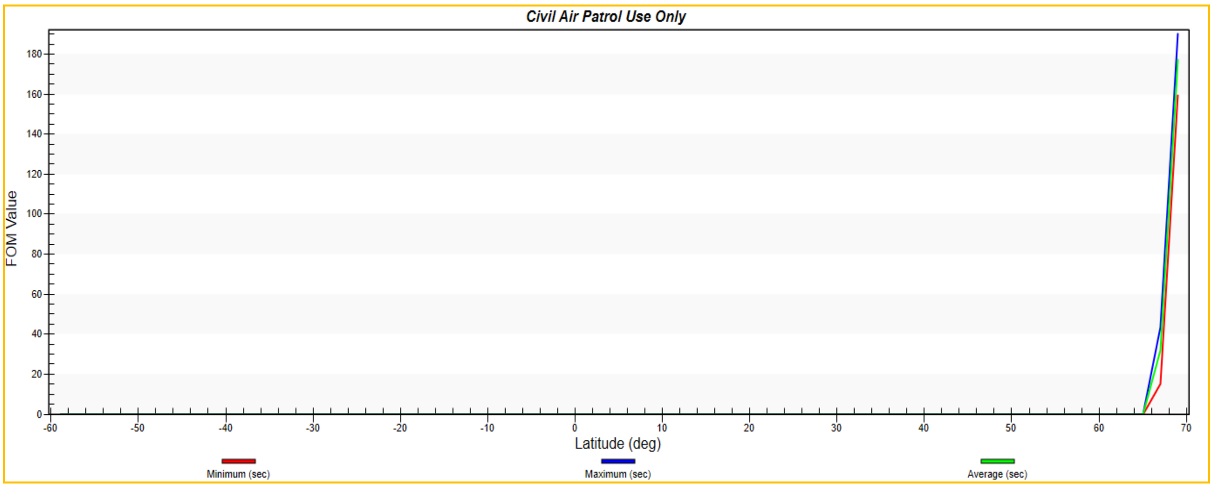


Figure 35: FOM of revisit time by latitude/option 24.17/STK 11.2 version

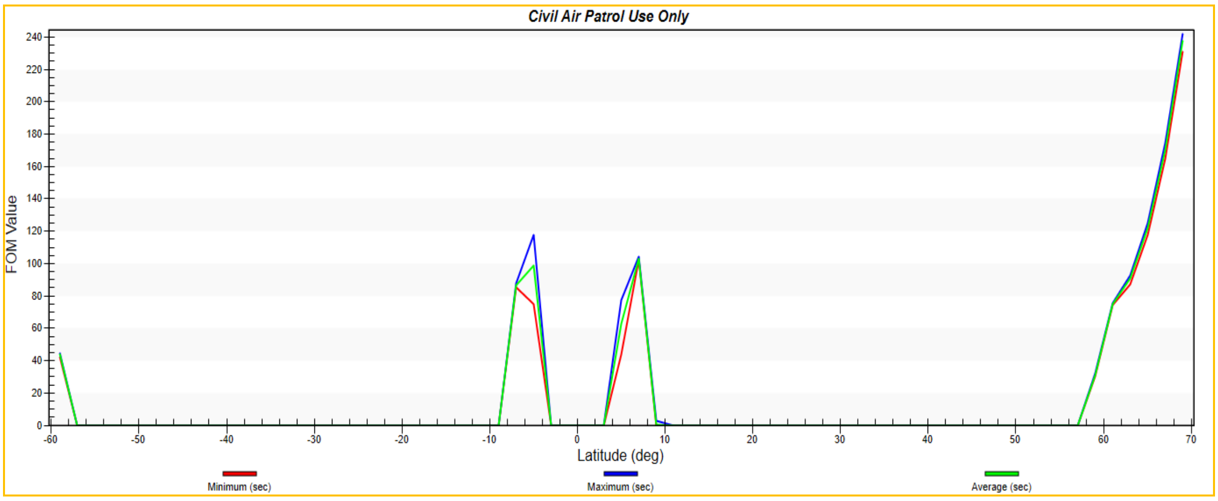


Figure 36: FOM of revisit time by latitude/option 24.23/STK 11.2 version

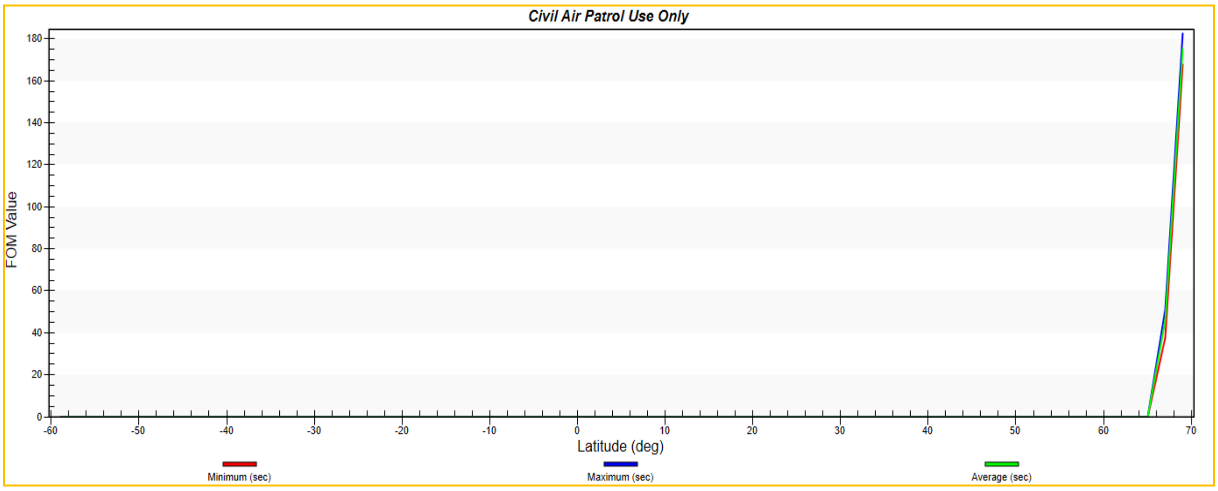


Figure 37: FOM of revisit time by latitude/option 24.29/STK 11.2 version

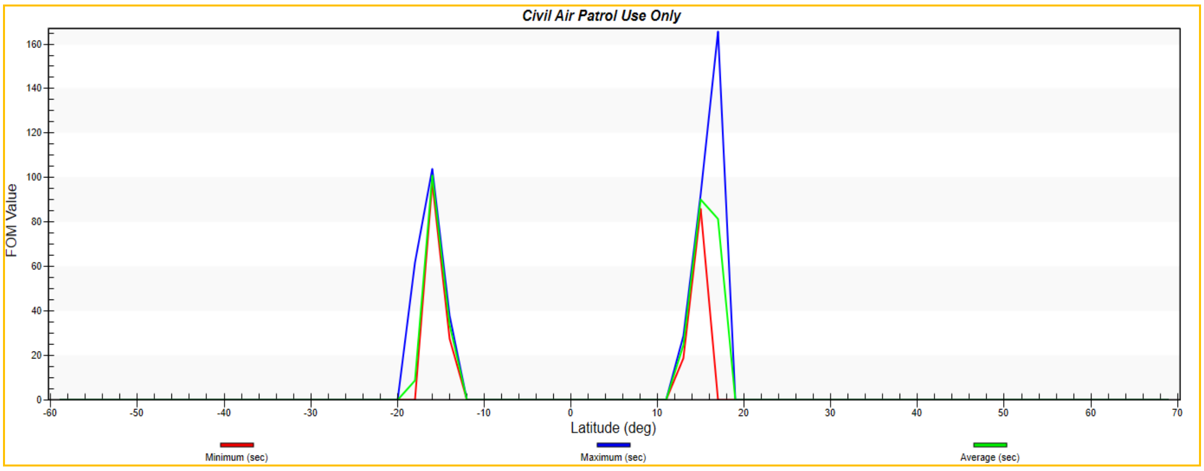


Figure 38: FOM of revisit time by latitude/option 24.30/STK 11.2 version

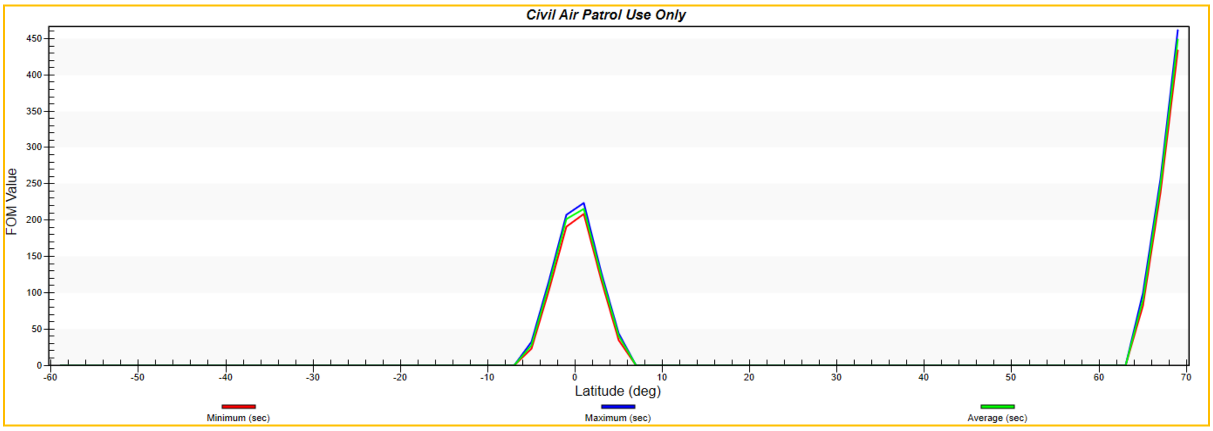


Figure 39: FOM of revisit time by latitude/option 24.35/STK 11.2 version

4.11 The scenario of Hellenic Interesting Region

We have calculated mean coverage and revisit time for the region between latitudes 70° north and 60° south. This region includes also the subpart which defined between latitudes 50° north and 30° north, and between longitudes 10° west and 40° east as depicted in figure 40 and 41. This defined region, is a great of interest for the Hellenic administration, due to strategic reasons not only for shipping but also for defense. As we can see, the Mediterranean, which plays a significant role in Hellenic interests, is included in the area. To cover the area of interest, and support the AIS system with minimum revisit time, we will calculate values of coverage and revisit time, for the same scenarios identified at the beginning of this work.

