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Integration Architecture of the Satellite Space Segment within the Modernization of the GMDSS Networks

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ABSTRACT

This paper presents contemporary integration architecture of the satellite space segment within the Global Maritime Distress and Safety System (GMDSS) modernization for enhanced service in the mission of the Satellite Distress and Safety System (SDSS) to organize Search and Rescue (SAR) operations of ships in emergency. Long before that, during the 18th century, ships navigating in international and coastal waters were depended on the Morse code to send any kind of distress signal to coastal authorities or ships in the nearby vicinity during an emergency. Therefore, today GMDSS network automates and improves emergency communications for the global shipping industry. The SAR system incorporates satellite communications and traditional voice and data radio technologies to provide modernized maritime emergency, security and safety communications for the 21st century. Existing and forthcoming space segment solutions of GMDSS network, such as Geostationary Earth Orbit (GEO) Inmarsat, Low Earth Orbit (LEO) Iridium, Cospas-Sarsat LEO LEOSAR, MEO MEOSAR and GEO GEOSAR networks as a modern GMDSS space segments, and other relating systems are discussed in this paper.

1. Introduction.

The Global Maritime Distress and Safety System (GMDSS) is an internationally recognized radio and satellite communication safety system for ships in distress replacing the previous ship to ship safety system, which relied on a manual Morse code system on 500 kHz and voice radiotelephony on Channel 16 and 2182 kHz. The GMDSS is an automated ship to shore system using satellites and digital selective calling technology. The GMDSS is mandated for ships internationally by the International Maritime Organization (IMO) Safety of Life at Sea Convention (SOLAS), 1974, as amended in 1988, and carries the force of an international treaty. The procedures governing use are contained in the International Telecommunication Union recommendations and in the International Radio Regulations, and also carry the force of an International Treaty.

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Thus, the GMDSS network was developed by maritime states of the IMO and resulted from their adoption of the 1988 amendments to the 1974 SOLAS International Convention. Based on the recent developments in maritime Radio and Mobile Satellite Communications (MSC), such as modern space and digital technology, the GMDSS network is designed to ensure maximum availability of safety-related communication for all passenger ships as well as for cargo vessels of 300 GT and upwards engaged in international voyages. The goal of the GMDSS is to virtually guarantee that complying vessels will be able to communicate with an onshore station at any time, from any location, in the event of distress or to exchange safety-related information [01, 02].

2. Architecture of the GMDSS Satellite Space Segment.

The space platform is an artificial object located in orbit around the Earth at a minimum altitude of about metricconverterProductID20 km20 km in the stratosphere and a maximum distance of about metricconverterProductID36,000 km36,000 km in space. The artificial platforms can have a different shape and designation but usually they have the form of aircraft, airship or spacecraft. In addition, there are special space stations and space ships, which are serving on more distant locations from the Earth's surface for scientific exploration and research and for cosmic expeditions.

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Satellite service communications or any purpose begins when it is located as a space platform in a desired orbital position in the space environment around the Earth surfacve, with its point farthest from Earth (Apogee) and the point of closest approach to Earth (Perigee). In fact, a satellite is an artificial object located by rocket in a space orbit following the same laws in its motion as the planets rotating around the Sun.

In distinction from natural satellites that orbit the Sun (Earth or any planet), whose orbits in space are almost elliptical, each artificial satellite launched into space can also have circular orbits for which the basic relation can be obtained by equalizing centrifugal and centripetal forces of the Earth. Whereas, an artificial satellite in a circular orbit goes through its revolution at a fixed altitude and with fixed velocity, while a satellite in an elliptical orbit can drastically vary its altitude and velocity during one revolution [03, 04, 05].

3. Satellite Orbital Parameters and Communication Principles.

Basically, a satellite remains in orbit when two forces, one caused by the gravitational pull of the Earth and the other by the centripetal acceleration due to its angular velocity, are in balance. The velocity (v) of the Geostationary Earth Orbit (GEO) satellite should ideally be zero relative to the Earth's surface, although small variations occur.

The satellite's orbital speed is 3,073 km/s^{-1} to allow it to maintain geosynchronous at all times. Small orbital variations occur due to the influence of other heavenly bodies but they are of no important as their effects are counteracted in the ground control station. Assuming that the average radius of the Earth (R) is metricconverterProductID6,371 km6,371 km in circular satellite orbit at altitude (h) above the Earth's equator, the circumferential path is given as: C = 2π (R + h) = 2π r.

The circumferential velocity (v) of satellite is constant, and so, the period of one orbit is shown by he following calculation:

$$T = 2\pi\ (R + h)/v \qquad (2.1.)$$

All satellites maintain their orbits with reference to velocity, mass and earth gravity, so the centripetal force on a satellite with a mass (m) is:

$$F_C = (R + h)/v \qquad (2.2.)$$

The Earth's gravitational pull is the product of gravity and mass (gm), where the value of the gravitational force is g = 9.81 *m/s*. The gravitational acceleration is therefore:

$$g' = g\ (R/R + h)^2 \qquad (2.3.)$$

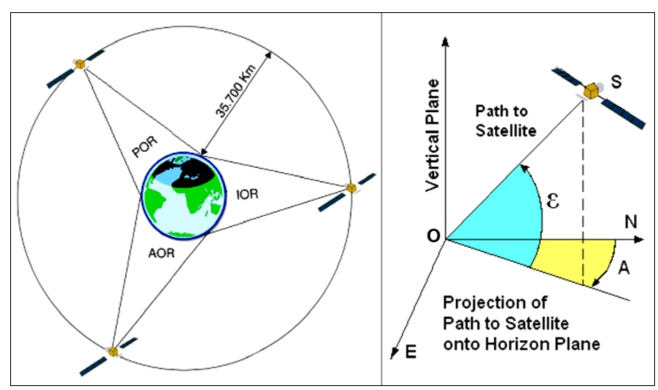
In order to maintain the satellite orbit, a relation for balancing the centripetal force against the gravitational force should be achieved as: $g\ (R/R + h)^2 = mv2/R + h$, and in such a way the equation for velocity is as follows:

$$v = R\sqrt{g/R + h} \qquad (2.4.)$$

At this point, substituting above value of v into the orbital period T formula and including numerical values gives: h = (5075T - 6371) km = 35,855 km (for a 24 hour period).

Since the Earth's square area is 510,100,933.5 km^2 and the extent of the equator is 40,076.6 km, only with three GEO mutually moved apart in the orbit by 120^o it is possible to cover a great area of the Earth's surface, shown in **Figure 1 (Left),** which shows (Atlantic Ocean Region (AOR), Indian Ocean Region (IOR) and Pacific Ocean Region (POR) satellite coverage**.** The horizon coordinates are considered to determine satellite position in correlation with an Earth observer, Ground Earth Station (LES) and Ship Earth Station (SES) terminals.

