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Maneuver of Satellites Constellation for Optimal Continuous Coverage

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Abstract: *This work aims to study the effect of conservative and non-conservative forces, like Earth's oblateness, third-body gravitational attraction and atmospheric drag on satellites in high elliptical Molniya and Tundra orbit types for coverage of high latitude regions. This work uses a Kyushu University computational model to make a simulation to propagate the effect of various perturbations on satellites constellation in Tundra and Molniya orbits for 10 years. The computational Model solves the Gaussian planetary equations numerically under effect of orbit perturbations and gives a high accuracy for the interval of propagation for Tundra and Molniya satellites constellations. The results show that the effect of theses forces on different eccentricities 0.2~0.7 is varying, and the daily coverage hours for this satellites constellation increase and decrease according to the change in the argument of perigee or the right ascension of the ascending node. Hence, the over lapping between these satellites in the constellation will be affected. A non-coplanar maneuver done for the satellites that affected by perturbations to correct their positions in order to make a continuous coverage.*

1. Introduction

For a long time, the geostationary satellites were the only solution to make continuous coverage for observes position on the Earth. Because there are a lot of disadvantages, like high cost, bad resolution of the pictures and uncovering the high latitudes regions, this solution became not satisfied. Russia and United States of America gave other solutions to avoid all of these problems by innovating the highly eccentric Molniya and Tundra orbits, respectively.

Satellites constellation on elliptical orbits with inclinations distinct from critical inclination were suggested by J. Draim [1], Various Satellites constellations for continuous global coverage and coverage of the Northern Hemisphere were obtained, including the case of orbits with critical inclination [2]. Methods of designing such constellations for elliptical orbits have been discussed already in [3] and [4].

Tundra and Molniya are two types of orbits that have useful characteristics of enabling observation of vast areas of the Northern Hemisphere for extended periods of time each day [5]. Both of these orbits have a critical inclination of 63.4 degrees to be able to observe the high latitude regions and also have a high altitude. The argument of perigee setting near to 270 degrees for maintaining the optimal visibility of the northern hemisphere. The orbital period of Molniya orbits is a half of sidereal day; it means the satellite will cover two different positions on the Earth, while for tundra orbit, the orbital period approximately one sidereal day. The eccentricity for Molniya orbit is higher than Tundra orbit, and the altitude of perigee for Molniya orbit is less than 1000 km, it means the atmospheric drag force will affect the Molniya orbit rather than Tundra.

To achieve long lifetime for these two kinds of orbits, the dominant perturbation should be studied carefully for each kind of orbit according to its characteristics to be able to maintain that effect in the proper time.

The main perturbation will affect on the Molniya orbit is the Earth's oblateness, atmospheric drag and the third-body gravitational attraction, while the atmospheric drag will not affect on Tundra orbit because the altitude of its perigee is higher than that of Molniya.

Tundra and Molniya orbits have the same objective for covering high latitude regions, but they have different ways to achieve this goal as demonstrated in Figure 1.

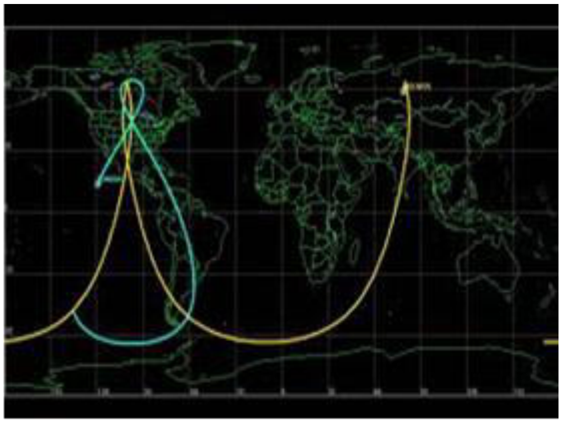


Figure 1. Ground track of Molniya and Tundra orbit

Figure 1 draws the ground tracks for Molniya and Tundra orbits in order to make a coverage for high latitude regions as North America, Russia and most of European countries. The shape of the ground track for Tundra orbit take a closed figure eight one time per day for the same position on the earth, while for Molniya orbit covers two different regions in two revolutions each day (ex. North America and Russia), and both kind of the orbits spends the most its time over the desirable region.

