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Small Satellite Remote Sensing Constellation for Fast Polar Coverage

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Abstract

As polar ice cover retreats due to climate change, economic and political interest in Earth's polar regions has increased. At the same time, however, environmental conditions in these regions remain hazardous, and any operations there require intensive remote sensing. Noting that remote sensing constellation missions targeting only certain regions on Earth are impractical to construct other than with relatively cheap small satellites, the current study has designed a small satellite constellation that can image the polar regions frequently. A Walker delta configuration of satellites is sufficient to provide the coverage in the 60 to 85° region, with two hours average time or less between images, at worst. The number of satellites needed depends on the altitude of the constellation: at a 1000 km altitude, four satellites are needed; at 725 km, six satellites; and at 450 km, eight. The altitude choice depends on the requirements of the imaging instrument. Based on the Walker delta geometry, when using secondary payload slots or group small satellite launches, an onboard propulsion system capable of delivering relatively high ΔV change to the satellite is needed to get the constellation satellites to their intended orbit parameters from the initial orbit in which they are left by the launcher. Differential orbits using natural precession are cheap ΔV alternatives to launcher selection and propulsion system maneuvers, but add significantly more time to the formation of the constellation. However, by either choosing a longer deployment period or a powerful small satellite propulsion system, a small satellite Walker delta constellation capable of fast coverage of the polar regions is possible.

1. Introduction

Satellite remote sensing is a widely used, essential part of modern day life. Groups of remote sensing satellites, such as constellations, enable completely new modes of remote sensing, since the overall temporal resolution and image periodicity of that particular area improves dramatically when several satellites image the same area with similar image parameters. Satellite constellations are generally intended for global service (i.e., navigation or telecommunication constellations, such as GPS or Iridium, which target the whole planet). However, several regions of the planet have specific requirements in terms of remote sensing or communication. Moreover, a speedy and reliable delivery of remote sensing data is essential in various operations that require remote sensing services. This translates into requirements for a constellation with

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specific properties, most notably, orbit geometry. Small satellites of the nano- and micro-scale have had success in constellation-type designs. Companies like Planet Labs (Lawler, 2013), Skybox Imaging (Perry, 2013) and the von Karman Institute's QB50-program (Asma, 2012) have implemented or are implementing spacecraft constellations with relatively small budgets compared to more traditional space missions. The U.S. Defense Advanced Research Projects Agency (DARPA) is studying the concept of a fractionated space mission using smaller, specialized satellites that work together (Brown and Eremenko, 2006), and small satellites are even planned to be used as a collective radio telescope (Dekens et al., 2014). The current work concentrates on describing the concept of remote sensing constellations serving the polar regions with satellites under 100 kg. The goal is to have the advantages of a small remote sensing platform, such as lower mission costs and better launch opportunities, and design a ground observing constellation that has a short revisit time in the polar regions.

This study's constellation aims to image ground and marine activities and conditions, rather than meteorological or atmospheric targets, the latter of which often require anywhere from 5 to 30 minutes of refresh rates (Key et al., 2003; Velden et al., 2005), which is even higher than the rates aimed for in this work. In addition, as the idea of the constellation is to serve a specific geographic area, its ground sample distance (GSD) must be relatively higher than that for meteorological and atmospheric targets, as the constellation concentrates on supporting operational activities in the area. This work is also remote sensing instrument-independent, considering only the imaging distance to the image targets.

The text that follows begins by introducing the requirements for the constellation, after which, a more general trade-off analysis is performed between several constellation geometries capable in theory of performing ground observations of the polar regions. The selected constellation geometry is then evaluated in-depth for a range of orbital parameters, and the analysis concludes by calculating the required ΔV and deployment time by using natural precession for deploying the constellation. Note that this paper does not discuss satellite "swarms," or groups of satellites cooperating directly with each other (Engelen et al., 2012); instead, the focus is on satellite "constellations," or satellites performing the same task, to reinforce each other's outputs.

1.1. Nano- and Micro-satellite Considerations

Satellites scaling down to less than 100 kg masses enable significantly cheaper and more versatile missions (Da Silva Curiel et al., 2005), as well as increased overall system flexibility, reliability, and resilience when used in a system such as a constellation (Daniels and Páte-Cornell, 2014). However, their use in a constellation presents some unique challenges, as well, such as how to get the satellites to their correct orbits so they can function as part of a constellation. Any maneuvers will cost significant amounts of ΔV, and this fact does not diminish as the satellite's mass decreases. In addition, the propulsion methods to achieve a required ΔV cannot scale down easily, as the complexity related to the propulsion methods do not scale proportionately. An attempt to scale down might even increase it, as a propulsion system needs to have some certain elements that do not scale in the same way (Lozano and Courtney, 2010).

Small satellite access to space has improved considerably. Secondary payload opportunities, such as piggyback launches or collective small satellite-dedicated launches have higher specific costs, but relatively affordable total costs (Crisp et al., 2013) for small satellite missions; however, they present limited orbit possibilities, and cannot deploy a whole small satellite constellation during one launch without special operational measures from the satellites themselves. Alternatively, choosing multiple launches will increase the complexity of the mission as a whole, as now the chosen launches will have to be synchronized with respect to each other, as well as having to take into account the orbit and launch requirements of the primary payload and other small satellites onboard. Thus, the current work also presents a ΔV budget for obtaining the chosen earth observation (EO) constellation geometry deployed using a combination of a launch with "close enough" orbit parameters and a low-thrust propulsion system onboard the satellites of the constellation. As an alternative, deployment using natural precession and the time it takes is also presented.

2. Desired Constellation Geometry

The design goals of a remote sensing constellation are defined by the requirements of the kind of coverage needed. This section concentrates on what is needed of a small satellite polar constellation to satisfy these requirements, comparing various existing designs that provide coverage at the Earth's poles, and presenting the chosen constellation geometry.