Figure 1: GEO Coverage and Look Angle Parameters.



Source: Pratt.

These specific and important horizon coordinates are angles of satellite elevation and azimuth, shown in **Figure 1 (Right),** respectively. The limit of the coverage area is defined by the elevation angle from LES above the horizon with elevation angle of view ε=0^o. Using radius of synchronous or geostationary orbits (r) the satellite is visible and its maximal central angle for GEO will be as follows:

$$\Psi = \arccos\ (R \cos \varepsilon/r) - \varepsilon\ \pi/2 - \arcsin\ (R/r) = \arccos\ (R/r) - \varepsilon = \arccos k - \varepsilon \qquad (2.5.)$$

Inserting the angular velocity of the Earth, the required radius for a GEO satellite is 42,164 km or about 35,786 km above the Earth's surface, which is included in the following calculation:

$$\Psi = \text{arc cos } 6{,}376.16/42{,}164.20 = \text{arc cos } 0.15126956 = 81^o 17' \, 58.18'' \quad (2.6.)$$

Thus, all SES and LES terminals with a position above $\Psi = 81^o$ will be not covered by GEO satellites. The satellite elevation (ε) is the angle composed upward from the horizon to the vertical satellite direction on the vertical plane at the observer point. From point (O) shown in **Figure** 1 **(Right)** the look angle of ε value can be calculated by the following relation:

$$\text{tg } \varepsilon = \cos \Psi - (R/r)/\sin \Psi = \cos \Psi - k/\sin \Psi \quad (2.7.)$$

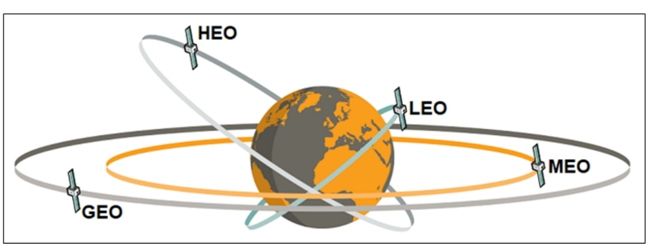
Where r = distance of the satellites from the centre of the Earth (r = R+h) or radius of path. Otherwise, considering latitudes (φ) and longitudes of satellite (λ), the azimuth value, looking from sub-satellite point (O), can be calculated as:

$$\text{tg } A = \sin \Delta\lambda/\text{tg } \varphi \text{ or } \sin A = \cos \varphi \sin \Delta\lambda \text{ cosec } \Psi \quad (2.8.)$$

The position of the satellite can be defined by true anomaly angle (Θ), which can be counted positively in the direction of movement of the satellite from 0^o to 360^o, between the direction of the perigee and the direction of the satellite (S). The position of the satellite can also be defined by eccentric anomaly angle (E), which transforms the elliptical trajectory into its principal circle, an angle counted positively in the direction of movement of the satellite from 0 to 360^o, between the direction of the perigee and the direction of the satellite. The relations for both mentioned anomalies are given by the following equations:

$$\cos \Theta = \cos E - e/1 - e \cos E \quad \cos E = \cos \Theta + e/1 + e \cos \Theta \quad (2.9.)$$

Figure 2: Type of Orbits for GMDSS Network.



Source: Ilcev.

The satellite track and geometry on the Earth's surface and the presentation of a satellite's position in correlation to the SES calculation from a spherical coordinate system, whose centre is the middle of Earth. Thus, the satellite position in any time can be determined by the geographic coordinates, sub-satellite point and range of radius.

Thus, the sub-satellite point is a determined position on the Earth's surface; above it is the satellite at its zenith. Using the argument of perigee (ω) and inclination angle (i), latitude (φ) and longitude (λ) as geographic coordinates of the sub-satellite point (O) can be calculated by the following equation:

$$\sin \varphi = \sin (\Theta + \omega) \sin i \quad \text{tg } (\lambda_S - \Omega) = \text{tg } (\Theta + \omega) \cos i \quad (2.10.)$$

The optimum number of GEO satellites to provide reliable global coverage can be determined by the following relation:

$$n = 180^o/\Psi \quad (2.11.)$$

The GMDSS space segment currently includes different types of satellites systems, each with a very different type of orbit for communication and SAR purposes.

The Inmarsat system as a main part of the GMDSS space network uses minimum 3 GEO satellites to provide Voice, Data and Video (VDV) communications almost everywhere on Earth, and sometimes due to not covered areas is using 4 GEO satellites for overlapping. The second MSC operator Iridium uses 66 Low Earth Orbit (LEO) operational satellites in 6 orbit planes of 11 spacecraft each [04, 06, 07, 08, 09].

4. Type of Orbits for GMDSS Network.

An orbit is the circular or elliptical path that the satellite traverses through space. This path appears in the chosen orbital plane in the same or different angle to the equatorial plane. All communication satellites always remain near the Earth and keep going around the same orbit, directed by centrifugal and centripetal forces.

Each orbit has certain advantages in terms of launching (getting satellite into position), station keeping (keeping the satellite in place), roaming (providing adequate coverage) and maintaining necessary quality of communication services, such as continuous availability, reliability, power requirements, time delay, propagation loss and network stability. Except GEO and LEO satellite orbits illustrated in **Figure 2**, in MSC systems are used Medium Earth Orbit (MEO) a Highly Elliptical Orbit (HEO).

Especially Big LEO and ICO or hybrid constellations such as Ellipso have had several years of serious economical and concept difficulties. It is sufficient to see **Table 1** to understand that the major reasons for LEO problems are enormous satellite cost, complex network and short satellite visibility and lifetime. The LEO/PEO constellations are the same or similar and because of differences in inclination angle of orbital plane and type of coverage they will be considered separately [03, 10, 11].

Table 1: The Properties of Four Major Satellite Orbits.

Orbital Properties	**LEO**	**MEO**	**HEO**	**GEO**
Development Period	Long	Short	Medium	Long
Launch & Satellite Cost	Maximum	Maximum	Medium	Medium
Satellite Life (Years)	3–7	10–15	2–4	10–15
Congestion	Low	Low	Low	High
Radiation Damage	Zero	Small	Big	Small
Orbital Period	<100 min	8-12 hours	½ Sidereal Day	1 Sidereal Day
Inclination	90°	45°	63.4°	Zero
Coverage	Global	Global	Near Global	Near Global
Altitude Range (km^{-3})	0.5–1.5	8–20	40/A – 1/P	40 (i=0)
Satellite Visibility	Short	Medium	Medium	Continuous
Handover	Very Much	Medium	No	No
Elevation Variations	Rapid	Slow	Zero	Zero
Eccentricity	0 to High	High	High	Zero
Handheld Terminal	Possible	Possible	Possible	Possible
Network Complexity	Complex	Medium	Simple	Simple
Tx Power/Antenna	Low	Low	Low/High	Low/High
Gain	Short	Medium	Large	Large
Propagation Delay	Low	Medium	High	High
Propagation Loss	High	Medium	Low	Zero

Source: Ilcev.