2. Perturbing forces

The perturbations are deviations from a normal, idealized, or unperturbed motion. The actual motion will vary from the theoretical two-body path to perturbations caused by other bodies (such as the Sun and Moon) and additional forces not considered in Keplerian motion (such as a non spherical central body and drag). In fact, the atmospheric drag has a strong influence on the motion of a satellite near Earth more than Earth's oblateness. Third-body effects and solar-radiation pressure have a big affect on high altitude satellites more than oblateness and drag [6].

The third-body gravitational attraction is conservative force, while the atmospheric drag is non-conservative force. Each one has an effect on the orbit according to its characteristics. In the previous work, we studied the effect of the Earth's Oblateness and lunisolar gravitational forces on Molniya and Tundra satellites constellations [7].

Because the Molniya orbit has a low perigee altitude less than 1000 km, the dominant perturbations affect on satellites in this orbit are the Earth's oblateness and atmospheric drag, and because Molniya orbit also has a high apogee altitude, the solar and lunar gravitational force expect to affect the satellites in this orbit, too. While the main perturbation affecting on the satellite motion in Tundra orbit is the lunisolar gravitational force, because the satellites in Tundra orbit has a high apogee altitude.

Once one of these perturbations affects on the satellite in its orbit, the orbital elements for this satellite will vary with time and deviate the satellite from its initial position. Therefore, the satellite may not be able to observe the desirable target for long time. In that case the satellite will need to maintain its position in the constellation to be able to make an overlapping with the neighbor satellite in order to get a continuous coverage.

Constellation satellites are required to perform orbital transfer maneuvers. Orbital transfer maneuvers, as opposed to orbital correction maneuvers, are seldom performed but require a substantial amount of propellant for each maneuver. The maneuvers are performed in order to obtain the desired constellation configuration that satisfies the coverage requirements [8].

3. Case study

For continuous observation of northern regions, constellations of two or three Tundra or Molniya satellites can provide a similar ground coverage as a single conventional geosynchronous satellite [9]. For a constellation of three Molniya satellites, all three satellites are placed in the same ground track but phased 8 hours apart, and the right ascension of the ascending node in this case are equally spaced (i.e. 120 degrees apart) [5]

But for Tundra satellites constellation has the same orbital elements but differ from Molniya orbit in semi major axis and Eccentricity as shown in Table 1.

Table 1. Initial orbital elements

Orbital elements	Tundra	Molniya
a (km)	42160	26500
e (-)	0.26	0.7
i (deg)	63.4	63.4
Ω (deg)	8, 128, 248	8, 128, 248
ω (deg)	270	270

These two satellites constellations will cover the most of countries in European region. This region defined by bounds in Longitude between –5 and 30 degrees and latitude between 40 and 55 degrees (see also Figure 2).