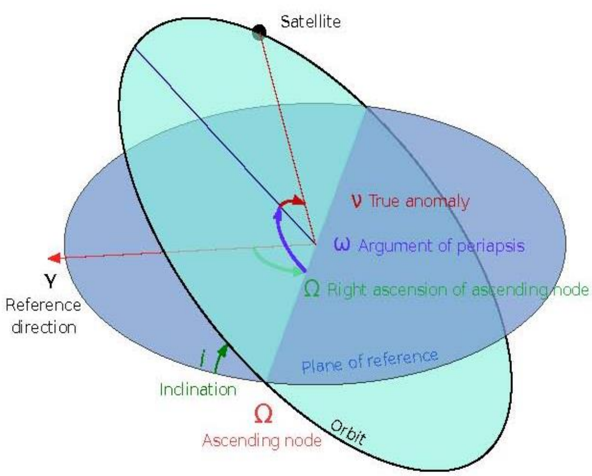
2.1. Orbit Definition

This work uses basic Kepler parameters, as seen in Figure 1a, and an Earth-centered inertial (ECI) frame. The limits of the coverage latitude are primarily directly related to the satellite inclination (shortened as parameter "i" in this Figure), altitude, and side-looking angle of the imaging instrument. Satellites with high-inclination polar orbits have a planetary-wide coverage determined approximately by their inclination (with their altitude and sidelooking angle potentially extending it further), as seen in Figure 1b; so if $i < 90°$, the coverage latitude is $i + \Delta\rho$, and for $i > 90°$, is $i - 90° + \Delta\rho$, where $\Delta\rho$ is the additional latitude added by the altitude and sidelooking angle of the satellite. In turn, the eccentricity and the argument of periapsis of the orbit influence the best area of coverage, as besides critically inclined orbits, the perigee rotates in time.

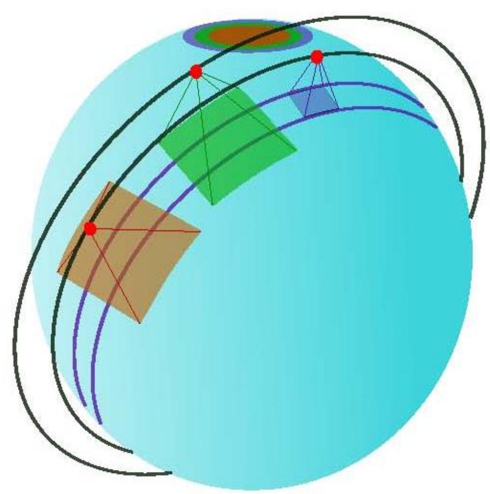
2.2. Constellation Coverage Requirements

This section explains the requirements for the selection of a suitable constellation, presenting a summarizing table of their quantitative values.

Maritime operations in the polar regions ranging from 60 to 85° northern and southern latitudes are the best source for a threshold of sufficient coverage for operational needs, as such operations are the most numerous in those regions. Based on the typical of operation of Global Navigation Satellite System (GNSS) ice drift beacons used in ice movement tracking (Acevedo et al., 2014), the targeted refresh rate (time interval between two images of the same target area) for the constellation is two hours for these latitudes, while ground sample distance should be 10 to 100 m, which is suitable for disaster monitoring (Sandau et



a)



b)

Figure 1. a) An example figure of a satellite's orbit parameters; and b) A 5° difference from a 90° inclination results in a 5° gap over the planet's poles in the chosen star-fixed frame of reference (seen as the dark blue spot on top, with an identical one at the south pole not seen here). The effect of altitude and side-looking angle (or just field of view for optical instruments) is also shown here, not to scale. When the imaging altitude is higher (middle green, with the correspondingly smaller green band around the pole), the coverage gap shrinks, with the same happening when increasing instead the side-looking angle (leftmost red, corresponding to the smallest coverage gap at the pole).

al., 2010). This way, essential remote sensing support for operations in the polar regions can be performed with the constellation designed in this work. Exclusion of certain parts of the polar regions is useful for improving the constellation refresh rates, as arctic ice retreats and the polar regions open up for operative use gradually, permitting, for example, transpolar shipping, thanks to an ice-free arctic projected by the mid-21st century (Parry et al., 2007). Thus, the polar caps and their immediate latitudes are not of practical interest during the near decades for operations that need fast satellite remote sensing data, such as resource exploration or shipping. Accordingly, an exclusion zone starting from the poles down to the 85° latitudes will shape the constellation geometry significantly.

Another important consideration (and the second requirement) is the altitude of the constellation; the higher the satellite, the larger coverage area it reaches, but the more demanding the requirements are on its imaging instruments. To encompass all operational scenarios considered by Sandau et al. (2010) that can be observed with a 10–100 m GSD, the lower limit of 10 m is chosen as a target GSD with which to define the altitude range of the constellation. For example, constraints on optics size due to limited available volume on small satellites sets a limit for the performance of hyperspectral instruments, with less than 6 m GSD on 100 kg satellite at 550 km being currently at the limits of feasibility (Villafranca et al., 2012). Instrument power requirements also inhibit small satellite orbit selection; in the case of radar instruments for example, according to the radar equation, the received power back from a target declines as the fourth power of the range between the instrument and the target. High altitudes are also much more demanding for attitude knowledge and pointing accuracy (Trishchenko and Garand, 2012). Thus, because of these and also to avoid the radiation environment of the inner van Allen belts, the upper limit of the altitude at which small satellite missions can operate is set to 1000 km, as the more economical commercial off-the-shelf (COTS) electronic components commonly used in small satellites are less tolerant of radiation. In the end, the lower the constellation, the better its instruments will perform and survive the environment; thus, lower orbits are a preference.