4.1. Low Earth Orbits (LEO) Satellite System.

The LEO satellite constellations shown in **Figure 2** are either elliptical or more usually circular orbits between 500 and 2,000 km above the surface of the Earth and bellow the negative effects of the Inner Van Allen Belt. The LEO satellite has several characteristics that can be advantageous for communications applications and new proposal to be included in GMDSS network as a Polar Earth Orbit (PEO), as summarized in **Table 1**.

The orbit period at these altitudes varies between 90 minutes and 2 hours. The radius of the footprint of a communications satellite in LEO varies from 3,000 to 4,000 km. Therefore, the maximum time during which a satellite in LEO orbit is above the local horizon for an observer on the Earth is up to 20 minutes. In this case, the traffic to a LEO satellite has to be handed over much more frequently than all other types of orbit. At this point, when a satellite, which is serving a particular user, moves below the local horizon, it needs to be able to quickly handover the service to a succeeding one in the same or adjacent orbit.

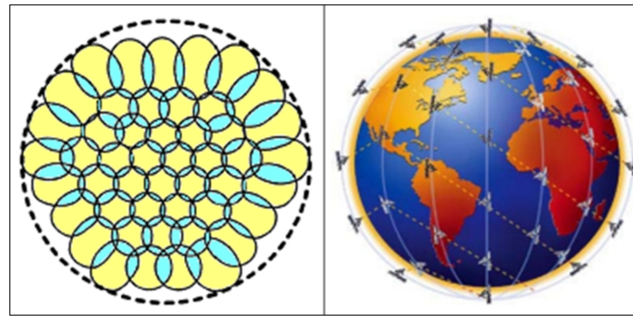
The Earth-satellite links are much shorter, leading to lower path losses, which result in lower needed power and smaller antenna systems. Propagation delay or latency is also less because of shorter path distances and it is about 25 milliseconds (ms) for one way and about 40 ms for round trip (up and down links), due to the short distance of about average 1,500 km, Thus, LEO satellites, with the proper inclinations, can cover high latitude locations, including polar areas, which cannot be reached by GEO satellites.

The major disadvantages of the LEO satellites are their restricted operations period, since the satellite is not at a fixed location in the sky, but instead sweeps across the sky for as little as 8-10 minutes from a fixed location on Earth. These satellites have many handovers and the ground station must actively track the satellite to maintain communications. If continuous global or wide area coverage is desired, a constellation of multiple LEO satellites is required, with interlinks between the satellites to allow for point-to-point satellite communications. Some current LEO satellite networks operate with 12, 24 and 66 satellites to achieve the desired coverage.

The oblateness (non-spherical shape) of the Earth will cause two major perturbations to the LEO satellite. The point on the equator where the LEO satellite crosses from South to North (the ascending node) will drift westward several degrees per day. Thus, these satellites can rotate in the orientation of the major axis in the plane of the orbit, either clockwise or counterclockwise. If the inclination is set to about 63^o, however, the forces that induce the rotation will be balanced and the major axis direction remains fixed.

The LEO orbit has found serious consideration for mobile applications, since the delay is law, about ~ 10ms and the small power and small antenna size of the earth terminals are a definite advantage. More LEO satellites are required to provide communications services comparable to the GEO case, but LEO satellites are much smaller and require significantly less energy to insert into orbit, hence total life cycle costs may be lower.

Figure 3: Iridium Spot Coverage and Satellite Constellation.



Source: Iridium.

Due to the relatively large movement of a satellite in LEO constellation with respect to an observer on the Earth, satellite systems using this type of orbit need to be able to cope with large Doppler shifts. In fact, satellites in LEO are not affected at all by radiation damage but are affected by atmospheric drag, which causes the orbit to gradually deteriorate. Satellites in LEO and MEO constellation are subject to orbital perturbation. For very LEO satellites the aerodynamic drag is likely to be significant and in general, some of the other perturbations, such as precession of the argument of the perigee, resolve to zero in the orbit is circular or polar. On the other hand, a perturbation is unlikely to have a serious effect on the operation of a multi-satellite constellation since it will usually affect all satellites of the configuration in equal measure and determination [02, 04, 07, 12, 13, 14].

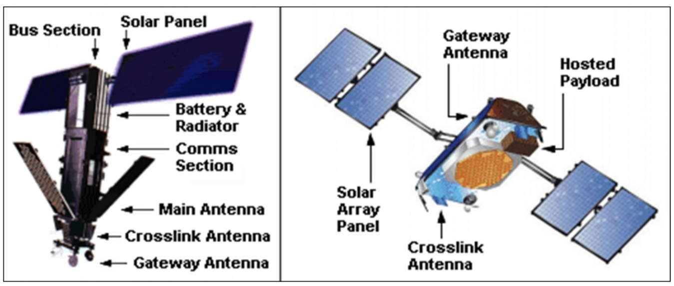
4.1.1. Iridium LEO Satellite Network.

The First generation of Iridium Big LEO satellites is situated in a near-polar orbit at an altitude of 780 km. They circle the Earth once every 100 minutes traveling at a rate of about 26,856 km/h. Each Iridium satellite is cross-linked (inter satellite link) to four other satellites; two satellites in the same orbital plane and two in an adjacent plane. In such a way, the Iridium constellation consists in 66 operational satellites and 14 spares orbiting in a constellation of six polar planes. Each plane has 11 mission satellites performing as nodes in the telephony network. The 14 additional satellites orbit as spares ready to replace any unserviceable satellite. This constellation ensures that every region on the globe is covered by at least one satellite at all times, so in such a way Iridium network is the best solution to provide global GMDSS coverage including both polar areas.

The Iridium satellites provide real coverage and roaming over the entire globe with 48 spot overlapping beams and the diameter of each spot of about 600 km, shown in **Figure 3 (Left)**. The 66 satellites enable 3,168 cells, of which only 2,150 need to be active to cover the whole Earth. At this point, each cell covers about 15 million km^2 and each satellite simultaneously serves an average of 80 and a maximum of 240 cells. The global throughput varies between nominally 171 and 500 thousand simultaneous calls. As the spacecraft moves with great speed, the user encounters adjacent beams about once a minute, which constellation of 66 satellites is illustrated in **Figure 3 (Right)**.

