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A REVIEW OF MULTIPLE TECHNIQUES FOR OBTAINING EFFECTIVE SATELLITE DATA OVER THE ARCTIC REGION

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Abstract—**For the most part because of its geographic location and auroral activity, the Arctic region is one of those that poses numerous difficulties when developing an accurate navigation system. There are a few satellites in this area, but not enough to offer precise positioning. The data is significantly degraded as a result of the auroral events, which also affect satellite signals. Continual observation of the Polar Regions from space is a significant technical challenge that is attractive to the international meteorological community. Continuous global coverage would be possible with a Geostationary Satellite Network and a Highly Elliptical Orbits (HEO) system. Practically, a small number of satellites in either Highly Elliptical Orbits (HEO) or Medium Earth Orbits (MEO) can provide continuous coverage of the polar areas. The loss of data resulting from ionospheric scintillation is examined in this work along with a number of potential remedies, including some of the many suggestions made by numerous researchers.**

Keywords—**Satellite Communication, Arctic Region, HEO, Ionospheric Scintillation, Radiation.**

I. INTRODUCTION

One of the world's most potential investment prospects is in the arctic areas. This area is crucial to several businesses, such as mining and maritime traffic [1]. Over the past 20 years, human settlement has steadily grown in the Arctic region. The longer fishing season and new fishing spots have been made possible by the melting of the ice caps. These new areas also enable more extensive mineral exploration. Since 2007, there have been more cruise ships travelling to the Arctic region. But satellite navigation in this region is still difficult and unreliable.

It is well known that the Arctic region, which is all of the land above 66.56 degrees north latitude, is difficult to navigate due to the region's extreme meteorological conditions as well as its poor communication and positioning infrastructure. Satellite positioning performance can be affected by disturbances in the ionospheric and tropospheric stratosphere, leading to erratic delays and scintillation of the satellite signals. These effects intensify as the spacecraft gets closer to the horizon [1]. What sources of information can we trust for precise navigation in this chilly environment? The goal of this review is to look at the fundamentals and a few fixes or substitutes that satellite navigation specialists advise.

Highly Elliptical Orbits

What aspects of Highly Elliptical Orbits (HEO) make them appropriate for satellite communication? What are they used for and what is their purpose? The curve in HEO is comparable to an ellipse. One of the most significant characteristics of an elliptical orbit is that a satellite moves significantly more quickly close to the earth than farther away from it. As part of its plan for the Global Observatory System (GOS) in 2025, the World Meteorological Organization (WMO) accepted the notion of a HEO satellite system at its sixty-one session (EC-LXI; WMO 2009) of its executive council. With the advantages of consistent free space losses and link budgets throughout the orbit, circular orbits with low eccentricity quickly became the standard. A satellite in a circular orbit can see a large area of the Earth, which is equivalent to 75° of latitude north and south [2]. The geostationary coverage ring is below the local horizon at higher latitudes. The satellites are hidden as a result. As a result of being visible for a longer period of time, satellites in a HEO are able to give improved coverage across any point of view on the earth. Russia and other nations that require coverage over polar and near-polar regions heavily rely on highly eccentric orbits (HEO). An HEO is oblong in shape, with one end farther from Earth than the other. Applications such as telecommunication, satellite radio, remote sensing, and others are well suited for HEO satellites.

The remainder of the study is divided into the following sections: Section 2, which discusses the critical issues, Section 3, which examines the application of HEO over the Arctic region, Section 4, which includes some further mitigation strategies, and Section 5, which concludes.

II. CRITICAL PROBLEMS

A. Perturbations Of Orbit

The force acting around the Earth is the centrifugal force, and according to Kepler's law, the orbit of the Earth is a perfect sphere. This force is intended to counteract the earth's gravitational pull. In actuality, additional forces also have a significant impact on the satellite's motion. The gravitational pull of the Sun, Moon, and atmospheric drag make up these forces. Geostationary earth satellites are more affected by the Sun and Moon, whereas low earth orbit satellites are more affected by air drag.