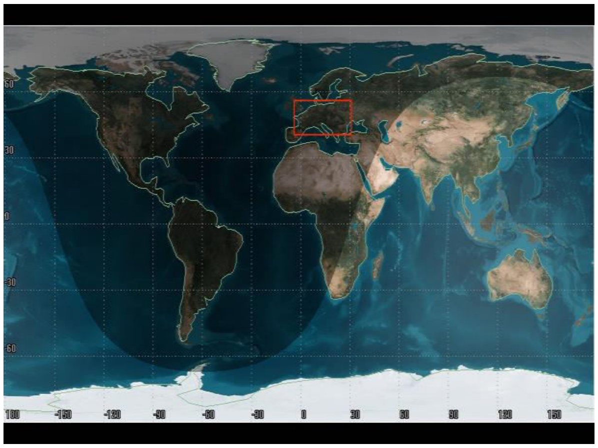


Figure 2. Interested target region

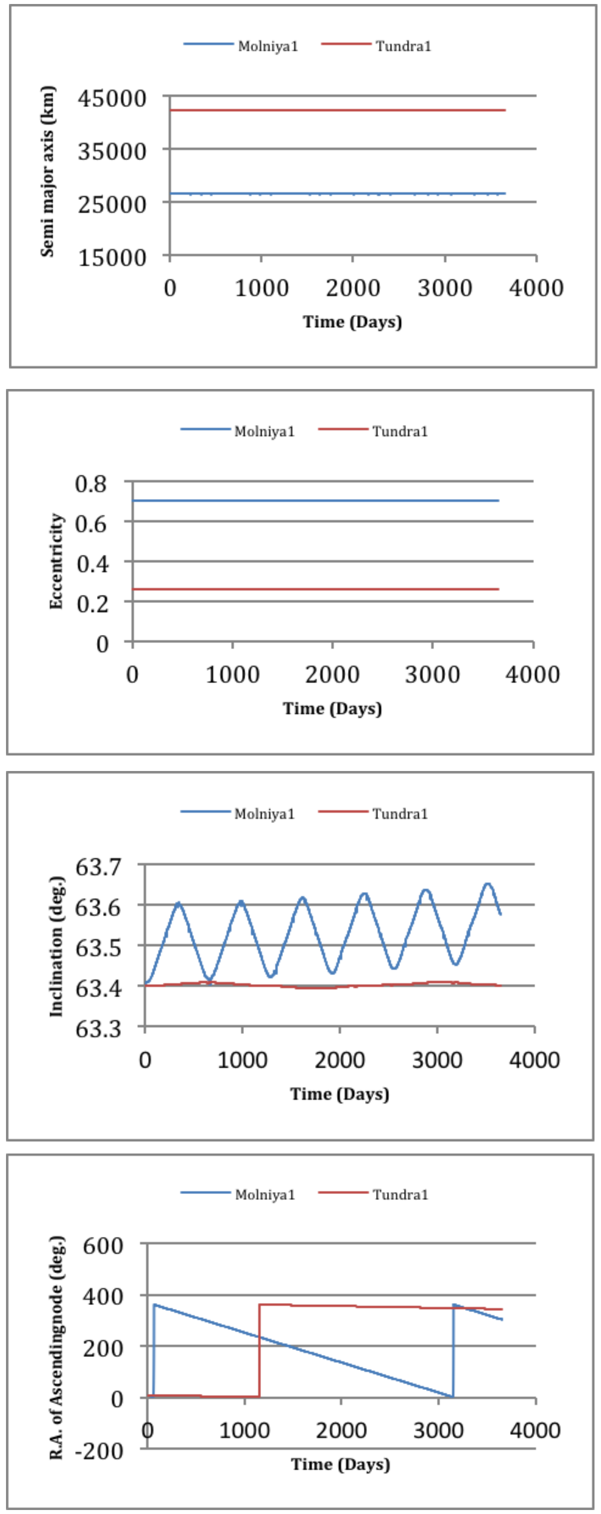
4. Results

The perturbations are the dominant problem that satellites constellation faces on in order to make continuous coverage for high latitude regions, since the continuous coverage relays on the overlapping between satellites in the constellation, and if an external force disturbs this homogeneous motion between satellites, this external force will affect the constellation as whole, and may be needed to make rephrasing again.

The perturbations affect the satellite's orbital elements and lead to deviate the satellite away from its initial position by changing its shape or rotate the orbital plane itself. Once this variation happens, the satellite starts losing the communication with the target gradually, and needs to maintain its position again. Of course, such maintains will cost a lot of money. Therefore, it is better to keep the satellites constellation in the optimal design by conducting maneuvers in the required time to avoid a lot of fuel consumption and not to spend a lot of money.

This work considers the conservative and non-conservative forces on satellites in the Tundra or Molniya constellations, which have special characteristics totally different from the others, so that this work investigates how orbital parameters change with each perturbation for 10 years to demonstrate how the satellites will behave under these perturbations.

Figure 3 through 5 show that the effect of various perturbations on Tundra and Molniya orbits in 10 years, respectively.