The new Iridium NEKST satellite constellation project (second generation) will also consist of 66 operational cross-linked (inter-satellite links) capable of covering the North and South Poles. Iridium's fixed price contract with Thales Alenia Space Company provides for the construction of the originally planned 72 operational satellites and in-orbit spares, plus an additional nine ground spares, which provide greater risk mitigation with respect to the new satellite constellation.

Figure 4: Iridium First and Second Generation of Spacecraft.

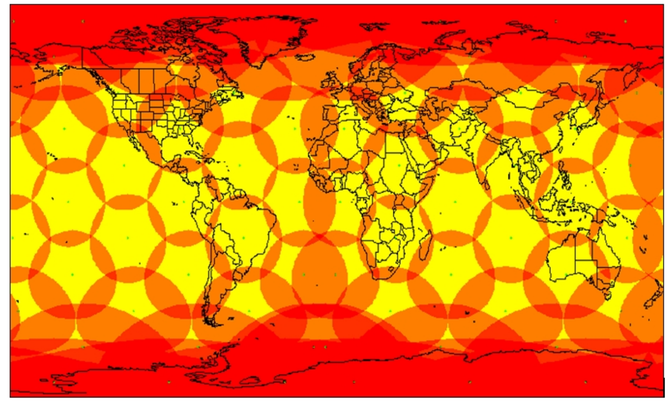


Source: Iridium.

The Iridium first generation spacecraft is illustrated in **Figure 4 (Left)** and the Second generation spacecraft is illustrated in **Figure 4 (Right)**, both with main components. The NEXT spacecraft payload employs an L-band phased array antenna for generation of the 48-beam, 4,700 km diameter cellular pattern on the Earth's surface for connection with subscribers/users. The Ka-band links are also provided for communication with ground-based Gateways and for crosslink with adjacent spacecraft in orbit. Thus, the cross-linked 66 Iridium satellite constellation forms a complete global network allowing communications from a ground or any mobile user in any location on Earth to virtually anywhere else on Earth, which coverage map is shown in **Figure 5.**

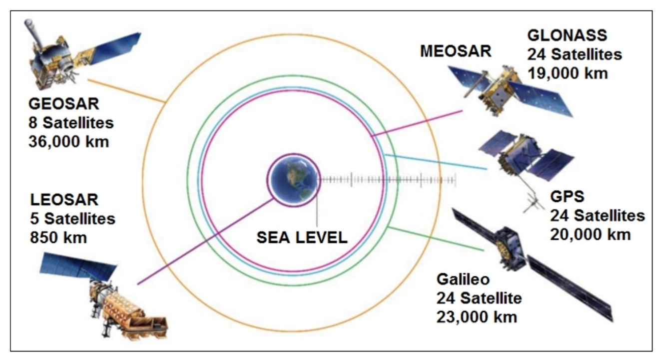
In addition to supporting all three satellite GMDSS services in one terminal, Iridium Connected GMDSS equipment enables other safety and non-safety capabilities including shore-to-ship distress calling, maritime assistance, and standard calling and messaging (SMS). Iridium GMDSS enhances safety at sea, offering reliable coverage where no other options exist, and it is designed to work in extreme conditions at sea. Iridium began the process of getting certification to become a recognized provider of the GMDSS service in 2013. The process took four years, and in May 2018 the Iridium network was recognized to meet all the criteria required by the Maritime Safety Committee of the IMO. In 2019, the International Mobile Satellite Organization (IMSO), which the IMO trusts as the GMDSS regulator, certified Iridium as a new satellite GMDSS provider. On December 19, Director General of IMSO officially presented a Letter of Compliance to the representative of Iridium. Thus, Iridium unique constellation of 66 cross-linked satellites in Low-Earth Orbit provides reliable coverage, even in adverse weather, around the entire globe, including over the Arctic and Antarctic waters in Sea Area A4 [04, 12, 14, 15].

Figure 5: Iridium Coverage Map.



Source: Lloyd.

Figure 6: Configuration of Cospas-Sarsat LEOSAR, MEOSAR and GEOSAR Satellites.



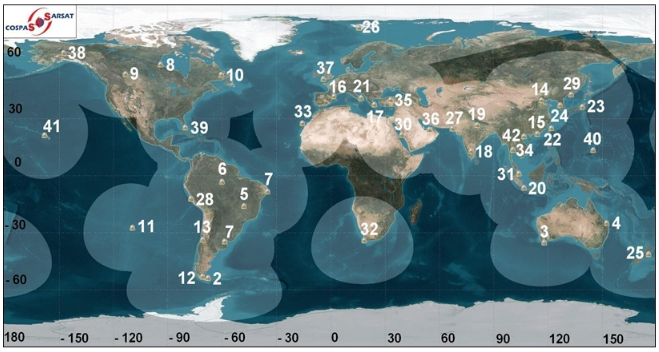
Source: NOAA.

4.1.2. *Cospas-Sarsat LEO LEOSAR Satellite Network.*

The LEOSAR system configuration is composed of 5 LEO or Polar Earth Orbit (PEO) satellites, 2 Cospas (Russia) and 3 Sarsat (USA), Canada and France) in near North-South polar orbit, with an orbital period of approximately 120 minutes, which is illustrated in **Figure 6.** The orbits of these satellites are arranged to scan the entire surface of the Earth. The satellites view an area of the Earth over 6,000 km wide as they orbit the globe, giving an instantaneous field of view or footprint (like the illumination from a torch beam) about the size of a continent. Each PEO satellite makes a complete orbit of the Earth around the poles in about 100 min, traveling at a velocity of 7 km/s.

The coverage of LEOSAR network is not continuous due to the orbital period of the PEO satellite, which map is shown in **Figure 7.** By the nature of the polar orbits, the waiting time for detection, can be greater in equatorial regions than at higher latitudes, on average it is 45 minutes. When the LEOSAR system detects Distress alert, it calculates the location of the Distress event using Doppler processing techniques. Doppler processing is based upon the principle that the frequency of the distress beacon, as "heard" by the satellite instrument, is affected by the relative velocity of the satellite with respect to the beacon. By monitoring the change of the beacon frequency of the received beacon signal and knowing the exact position of the satellite, the LEOSAR satellite system is able to calculate the location of the beacon with an accuracy of within 5-10 km.

Figure 7: LEOSAR Coverage Map.



Source: Cospas-Sarsat.

Their orbits are inclined 99^0 from the equator which means LEOSAR satellites are polar orbiting. Since these satellites are close to the Earth, they "see" less territory because of the limited field of view from the antennas onboard each satellite. Their low altitude, combined with the relatively small number of satellites in this constellation, LEOSAR satellites must fly over an activated distress beacon to pick up the signal and then be in view of a LEOLUT (ground station) to transmit the signal. This is what is called non-continuous coverage, however, if LEOSAR satellites are not in direct Line of Sight (LOS) with the LEOLUT ground receivers, the receiver processor on the LEOSAR satellite stores the distress signal and send it down when the LEOSAR stellite comes into LOS with LEOLUT station.

