TUNDRA DISPOSAL ORBIT STUDY

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ABSTRACT

Tundra orbits are high-inclination, moderately eccentric, 24-hour period orbits. A constellation of two Tundra satellites can provide similar ground coverage as a single traditional geosynchronous satellite. However, they can be configured to have finite orbital lifetime, in contrast to stable near-geosynchronous storage disposal orbits which result in indefinite accumulation of disposed geosynchronous satellites. A study was performed to determine the potential reduction of orbital lifetime and collision risk when using Tundra orbits as an alternative to traditional geosynchronous orbits. Results show that Tundra disposal orbit lifetime can be reduced to below 100 years. Results also show that Tundra disposal orbits have much lower collision probability over orbital lifetime, by at least two orders of magnitude, than both near-geosynchronous storage disposal orbits and comparable 25-year lifetime low Earth orbits. It is recommended that international debris mitigation guidelines be extended to permit use of Tundra disposal orbits with orbital lifetime less than 100 years and cite their benefits for long-term debris mitigation.

1 INTRODUCTION

Tundra orbits are high-inclination, 24-hour period orbits [1-2]. They are usually critically inclined (inclination of 63.4 deg) to freeze apsidal rotation and have moderate eccentricity (typically 0.2 to 0.3) to extend dwell time over a selected region of coverage. In contrast, traditional geosynchronous orbits are typically 24-hour period orbits that usually have low eccentricity (0.003 or less) and inclination in the range from 0 to approximately 16 deg. In this paper, the acronym "GEO" will be used to refer to such traditional geosynchronous orbits. The term "GEO region" will be used to refer to the torus bounded by the altitude range GEO +/- 200 km and the latitude range +/- 16 deg, citing values from the Inter-Agency Space Debris Coordination Committee (IADC) Debris Mitigation Guidelines [3-4]. Satellites have also been placed in GEO orbits with inclination higher than 16 deg. The term "high-inclination GEO" will be used to refer to this type of orbit in this paper.

A study performed by Wilson et al. [1] showed that a constellation of two to three Tundra orbits can provide similar ground coverage as a single traditional GEO orbit. The Sirius 1-3 satellites that were launched in 2000 operated on Tundra orbits.

Due to their higher inclination, Tundra orbit elements undergo much larger variations due to luni-solar gravity than traditional GEO orbit elements. In particular, there are large excursions in eccentricity. The analyses in [1-2] considered the station-keeping required to maintain the original orbital elements. However, analyses at Aerospace since 2013 have shown that these eccentricity excursions can be used to cause perigee to dip into the atmosphere, resulting in re-entry and limiting the lifetime of the orbit.

In contrast, storage disposal orbits near GEO are very stable and do not undergo atmospheric re-entry. There is no known natural mechanism to remove satellites in near-GEO orbits. As a result, disposed GEO satellites will accumulate indefinitely in their disposal orbits and possibly collide with each other. Collisions between large GEO satellites can generate large amounts of untrackable debris that can spread into the GEO region. This chance for collisions is due to the spread of inclination and right ascension of ascending node (RAAN) amongst objects in the background population near GEO. The resulting cross-track component of relative collision velocity ranges up to 1.6 km/s.

From a debris mitigation perspective, Tundra orbits have better disposal characteristics than near-GEO storage disposal orbits. This paper presents a study to determine the potential reduction of orbital lifetime and collision risk when using Tundra orbits as an alternative to traditional GEO orbits.

2 REFERENCE CASE

The reference case used for the study in this paper is as follows:

- Disposal epoch: August 26, 2018, 00:00:00 GMT
- Semi-major axis = 42164.17 km

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- Eccentricity = 0.26814 (average of Sirius 1-3 orbit eccentricities from the unclassified USSTRATCOM catalog of resident space objects dated March 27, 2013)
- Inclination = 63.4 deg (critical inclination, apsidal rotation is frozen)
- RAAN was varied from 0 deg to 360 deg at 1 deg increments
- Argument of perigee = ω_p = 270 deg
- Spacecraft mass = 2000 kg
- Spacecraft projected area = 20 m^2

The resulting apogee altitude is 47092 km and perigee altitude is 24480 km. The orbit is therefore above the satellite constellations in medium Earth orbit.