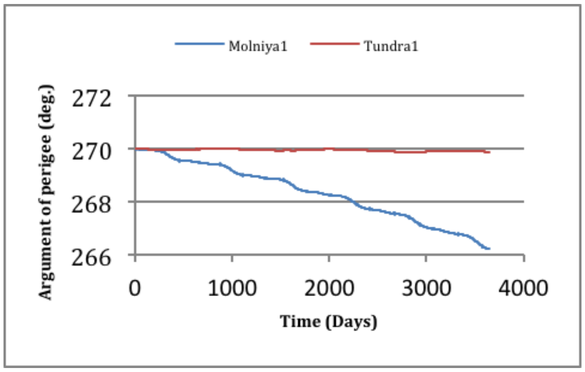
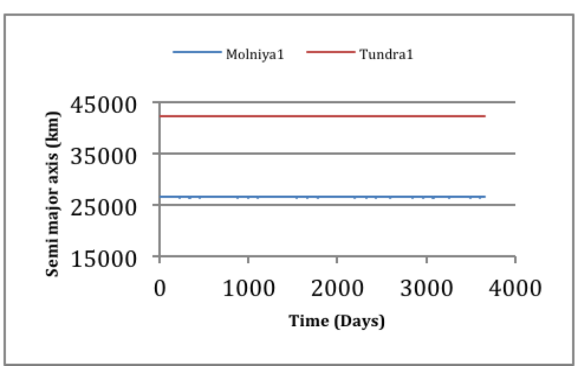


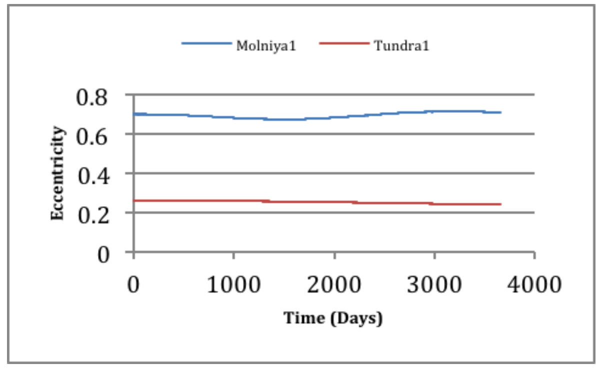
Figure 3. The effect of J2 +Atmospheric drag in 10 years

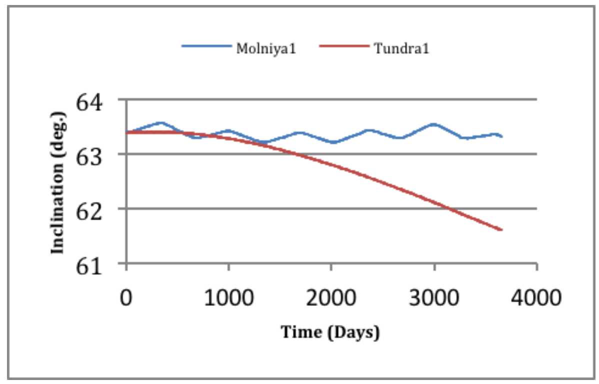
It is clear from Figure 3 that the Earth's oblateness and atmospheric drag do not affect the semi-major axis and eccentricity of both Tundra and Molniya orbit. The change of the inclination, right ascension of the ascending node and argument of perigee can be observed only in Molniya orbit but not in Tundra orbit. This difference is because the inclination of Molniya orbit has a periodic variation with a low value while the right ascension of the ascending node and argument of perigee of Molniya orbit have a secular variation with a high value. Especially, the ascending node rotates counterclockwise and completely within 10 years.

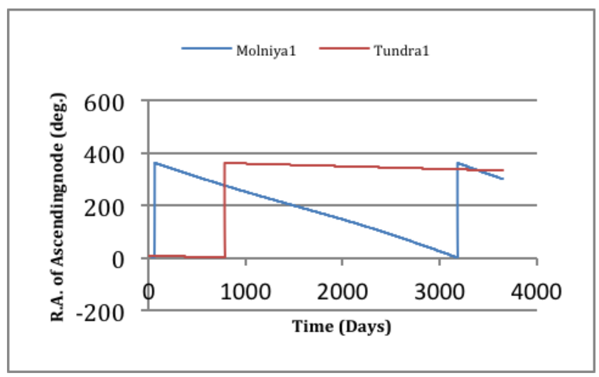
By adding the lunar gravitational force as a third-body perturbation to the pervious perturbations, the semi-major axis and eccentricity of Molniya and Tundra orbits do not change a lot, while the inclination of Molniya orbit has a periodic variation with a value in comparison to the inclination of Tundra orbit, as demonstrated in Figure 4.