The distress beacons emit radio signals at 406 MHz which are detected by Cospas-Sarsat LEOSAR or MEOSAR and GEOSAR satellites. The information is then transmitted, along with the location and casualty ID, via ground LELUT or MEOLUT ad GEOLUT stations to the appropriate Mission Control Centre (MCC), which is responsible for receiving and distributing distress signal alerts from shipborne Emergency Position Indicating Radiobeacon (EPIRB) stations. The tasks of the MCC terminals are also to receive distress signals from Personal Locator Beacons (PLB) from land vehicles (road and rail) or persons and Emergency Locator Transmitters (ELT) from aircraft. Then, analyzed distress signals in the MCC terminals are received by the Rescue Ccoordination Centre (RCC) stations, which organize a d conducts SAR operations of the ship and crew (passengers) in distress [04, 17, 18, 19].

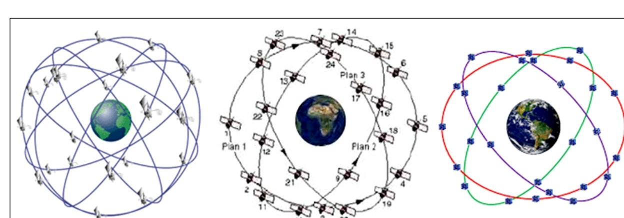
4.2. Medium Earth Orbits (MEO) Satellite System.

The MEO satellite constellations, known also as Intermediate Circular Orbits (ICO), are circular orbits located at an altitude of around 10,000 to 20,0000 km between the Van Allen Belts. The MEO satellite system is operated in a similar way to Big LEO system providing global coverage, which orbit is shown in **Figure 2,** and which characteristics are presented in **Table 1.** Compared to the LEO satellites, the MEO constellation can only be in circular orbit; Doppler effect and handover is less frequent; propagation delay is about 70 ms for one way and about 125 ms for round trip with greater free space loss; satellites are affected by radiation damages from the Inner Van Allen Belt only during the launching period; fewer eclipse cycles means that battery lifetime will be more than 7 years; cosmic radiation is lower, with subsequently longer life expectancy for the complete MEO configuration; higher average elevation angle from users to satellite minimizes probability of LOS blockage and higher RF output power required for both indoor and handheld terminals.

The MEO satellite constellation for MSC global coverage requires around 10 satellites in two or three orbital planes, each plane inclining 45^o to the equator. Their orbit period measures about 6 to 8 hours, providing slightly over 1 hour local visibility above the horizon for an observer on the Earth and handover from one to the next satellite is every 6 hours minimum. There is in exploitation a special model of MEO constellation known in practice as Highly Inclined Orbit. This orbit is of interest because it has been chosen for existing and proposed Global Navigation Satellite System (GNSS) systems such as Navstar (GPS), GLONASS and the newly developed Galileo. In all, complete implementation of this orbit configuration would have 24 satellites in 3 orbital planes equidistant from each other, at an altitude of 20,000 km and at an inclination of 55^o. In comparison with existing GNSS the new Galileo system will have 30 satellites in high MEO of about 28,000 km and at a similar inclination of 56^o, (Sheriff 2001; Maral 2009; Maini AK, 2007; Ilcev 2016).

Since the 3 operational GNSS networks, US GPS, Russian GLONASS and EU Galileo use MEO satellites for SDSS operations, the Cospas-Sarsat organization has developed new MEOSAR SAR payloads carrying GNSS satellites. The latest evolution of SDSS for Cospas-Sarsat is the addition of GNSS 3 MEOSAR satellites (GPS, GLONASS and Galileo) to the system, which are shown in **Figure 6.** Their primary function is to provide signals from space that transmit positioning and timing data to GNSS (GPS, GLONASS or Galileo) receivers. The GNSS receivers then use this data to determine the locations of distress signals received from EPIRBS, PLB or ELT emergency beacons. Precision atomic clock timing sources coupled with an ultra stable oscillator are required at MEO satellite orbits [04, 07, 12, 17].

Figure 8: GPS, GLONASS and Galileo MEOSAR Satellite Constellations.



Source: GNSS.

4.2.1. Cospas-Sarsat MEO MEOSAR GPS Satellite Network.

The Global Positioning System (GPS) is a US-owned military utility that provides precise satellite navigation services to different users and is a recently integrated into the third newly designed MEOSAR sub-segment as part of the Cospas-Sarsat network along with the GLONASS and Galileo systems. The GPS network consists of three segments: the space segment, the control segment, and the user segment. The US Space Force develops, maintains, and operates the the space and control segments initially available only to the US military, and on after that, based on the decission of the US government, GPS was adapted to be used for civilian fixed and mobile purposes globally.

The GPS space segment consists of a nominal constellation of 24 satellites fully operational since 1993 transmit one-way signals that give the current GPS satellite Position, Velocity and Time (PVT) to military and civilian uses, position and time, which satellite is shown in **Figure 6.** The satellites in the GPS constellation are arranged into six equally-spaced orbital planes surrounding the Earth. Each plane contains four "slots" occupied by baseline satellites, which constellation is shown in **Figure 8 (Left).** This 24-slot arrangement ensures GPS users can view at least four satellites from virtually any point on the planet. All GPS satellites fly in MEO constellation at an altitude of approximately 20,200 km (12,550 miles), and each satellite circles the Earth twice a day.

The control segment consists of worldwide monitor and control stations that maintain the satellites in their proper orbits through occasional command maneuvers, and what is very important it adjust the satellite clocks. It tracks the GPS satellites, uploads updated navigational data, and maintains health and status of the satellite constellation.

The user segment consists of the GPS receiver equipment, which receives the signals from the GPS satellites and uses the transmitted information to calculate the user's three-dimensional position and time. There are different GPS users primarily for military, then civilian for fixed and all mobile applications, including ships [20, 21, 22].

4.2.2. Cospas-Sarsat MEO MEOSAR GLONASS Satellite Network.

The Russian Global Navigation Satellite System (GLONASS) is an GNSS that works together with GPS to provide PTV data to compatible devices for fixed and civil applications, which satellite is shown in **Figure 6.** The first GLONASS satellite was launched in 1982 and the system is fully operational in 1993, and currently, it has a full deployment of 24 satellites that sends GNSS signals on 2 frequency sub-bands (L1∼1602 MHz and L2∼1246 MHz), which constellation is shown in **Figure 8 (Middle).** This GNSS network transmit consists of a space, control and user segment.