The study by Wilson et al. [1] showed that a two-satellite Tundra constellation with orbit RAANs separated by 180 deg can achieve complete coverage of a region 100% of the time. This constellation is illustrated by visualization images in Figures 1-2. The region of coverage is determined by selection of longitude and frozen argument of perigee. In this case, those parameters are selected to yield coverage of the greater European continent. Figure 1 shows how the eccentricity of the Tundra orbit enables it to clear the GEO region.

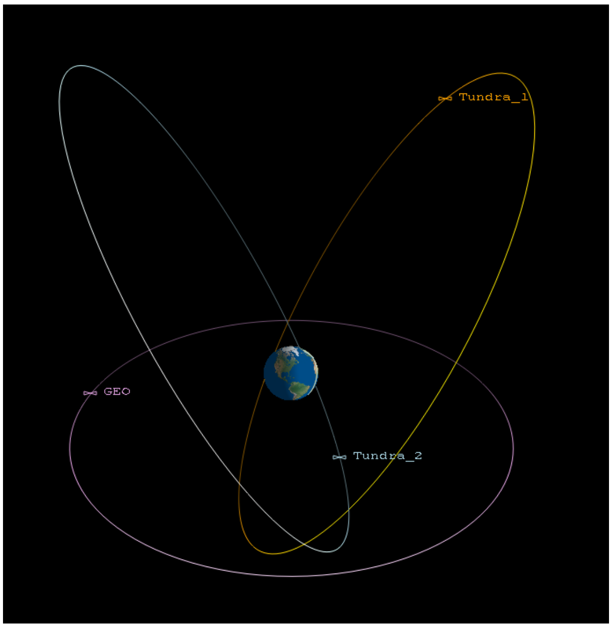

Figure 1. Two-satellite Tundra constellation: view of the orbits in the Earth-Centered Inertial (ECI) frame.

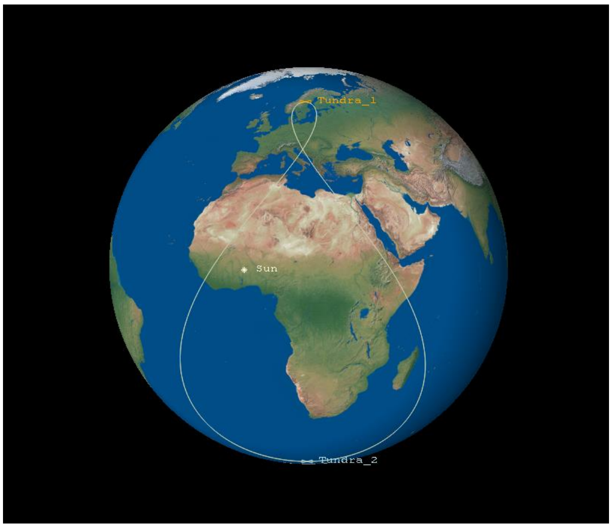

Figure 2. Two-satellite Tundra constellation: ground trace of the orbits.

Figure 3 shows the ground trace and a color map of coverage provided by the two-satellite Tundra constellation. This map was generated using the Aerospace coverage software tool REVISIT. The entire greater European continent and some peripheral areas are in the region that is covered 100% of the time (indicated by purple).

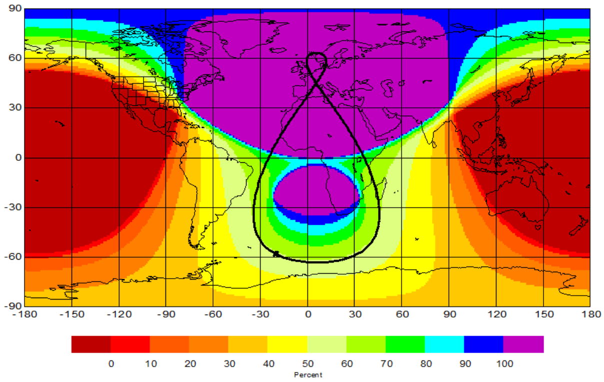

Figure 3. Coverage map for the two-satellite Tundra constellation.