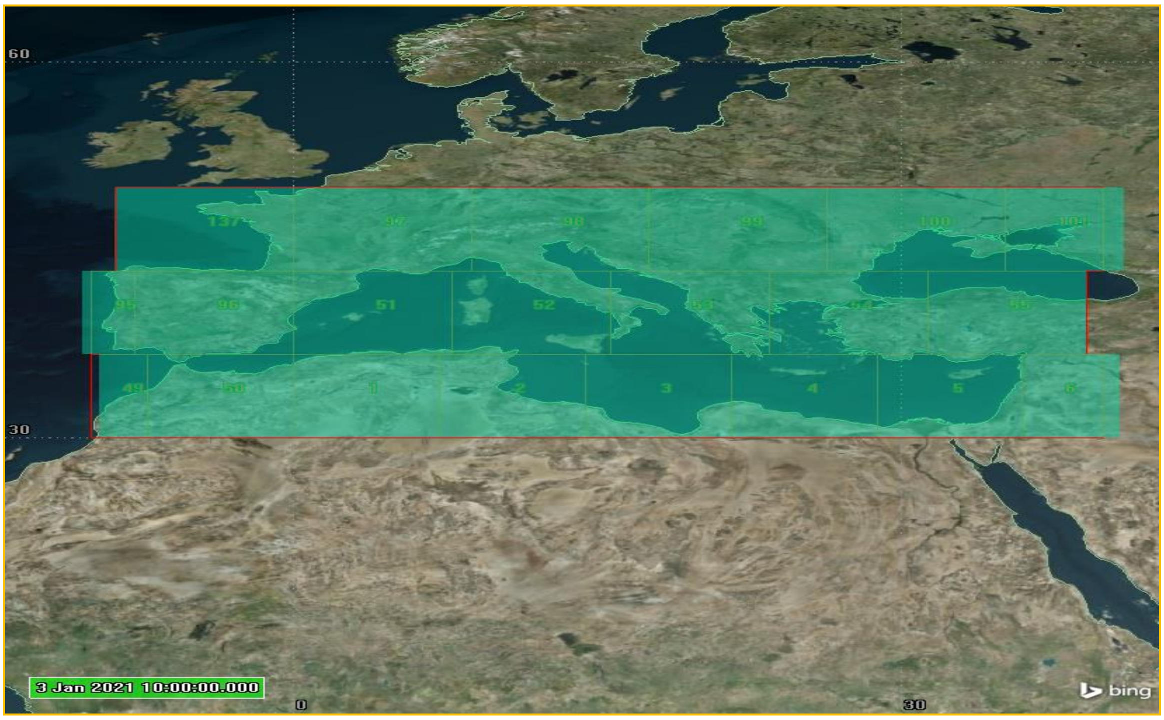
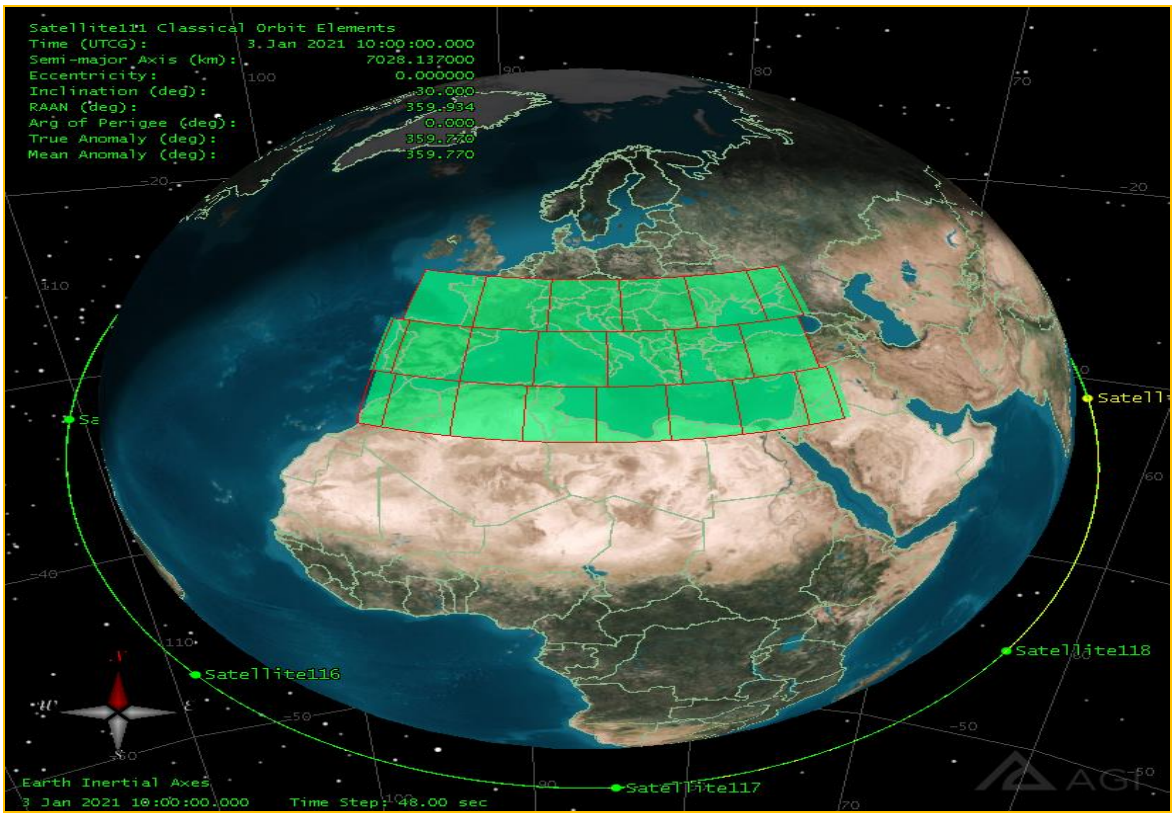


Figure 40: Region of Hellenic Interests/STK 11.2



```
Satellite111 Classical Orbit Elements
Time (UTCG):              3.Jan 2021 10:00:00.000
Semi-major Axis (km):                 7028.137000
Eccentricity:                            0.000000
Inclination (deg):                         30.000
RAAN (deg):                               359.934
Arg of Perigee (deg):                       0.000
True Anomaly (deg):                       359.770
Mean Anomaly (deg):                       359.770
```

Figure 41: Region of Hellenic Interests/STK 11.

Walker Delta Parameters Design 8 Sat Max Revisit Time Figure of Merit-FOM-HELLENIC REGION					
Option 8.	**Altitude Km**	**Inclination Degrees**	**Planes**	**Revisit Time (Hours)**	**Mean Coverage (%)**
1	650	30°	1	8.3	31.12
2	650	45°	1	7.23	38.50
3	650	60°	1	6.4	44.42
4	1350	30°	1	6.9	47.36
5	1350	45°	1	6.2	49.92
6	1350	60°	1	5.5	59.69
7	650	30°	2	3.3	28.85
8	650	45°	2	1.11	41.60
9	650	60°	2	56.42 min	45.28
10	1350	30°	2	49 min	61.22
11	1350	45°	2	12.28 min	72.28
12	1350	60°	2	11.47 min	73.90
13	650	30°	4	41.42 min	32.51
14	650	45°	4	31.12 min	46.89
15	650	60°	4	22.05 min	45.54
16	1350	30°	4	28.15 min	62.30
17	1350	45°	4	15.08 min	74.51
18	1350	60°	4	14.55 min	72.81
19	650	30°	8	50.55 min	32.36
20	650	45°	8	33.23 min	46.47
21	650	60°	8	28 min	46.62
22	1350	30°	8	31.05 min	62.38
23	1350	45°	8	22.17 min	76.28
24	1350	60°	8	14.25 min	81.50

Table 16: Results Hellenic Region options of 8 satellites/ STK Version 11.2

In table 16, which summarized options for the scenario of eight (8) satellites, option 12.24 is the best for mean coverage, while option 12.12 gives the minimum revisit time. Both options can be used for constellation design to support a similar performance. Also, option 12.11 has equal coverage and revisit time. Option 12.11 is preferred due to fewer planes, which entails an easier and chipper way to launched satellites into orbits.