The revisit times should occur as regularly as possible per time period (i.e., a day), both in terms of local time and the time interval between visits. This enables an image to be obtained without too much variance in the exact picture location and operational conditions, with ideally the coverage regularity being a constant two hours refresh rate or less throughout the target area, the same as the targeted refresh rate. Fast coverage should also be available as uniformly as possible in a target coverage area, as most operations in the polar regions tend not to stay in a particular area. The constellation geometry should then supply observations per day that are evenly spread with respect to the target, to offer as constant service as possible. The coverage per time period for the latitudes between 60 and 85° should be as similar as possible, but as a secondary requirement, the coverage peak should fall within these latitudes for maximum performance (see Figure 2 for a graphical description of coverage regularity and uniformity). However, the trade-off between constellation geometries is more effectively done qualitatively, as all the constellation geometries compared offer dramatically different types of coverage uniformities.

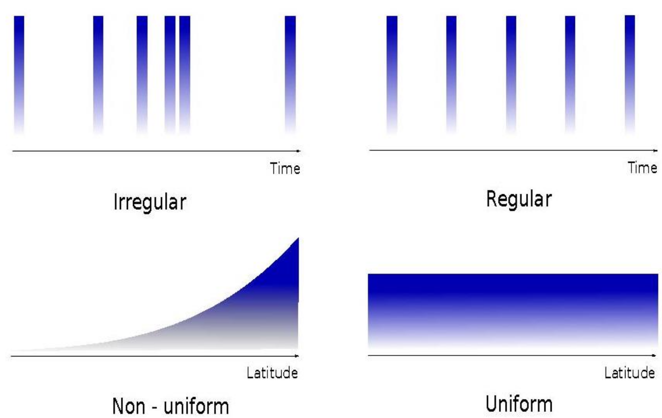


Figure 2. Coverage uniformity and regularity definitions.

The constellation should be able to provide identical coverage with respect to both poles. This requirement enables the supply of remote sensing data with the same parameters in two regions of Earth that have similar remote sensing data needs, and thus effectively double the efficiency of the satellite constellation.

Once collected, the remote sensing data must be downlinked as quickly as possible to the operation in the target region. This requirement has two parameters, the constellation geometry and the ground station locations; the optimum result is a balance of both. The ground segment coverage and ground station locations are not explored in this study; an in-depth analysis of downlinking possibilities for small satellites is presented in Spangelo's work (2013).

In addition to these considerations, how the satellites are launched to their target orbits is an indirect but necessary point that must be taken into consideration for each constellation geometry. While the total launch costs of a small satellite are relatively low compared to more traditional satellite missions, as a percentage of cost launches remain the most expensive part of a small satellite mission, and can in fact (for piggyback launches) have larger per kilogram costs than the specific costs for the launch vehicle itself (Crisp et al., 2013, p. 4, section 2.3 and Tables 3 and 4).

Table 1 summarizes all requirements used in this work, and provides quantitative values with which to proceed in finding out an optimal constellation geometry.

As stated in the introduction, the low cost of a small satellite mission is one of its advantages. Thus, any solution on the part of the constellation geometry that would provide the perfect solution (e.g., one that would satisfy all the requirements in Table 1), but would cost significantly more, loses this advantage. Cost is not directly added directly as a quantifiable requirement when choosing a suitable constellation geometry, and instead comes out as a way to trade off the different constellation geometry in terms of the number of satellites and launchers they need (for example, one launch is better than several, and in turn, several launches with existing technology are better than one launch that needs development of a new launcher).

2.3. Constellation Geometry Comparison

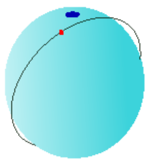
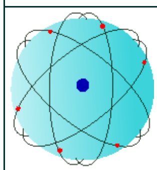
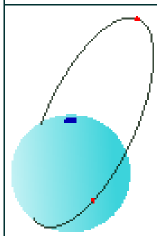
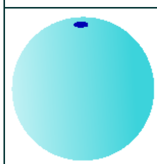
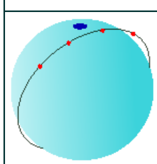
A prerequisite for the selected constellation geometries was their suitability to covering the polar areas, and they were evaluated for how well they satisfy the previously explained constellation requirements. With one satellite, the time of revisit on each target area is almost constant, as it changes only if its orbit parameters change. However, when a constellation of satellites is considered, each with their own imaging instrument's side-looking angle constraints, the revisit time on an arbitrary spot on the planet for all the satellites acting as one constellation becomes much more complex. A single polar orbit was included as a reference to argue for a constellation, as well as an example of each constellation case. Table 2 summarizes the first trade-off analysis performed between different constellation geometries, based on the requirements in Table 1. This summary does not go into great detail, as its intent was to identify the more obvious clashes with the given requirements. As can be seen, a Walker delta pattern-type of constellation (also known as a Rosette constellation by Ballard) performs best in most aspects, including the most important ones.

Table 1. Most important requirements (from left to right) and Ideal Parameters for Evaluating the Different Constellation Geometries Observing Ground Operations in the Polar Regions[1]

Revisit Time	Altitude	Coverage Uniformity	Coverage Regularity	Pole Coverage	Time to Downlink	Launches Needed
Two hours or less between observations for the target latitude range 60–85°	Earth orbit; the lower the better, but with maximum altitude of 1000 km	Coverage between 60 to 85° uniform, or at least coverage peak is within these latitudes	Coverage regularity has to be at least equal to the required minimum revisit time; two or less hours between consecutive observations	Both poles	As quickly as possible after observation, preferably immediately	Ideally, one launch for the whole constellation

[1]Cost of the mission is evaluated in terms of amount of satellites and launches needed, and so is used inherently in the actual trade-off process.