B. Effects Of Non-Spherical Earth

The satellites' orbital paths around the primary differ slightly because Earth's form is not a perfect spherical. The forces that come from an oblate Earth acting on the satellite cause an alteration in the orbital parameters as the Earth protrudes from the equatorial belt. As a result of the nodes' regression and the point of perigee's latitude, the satellite begins to drift. The line of apsides rotates as a result. The values of the argument of perigee and right ascension of ascending node change as a result of the orbit's movement with respect to the Earth. One such phenomenon known as the "Satellite Graveyard" is seen as a result of the non-spherical shape of the Earth. The tiny value of eccentricity at the equatorial plane results from the non-spherical shape. The GEO satellites are affected by this gravity gradient, which leads them to drift to one of the two stable spots that meet the minor axis of the equatorial ellipse. The centrifugal force of the rotating cosmos overcomes the gravitational force at a precise altitude of 35,900 km above the equator. A stationary satellite should be parked in this location.

C. Effects Of Ionospheric Activities On Satellite Data

Free negatively charged electrons dominate the ionosphere's electromagnetic signal environment. The frequency determines the degree of the signal delay, which is different for GPS L1 and L2 frequencies. GPS L1 pseudo ranges slide by 5–15 metres during the day and 1-3 metres at night due to the usual signal delay. Large gradients of Total Electron Content(TEC) are produced by higher electron precipitation in the Arctic area. Ionospheric range error can practically quadruple, however research indicates that it only lasts 10 minutes in the Arctic. Real-time ambiguity resolution is made difficult or impossible by significant TEC gradients in the ionosphere. Scintillation happens when satellite signals encounter "lumps" of electrons in the ionosphere, changing the phase and amplitude of the signal. Large TEC gradients and high auroral activity are strongly connected with it, and it makes GNSS receivers lose lock on the satellite signals. Scintillation occurrences can last for a variety of times. One signal is frequently just briefly interrupted, while a scintillation event can strike a receiver for up to an hour.

The satellites not only deliver data but also ranging information. The loss or corruption of the data bits can occur when scintillation results in the loss of a signal. Ephemeris data, which includes the satellite's coordinates and the status of its clock, is broadcast by GPS satellites. Parity bits that serve as error detectors typically accompany these data. To determine if two cycles of identical data are identical or not, the receiver end must receive at least two cycles of that data in an uncorrupted and complete form. A satellite will only be used if they turn out to be identical. The employment of additional satellites is not possible if scintillation interferes with the successful decoding of these communications. The polar cap and the auroral oval are the two main areas in the high latitudes where significant magnetospheric-ionospheric processes take place and space weather is initiated. The boundaries of these zones are dynamic and change as a result of variations in the solar wind and the Interplanetary Magnetic Field (IMF). Phase scintillation and rapid spikes in range readings due to abrupt changes in Total Electron Content (TEC) are the two main problems for Global Navigation Satellite System (GNSS) users. Ionospheric abnormalities that develop in reaction to solar and geomagnetic activities are what cause scintillation. Numerous variables show how scintillation affects performance at a specific moment and location. The stability of the satellite's axial geometry and the level of scintillation are the two most important variables.

The majority of the time, scintillation only affects one or two satellites, resulting in sporadic outages and a slight rise in noise. The user's overall performance won't be greatly impacted by the loss of one or two signals if there are numerous, evenly distributed signals available to them. Even low quantities of scintillation could interfere with the user's functioning if their satellite coverage is initially inadequate. Many satellites may be considerably impacted when scintillation is extremely strong.