Walker Delta Parameters Design 12 Sat Max Revisit Time Figure of Merit- FOM HELLENIC REGION					
Option 12.	**Altitude Km**	**Inclination Degrees**	**Planes**	**Revisit Time (Hours)**	**Mean Coverage (%)**
1	650	30°	1	8.4	35.45
2	650	45°	1	7.2	46.02
3	650	60°	1	6.4	48.99
4	1350	30°	1	6.8	49.08
5	1350	45°	1	6.1	55.22
6	1350	60°	1	5.5	60.83
7	650	30°	2	3.0	49.34
8	650	45°	2	46.28 min	70.47
9	650	60°	2	48.36 min	67/64
10	1350	30°	2	39.51 min	87.32
11	1350	45°	2	1.51 min	98.77
12	1350	60°	2	2.20 min	97.30
13	650	30°	3	36.25 min	48.82
14	650	45°	3	12.25 min	63.16
15	650	60°	3	50.37 min	55.89
16	1350	30°	3	8.50 min	81.57
17	1350	45°	3	15.07 min	74.51
18	1350	60°	3	14.55min	72.81
19	650	30°	4	22.20 min	40.63
20	650	45°	4	19.39 min	56.22
21	650	60°	4	15.18 min	59.69
22	1350	30°	4	17.35 min	64.29
23	1350	45°	4	10.20 min	78.61
24	1350	60°	4	10.00 min	86.05
25	650	30°	6	21.48 min	46.40
26	650	45°	6	13.28 min	65.87
27	650	60°	6	14.20 min	63.66
28	1350	30°	6	11 min	79.78
29	1350	45°	6	3.03 min	94.10
30	1350	60°	6	5.05 min	90.68
31	650	30°	12	42.30 min	48.59
32	650	45°	12	25.24 min	70.12
33	650	60°	12	22.02 min	69.37
34	1350	30°	12	21.10 min	83.08
35	1350	45°	12	11.45 min	92.21
36	1350	60°	12	5.34 min	95.82

Table 17: Results Hellenic Region options of 12 satellites/ STK Version 11.2

Walker Delta Parameters Design 24 Sat Max Revisit Time Figure of Merit- FOM HELLENIC REGION					
Option 24.	**Altitude Km**	**Inclination Degrees**	**Planes**	**Revisit Time (Hours)**	**Mean Coverage (%)**
1	650	30°	1	8.31	37.24
2	650	45°	1	7.15	47.11
3	650	60°	1	6.3	51.03
4	1350	30°	1	6.8	50
5	1350	45°	1	6.11	55.87
6	1350	60°	1	5.45	61.37
7	650	30°	2	2.85	72.92
8	650	45°	2	40.10 min	93.12
9	650	60°	2	40.30 min	91.4
10	1350	30°	2	31.10 min	95.04
11	1350	45°	2	1.4 sec	100
12	1350	60°	2	0	100
13	650	30°	3	22 min	85.46
14	650	45°	3	28 sec	99.47
15	650	60°	3	37.50 min	83.89
16	1350	30°	3	51.20 min	94.38
17	1350	45°	3	0 sec	100
18	1350	60°	3	15 sec	99.76
19	650	30°	4	5.29 min	81.75
20	650	45°	4	2.21 min	95.38
21	650	60°	4	3.38 min	94.32
22	1350	30°	4	5 sec	99.87
23	1350	45°	4	0 sec	100
24	1350	60°	4	0 min	100
25	650	30°	6	8.21 min	79.84
26	650	45°	6	1.37 min	98.27
27	650	60°	6	1.50 min	97.22
28	1350	30°	6	4.8 sec	99.91
29	1350	45°	6	0 sec	100
30	1350	60°	6	0 sec	100
31	650	30°	8	6 min	80.85
32	650	45°	8	42 sec	98.44
33	650	60°	8	5.1 min	88.08
34	1350	30°	8	0 min	100
35	1350	45°	8	0 sec	100
36	1350	60°	8	14 sec	99.95

Table 18**:** Results Hellenic Region options of 24 satellites/ STK Version 11.

Walker Delta Parameters Design 24 Sat Max Revisit Time Figure of Merit- FOM HELLENIC REGION (cont 2)

Option 24.	Altitude Km	Inclination Degrees	Planes	Revisit Time (Hours)	Mean Coverage (%)
37	650	30°	12	8.24 min	84.22
38	650	45°	12	36 sec	99.12
39	650	60°	12	6.05 min	86.84
40	1350	30°	12	27 sec	99.80
41	1350	45°	12	0 min	100
42	1350	60°	12	0.5 sec	100
43	650	30°	24	32.45 min	65.89
44	650	45°	24	18.27 min	81.36
45	650	60°	24	14.51 min	82.49
46	1350	30°	24	12.48 min	88.96
47	1350	45°	24	6 min	94.98
48	1350	60°	24	2.08 min	98.24

Table 19: Results Hellenic Region options of 24 satellites/ STK Version 11.2

In table 17, are summarized the results of the scenario of twelve (12) satellites. We can conclude that there are six (6) similar solutions with a maximum mean coverage of the interesting area and the minimum revisit time for every grid time. Also, we observe that all six options incline 30° and 45° at the same altitude of 1350 km. From the altitude of 650 km, there are four options (amber color), with sufficient results in revisit time and mean coverage.

In table 18 and 19, are summarized results of the scenario of twenty-four (24) satellites. This scenario, it provides results with max mean coverage (100%) and the minimum revisit time (0 sec) of the region we defined. We notice that the inclinations of 45° and 60°, give the best results. There are some exceptions, such as options, 24.22, 24.28, and 24.40, which all have the same inclination of 30°.