Table 2. Trade-off Analysis Performed Between Different Constellation Geometries Based on the Requirements in Table 1, as well as Most Types of Constellations Possible for Imaging the Polar Regions[1]

Constellation	Description	Revisit Time	Possible Altitude	Coverage Uniformity	Coverage Regularity	Pole Coverage	Time to Downlink	Launches Needed	Existing Examples
	A common, single polar orbit	At best 12 hours	Low earth orbit	Dependent on the target latitude	The orbit repeats its ground track regularly, but too sparsely	Both poles are covered symmetrically	Next available station after imaging	One	Radarsat-2
	A symmetric, rosette; like configuration (Walker, 1984)	Roughly, 12–24 hours divided by the amount of constellation satellites	Low earth orbit	Highest revisit time within 70–80° latitudes	Two or less hours between revisits achieved with 8 satellites at 60 and 85° latitudes at 450 km altitude	Both poles are covered symmetryically	Next available station after imaging	Separate launches for each RAAN	Radarsat next; constellation
	Highly elliptic, 16 hour period TAP; orbit in critical inclination (Trishchenko et al., 2011)	A constant visibility of one of the poles down to 60° latitude with two satellites	Very large distances from the apogee for imaging, with more than 43493 km apogee altitude	Uniform coverage	Coverage almost constant	Only one pole; twice the satellites needed (4 in total) to cover both poles	Almost constant visibility to a ground station	Launches uncommon	Russian communiction infrastructure
	Pole sitter: a satellite at a fixed position compared to one of the poles (Heiligers et al., 2014)	Constant visibility over the whole pole	Very large operational altitudes (more than 2.5 million km) from the stable point	Same in all parts of the coverage area	Constant coverage	Both poles need two satellites; this might not be prohibitively expensive for a small satellite mission	Visible constantly to a ground station at one pole	Challenging launch and deployment; none exists yet	None
	Several satellites phase; offset in the same orbit, with for example Cosmo-SkyMed (Grandoni et al., 2014)	The constellation has a repeat ground track of 16 days, with constellation revisit time around 12 hours for Cosmo-Skymed	Low to medium earth orbit	Same in all parts of the coverage area	Very irregular at the poles; the satellites pass the target quickly one after another	Both poles	Next available station after imaging	Launch to one orbit and phase offsetting between all satellites	Cosmo-SkyMed

[1]The difference between this and Table 1 is the consideration here of the rough altitude possible for the constellation geometry, and comparing it with the ideal altitude in Table 1. The driving requirement is two hours of revisit time above 65 degrees latitude. Green indicates the requirement is satisfied, orange signifies the geometry has some non-critical limitations, and red that it does not meet the requirement, and is discarded.

A combination of these orbits in one constellation is also possible, but makes their evaluation even more complicated and so is not examined in-depth in this work; a thorough framework for designing reconfigurable constellation geometries, including the constellation phasing, has been developed by Legge (2014).

2.4. Chosen Constellation Geometry for Polar Observation Missions

The chosen constellation geometry, Walker delta, is symmetric from the point of view of a chosen star-fixed frame of reference, each satellite having an equal separation away from the previous with respect to their Right Ascension of Ascending Node (RAAN) according to 360/N, N being the number of satellites in the constellation (see Figure 3). The constellation has the same altitude and inclination for all satellites, as well as a common zero eccentricity. Thus, from hereon, the orbit parameters of the constellation will be referred to collectively (i.e., "collective inclination," etc.).

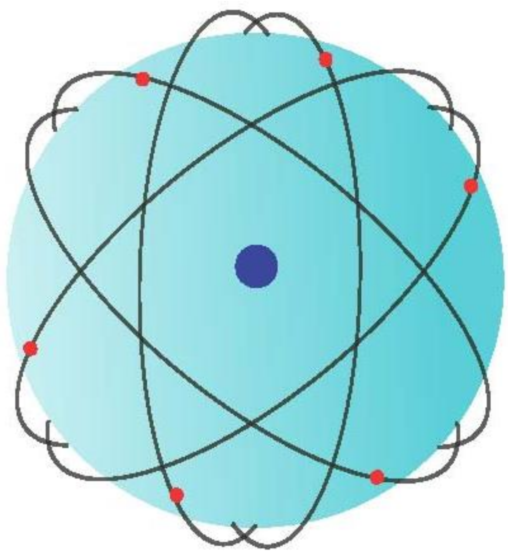


Figure 3. As an example, a pole-view of the rosette-like Walker delta 6-satellite configuration. The red dots represent satellites.

As for the launch of the Walker delta satellites, many launches available to small satellites tend to target Sun-synchronous low-Earth orbits (LEO) with high inclination, minimizing the effect of the harsh radiation conditions created by the van Allen belts at higher altitudes, which is suitable for the small satellite Walker delta. Assuming all targets up to a side-looking angle of 60 degrees can be imaged by the spacecraft, the revisit time over the polar regions of the Walker delta is sensitive to the inclination of the constellation orbits. The inclination of the satellite orbits is also an effective way to control the focus of the combined coverage area of the constellation satellites, as their collective inclination limits the highest latitudes available for imaging and increases revisit times at the lower altitudes. Figures 4, 5, and 6 show the characteristic shape on revisit times for a constellation geometry at the collective altitudes of 450, 725, and 1000 km, respectively. Depending on orbit altitude, but especially at lower altitudes, the revisit times per day tend to peak in a certain latitude range, and drop rapidly when moving away from this latitude range in either direction. Overall, higher collective altitude orbits provide more uniform coverage. The constellation inclination also has an effect, with higher (closer to and including 106°) collective inclinations causing the rapid decrease of revisit time at higher latitudes. The Walker delta geometry thus concentrates the revisit times to certain high latitudes, and is symmetrical with respect to the poles.

At 450 km altitude, the minimum number of satellites (above the horizontal red line) is six; the different studied inclinations influenced the revisit times so that inclinations closer to the pole imbalance the revisit times per day to be very frequent at higher latitudes, especially for inclinations of 94 degrees and less, while dwindling in value closer to the lower latitudes of the range of interest. In the 60 to 75 degree range, in nearly all cases, it is better to have a higher collective inclination (closer to 106 degrees). At 725 and 1000 km, four satellites are sufficient to fulfill the revisit time requirement, and again better revisit time per day is achieved with collective inclinations closer to 106 degrees.