3 LONG-TERM PROPAGATION ANALYSIS

For the long-term orbit propagation of the reference case, the precision integration code TRACE was used to propagate the spacecraft. The use of this code for the RAAN sweep discussed in the following material was made possible by the availability of cluster computing. The force model settings were as follows:

- NRLMSISE-00 atmosphere model
- 70 x 70 modified WGS84 Earth gravity model
- Sun and Moon gravity
- Solar radiation pressure (SRP); assumed

reflectivity coefficient = 1.3.

- 50-percentile level of solar flux ($F_{10.7}$) and geomagnetic index (A_p); used NASA Marshall Space Flight Center (MFSC) monthly predictions (based on NOAA data) from January 2017 to 2030; for years after 2030, repeated last 11-years of MSFC predicted data.

Figure 4 shows the resulting variation of Tundra disposal orbit lifetime with initial RAAN. The maximum propagation time period is 200 years, so the curve is limited at 200 years. The plot shows that there are intervals of initial RAAN during which lifetime is significantly reduced. There are four lifetime wells that are below 100 years, and one is even below the recommended lifetime limit of 25 years in the IADC Guidelines. For the rest of the paper, two example satellites are used with initial RAAN = 80 and 260 deg, respectively. These initial RAANs are separated by 180 deg to realize a Tundra constellation of two satellites that achieves coverage of the target region 100% of the time.

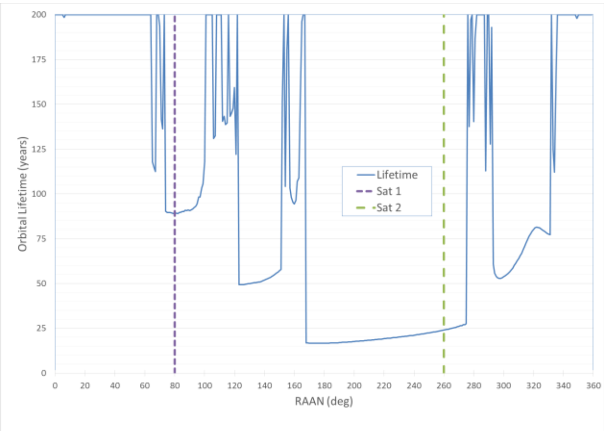

Figure 4. Variation of Tundra disposal orbit lifetime with initial RAAN.

Figures 5-6 show the time evolution of the Tundra disposal orbit with initial RAAN = 80 deg. Figure 5 shows the apogee and perigee altitude histories. The apogee and perigee altitudes both undergo a wide range of motion, with the perigee moving into the atmosphere at 89.5 years, resulting in re-entry. Figure 6 shows the argument of perigee history. The argument of perigee remains within 20 deg of the initial value of 270 deg during the first 40 years. It then undergoes a larger excursion during the remaining 49 years. During this later time period the Tundra disposal orbit may cross the GEO region a few times, but the crossing time will be short due to the high rate of change of the argument of perigee.

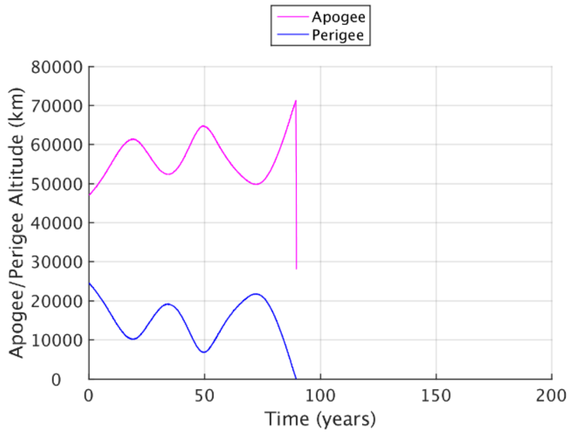

Figure 5. Tundra disposal orbit apogee and perigee altitude evolution when initial RAAN = 80 deg.