Chapter 5

ANALYSIS OF RESULTS-CONCLUSIONS

5.1 Best Options of the Calculations

Best Options for Coverage and Revisit Time of all Scenarios									
Options	**Satellites**	**Altitude**	**Inclination**	**Planes(p)**	**Sats per Plane(s)**	**Mean Coverage**	**Revisit time(sec)**		
Number	**Number**	**Km**	**Degrees**	**Number**	**Number**	**%**	**Min**	**Max**	**Mean**
8.17	8	1350	45°	4	2	72.16	724	2529	1283
12.17	12	1350	45°	3	4	85.51	187	1086	544
12.29	12	1350	45°	6	2	83.74	108	1594	560
24.17	24	1350	45°	3	8	99.97	0	190	2.1
24.23	24	1350	45°	4	6	99.66	0	242	14.5
24.29	24	1350	45°	6	4	99.96	0	182	2.2
24.30	24	1350	60°	6	4	99.96	0	165	6.2
24.35	24	1350	45°	8	3	99.46	0	462	22

Table 20: Best options for higher mean coverage and minimum Revisit Time

Having simulated all the possible combinations of satellite constellation, according to the Walker-delta method in the STK program, we created table 20, which illustrates the best solutions to create our satellite constellation. We can observe that the higher coverage and the minimum revisit time are depicted in option 24.17. Also, we can see that almost the same results exist in option 24.30. The differences between the two options are the number of planes and the inclination. In 24.17 there are 3 planes, while in option 24.30 there are 6 planes. In the same option, we see the smaller variation between minimum and maximum revisit time. Moreover, the best performance scenario has in common the inclination of 45° and the altitude of 1350 km.

In most of the options of table 20, prevails the scenario of 24 satellites, which is very sensible in common perception. There are two options with 12 satellites, which give a very good revisit time of almost 10 minutes. Also, these options offer a satisfactory percentage of coverage (83-85%). Figure 43 shows the results accumulated in a graphic.

The final decision for the best option depends on the placeholder's budget, the requirements of the constellation, and constraints of time to complete the project. Moreover, the lifetime (appendix D) of a satellite, which depends basically on the altitude of orbit, complements the criteria to make the decision. We notice that all the best performance options have in common the altitude of 1350 km.

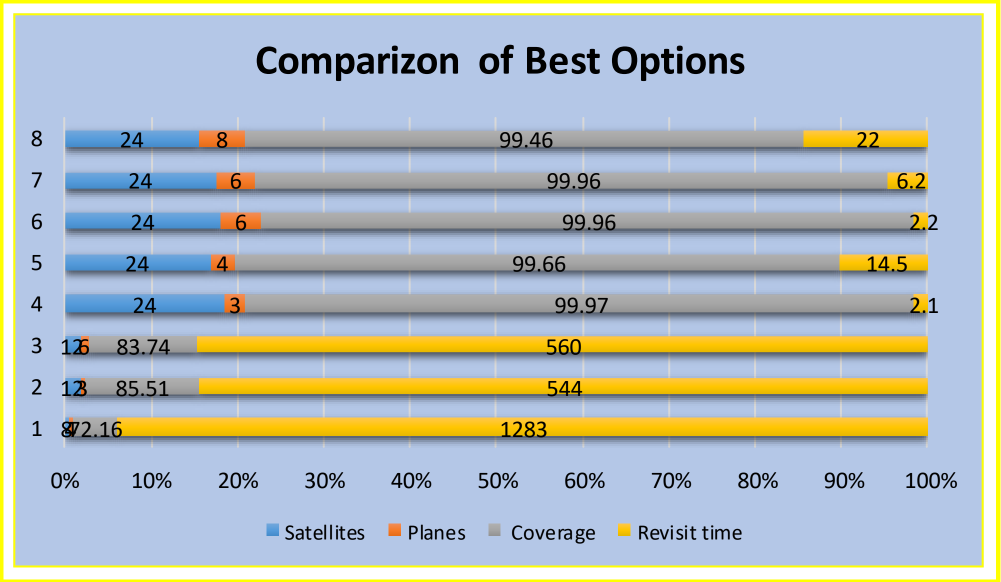


Figure 42: Illustration of Results of Best Options

Analyzing the simulations of the Hellenic interest region (table 21), it is worth saying that, there are many options of satellite constellations with satisfactory outcomes. All scenarios of eight (8), twelve (12), and twenty-four (24) satellites can fulfill the demands of the placeholders. Depending on the budget and the mission of the satellite constellation, there are plenty of options to select the optimum combination of the constellation. Best performance of these combinations illustrated in table 21. Most of them are combinations of the twenty-four (24) satellites, and only two options are designed with eight (8) satellites. Also, the best coverage could be achieved from an altitude of 1350 km and an inclination of 45°.

Best Options for Coverage and Revisit Time of all Scenarios Hellenic Region					
Option	**Altitude Km**	**Inclination (°)**	**Planes**	**Revisit Time (min- sec)**	**Mean Coverage (%)**
24. 12	1350	60°	2	0 sec	100
24.17	1350	45°	3	0 sec	100
24.23	1350	45°	4	0 sec	100
24.24	1350	60°	4	0 sec	100
24.29	1350	45°	6	0 sec	100
24.30	1350	60°	6	0 sec	100
24.34	1350	30°	8	0 sec	100
24.35	1350	45°	8	0 sec	100
24.41	1350	45°	12	0 min	100
24.42	1350	60°	12	0.5 sec	100
24.11	1350	45°	2	1.4 sec	100
24.22	1350	30°	4	5 sec	99.87
24.28	1350	30°	6	4.8 sec	99.91
24.36	1350	60°	8	14 sec	99.95
24.18	1350	60°	3	15 sec	99.76
24.40	1350	30°	12	27 sec	99.8
24.38	650	45°	12	36 sec	99.12
24.32	650	45°	8	42 sec	98.44
12.11	1350	45°	2	1.51 min	98.77
12.12	1350	60°	2	2.20 min	97.3
12.29	1350	45°	6	3.03 min	94.1
12.3	1350	60°	6	5.05 min	90.68
12.36	1350	60°	12	5.34 min	95.82
12.35	1350	45°	12	11.45 min	92.21
12.14	650	45°	3	12.25 min	63.16
12.26	650	45°	6	13.28 min	65.87
8.24	1350	60°	8	14.25 min	81.5
12. 21	650	60°	4	15.18 min	59.69
8.23	1350	45°	8	22.17 min	76.28

Table 21: Best performance options at HELLENIC Region/STK 11.2

In table 22, we compare the best performance option of coverage and revisit time at an altitude of 650 km. We can see that option 24.26 has the best performance followed by option 24.32 with the best performing combination of coverage and revisit time.