When the border latitudes of 60 and 85° are evaluated for a time period of two months, the average longest gap between two observations is as seen in Table 3

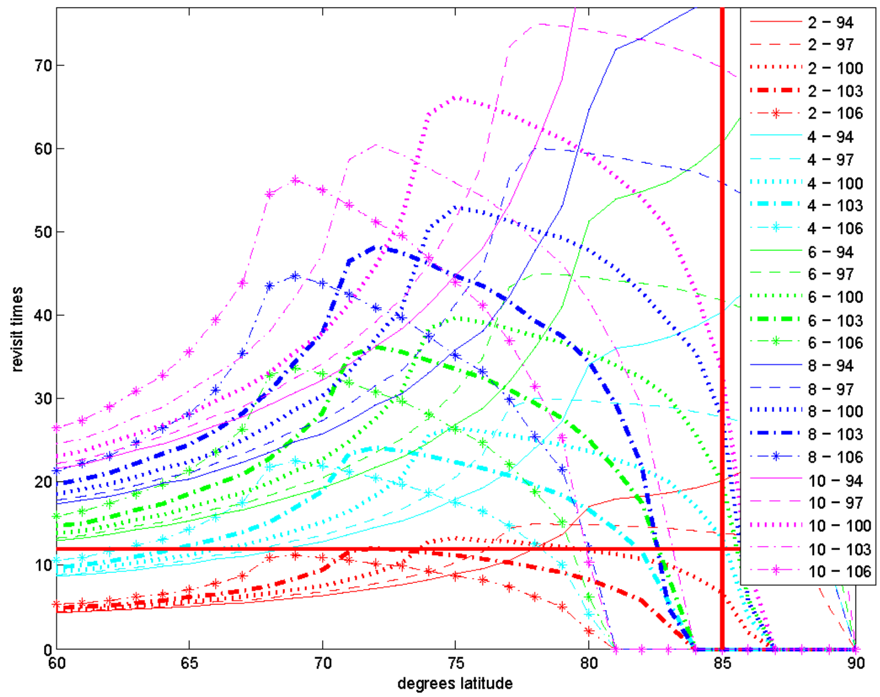


Figure 4. The times per day a latitude is seen by 2-, 4-, 6-, 8-, and 10-satellite Walker delta constellations at 450 km collective altitude, with 94, 97, 100, 103, and 106◦ collective inclinations, and a sidelooking angle of up to 60 degrees for each satellite. The horizontal red line indicates the minimum revisit times needed to fill the revisit requirement, while the vertical red line indicates the highest latitude (85◦) of interest.

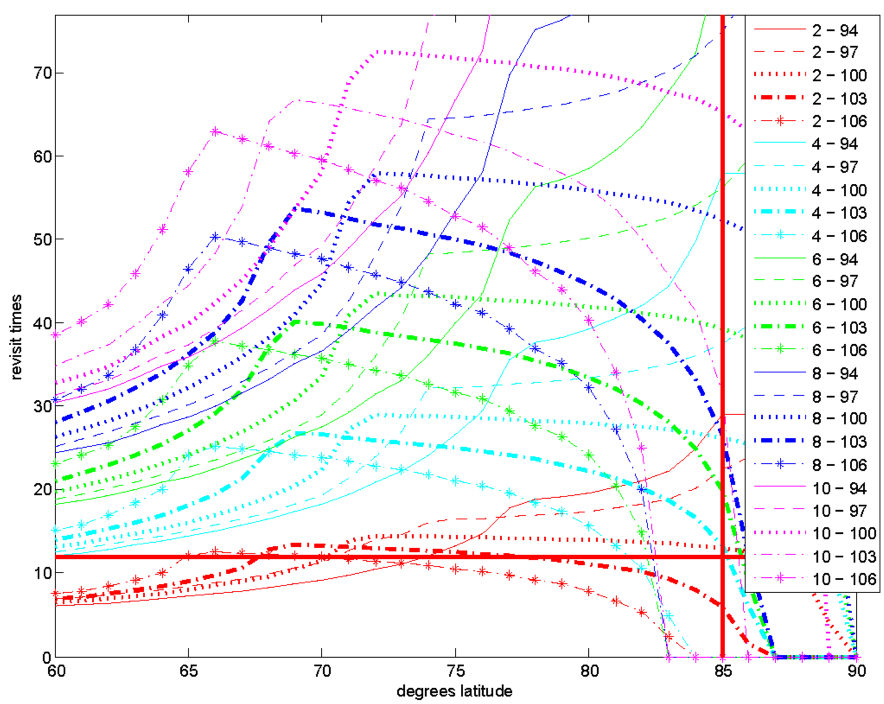


Figure 5. The times per day a latitude is seen by 2-, 4-, 6-, 8-, and 10-satellite Walker delta constellations at 725 km collective altitude, with 94, 97, 100, 103, and 106◦ collective inclinations, and a sidelooking angle of up to 60 degrees for each satellite. The horizontal red line indicates the minimum revisit times needed to fill the revisit requirement, while the vertical red line indicates the highest latitude (85◦) of interest.