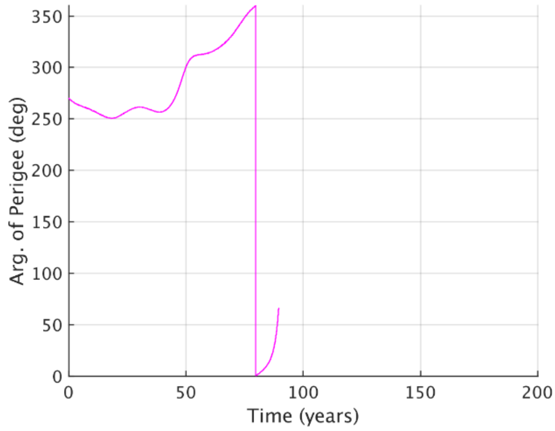

Figure 6. Tundra disposal orbit argument of perigee evolution when initial RAAN = 80 deg.

Figures 7-8 show the same plots but for the Tundra disposal orbit with initial RAAN = 260 deg. In this case the apogee and perigee altitude excursion is more rapid than that for initial RAAN = 80 deg, and perigee moves into the atmosphere at 24 years. The argument of perigee excursion is more rapid in the beginning than that for initial RAAN = 80 deg, but the overall range of the excursion is less, lowering the likelihood that the Tundra disposal orbit will cross the GEO region.

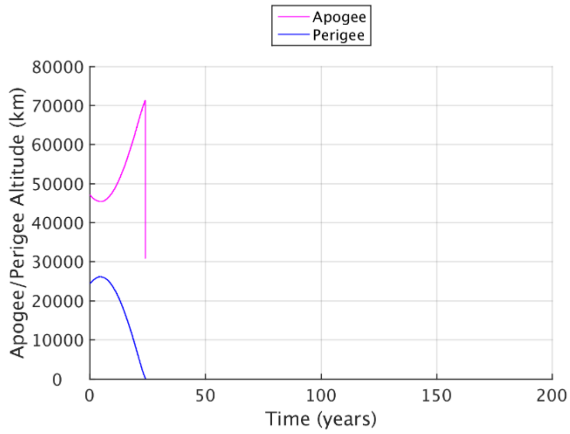

Figure 7. Tundra disposal orbit apogee and perigee altitude evolution when initial RAAN = 260 deg.

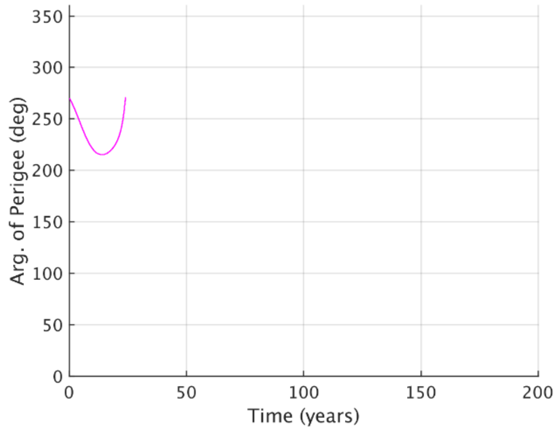

Figure 8. Tundra disposal orbit argument of perigee evolution when initial RAAN = 260 deg.

4 COLLISION PROBABILITY ASSESSMENT

A collision probability assessment was performed to quantify the risk reduction achieved by reducing orbital lifetime. The background population from the Aerospace Debris Environment Projection Tool (ADEPT) [5] was used for the analysis. An orbit trace crossing (OTC) method was used to compute collision probability. For each pairing of objects, all crossings of the orbit traces (OTC events) over the assessment time interval are determined. The evolution of the orbit traces is accounted for by using the TRACE results for the spacecraft and background object orbital element files from ADEPT. The collision probability at each OTC event is computed assuming the in-track positions (mean anomalies) of the objects are uniformly distributed over 360 deg. The mean number of collisions is determined by summing collision probabilities from all OTC events in the assessment time interval. A description of this method and a comparison with a conjunction miss distance method are presented in [6]. These runs were executed on a computing cluster.