Discussion of use of HEO over Arctic region

1) ARCTIC REGION AND HEO

As of 2002, calculations of wind field vectors in polar regions (latitudes above 65°N) using Moderate Resolution Imaging Spectroradiometer (MODIS) observations from the low-orbiting Terra and Aqua Earth-observing system satellites have been added to the initial data from the crucial geostationary satellites [3]. The primary reason for placing these systems in highly elliptical orbits is to have access to quasi-continuous satellite hydro meteorological data that covers areas north of 60 degrees north latitude in the Arctic using equipment that is similar to the cutting-edge imagers on traditional geostationary meteorological satellites [3].To demonstrate monitoring hydro meteorological conditions in the Arctic region and within the Earth's northern territories using the current scientific and technological surface-based infrastructure, Roscommon and Roshydromet proposed to form and introduce the Arctica highly elliptical orbit satellite system [3].

The HEO with the adopted settings guarantees:
(1) Near-constant monitoring of the Arctic regions at latitudes north of 60 degrees;
(2) Constant radio-visibility of the satellites during operating orbital segments for northern receiving locations [3].

Because they enable the use of scanner pictures from the geostationary satellites with a somewhat improved quality. It has been shown that HEO with an apogee of 40 km and an orbital period of 12 hours is preferable. Additionally, due to better radiation circumstances, it has a usable lifetime of at least seven years.

2) Optimization Approach For Selecting Heo

John E. Drain and others have investigated, created, and advocated for high elliptical orbits in great detail. The selection of HEO for a particular satellite is heavily influenced by the inclination of the satellite's orbit. It is the angle formed by a line parallel to the orbital plane and a line that passes across the poles. This suggests that an orbit that travels directly over the equator will be inclined to 0° or 180°, whereas an orbit that crosses over the poles will be inclined to 90°. An orbit has an inclination of between 25 and 155 degrees. The eccentricity of the orbit must be larger than 0.05 and the amount of the orbit may be a multiple of the geostationary satellite orbit. Each satellite must maintain contact during its full orbital cycle due to the coverage geometry. In Kidder and Vonder Haar (1990), the basic characteristics of the very elliptical Molniya orbit are covered. This analysis has been expanded by Trishchenko and Garand (2011) to provide a detailed explanation of the spatial and temporal sampling of the polar regions as well as the trade-off space for selecting a suitable two-satellite Molniya mission configuration [4]. According to research, the Molniya orbit, which has an eccentricity between 0.73 and 0.74 and a perigee height between 500 and 800 km, offers imaging geometry similar to that of quasi-geostationary conditions [4]. Like GEO satellites, this orbit provides excellent imaging capabilities over the polar areas, however this is frequently at the expense of fluctuating altitude and speed in comparison to other orbit satellites [4].The HEO constellation benefits from being within the sheet or within the planes with the crucial inclination of 63.4358°, which reduces orbit maintenance costs related to drift. This drift limits the coverage of high-latitude regions by moving the apogee to a lower latitude over time [5]. The final visual representation of an elliptical orbit and the list of Keplerian orbital components are shown in Fig. 1. The centre of the world is designated as Point O. Along the spin axis of the earth, axis z points north. The vernal equinox point is the focal point of axis x. The apogee point is the point that is farthest from the centre of the earth, while the perigee point is the point that is closest to it.The angle ‘i’ is known as the orbit inclination [5] and is the angle between the sheets and the equatorial plane.

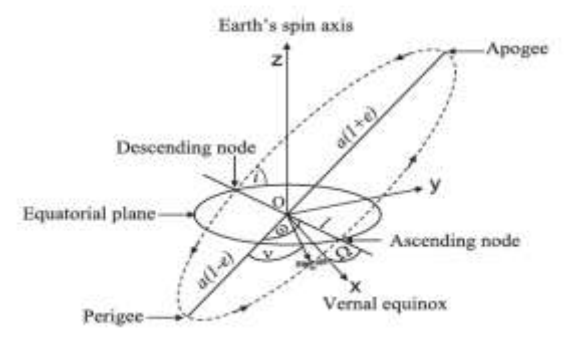


Fig.1 Graphical layout of the elliptical orbit and definition of Keplerian orbital elements [4].