Best Options for Coverage and Revisit Time of all Scenarios 650 km							
Options	Satellites	Altitude	Inclination	Planes(p)	Sats per Plane(s)	Mean Coverage	Revisit Time
Number	Number	Km	Degrees	Number	Number	%	Mean
8.14	8	650	45°	4	2	40.78	2530
8.20	8	650	45°	8	1	37.3	2739
8.21	8	650	60°	8	1	35.14	3078
12.14	12	650	45°	3	4	56.91	2490
12.20	12	650	45°	4	3	45.75	1847
12.26	12	650	45°	6	2	52.21	1315
12.27	12	650	60°	6	2	52.13	1546
12.32	12	650	45°	12	1	55.95	2246
24.14	24	650	45°	3	8	88.26	1668
24.20	24	650	45°	4	6	86.04	726
24.21	24	650	60°	4	6	78.81	1944
24.26	24	650	45°	6	4	93.59	228
24.27	24	650	60°	6	4	85.74	448
24.32	24	650	45°	8	3	85.67	411
24.33	24	650	60°	8	3	80.79	547
24.38	24	650	45°	12	2	84.39	520
24.39	24	650	60°	12	2	75.03	765
24.44	24	650	45°	24	1	69.46	1781

Table 22: Best performance options at an altitude of 650 km/STK 11.2

5.2 Future Applications of LEO Satellite Constellations in Shipping

Satellite constellations in LEO orbits support a wide range of applications in the maritime industry. Space-borne AIS transponders have already been used to monitor shipping management traffic and for safety reasons. At the same time, data provided by AIS, are used from shipping companies and ship owners, to manage their fleet, and to support maintenance, to control their expenditure.

In recent years, many security problems have been emerged, because of piracy actions and terrorism attacks. The world is getting much more dangerous, due to instability in international relations, for economic reasons. Furthermore, maritime security is under consideration by ESA, in the framework of European crisis response space architecture (Maria Daniela Graziano, Constellation analysis of an integrated AIS/remote sensing spaceborne system for ship detection, 2012). Besides, fishing control is a mandatory issue due to a strong reduction of biodiversity. Furthermore, tanker accidents, rescue support missions, oil spills, monitoring pollution caused by ships, border control, need to be managed.

Concerning these needs and issues, remote sensing satellites in LEO orbits can greatly play a vital role in maritime security applications. To counter piracy, illegal fishing, and sea pollution by ships, a wide area of interest needs to be covered for observation and monitoring. In most fields, ship detection can be achieved by SAR (Synthetic Aperture Radar) from space-borne assets, which is the key technology to detect ships. Space-based AIS system in synergy with SAR Spaceborne assets, all in LEO constellation, can contribute to increasing performance capabilities of security and safety of the modern shipping industry.

5.3 Strategic Value of Microsatellites applications in LEO Orbits

Nowadays, we stand on the verge of the most meaningful transformation of technology. The miniaturization of electronic devices and widespread knowledge is bringing new challenges. The proliferation of cutting edge technology, and international cooperation, and the commercialization of space exploration, have changed completely the way we are thinking. More countries and companies can develop space projects, to fulfill their needs. The low-cost small satellites have similar or better capabilities than the larger. Moreover, private international companies offer services in communication, remote sensing, or navigation. In 219, more than 420$ billion has been spent on space economy and is expected to be invested 1-3$ trillion.

The strategic importance of space economy in global interdependence will manipulate the willingness and the intention of everyone to prevail in space applications. The most important is the fact that countries with small budgets in their economies can invest in space, to support their needs for communication, remote sensing, and resource monitoring. The LEO satellites could support the aspirations, of small countries in a faster, chipper, and better way.

On the other hand, the interaction between placeholders, and the interdependence of their actions, could expedite a tremendous competition for domination.

5.4 Conclusions

We have identified that the space-based AIS system has been already introduced, to support global maritime surveillance. A constellation in the LEO orbit of AIS microsatellites could provide updated ship information globally. To support the best performance coverage around the earth, we have limited the coverage area into the range between 70° north and 60°south, where the majority of routes vessels exist. Besides, we considered the swath width concerning altitude for better ground coverage. Moreover, we did some assumptions taking into account that transponders of AIS do not affect by various phenomena into the atmosphere, and management of congested signals received from vessels.

To select the best performance of coverage and the minimum revisit time, the walker-delta method has been selected, as is provide the best results with minimum use of the number of satellites. In that way, we have designed 108 different subclasses to simulate all cases. We have concluded that the best constellation is that one, with twenty-four (24) satellites, at 1350 km, with an inclination of 45°, in 3 planes and 8 satellites per plane (table 20). Similar results have been noted in the scenario with six (6) planes and four (4) satellites per plane.

Moreover, in case the situation dictates the use of fewer satellites due to restricted budget or limited area of interest, the scenario with twelve (12) satellites, at 1350 km, in 3 planes, an inclination of 45°, is the best with better performance. In the same way, there is a scenario with eight (8) satellites, in four (4) planes which is the best among similar subclasses with eight (8) satellites. At an altitude of 650 km, the best coverage with minimum revisit time, presents the scenario with twenty-four (24) satellites, in six (6) or four (4) planes. It is worth saying that, at 650 km scenarios with eight (8) and twelve (12) satellites are not fulfilled adequate area (55%).

As concerning the results for the Hellenic Region of interest, the analysis has shown that there are plenty of options with twenty-four (24) satellites which present the best performance. The scenario with eight (8) satellites has two best performance cases, both at an altitude of 1350 km with an inclination of 45° and 60° in eight (8) planes.

A future satellite constellation aiding in maritime security applications and management of traffic ships could be designed by a synergic utilization of sensors of earth observation and the AIS system. Besides, the advent of IoT (Internet of things) system and the integration of many space-based sensors, could simplify and increase the quantity and quality of earth coverage and revisit time.

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Appendix *A*

A. Notes of STK Planning Program for all Scenario Options

I. Initially, we should set up the STK program with fixed information to initialize the aforementioned parameters.

II. To compute the satellites' actual force environment, we are going to use one of the options STK offers; Two-Body, J2Perturbation, and J4Perturbation are analytical propagators that generate ephemeris by evaluating a formula. Two-Body's formula is exact (i.e. the formula generates the known solution for a vehicle moving about a central body considering only the effect of the body viewed as a point mass) but is not an accurate model of a vehicle's. J2Perturbation includes the point mass effect as well as the dominant effect of the asymmetry in the gravitational field (i.e. the J2 term in the gravity field, representing the North/South hemisphere oblateness). J4 additionally considers the next most important oblateness effects (i.e., the J2^2 and J4 terms in addition to J2). None of these propagators model atmospheric drag, solar radiation pressure or third body gravity; they only account for a few terms of a full gravity field model. They only account for a few terms of a full gravity field model (Two-Body, J2 Perturbation & J4 Perturbation Propagators, 2020). This J2 is often used in early studies (where vehicle data is usually unavailable for producing more accurate ephemeris) to perform trending analysis: J2 Perturbation is often used for short analyses (weeks).