The collision radius for each object pair is required for the collision probability computation. The spacecraft mean contact radius was assumed to be 2.52 m. Contact radii of the current background objects are part of the ADEPT model. For each object pair, the mean collision radius is the sum of the mean contact radii of both objects.

ADEPT models the current and future Earth orbital background population. It includes orbit trajectories and sizes for each object. The following populations were used in this analysis:

1. Catalog population: Objects from the unclassified USSTRATCOM catalog of resident space objects.
2. A future launch model (FLM) population.
3. First generation debris from future collisions.

Only inactive objects were included in the collision probability assessment. The catalog population is from April 3, 2016; the reference start date for the FLM satellite populations is the same. Only objects larger than 10 cm are included in this collision probability analysis. A general rule of thumb is that collisions with objects larger than 10 cm are catastrophic (create large amounts of debris).

The FLM population consists of satellites, rocket bodies, and mission related objects that are placed into Earth orbit in the future. The FLM objects are divided into several groups: a group of objects associated with continuously replenished constellations (CRC group); a group of objects associated with satellites in GEO orbits; and remaining non-CRC objects (NONCRC group). The CRCs are constantly replenished to maintain the full constellations. The GEO population was generated by reproducing launches over the 15-year period prior to the simulation reference start date. The NONCRC population was generated by reproducing launches over the 10-year period prior to the simulation reference start date. After mission operations were over, each FLM satellite was moved to a disposal orbit. The version of the FLM for the “100% Post Mission Disposal (PMD)” scenario was used in this analysis. In this scenario, all world-wide future satellites and rocket bodies are placed in disposal orbits that comply with the IADC Guidelines. All future LEO satellites are left on disposal orbits with lifetime < 25 years or moved to a storage disposal orbit above LEO (perigee altitude > 2000 km). All future GEO satellites are left on storage disposal orbits above GEO altitude according to a formula in the IADC Guidelines [3].

Figures 9-10 show cumulative collision probability vs. time for the generic satellite on Tundra disposal orbits with initial RAAN = 80 deg and 260 deg, respectively.

The collision probabilities are averaged over 100 Monte Carlo cases. The collision probabilities ramp up most rapidly just before re-entry as the perigee passes through LEO, and then become flat after re-entry. Total collision probability is 6.16 x 10^{-6} for the case with initial RAAN = 80 deg, and 2.5 x 10^{-6} for the case with initial RAAN = 260 deg. The collision probability is low because the effective time spent in the LEO region is very limited, even for the case when lifetime is 89.5 years (initial RAAN = 80 deg).

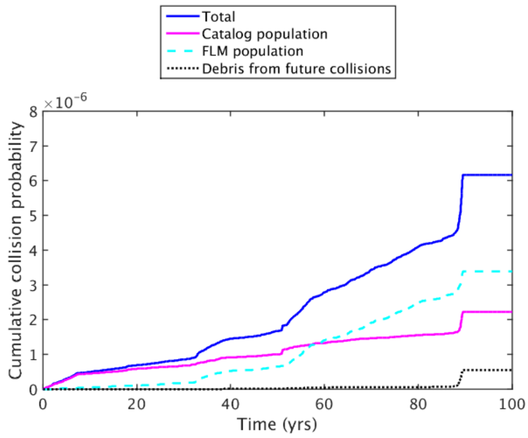

Figure 9. Tundra disposal orbit cumulative collision probability vs. time when initial RAAN = 80 deg.

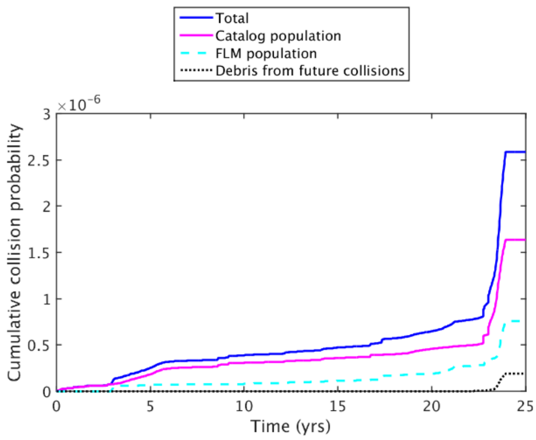

Figure 10. Tundra disposal orbit cumulative collision probability vs. time when initial RAAN = 260 deg.