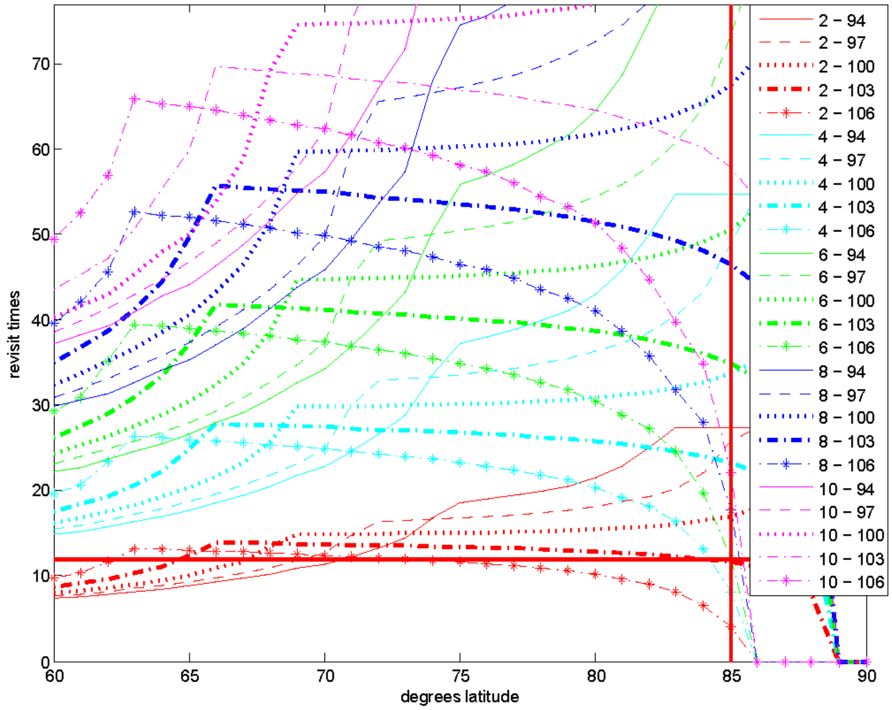


Figure 6. The times per day a latitude is seen by 2-, 4-, 6-, 8-, and 10-satellite Walker delta constellations at 1000 km collective altitude, with 94, 97, 100, 103, and 106◦ collective inclinations, and a sidelooking angle of up to 60 degrees for each satellite. The horizontal red line indicates the minimum revisit times needed to fill the revisit requirement, while the vertical red line indicates the highest latitude (85◦) of interest.

Table 3. Coverage regularity: Smallest Time Gap Between Two Consecutive Observations at 450, 725, and 1000 km Altitudes for 2-, 4-, 6-, 8-, and 10-satellite Walker Constellations in 94, 97, 100, 103, and 106◦ Inclinations[1]

450 km	**2**	**4**	**6**	**8**	**10**
94°	8.02 / 4.69	5.94 / 1.48	4.39 / 1.47	2.82 / 1.47	2.83 / 1.47
97°	4.69 / 9.37	4.39 / 1.50	2.82 / 1.49	1.77 / 1.48	1.76 / 1.48
100°	9.56 / 14.05	4.38 / 3.11	3.31 / 1.53	2.83 / 1.52	2.82 / 1.52
103°	9.55 / –	3.31 / –	3.10 / –	2.84 / –	1.73 / –
106°	11.08 / –	4.84 / –	4.40 / –	2.83 / –	1.53 / –
725 km	**2**	**4**	**6**	**8**	**10**
94°	6.82 / 1.59	4.62 / 1.54	2.96 / 1.54	1.59 / 1.53	1.35 / 1.53
97°	7.14 / 1.73	4.61 / 1.56	1.84 / 1.54	1.84 / 1.54	1.35 / 1.54
100°	8.46 / 9.93	2.98 / 1.58	1.85 / 1.57	1.60 / 1.56	1.34 / 1.56
103°	8.47 / 14.89	3.47 / 3.29	3.03 / 1.63	2.97 / 1.61	1.35 / 1.60
106°	10.09 / –	3.48 / –	3.02 / –	1.39 / –	1.39 / –
1000 km	**2**	**4**	**6**	**8**	**10**
94°	5.48 / 1.64	4.85 / 1.60	3.10 / 1.60	1.40 / 1.59	1.38 / 1.59
97°	7.19 / 1.69	3.13 / 1.62	1.67 / 1.61	1.43 / 1.60	1.39 / 1.60
100°	7.2 / 5.26	3.12 / 1.64	1.92 / 1.62	1.42 / 1.62	1.38 / 1.62
103°	8.87 / 10.51	1.98 / 1.66	1.75 / 1.66	1.46 / 1.65	1.43 / 1.65
106°	8.94 / 15.76	3.36 / 3.49	1.49 / 1.73	1.43 / 1.72	1.41 / 1.71

[1]The gaps for each border latitude are presented in hours, in the form of "hours at 60°/hours at 85°" per constellation satellites and inclination. The constellation satellites are assumed to be in the same phase. The "–" sign denotes that no coverage is available. Green values indicate chosen constellations.

for all the different constellation geometries considered. To evaluate the gap times, the constellation satellites were placed in the same phase, resulting in a lower limit of 1.3–1.7 gap times seen in the Table (especially with the 8- and 10-satellite constellations). Optimizing the constellation phases might result in improved gap times, but is not considered in this work.

Table 3 shows how in almost in all cases 2- and 4-satellite constellations do not satisfy the requirement of minimum revisit time between consecutive observations to be less than or equal to two hours at both latitudes of interest. Six and eight satellites satisfy the requirement at 725 km and 1000 km altitudes, with obviously more satellites and higher altitudes giving a better performance.

The revisit time plots and revisit time worst-case gap table indicate that the altitude has a significant role in the choice of a suitable Walker constellation for polar observation. However, depending on the onboard imaging instrument requirements, the constellation can be altitude constrained, and should be taken into consideration. Overall, the best constellation is only a 4-satellite, 103 degree inclination constellation at 1000 km; it is able to supply at minimum an average revisit time per day of 1.3 hours, with coverage peak centered at 65 degrees latitude, and a worst-case gap of 1.98 hours at 60 degrees latitude between two consecutive observations. However, as the preference is in as low as possible altitude, considering the constraints of small satellites on the imaging instruments, the best constellation for the 725 km is a 6-satellite, 100 degrees inclination constellation, which is able to supply at minimum 1.2 hours average revisit time per day, with its coverage peak centered at around 73 degrees latitude, and a worst-case gap of 1.85 hours at 60 degrees latitude between two consecutive observations. This requires more satellites and is thus more expensive, but the 100 degrees collective altitude will in turn lessen the required ΔV (treated next in this work) and deployment strategy from an SSO orbit. Finally, with a 450 km altitude, an 8-satellite, 97 degrees inclination constellation performs best, with a minimum 1.6 hours average revisit time per day coverage peak centered at around 78 degrees latitude, and a worst-case gap of 1.77 hours between two consecutive observations.