For satellites travelling on circular orbits, or with eccentricity, the dwelling duration over the polar zone is directly proportional to the angular size of the arc enclosing the segment of the orbit located inside the area of interest [5]. If the orbit's eccentricity rises, a greater percentage of the satellite's time will be spent over the poles [5]. One can approximate the orbit by thinking of it as an ellipse.

The study demonstrates that the orbit's altitude has an effect on coverage as well; the higher the altitude, the wider the coverage, albeit this effect is nonlinear and eventually reaches saturation [5].

One may now typically draw the conclusion that eccentricity (e) 0.5 is preferred in order to necessitate the benefit of HEO observations in terms of coverage and viewing geometry [5]. The main factors that went into choosing the orbits are outlined in this section. It closely adheres to the earlier investigation by Trishchenko et al (2011). Fig. 1 displays the definitions of the orbital elements. The angle between the direction of a node and X-axis is termed the proper Ascension of node and is denoted as X. The orbital position with point O is the centre of the globe. Axis Z is pointed north along the Earth's spin axis, while axis X is pointed at the vernal equinox point. The perigee point and apogee point are the two points on the Earth's surface that are in relation to its centre, respectively. The proper ascension of a node, which is represented by the letter X, is the angle between a node's direction and the X-axis. The angle which is verity anomaly, determines the satellite's orbital position [6].

The semi-major axis, which is uniquely associated with the amount of the orbit, and the eccentricity of the orbit, or "e," which determines the shape of the ellipse and, consequently, a dwelling time within the vicinity of the apogee region, are important orbital components for the observational performance of a HEO system. The inclination, or ‘i’ which affects the polar areas' orbital maintenance and coverage properties.

To be able to study the high latitude regions for an extended period of time, the satellite should be placed into an elliptical orbit with a high eccentricity when it is launched. The satellite stays closer to the apogee point for a longer period of time the higher the eccentricity. The tilt of the sheet must be high enough to take use of this property for monitoring polar regions. Trishchenko et al. derived the equation for the satellite residence time over the area above the circle of latitude[6]. For these orbits to ensure appropriate polar coverage, the inclination must be raised. Additional study from several experiments revealed that the protective thickness barely changes when the orbital inclination is changed from critical value to 90° [6]. Also take note that eccentricity values below 0.3 cannot be used to achieve acceptable continuous coverage of the polar areas [6]. In conclusion, one specific set of Keplerian orbital components was discovered for each value of the orbital period between 6 and 24 hours. To confirm that the polar areas were completely covered, this mixture was created [6]. As a result, the continuum of six Keplerian orbital elements' six-dimensional analysis was condensed into 19 particular examples, which were then used to estimate radiation for the HEO system [6].

3) Radiation Environment In Heo

As a result, the continuum of six Keplerian orbital elements' six-dimensional analysis was condensed into 19 particular examples, which were then used to estimate radiation for the HEO system [6].The geomagnetic field of the globe traps high concentrations of particles (protons or electrons) in two radiation belts, whereas the geomagnetic field also defines regions with comparatively low particle concentrations [6]. The fluxes of the relativistic electrons within the outer radiation belt can shift by several orders of magnitude in a short amount of time since the inner radiation belt is very steady [6]. The many fluctuations in the near-Earth energetic particle environment have many recognized sources, including geomagnetic storms and solar energetic particle events [6].

III. SOME OTHER MITIGATION SOLUTIONS

The phrase "The Most Sensitive Regions of the Earth's Climate" is frequently used to describe Polar Regions. They do, in fact, have a significant impact on weather patterns around the world and are more sensitive to climate change. Poor GNSS and real-time performance, scintillation in phase and amplitude, a lack of radio-navigation infrastructure, the impact of ionospheric activities, and other issues are listed as the top issues frequently encountered in the Polar Regions. Numerous studies are available for this area to ensure effective satellite communication. The physics of orbit prevent GEO-style imaging above the poles. Currently, polar regions are observed by low Earth orbiting (LEO) satellites that rotate the Earth once every 100 minutes at an altitude between600 km and 900 km [7].