For comparison, the case of a generic satellite on a near-GEO storage disposal orbit determined by the IADC formula is considered. Figures 11-12 show the associated apogee/perigee altitude evolution and cumulative collision probability vs. time, respectively. The initial perigee altitude is GEO + 248 km and initial eccentricity is 0.003. The initial inclination was selected to be 0.1 deg (typical geostationary inclination), and initial RAAN was selected to be 80 deg for consistency with one of the Tundra disposal orbit case. As for the Tundra disposal orbit collision probability computation, the 100% PMD FLM scenario in ADEPT is used to yield an apples-to-apples comparison. Total collision probability over 200 years is 2.52 x 10^{-3}. The growth in collision probability with time is driven by accumulating disposed GEO satellites. Collision probability will continue to grow after this time period. In comparison, Tundra disposal orbit collision probability is much lower (by at least two orders of magnitude). This is attributable to the fact that the Tundra disposal orbit spends much less effective time passing through the population near the GEO region.

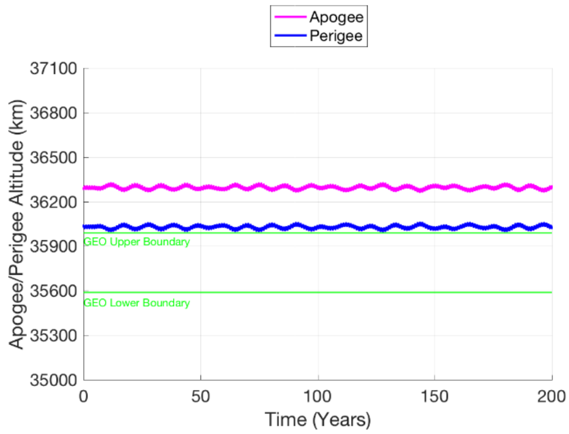

Figure 11. GEO storage disposal orbit apogee and perigee altitude evolution.

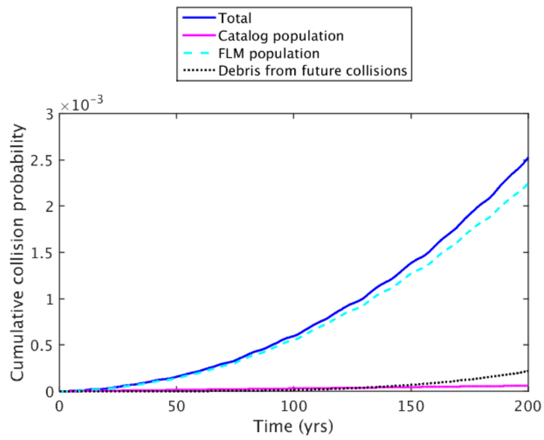

Figure 12. GEO storage disposal orbit cumulative collision probability vs. time.

Also for comparison, the case of a generic satellite on a LEO disposal orbit with orbital lifetime approximately equal to 25 years considered. Figure 13 shows the associated cumulative collision probability vs. time. This plot was created from the data generated in the analysis of [7]. The disposal orbit has a semi-major axis altitude of 600 km and inclination of 70 deg. As for the Tundra disposal orbit collision probability computation, the 100% PMD FLM scenario in ADEPT is used to yield an apples-to-apples comparison. Total collision probability over orbital lifetime is 4.06 x 10^{-3}. In comparison, Tundra disposal orbit collision probability is much lower (by at least two orders of magnitude). This is attributable to the fact that the Tundra disposal orbit spends much less effective time in the LEO region.