3. Constellation Geometry Construction

3.1. Constellation Orbit Insertion

As discussed in section 1.1, the satellites most likely need to perform limited orbit maneuvers after deployment from the launcher to attain their correct final orbits in the chosen constellation geometry. These include a change of altitude, as well as inclination/RAAN changes. The essential part is the order of steps taken by each satellite, so as to minimize the following considerations (in order of priority):

- the total time taken for the constellation to form; and
- the required ΔV.

Condition 1 shortens the total lifespan of the mission due to the constellation having to spend time in the space environment forming the full constellation geometry, while Condition 2 determines largely what type of launch opportunities and propulsion systems the constellation satellites need to have. Each step influences either the constellation formation time or the efficiency of the performed maneuver. Once the satellites have been inserted into their initial orbits, the constellation satellites need to make an inclination adjustment Δi with a cost of ΔV given by

$$\Delta V = V\sqrt{2 - 2cos\frac{\pi}{2}\Delta i} \tag{1}$$

(Ruggiero et al., 2011), where V is the circular velocity of the spacecraft at its initial orbit. The propellant going into the altitude change can then be calculated by the textbook difference between the velocities of two circular orbits:

$$\Delta V_a = \sqrt{\mu\left|\frac{1}{r_{high}} - \frac{1}{r_{low}}\right|} \tag{2}$$

The ΔV for the RAAN maneuver can be estimated with

$$\Delta V = \frac{\pi}{2}V|\Delta\Omega|\, sin(i) \tag{3}$$

(Edelbaum, 1961) where i is the current inclination of the satellite, V is its velocity, and $\Delta\Omega$ is the desired RAAN change. As they essentially are expressions measuring the change in the direction of the satellite's velocity vector, Equations 1 and 3 indicate that inclination and RAAN change are the most ΔV demanding, as can also be seen in Figure 7, where some degrees of inclination (which varies with initial altitude where inclination change is performed) and one degree of RAAN change require significantly more ΔV than changing the altitude of a circular orbit by several hundred kilometers. Thus, when constructing a Walker delta out of small satellites, the secondary payload launches should be as close as possible to the target orbit parameters. The satellite's RAAN can be influenced by the time of the launch, so the construction of the constellation geometry can be helped significantly with just choosing a correct time for each satellite's launch.

As an example, if the imaging instrument requirements constrain the constellation altitude to as low as possible, and a Walker delta with 450 km altitude and a 97 degree inclination is chosen as a target orbit for the constellation (considering that often launches available for secondary payloads are popular circular SSOs with altitudes of 500 and 1000 km), the estimated ΔV needed by the spacecraft can be seen in Figure 7, which shows the total ΔV needed for performing three continuous, separate low-thrust maneuvers, a RAAN change, an inclination change (to the chosen Walker constellation of 97 degrees, as well as the rest of the range of 94, 100, 103, and 106 degrees for comparison), and altitude change, all from an SSO to the target one. Changes due to the J_2 effect are not considered in these calculations, and will be treated later. The RAAN changes can be influenced by the chosen secondary payload launch, so the assumption here is that correct RAAN parameters for the constellation are attained with good launch choices, leaving around one degree of change that needs to be performed by the onboard propulsion system. As both inclination and RAAN maneuvers are altitude dependent, the needed ΔV changes as a function of the initial altitude to which the launcher brings the satellite.

Even if all launches are timed with respect to the constellation RAAN parameters, depending on the initial orbit, roughly 540 to 730 m/s worth of propellant must be onboard each 97 degrees inclination, 450 km

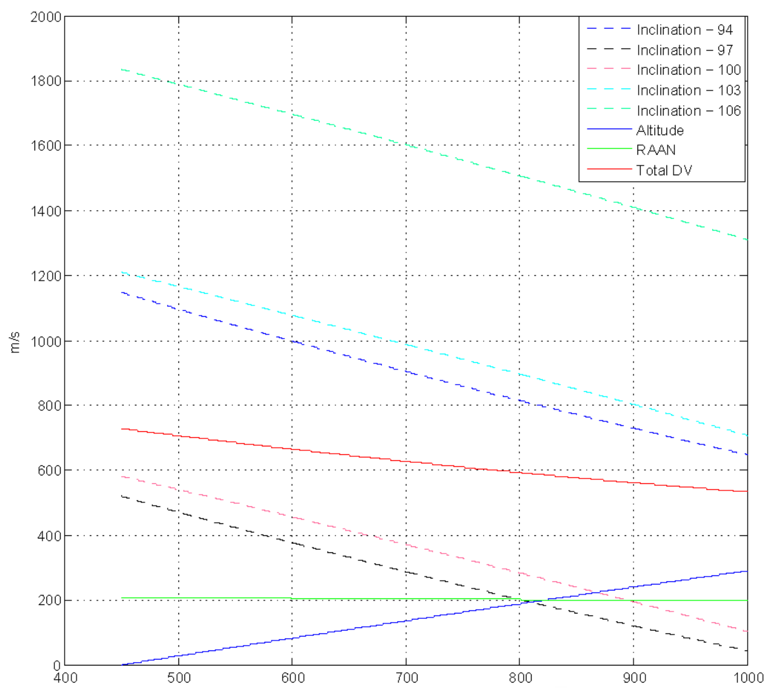


Figure 7. Total ΔV for an altitude change to a 450 km orbit from an initial circular orbit of 500 to 1000 km, an inclination change from SSO to 94, 97, 100, 103, and 106 degrees, with the total ΔV calculated for change to 97 degrees, and a RAAN change of 1°.