A. Implementing Multi-Channel L-Band Frequencies In Satellite Systems

In satellite positioning, a mistake brought on by the ionosphere is removed by combining two signals linearly. The L-band frequency is most frequently used for satellite communication since it has significant properties. With it, there is the potential for global broadband communication between mobile users, uninterrupted worldwide network coverage, and the ability to continue global operations even when unfavourable atmospheric conditions predominate in complex regional locations. Multiple L-band frequencies for GPS and Galileo are one of the potential solutions that are already under development. The positioning algorithms work better as there is more data to feed them as there are more frequencies available. Furthermore, since more observations at various frequencies may be integrated, more frequencies offer a better technique to cope with ionospheric effects.

B. Integrating INS with Gnss

The use of Inertial Guidance Systems (IGS) in conjunction with GNSS is another obvious solution that is partially already available. To bridge the navigation solution during scintillation gaps and to lessen the impact of extremely large unexpected TEC gradients, inertial sensors are coupled with GNSS. Due to the almost vertical earth rotation rate vector obtained by traditional gyroscopes, IGS has less accurate heading at high latitudes. As a result, users are more dependent on GNSS to determine heading. Additionally, IGS has the ability to support autonomous integrity against rapid TEC variations.

The Kalman filtering algorithm can be used to accomplish this integration [8]. The output of the inertial navigation system after feedback correction is the output of the integrated system, which considerably reduces the speed of north and east, latitude and longitude position errors. For the exact operation of a small agricultural UAV(Unmanned Aerial Vehicle), this inaccuracy won't become worse over time, and the entire process runs faster. According to tests, the speed and location mistake doesn't clearly rise over a long length of time. This demonstrates the great robust ability of the proposed GNSS/INS combined navigation algorithm [8].

C. VARIATIONAL MODE DECOMPOSITION (VMD) AND MULTIFRACTAL DETRENDED FLUCTUATION ANALYSIS (MFDFA)

Variational Mode Decomposition (VMD), an adaptive time-frequency decomposition technique, was introduced for the estimation and reduction of ionospheric scintillation effects on a satellite signal. For a while now, the geophysical and medical industries have used Multifractal Detrended Fluctuation Analysis (MFDFA) to identify self-similarities and long-range correlations in the signals. Research found that using VMD and MFDFA together allowed for the estimation, mitigation, and re-acquisition of GNSS signals even when ionospheric scintillation effects were intense [9].

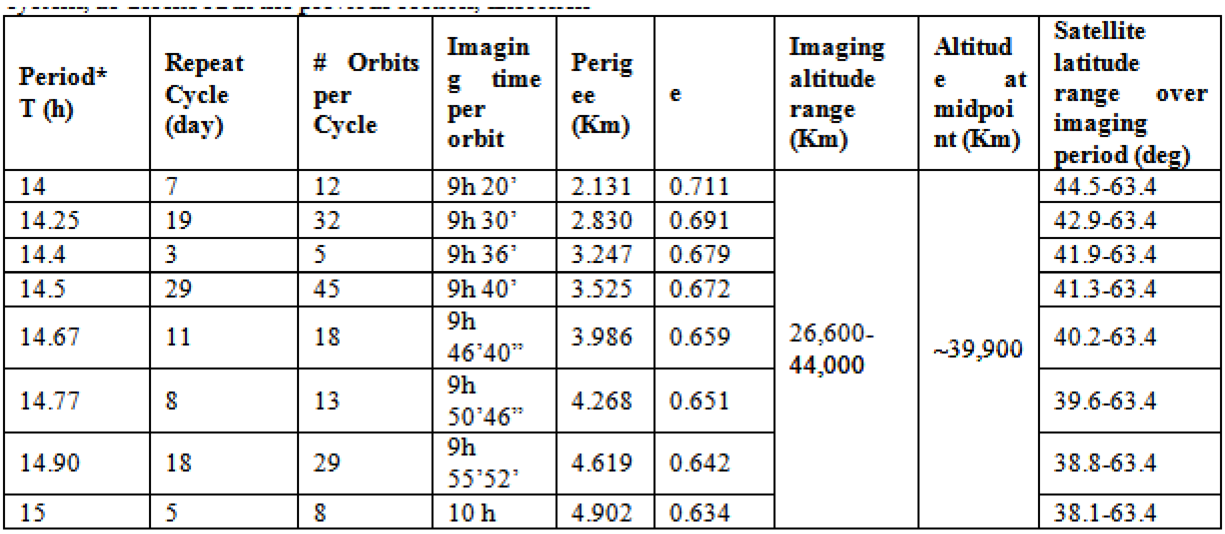
Based on the properties of the signal itself, the VMD approach adaptively divides non-stationary signals into a number of components (modes) of different scales. It simultaneously breaks down a given signal into a collection of intrinsic mode functions [10]. The purpose of VMD is to deal with the variational problem of signals in all its forms, build noise-free IMFs, and eliminate them. In order to address the fluctuation (variational) problem of signals caused by obstructions and atmospheric disturbances, the VMD decomposition procedure was developed [9].