III. The solutions produced by the J2Perturbation and J4Perturbation propagators are approximate, based upon Keplerian mean elements. In general, forces on a satellite cause the Keplerian mean elements to drift over time (secular changes) and oscillate (usually with small amplitude). In particular, the J2 terms cause only periodic oscillations to the semi-major axis, eccentricity, and inclination, while producing drift in the argument of perigee, right ascension, and mean anomaly. STK's J2Perturbation propagator model only the secular drift in the elements (the drift in mean anomaly can best be seen as a change to the period of motion of the satellite). Many of the ideal maintained orbits are designed in a manner to take advantage of the prevailing secular drift caused by J2 to achieve their missions (Two-Body, J2 Perturbation & J4 Perturbation Propagators, 2020).

IV. Analytical numerical calculations simulations will be executed to define the characteristics of coverage and its quality. The duration of all case computations will be 24 hours (1 day), to avoid complicated calculations and increased required time to simulate any scenario with an existing computer system (home version). The duration time begins on the 3rd of January 2021 at 10:00 and ends on the 4th of January 2021 at 10:00.

Appendix *B*

B. Results of STK simulations

I. Results of STK simulations for Scenario of eight (8) Satellites

II. Results of STK simulations for Scenario of twelve (12) Satellites

III. Results of STK simulations for Scenario of twenty-four (24) Satellites

IV. Each scenario contains the following archives:

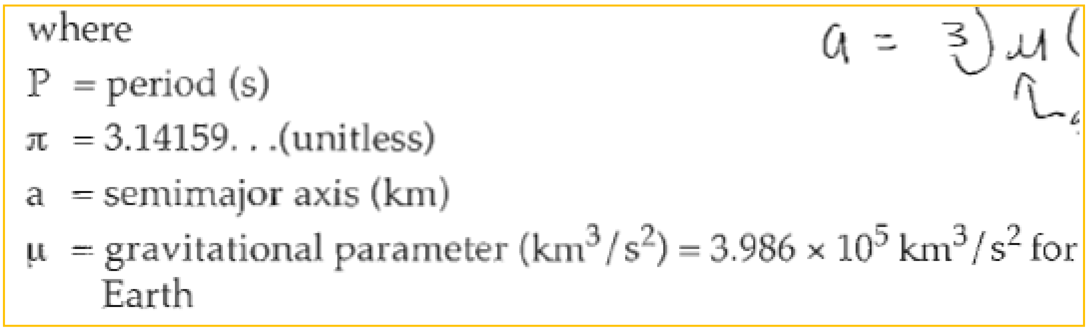
- Coverage Definition Percent Coverage
- Figure Of Merit2 Grid Stats Over Time
- Figure Of Merit2 Grid Stats (Revisit time)
- Figure Of Merit2 Value By Latitude (Revisit time)

Appendix C

Calculation of a Period of a Satellite.

$$P = 2\pi\sqrt{\frac{a^3}{\mu}}$$

Equation 3: Period (P) of a Satellite Orbiting Earth/



where

P = period (s)

π = 3.14159. . .(unitless)

a = semimajor axis (km)

μ = gravitational parameter (km^3/s^2) = 3.986×10^5 km^3/s^2 for Earth

a = 3) μ (

Implemented equation 1 for the two different altitudes, we calculated the period of the satellite, as illustrated in table 23.

Period of Satellite				
Option	**Altitude Km**	**Inclination (°)**	**Semimajor Axis (α) km**	**Period(min)**
1	650	30°	7028	97.7
2	650	45°		
3	650	60°		
4	1350	30°	7728	112.6
5	1350	45°		
6	1350	60°		

Table 23: Period of Satellite according to Altitude

Appendix *D*

The lifetime of a satellite orbiting at 650 km with an inclination of 30° and 45° is 2.7 years, while the inclination of 60° is 2.9 years. The lifetime of a satellite plays a significant role in the budget. So, the design of the satellite constellation is affected, to select the best performance for the given time of operation. Figures 43 to 45 show the respective lifetime.

Respectively, the lifetime of a satellite at 1350 km, neither depends on atmospheric drag nor the perturbations due to oblateness. So, the value of a lifetime, in this case, is 420,8 years (fig. 46). It is only affected by the functionality of the satellite systems into time.