The GLONASS constellation provides visibility to a variable number of satellites, depending on your location. A minimum of four satellites in view allows a GLONASS receiver to compute its position in three dimensions and to synchronize with system time. With an additional 24 satellites to utilize, GLONASS compatible receivers can acquire satellites up to 20% faster than devices that rely on GPS alone. Turning on GLONASS may require changing the GPS Setting on your device to GPS+GLONASS for military and civilian users [20, 21, 23].

4.2.3. Cospas-Sarsat MEO MEOSAR Galileo Satellite Network.

The Galileo GNSS network is an initiative launched by the European Union (EU) and the European Space Agency (ESA) to provide an independent worldwide satellite navigation system for civilian fixed and mobile applications, which satellite is shown in **Figure 6.** It is conceived as being both a competitor and a complement to the existing American GPS service and to other GNSS like the Russian GLONASS.

When Galileo, Europe's own GNSS, is fully operational, there will be 24 satellites plus spares in MEO at an altitude of 23222 kilometres. Eight active satellites will occupy each of three orbital planes inclined at an angle of 56° to the equator, which constellation is shown in **Figure 8 (Right).** These satellites transmit along the L-Band spectrum, labelling their frequencies E1 (1575.42 MHz), E5 (1191.795 MHz), E5a (1176.45 MHz), E5b (1207.14 MHz) and E6 (1278.75 MHz). The Galileo system is divided into three major segments: Space Segment, Ground Segment and User Segment. The complete Galileo system is divided into three main segments: the space segment, the ground segment and the user segment.

The Galileo space segment comprises of 30 satellites placed in MEO orbit, with 10 satellites placed in each of 3 orbital planes (at 56 º nominal inclinations) distributed evenly round the equator. The active constellation comprises of 24 satellites (Walker 24/3/1), including 6 spare satellites, which can replace any failed satellite within the same plane, thereby reducing the impact of failures upon quality of service. All satellites are identical in terms of design, performance capability and fuel load. Each satellite broadcasts navigation timing signals together with navigation data providing the clock and ephemeris correction data which are essential for navigation.

The Galileo ground segment comprises two control centres, a global network of transmitting and receiving stations implementing monitoring and control functions and a series of service facilities which support the provision of the Galileo services. The core of the Galileo ground segment is the two Galileo Control Centres (GCC). Each control centre manages control functions supported by a Galileo Control Segment (GCS) and mission functions, supported by a dedicated Galileo Mission Segment (GMS).

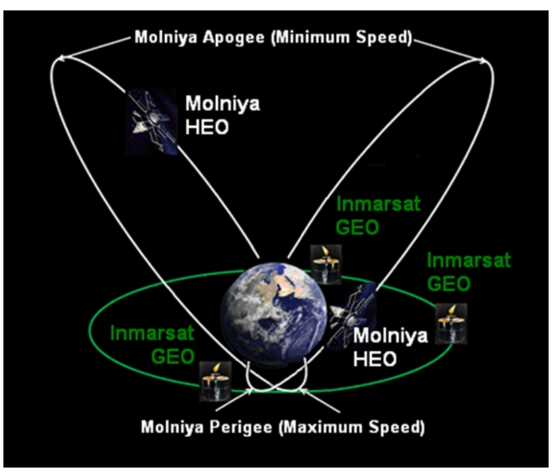
The Galileo user segment consists of all compatible receivers that, like GPS and GLONASS, are used by individual and mobile phones, maritime transport (ships), land transport (road and rail), aviation transport (aircraft), precision agriculture equipment, environment and civil protection and surveillance. A Galileo receiver is a device capable of determining a navigation solution (PVT) by processing the signal broadcasted by Galileo satellites. Once the signal is acquired and tracked, the receiver decodes the navigation message. The navigation data contain all the parameters that enable the user to perform positioning service [20, 21, 24].

4.3. Geostationary Earth Orbits (GEO) Satellite System.

The GEO satellite system has a circular orbit in the equatorial plane, with an orbital period equal to the rotation of the Earth of 1 sidereal day, which is achieved with an orbital radius of 66,107 (Equatorial) Earth Radii, or an orbital height of 35,786 km. Otherwise, a satellite in a GEO will appear fixed above the surface of the Earth, and remain in a stationary position relative to the Earth itself. Theoretically, this orbit is with zero inclination and track as a point but in practice, the orbit has small non-zero values for inclination and eccentricity, causing the satellite to trace out a small figure eight in the sky.

The footprint or service area of a GEO satellite provides coverage of almost 1/3 of the Earth's surface or 120^o in longitude direction and up to 75^o–78^o latitude North and South of the Equator but cannot cover the placePolar Regions. In this way, near-global coverage can be achieved with a minimum of three satellites in orbit moved apart by 120^o, that revolves in the same direction the Earth rotates (West to East), although the best solution is to employ four GEO satellites for better overlapping, which is illustrated in **Figure 2,** and its characteristics are presented in **Table 1.**

Figure 9: Hybrid GEO and HEO System.



Source: Ilcev.

This type of orbit is essentially used for all mobile communication systems including for MSC service with the following main advantages:

1. The GEO satellite remains stationary with respect to one point on the Earth's surface, and so, LES terminal antenna need not be steerable (directed) and consequently could be made to a simpler design;
2. There is no relative movement between the satellite and many LES terminals and consequently no Doppler frequency shift of the communications frequency is introduced; and
3. Continuous communications, between a SES and LES terminals are possible because the satellite is always in view.

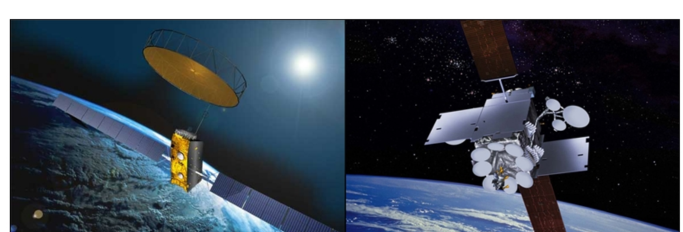
Otherwise, the Inmarsat GEO mobile satellite system is one of the major integrator of GMDSS network. The main advantage of Inmarsat and other GEO satellites is that are always in same position relative to Earth, because the satellite appears to be stationary or fixed when viewed from the Earth and no tracking required for Earth station antennas. In addition, about 40% of the Earths surface is in view from one GEO satellite and so this type of orbit is more reliable than LEO and MEO constellations.