A time-frequency approach known as VMD in conjunction with MFDFA was used to examine how well GNSS receivers performed when subjected to ionospheric scintillation effects. The information used was divided into synthetic (scintillated) data produced at various stages [9]. According to observation, when compared to other techniques for rectifying scintillated signals, VMD-MFDFA performance was the best and most efficient [9]. Therefore, VMD-MFDFA is more effective since it can accurately separate noise components from the amplitude-scintillated signal regardless of how near the frequency components are to one another. From the experimental analysis in this study, the suggested VMD-MFDFA approach provided an adequately denoised ionospheric scintillated signal. The effect of ionospheric scintillation on satellite signals can therefore be estimated and mitigated using VMD-MFDFA, which is a more effective and appropriate decomposition technique [9].

D. MULTIPLE APOGEE SYSTEM

A variety of orbits with multiple apogees are shown in Table 1. (MAPs). Recent radiation study has confirmed that HEO orbits are suitable for ongoing polar monitoring [7]. Because the eccentricity is between 0.63 and 0.71, there is enough time for the apogee point to be over the polar zone [7]. For a two-satellite system, as described in the previous section, unbroken coverage requires 16 hours of imaging time each day over the cold zone. Due to the second zonal harmonics of the planet's field of force, which guarantee a steady position of apogee across the climatic zone, critical inclination corresponds to zero rates of apogee drift [7]. The apogee slowly moves toward the equator if the HEO orbit inclination deviates from the critical value. To maintain the desired orbit position, orbital manoeuvres are therefore needed. More resources are needed to maintain the orbit the further the orbit's inclination is from the critical value. Therefore, it is strongly advised that the HEO system's orbital inclination be set at the critical value.

The space weather study is in a manner that is comparable to a HEO orbit (i.e., it measures magnetic flux and radiation in place). The capacity of the HEO orbit to better characterise the carbon cycle over the Arctic and boreal zone using infrared (IR) and visible-ultraviolet (VIS-UV) spectrometers has also been demonstrated in studies [7]. The Polar Regions are anticipated to be continually scanned in an ideal manner by the MAP HEO constellation, which consists of two satellites per hemisphere. These systems are put into orbit at a critical inclination, which corresponds to a radiation area minimum with a relatively modest proton component. These characteristics make orbital maintenance easier to do and need less radiation shielding.