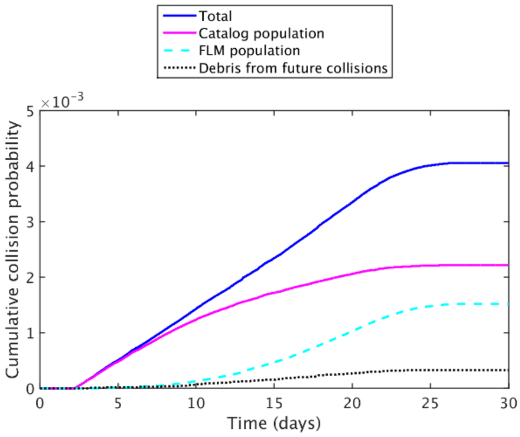

Figure 13. Cumulative collision probability vs. time for a LEO disposal orbit with orbital lifetime of approximately 25 years.

5 EFFECT OF ORBITAL PERTURBATIONS ON COVERAGE DURING THE MISSION

The strong luni-solar perturbations which enable a Tundra orbit to have a finite orbital lifetime will also cause changes to the Tundra orbit during the time frame of its mission. The analysis by Wilson et al. [1] determined delta-V required to maintain the orbital elements of a Tundra orbit. The delta-V was shown to vary strongly with RAAN, consistent with the results presented in Figure 4 of this paper. As would be expected, large delta-V values are required for the same values that achieve reduced orbital lifetime. It would be a disadvantage if significant amounts of propellant are needed to suppress eccentricity and argument of perigee motion during the mission. The ideal situation would be if the Tundra orbit can be allowed to vary under the effects of perturbations, with no expenditure of propellant except to control geographic longitude. Figure 14 shows the ground trace and color map of coverage provided by the same two-satellite Tundra constellation used for Figure 3, but after a 10-year mission during which the orbital elements are allowed to drift freely under the effect of orbital perturbations, and only geographic longitude is maintained. The figure shows that the ground traces and map patterns have been significantly changed due to the variations in the Tundra orbits. Nevertheless, the entire greater European continent is still covered 100% of the time (indicated by purple). In this case, it is therefore unnecessary to consume propellant to maintain orbital elements other than geographic longitude. In general, the size of the region of coverage will determine if maintaining the other orbital elements is needed.

Wilson et al. [1] also discuss other operational and design issues that should be taken into account when considering the use of a Tundra constellation as an alternative to a traditional GEO satellite. These include designing hardware and software to accommodate variations in elevation and azimuth angles, range and range rate, and to achieve pointing of solar arrays toward the Sun.

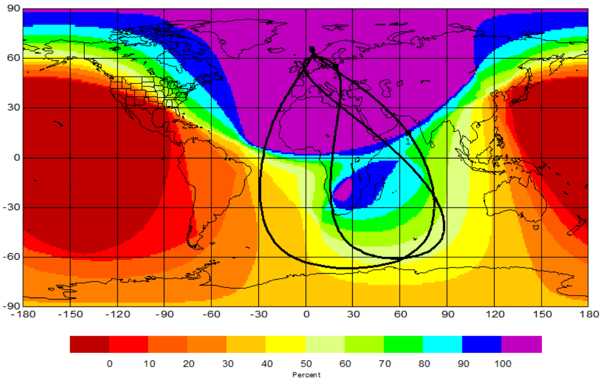

Figure 14. Coverage map for the two-satellite Tundra constellation at end of a 10-year mission.

6 RESULT OF MOVING THE TUNDRA DISPOSAL ORBIT ABOVE GEO

International debris mitigation guidelines specify that satellites operating in the GEO region move to a disposal orbit above GEO. A satellite on a Tundra mission orbit would have to expend significant propellant to raise perigee above GEO to follow a similar disposal approach. Figure 15 shows the resulting apogee/perigee altitude evolution of the reference orbit of this study with perigee altitude raised to the boundary specified by the IADC formula. An initial RAAN of 80 deg was selected to yield an apples-to-apples comparison with one of the Tundra orbits considered in this study. The plot shows that the perigee undergoes a large excursion downward, causing the orbit to pass through the GEO region after only a few years.