The right ascension of the ascending node is not affected by the lunar gravitational force at all for both orbit, but the argument of perigee is affected. The argument of perigee of Molniya orbit behaves in periodic variation, whereas the argument of perigee of Tundra orbit behaves in secular variation.









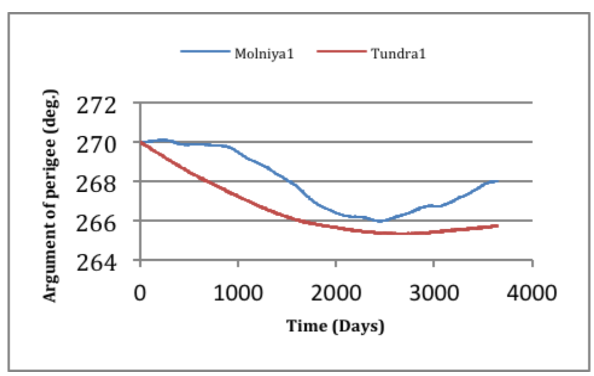
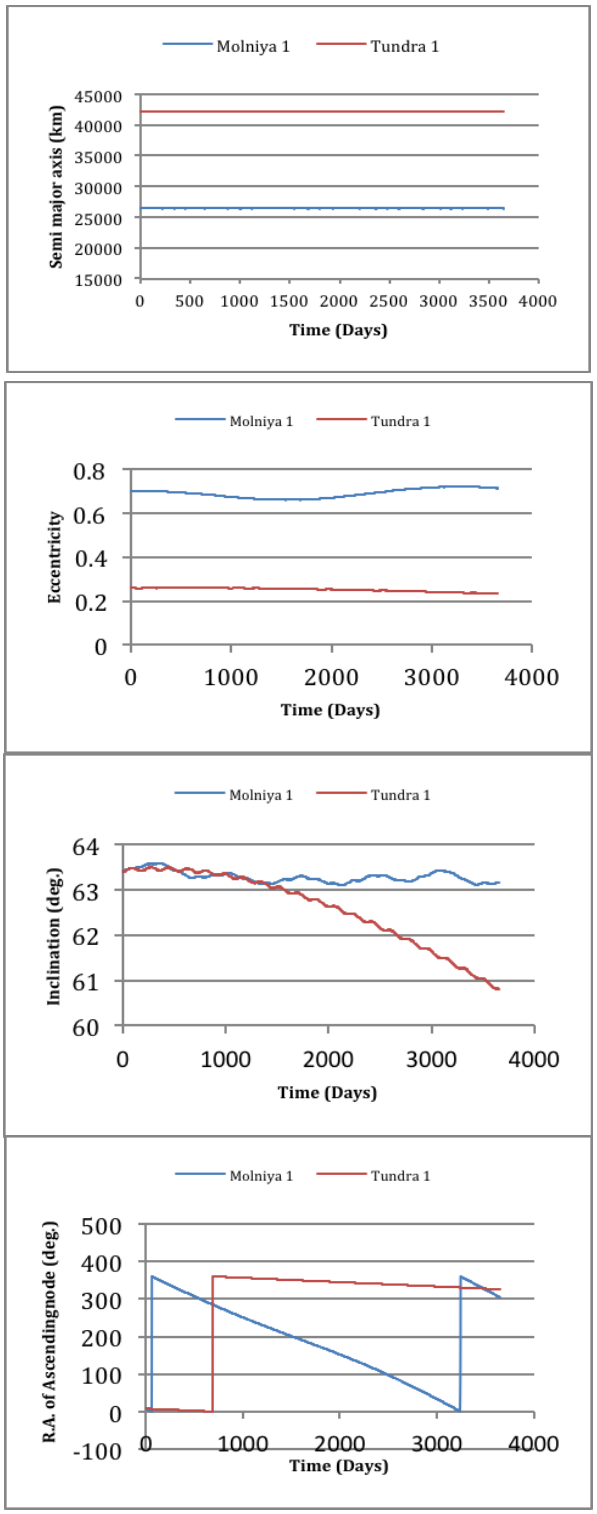


Figure 4. The effect of J2 + Atmospheric drag + Lunar gravity in 10 years

Since the Tundra orbit has a high apogee altitude, the solar gravitational force has a great effect on its orbital elements except for the semi-major axis and eccentricity as demonstrated in Figure 5.