Period* T (h)	Repeat Cycle (day)	# Orbits per Cycle	Imaging time per orbit	Perigee (Km)	e	Imaging altitude range (Km)	Altitude at midpoint (Km)	Satellite latitude range over imaging period (deg)
14	7	12	9h 20'	2.131	0.711	26,600-44,000	~39,900	44.5-63.4
14.25	19	32	9h 30'	2.830	0.691			42.9-63.4
14.4	3	5	9h 36'	3.247	0.679			41.9-63.4
14.5	29	45	9h 40'	3.525	0.672			41.3-63.4
14.67	11	18	9h 46'40"	3.986	0.659			40.2-63.4
14.77	8	13	9h 50'46"	4.268	0.651			39.6-63.4
14.90	18	29	9h 55'52'	4.619	0.642			38.8-63.4
15	5	8	10 h	4.902	0.634			38.1-63.4

Table 1. Some features of the MAP HEO orbit [7]
*Assuming sidereal day 24 h for simplicity. Apogee altitude H ≤ 44,000 Km for all orbits.

In comparison to traditional HEO systems with some apogees, just like the classical 12-h Molniya concept, a MAP HEO constellation with multiple apogees achieves a more uniform geometrical sampling, which reduces view angle–dependent biases. These observational conditions are beneficial for high-latitude. A MAP HEO constellation with numerous apogees achieves a more uniform geometrical sampling than standard HEO systems with a few apogees, similar to the traditional 12-h Molniya idea, which lessens view angle-dependent biases. Applications involving high-latitude meteorology and climate benefit from these observational circumstances [7]. The 12-hour Molniya orbit combines the so-called "critical inclination" (63.4°), which results in an apogee position that is remarkably stable, and an excessive eccentricity [7].LEO orbits are unable to give continuous coverage of the entire polar region, which is sometimes achieved by just two imagers in Molniya HEO orbit for each hemisphere [6]. In actuality, a constellation made up of two pairs of HEO satellites and a number of GEO satellites could watch weather patterns anywhere in the world at any moment [6]. Trishchenko et al. carried out a replacement study to lessen exposure to proton radiation. In terms of trade-offs between the proton radiation environment and requirements for the meteorological imaging, such as spatial resolution, temporal coverage, orbit maintenance, repeatability of diurnal observational conditions, data reception, and satellite ground speed during the imaging phase, it was absolutely suggested that a 16-h orbit represents an optimal solution for HEO orbital configuration [6]. With three apogees separated by 120° in longitude, this orbit has a repeating ground track over a two-day period, among other unusual characteristics. Understanding and forming the longer-term HEO satellite system for Arctic observations required careful consideration of the variables used by the researchers for the optimization and selection of a HEO orbit for polar observations [6].

According to a study, the HEO configuration, which includes two satellites in a single orbital plane and, as a result, four apogees spaced 90 degrees apart, offers an advantage over the arrangement with two orbital planes. When observing land masses from the nadir (lowest point) direction, an apogee configuration with four equal points enables a more balanced sample of the polar region and better viewing conditions [6].

IV. CONCLUSION AND FUTURE SCOPE

GPS users are now well-aware of the ionosphere's scintillation phenomenon. This is one of the primary obstacles to satellite systems in the Arctic region. Scientists are working to create models that can forecast the number of scintillation cells as part of their efforts to collect accurate satellite data for the Arctic region. Transition Region Explorer (TREx) Network, combining variational mode decomposition into GNSS analysis, and building extremely elliptical orbits are forecasting tools that can alert users in advance when a certain region will be impacted by scintillations that exceed a given level. However, the practical suggestions include using several L-band frequencies in satellite systems and deploying HEO satellite constellations across the relevant area. Ionosphere scintillations are now a well-known phenomenon. Two satellites in any orbit can sustain continuous and permanent coverage in HEO, according to observations. Additionally, HEO can reduce the amount of time that satellites are in motion if the inclination is chosen properly. It has been widely agreed that in the long run, the World Observing System's satellite component needs to include satellites in very elliptical orbits, as this would guarantee ongoing monitoring of the pole region outside of GEO coverage.

By looking at HEO orbits that would be appropriate for ongoing monitoring in the Arctic region and serving as a benchmark in this regard, this study fills that need. The current study leads us to the conclusion that trapped protons dominate the space environment in orbits lasting longer than 13 hours, whereas trapped electrons dominate orbits lasting longer than 14 hours. Except for orbits with the shortest length (6-7 hours), most HEO orbits have high inclinations and altitudes above climatic zones, which reduces the effectiveness of geomagnetic shielding and makes them more vulnerable to solar energetic particles. All of these ideas have been prototyped and tried in small settings, but no workable solution has yet been used in a widespread manner.