The main disadvantages of Inmarsat GEO satellite systems are larger propagation delay of 238 to 284 ms in satellite communication than in terrestrial communication, high attenuation level of power loss at 200dB on the path and what is critical GEO satellites can only be above the equator and therefore placePolar Regions cannot be covered beyond 81^o latitudes. The lack of Polar coverage is not a problem for most users, while for aeronautical is important because of flights over North Pole. In the similar way, new Arctic shipping routes as the maritime paths used by vessels to navigate through parts or the entirety of the Canadian and Russian coastal placeArctic Ocean will need more reliable satellite communications system than MF/HF radio. Thus, to solve this problem GMDSS infrastructure will need some sort of Hybrid Satellite Orbits (HSO), such as combination of GEO and HEO (Molniya) satellite constellations, or simply to integrate existing Big LEO Iridium satellite constellation.

The overall goal of HEO integration with GEO constellation in the HSO system is to enhance the options of MSC system focused on provision of GMDSS, Ship Traffic Control (STC) dedicated mainly to ships sailing in Arctic costal waters of the northern part of Earth. This study aims at defining a reference system architecture and preliminary system design, such as HSO constellation between Inmarsat GEO and Twins (two) HEO Molniya satellites for entire Arctic coverage, which scenario is shown in **Figure 9.**

The HEO constellation system of Molniya satellites is already designed by former-USSR, today placecountry-region Russia, for civilian and military communications satellite service coverage at high latitudes of vast Russian land and sub place-Polar Regions. In fact, Molniya satellite has an orbital period of slightly less than 12 hours (semisynchronous orbit), inclination of 63.4° and high eccentricity of 0.722. In the apogee, where the Molniya satellite lingers over the service coverage area at 25,000 miles (40,000 kilometers), the satellite in perigee at only300 miles (500 kilometers) is not visible.

Figure 10: Inmarsat-4 and newest Inmarsat-5 Spacecraft.



Source: Inmarsat.

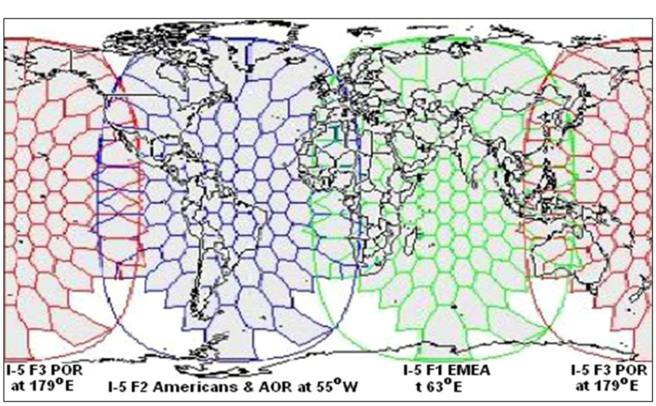
Thus, the Molniya orbits fill the gap with the twins (two) Molniya spacecraft provide approximately nadir pointing surfaces and coverage over high latitudes. Such an arrangement is ideal for HSO integration of 3 GEO and 2 HEO spacecraft of real global and very reliable satellite system for distress and commercial communications. Since the two spacecraft have a significant offset in their orbital phases (apogees at different 12 hours times), the pair can provide continuous coverage with a dual platform viewing for a main portion of Earth surface [04, 12, 25, 25].

4.3.1. Inmarsat GEO Satellite Network.

Inmarsat is a British company located in London for MSC including maritime communications offering global mobile services since 1982. It provides Voice, Data and Video (VDV) services to users worldwide, through portable or mobile terminals that communicate with LES terminals via 14 GEO communications satellites. Inmarsat's network provides communications services to a range of governments, aid agencies, media outlets and businesses (particularly in the shipping, land mobile (road and rail), aviation, agriculture, mining and other industries, with a need to communicate in remote and rural regions or where there is no reliable cellular and terrestrial networks.

The Inmarsat space segment consists of 5 satellite transponders located in GEO above the equator at an altitude of 35,000 km with precise geographical coordinates relative to the Earth, which type of orbit is shown in **Figure 2**. The satellite transmitters have a nominal power of 2800 W and today cover almost the entire Earth's surface, except for small circumpolar areas outside the 70s North and South. Inmarsat network has a total of 11 GEO satellites orbiting the Earth, but only 5 of them operate on the 1.5-1.6 GHz for maritime applications, which two generations of current Inmarsat satellites I-4 and I-5 are illustrated in **Figure 10 (Left and Right)**. The Inmarsat GEO satellites are also providing service for land (road and rail), aeronautical, fixed and personal applications, which coverage of Inmarsat-4 satellite constellation is illustrated in **Figure 11.**

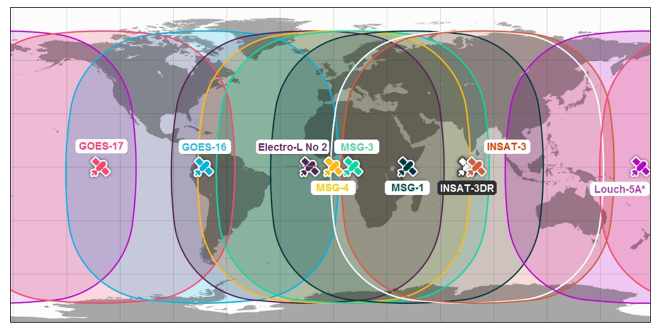
Figure 11: Inmarsat I-5 Global and Spot-Beam Coverage.



Source: Boeing.

The Inmarsat ground segment consists of many LES terminals as the gateways to ground networks. Each LES has a two or three-digit numeric identifier and is owned by the state in whose territory it operates. In addition, each ocean area has Network Coordination Stations (NCS), which provide free channels to ship and shore-based ground stations and monitor the use of dedicated channels. The Satellite Control Centre (SCC) located in the Inmarsat headquarters in placeCityLondon, performs the main control functions of the service, and Satellite Control Centre (SCC) located in the Inmarsat headquarters, performs the main coordination functions of the space segment.

Figure 12: Cospas-Sarsat GEOSAR Satellite Constellation.



Source: NOAA.

The Inmarsat users segment consists of mobile, fixed and personal satellite stations fixed on ships, land vehicles, aircraft, fixed and personal handhelds [04, 25, 26, 27, 28].

4.3.2. Cospas-Sarsat GEO GEOSAR Satellite Network

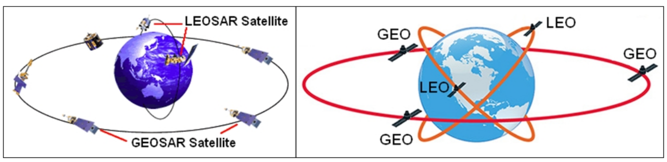
The configuration of the GEO GEOSAR space segment has been assembled of 8 - 9 GEO multipurpose satellites located at approximately 36,000 km above the Equator at different lines of longitude, giving an instantaneous footprint of the whole of the Earths surface nominally between 70^0 North and 70^0 South, which sample is shown in **Figure 6.** The GDSS service of the GEOAR satellites has the ability to receive distress emergency signals from the Cospas-Sarsat 406 MHz emergency beacons and retransmit them to the GEOLUT ground terminals. These satellites carry various payloads in addition to the Cospas-Sarsat 406 MHz SAR mission payload. The GEOSAR payload consists in the 406 MHz antenna, an Rx (receiver) and the downlink Tx (transmitter).