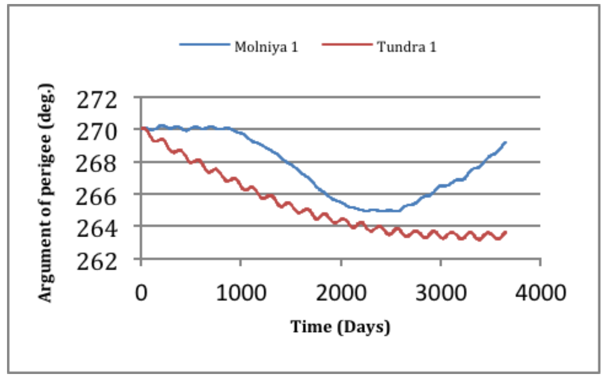


Figure 5. The effect of J2 + Atmospheric drag + Lunar and Solar gravity in 10 years

The solar gravitational force affects the inclination and argument of perigee of Tundra orbit in a periodic variation, but the right ascension of the ascending node does not change because the time-averaged distance of Molniya orbit is lower than that of Tundra orbit".

. Therefore, the solar gravitational force does not affect all the orbital elements except for the argument of perigee. The affected orbital parameters behave in both periodic and secular variations.

According to Figure 3 through 5, the Earth's oblateness and atmospheric drag have a great effect on the orbital rotation for Molniya orbit, while Tundra orbit rotation is affected by lunar and solar gravitational forces rather than the other perturbations. On the other hand, the orbital geometry of both orbits does not change at all.

Molniya and Tundra satellites constellation can provide a continuous coverage for high latitude regions according to initial orbital elements summarized in Table 1. The interesting region in this work is most of European region. The mechanism of both constellations is by making an overlapping between each satellite and the neighbor one in the constellation, where each satellite can achieve daily coverage at least 8 hours as shown in Figure 6 and 7.

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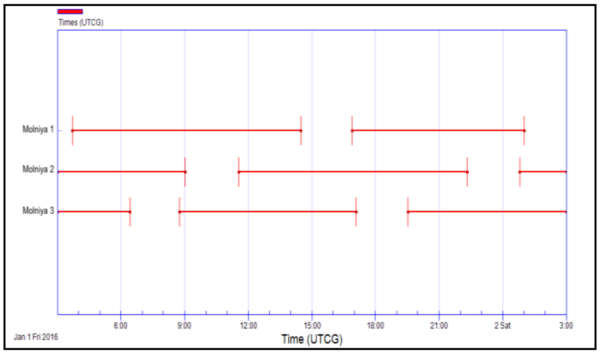

Figure 6. The optimal continuous coverage for European region by Molniya constellation

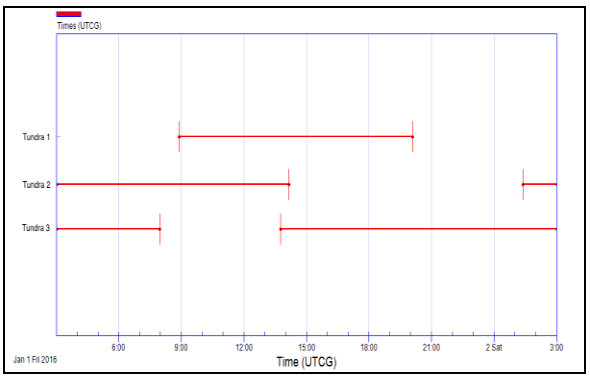

Figure 7. The optimal continuous coverage for European region by Tundra constellation

The optimal design for satellites constellation by making an overlapping between satellites will maintain the continuous coverage during observation on the target region, since at least two satellites will observe the target region in the same time, and also have to protect the whole constellation against the perturbations, not so long.