V. REFERENCE

[1] Yastrebova A., Höyhtyä M., Boumard S.,Lohan E. S., Ometov A., (2021).Positioning in the Arctic Region: State-of-the-Art and Future Perspectives, IEEE Access, Vol.9, (pp.53964-53978).

[2] Wood L., Lou Y., Olusola O., (2014). Revisiting elliptical satellite orbits to enhance the O3b constellation, Journal of the British Interplanetary Society, Vol.67, No.3,(pp.110-118).

[3] Asmus V. V.,Dyadyuchenk V. N.. Nosenko Y. I., Polishchuk G. M., Selin V. A., (2007).A Highly Elliptical Orbit space system for hydrometeorological monitoring of the Arctic region, WMO Bulletin, Switzerland, Vol.56 (4).

[4] Trishchenko A. P., Garand L.,Trichtchenko L. D., (2011).Three-Apogee 16-h Highly Elliptical Orbit as Optimal Choice for Continuous Meteorological Imaging of Polar Regions, The Journal of Atmospheric and Oceanic Technology, Vol.28, Issue.11, (pp.1407-1422).

[5] Trishchenko A. P.,Garand L.,Trichtchenko L. D., (2019). Observing Polar Regions from Space: Comparison between Highly Elliptical Orbit and Medium Earth Orbit Constellations, The Journal of Atmospheric and Oceanic Technology, Vol.36, Issue.8, (pp.1605-1621).

[6] Trichtchenko L. D.,Nikitina L. V.,Trishchenko A. P., Garand L., (2014). Highly Elliptical Orbits for Arctic observations: Assessment of ionizing radiation,

Advances in Space Research, Vol.54, Issue.11, (pp.2398-2414).

[7] Trishchenko A. P.,Garand L.,Trichtchenko L. D., Nikitina L. V., (2016). Multiple-Apogee Highly Elliptical Orbits for Continuous Meteorological Imaging of Polar Regions - Challenging the Classical 12-h Molniya Orbit Concept, Bulletin of the American Meteorological Society, United States, Vol.97, Issue.1, (pp.19-24).

[8] Wang G., Han Y., Chen J., Wang S., Zhang Z., Du N., Zheng Y., (2018). A GNSS/INS Integrated Navigation Algorithm Based on Kalman Filter, IFAC, Vol.51, Issue.17, (pp.232-237).

[9] Ahmed W. A.,Wu F.,Marlia D., Ednofri,Zhao Y., (2019). Mitigation of Ionospheric Scintillation Effects on GNSS Signals with VMD-MFDFA, Computer Graphics and Applications, Journal of IEEE Access , Vol.11, Issue-23.

[10] Dragomiretskiy K.,Zosso D., (2013). Variational mode decomposition, IEEE Transactions on Signal Processing, Vol.62, Issue.3, (pp.531-544).

[11] Hastings D., Garrett H., (2009). Spacecraft-Environment Interactions, Cambridge University Press, Massachusetts Institute of Technology, United States.

[12] Blake, J. B., Cox, J. E., (1988). The radiation dose in a Molniya-type orbit, Aerospace Report, SD-TR, (pp. 88-107).

[13] Garand L., Morris, A., (2011). Polar communications and weather (PCW) user’s requirements documents, Version 6.1, Available from the Canadian Space Agency, (pp. 87).

[14] Trichtchenko, L. D., (2012). Radiation environment analysis for Canadian polar communication and weather mission – Geological Survey of Canada, Open file,(pp.139).

[15] Emmanuel, A., Raghavan J., Harris, Ferguson P., (2014). A compariosn of radiation shielding effectiveness of materials for highly elliptical orbits, Advance Space Research, 53, (pp. 1143-1152).