Circularizing the orbit will help delay the perigee excursion. Additional propellant would be required for a Tundra orbit satellite to bring its apogee down to circularize the orbit. Figure 16 shows the resulting apogee/perigee altitude evolution for the same case as in Figure 15 but when apogee has been lowered to achieve an initial eccentricity of 0.003. While the downward excursion of perigee has been delayed, perigee still moves down, and the orbit passes through the GEO region after a few decades. The IADC formula was not designed for high-inclination orbits and, as this study demonstrates, it is not effective at those high-inclinations.

For both cases, raising the perigee above the GEO altitude does not prevent the orbit from passing through the GEO region and is propellant-wasteful. For Tundra orbits, it is better to leave the orbit unchanged at end of mission, or to only slightly modify it if a replacement satellite will be placed into the same staring orbit in the constellation.

For high-inclination GEOs at critical inclination, it is better to increase eccentricity just enough so that the disposal orbit clears the GEO region, essentially becoming a Tundra orbit and achieving its better disposal characteristics.

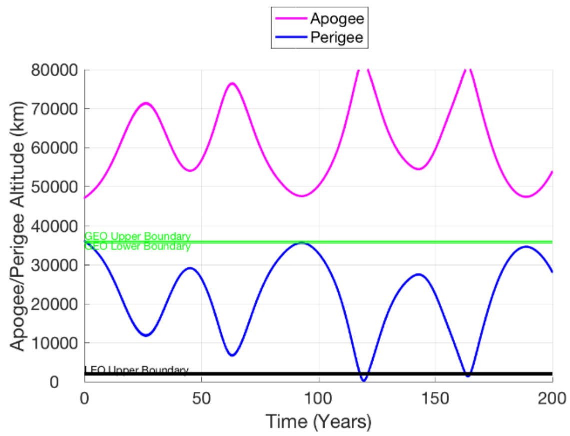

Figure 15. Tundra disposal orbit apogee and perigee altitude evolution when perigee is raised above GEO.

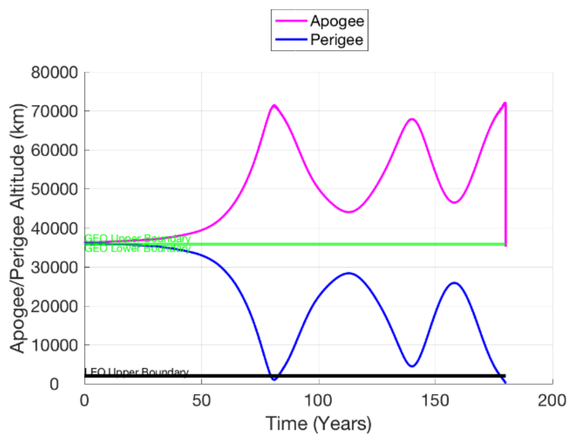

Figure 16. Tundra disposal orbit apogee and perigee altitude evolution when perigee is raised above GEO and apogee is lowered to circularize the orbit.

7 CONCLUSIONS

A constellation of two Tundra orbits can provide similar coverage as a single traditional GEO satellite. The results of this study show that Tundra orbits have better characteristics for disposal and long-term debris mitigation. In the example scenario presented in this paper, it was possible to achieve coverage of the greater European continent 100% of the time over 10 years with only two satellites without requiring extra propellant to maintain orbital elements other than geographic longitude. Tundra disposal orbits can be configured to have finite orbital lifetime (< 100 years) by selection of initial RAAN. The resulting Tundra disposal orbits have much lower collision probability over orbital lifetime than traditional near-GEO storage disposal orbits and comparable 25-year lifetime LEO orbits, by at least two orders of magnitude. For high-inclination GEOs at critical inclination, rather than move to a disposal orbit above GEO, it is better to increase eccentricity just enough so that the disposal orbit clears the GEO torus, essentially becoming a Tundra orbit and achieving its better disposal characteristics. It is recommended that international debris mitigation guidelines be extended to permit use of Tundra disposal orbits with orbital lifetime less than 100 years and cite their benefits for long-term debris mitigation.

8 ACKNOWLEDGMENTS

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