If the perturbations affect the orbital elements of a satellite in the constellation, the satellite will deviate away from its initial position. Therefore, the overlapping between satellites will decrease gradually until the gap in coverage time will happen.

Figure 8 and 9 illustrate how the change in the orbital elements of satellite will change the position of satellite relative to the neighbor, and the constellation could not observe the target region continuously. Since the change in the position of satellite relative to the next one in the constellation will cause a coverage gap, the satellites need to maintain the relative position in the constellation as whole, but this maintenance may cost a lot.

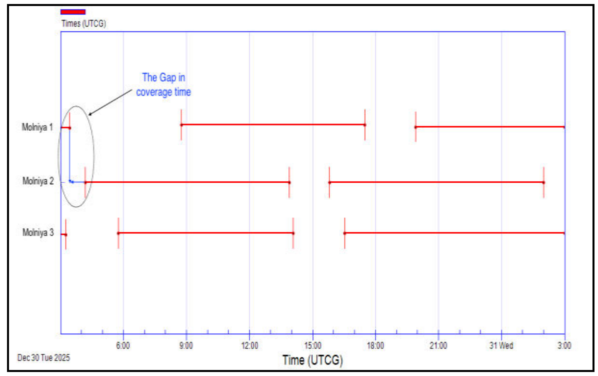

Figure 8. The daily coverage by Molniya constellation after 10 years

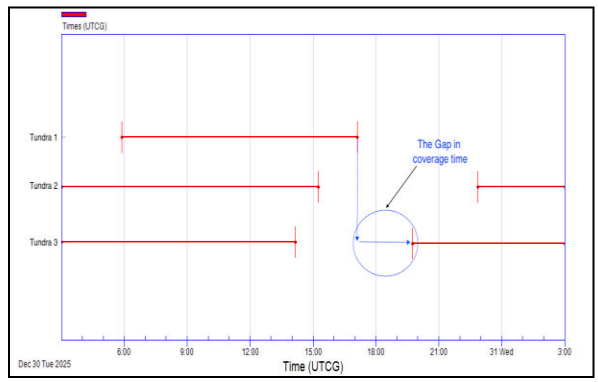

Figure 9. The daily coverage by Tundra constellation after 10 years

The most appropriate method is to rephrase satellites relative positions by doing maneuver for only one satellite that can cover the gap, by changing either the inclination with right ascension of ascending node or by changing the argument of perigee which achieve low cost to return it back to its initial elements.

It is obvious form Figure 8 that Molniya 1 and Molniya 2 have a small gap between them for approximately one hour, although each satellite can cover the target region for 8 hours per day in different times. Therefore, it may be easy to compensate this gap by changing the position of Molniya 1 or Molniya 2. Since Molniya 2 also has a gap with Molniya 3 twice a day, it may be better to change the position of Molniya 2.

It is also obvious from Figure 9 that Tundra 1 and Tundra 3 have a big gap between them approximately 3 hours, so that at least two satellites need to change their positions to compensate the gap.

One of the most important things to launch any satellites constellation is to minimize cost. It is highly recommended to reduce the number of maneuvers for satellites in the constellation as much as possible.

Figure 10 and 11 show how the correction to the right ascension of the ascending node and inclination or the argument of perigee can compensate the gap between satellites in the constellation but for different coverage interval.

For Molniya constellation in Figure 10, the correction to the right ascension of the ascending node and inclination is sufficient to compensate the coverage gaps between Molniya 1, Molniya 2 and Molniya 3. The correction to the argument of perigee is sufficient for the gap between Molniya 1 and Molniya 2, but not for the gap between Molniya 2 and Molniya 3, however.