In **Figure 12** is shown 9 GESOAR coverages, which include the following satellites:

1. 2 satellites of the US National Oceanic and Atmospheric Administration (NOAA) Geostationary Orbiting Environmental Satellites (GOES) for meteorological observation and GEOSAR service: GOES-16 and GOES-17;
2. 2 satellites, 1 of the Russian GEO meteorological mission developed b Roshydromet, Planeta and Roscosmos (Russian Federal Space Agency), a successor spacecraft to GOMS (Geostationary Operational Meteorological Satellite), also referred to as Electro-L, and 1 Louch-5A is a Russian Louch GEO relay satellite which transmits data from the Russian Orbital Segment of the International Space Station (ISS), and from other satellites in low Earth orbit.

3. 3 MSG (Metosat Second Generation) MSG-1, MSG-3 and MSG-4 GEO satellites that served for meteorological and GEOSAR applications.
4. 2 INSAT (Indian National Satellite) GEO satellites: INSAT-3 and INSAT-3DR were developed by the Indian Space Research Organization (ISRO) for satellite meteorological and GEOSAR missions [04, 29, 30].

Figure 13: Combination of GEO-PEO and GEO-LEO Constellations.



Source: Ilcev.

4.4. Highly Elliptical Orbit (HEO) Satellite System.

The first prototype Highly Elliptical Orbit (HEO) Molniya satellite was launched in 1964 and to date more than 150 have been deployed, primarily produced by the Applied Mechanics NPO in Krasnoyarsk, former USSR. The HEO is the only non-circular orbit of the four. It operates with in an elliptical orbit, with a maximum altitude (apogee) similar to the GEO, and a minimum altitude (perigee) similar to the LEO, which is illustrated in **Figure 2,** and his orbital characteristics are presented in **Table 1.**

5. Hybrid Satellite Orbits (HSO).

The Hybrid satellite constellation can be configured with several types of existing satellite orbital solutions today. In this context, only five hybrid satellite constellation systems will be introduced shortly, which are currently used in mobile satellite systems or for development of new MSC and navigation systems, such as:

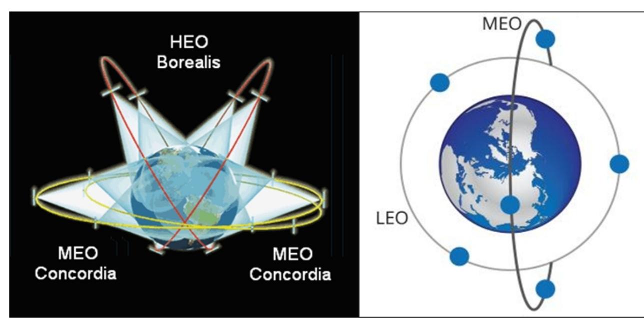
1. Combination of GEO and HEO Constellations – The overall goal of HEO integration with the GEO constellation in the HSO network is to improve of satellite communications options aimed to provide an improved GMDSS network on the northern and polar routes. The aim of this study is to define the system architecture and preliminary design, such as the HSO constellation between Inmarsat GEO and the twin (two) HEO Molniya satellites for total coverage of the Arctic and Russian coasts for new ship routes between the Atlantic and Pacific, which scenario of HSO network is shown in **Figure 9.**

2. Combination of GEO and PEO Constellations – The current combination of GEO and PEO satellites was developed through the efforts of Cospas-Sarsat, with the help of International Maritime Organization (IMO), Inmarsat and other international and regional contributors. This HSO system used in GMDSS network is a combination of few GEO operational satellites of the subsystem called GEOSAR and PEO operational satellites in LEO subsystem called LEOSAR, which constellation is illustrated in **Figure 13 (Left).**

3. Combination of GEO and LEO Constellations – Celestri is the Motorola trademark name for a proposed GEO and LEO satellite hybrid communication network, shown in **Figure 13 (Right).** The network will combine 9 GEO and 63 LEO satellites in 7 planes with Earth-based control equipment and provide interfaces to existing telecommunication infrastructures, the Internet and corporate and personal networks. The system will offer a 64 Kb/s voice circuit from anywhere in the world. The architecture is not limited to fixed sized channels but permits dynamic bandwidth assignment based on application demand. Business users will benefit by Celestri's to provide remote access to LAN infrastructures.

4. Combination of MEO and HEO Constellations – The new Ellipso satellite system is combination with an initial complement of seven Concordia satellites deployed in a circular equatorial MEO at an altitude of metricconverterProductID8,050 km8,050 km and ten Borealis satellites in two HEO planes inclined at 116.6^o. They have apogees of 7,605 km and perigees of 633 km and a three-hour orbital period. This combination of two constellations, shown in **Figure 14 (Left)** would provide coverage of the entire Northern Hemisphere including North Pole areas and part of the Southern Hemisphere up to 50^o latitude South.

Figure 14: Combination of MEO-HEO and MEO-LEO Systems .



Source: Ilcev.

5. Combination of MEO and LEO Constellations – The Kompomash consortium for space systems in Russia have prepared the Gostelesat satellite system for MSS, shown in **Figure 14 (Right),** using 24 satellites in MEO and 91 in LEO satellite constellation. Thus, this satellite project is provided for future global MSC and navigation applications with possibility to cover both pole regions [04, 07, 25, 26].

Conclusions.

The GMDSS radio and satellite SAR infrastructure network became fully operational on dateMonth2Day1Year19991 February 1999 as a worldwide automated emergency communications network for all cruisers and cargo ships over 300 gross tonnages at sea. All maritime vessels must be equipped with appropriate radio and satellite equipment in accordance with international standards established by the IMO and the SOLAS

Convention as an international maritime treaty that sets minimum safety standards in the construction, equipment and operation of merchant ships. After the establishment of the GMDSS network and its space segment using only the satellite system Inmarsat was for a long time the only maritime mobile satellite service. The Cospas-Sarsat LEO and GEO satellite service for distress satellite communications was also used for a long time. However, there was a need to modernize the original GMDS network with new satellite space segments, such as Iridium, hybrid satellite constellations and the new Cospas-Sarsat MEOSAR network. In this way, the new architectures of satellite space segment integration within the modernization of GMDSS networks described in this article will be able to make a practical impact in its further successful improvements.

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