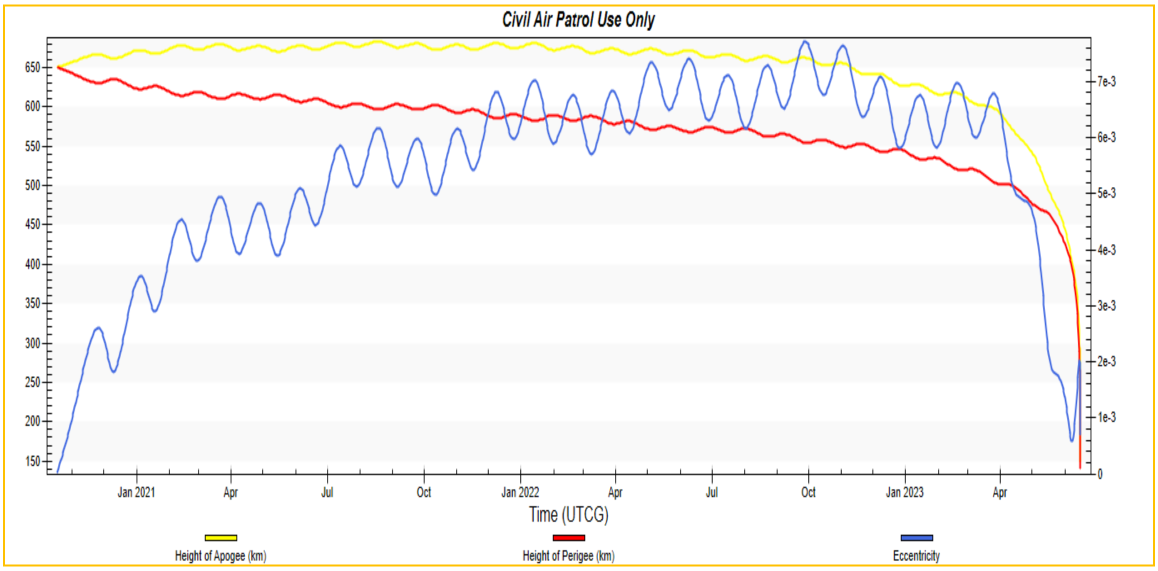


Figure 43: Lifetime of Satellite at 650 km, 30° inclination/STK 11.2

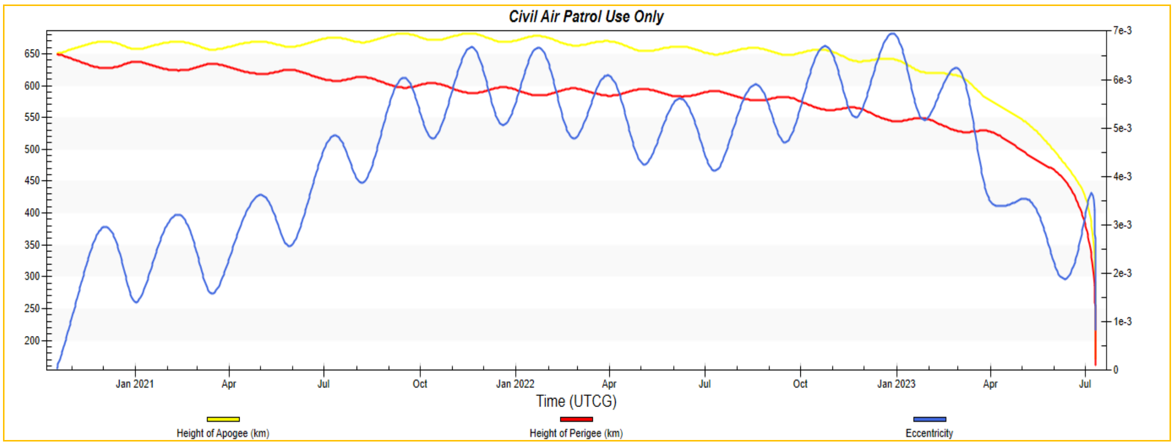


Figure 44: Lifetime of Satellite at 650 km, 45° inclination/STK 11.2

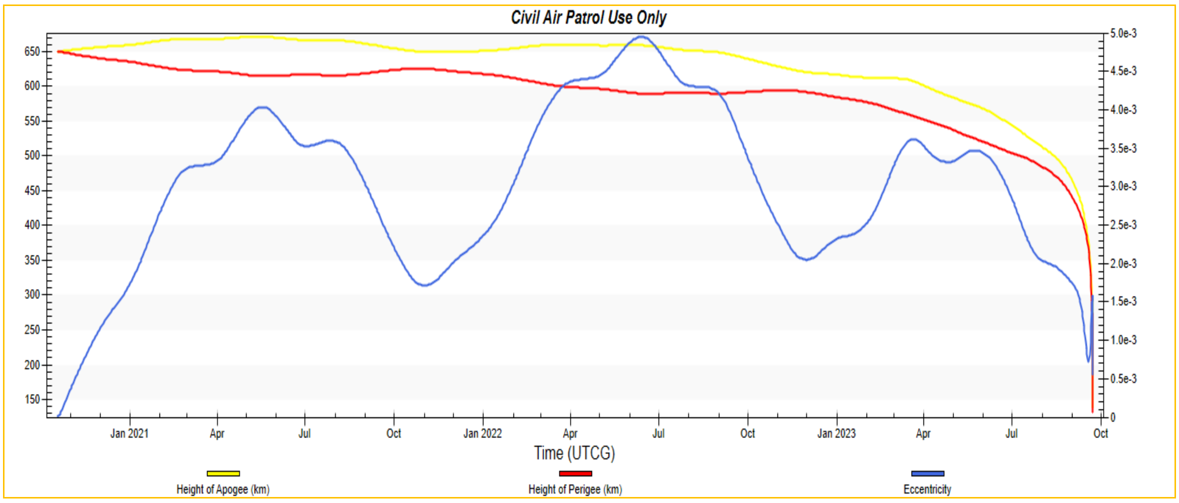


Figure 45: Lifetime of Satellite at 650 km, 60° inclination/STK 11.2

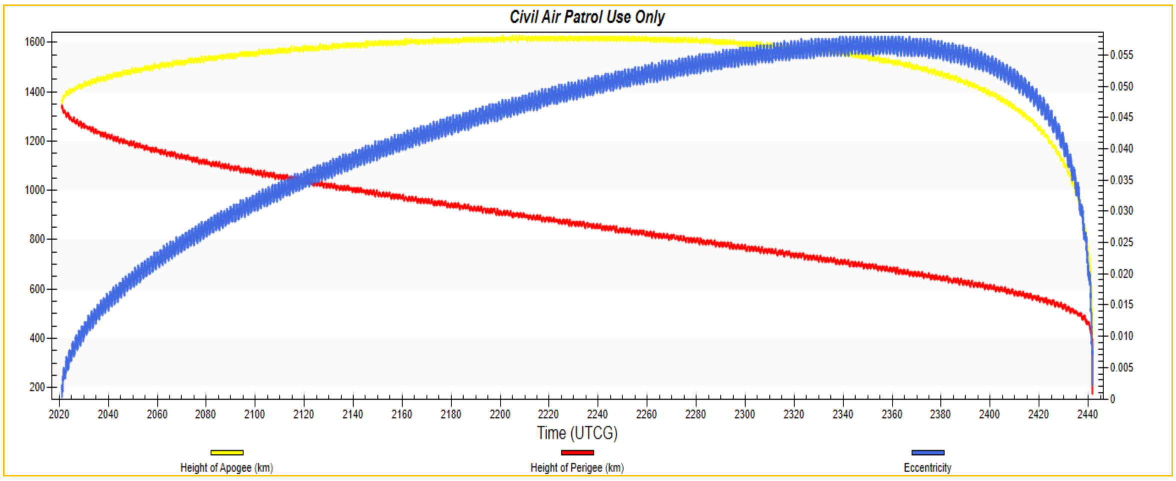


Figure 46: Lifetime of Satellite at 1350 km, 45° inclination/STK 11.2