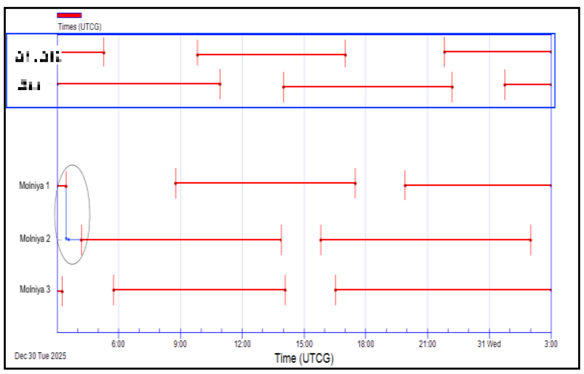

Figure 10. The correction for Molniya 2 by maneuver

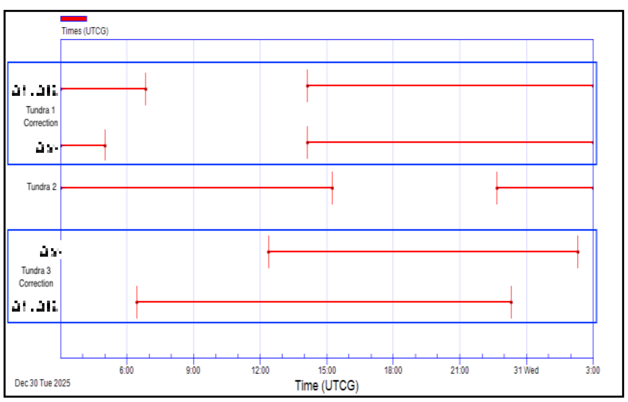

Figure 11. The correction for Tundra 1 & 2 by maneuver

For Tundra constellation in Figure 11, on the other hand, Tundra 1 and Tundra 3 need to maneuver to compensate the coverage gap. For Tundra 1, the correction to both the right ascension of the ascending node and inclination or to only the argument of perigee can compensate the coverage gap. For Tundra 3, it is better to correct both the right of ascension of the ascending node and inclination, so that Tundra 3 can compensate the gaps not only with Tundra 1 but also with Tundra 2.

It is obvious that all maneuvers for Molniya 2, Tundra 1 and Tundra 3 will achieve a continuous coverage, so that a criterion necessary to consider herein may be velocity increment required to correct the orbit.

The constellation that needs less maneuvers and a small velocity increment will give a best budget and will be the best choice for high latitude continuous coverage.

Table 2 summarizes the velocity increment required for Tundra 1, Tundra 3and Molniya 2 to correct both the right ascension of the ascending node and inclination and only the argument of perigee.

Table 2 indicates that the velocity increment required to correct both the right ascension of the ascending node and inclination is smaller than that required to correct to only the argument of perigee.

Table 2. The required velocity change for Molniya and Tundra constellations

Variation of orbital elements	Tundra 1	Tundra 3	Molniya 2
	Δv (Km/s)		
$\Delta\Omega.\Delta i$	0.53	0.64	1.28
$\Delta\omega$	1.1	0.97	1.44

Table 2 indicates that the velocity increment required to correct both the right ascension of the ascending node and inclination is smaller than that required to correct to only the argument of perigee.

The minimum velocity increment required for Tundra constellation is approximately 1.17 km/s and is smaller than that for Molniya 2, The main purpose is to reduce the cost for whole constellation, however. Therefore, one maneuver for one satellite in Molniya constellation is better than two maneuvers for two satellites in Tundra constellation.

5. Conclusion

The constellations of satellites in Tundra and Molniya orbits can provide a continuous coverage on high latitude regions for long time. The satellites in Molniya constellation have the stability to keep a continuous coverage on the target region even under the various orbit perturbations in comparison to the satellites in Tundra constellation. The coverage gap in Molniya constellation after long time is smaller than that in Tundra constellation.

The criteria adopted herein are the number of maneuvers necessary to correct the position of satellites and a higher stability to keep a continuous coverage on the target regions for long time.

Tundra constellation has to maneuver two satellites once, whereas Molniya constellation has to maneuver only one satellite once. Even though the minimum velocity increment required to maintain Tundra constellation is smaller than that required to maintain Molniya constellation, Molniya constellation may require low cost in comparison to Tundra constellation.

Finally, launch cost required to place a satellite into a Molniya orbit is lower than that to place a satellite into a Tundra orbit. The resolution of images taken with the satellites in Molniya constellation is higher in comparison to Tundra constellation.

Therefore, this work recommends a Molniya satellites constellation for high latitude continuous coverage.

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