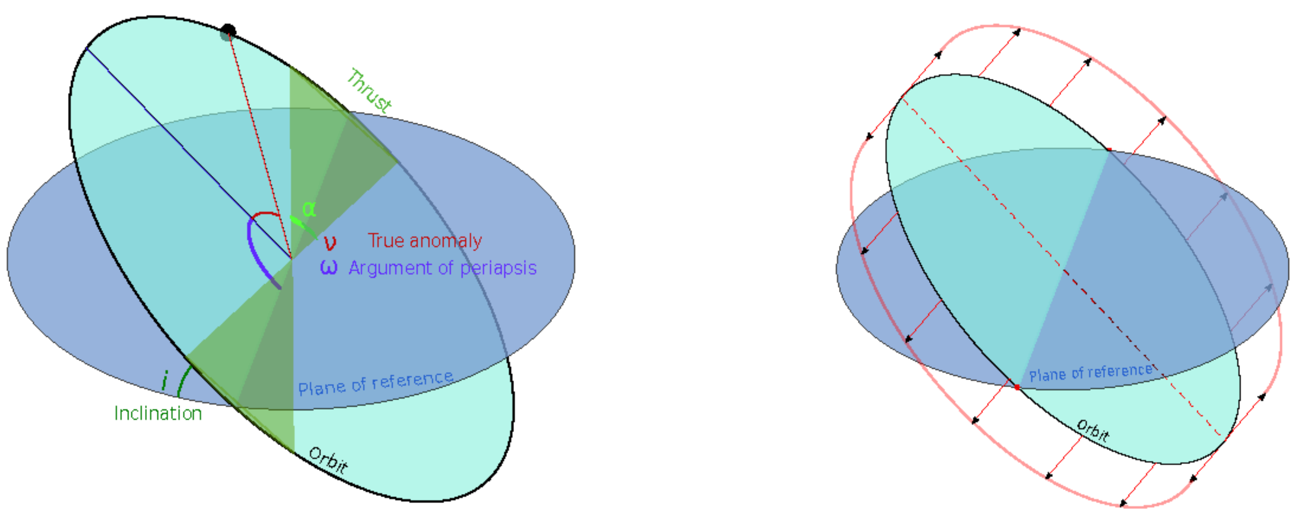
constellation satellite to achieve the needed maneuvers and get to their target orbits. Note that this does not include the propellant needed for orbit maintenance. As an example, using basic Tsiolkovsky's equation, for a 100 kg satellite and a propulsion system with 1500 s I_{sp}, this translates into 3.6 to 4.8 kg of propellant. To fit this much propellant into a relatively small space in turn increases the difficulties in such a system.

When the efficiency of the orbit maneuvers is evaluated, inclination and RAAN change at higher altitudes are less expensive in terms of ΔV (the velocity term in Equations 1 and 3), and going first to lower altitudes might increase the air drag experienced by the satellite. The rate of the inclination/RAAN change is however inversely dependent on the satellites altitude, so at lower altitudes the RAAN and inclination changes will be faster. Equations 4 and 5 represent this efficiency of thrust from an engine at a certain part of the orbit. Based on Ruggiero et al. (2011), the efficiency for the inclination/RAAN maneuvers is

$$\eta_i = \frac{|\cos(w+v)|}{1+e\cos(w)}\left(\sqrt{1-e^2}sin^2(v) - e|\cos(v)|\right) \tag{4}$$

$$\eta_\Omega = \frac{|\sin(w+v)|}{1+e\cos(w)}\left(\sqrt{1-e^2}sin^2(v) - e|\cos(v)|\right) \tag{5}$$

in which v is the satellite's true anomaly with respect to the perigee, w the argument of perigee, e the eccentricity, and where the maximum points of efficiency are at a true anomaly of 90° and 270° for inclination changes and 0° and 180° for RAAN changes. This points out that a low-thrust inclination change should be performed only at certain sections of the orbit. For example, if the thrust efficiency should be higher than 75 percent, it will cover an angle of 90° of the orbit (when the eccentricity is zero) centered around 90° and 270° of true anomaly (as seen in Figure 8a), and will save four times more fuel while producing the same ΔV. As a consequence, this would also lengthen the thrusting period for the inclination change by the same four times, assuming the fuel consumption is linear. When thrusting at or near these critical points of the orbit, the thrust vector of the satellite has to be pointed according to the phase of the orbit, as can be seen in Figure 8b. Notice how both efficiency parameters 4 and 5 change with a phase difference of 90°.



a) b)

Figure 8. a) Inclination change operation during a single orbit, wherein the green part is where the propulsion thrust occurs; and b) Inclination changing thrust vector pointing directions throughout the orbit.

These two maneuvers are coupled; depending on which part of the orbit the satellite thrusts (assuming a steady thrust throughout the whole orbit), it will affect both of these two orbit parameters with levels varying along with the true anomaly of the satellite (Ruggiero et al., 2011). This also means that both an inclination and RAAN change can be performed at the same time by changing the thrust vector of the spacecraft, wherein the engine burn for the assisted parameter change is performed continuously throughout a greater part or even the complete orbit, shortening the time period it takes for these otherwise two separate maneuvers to be performed.

3.1.1. Differential Orbit Precession for Small Satellites

As seen by Equation 3 and Figure 7, just one degree of RAAN change costs around 200 meters per second ΔV. In turn, launching each satellite separately depends on the availability of the right type of launches. When constructing a symmetric constellation such as a Walker delta, a way to perform the needed maneuver without having to provide as much ΔV is by using the natural precession caused by altitude differences between two or more satellites. This deployment approach is particularly suitable for small satellites as a part of a constellation, as they are identical and fit more easily as secondary payloads onboard a launcher targeting a different altitude orbit than the target altitude of the constellation.

After the launch, if one satellite is left to the initial drop-off orbit altitude and the other maneuvered immediately into the final constellation orbit altitude, the satellite orbits will start to precess with respect to each other. The result is that two or more satellites are in a series of consecutively lower orbits, as seen in Figure 9. Each satellite's altitude will not be separated with a constant altitude difference. Rather, the higher the satellite is in the precession configuration, the larger the altitude difference will be compared to its neighbors in the configuration. This altitude difference between each satellite can be determined by considering the time it takes for two satellites with a certain difference in orbit altitude to precess some number of degrees within a given time period with respect to each other.

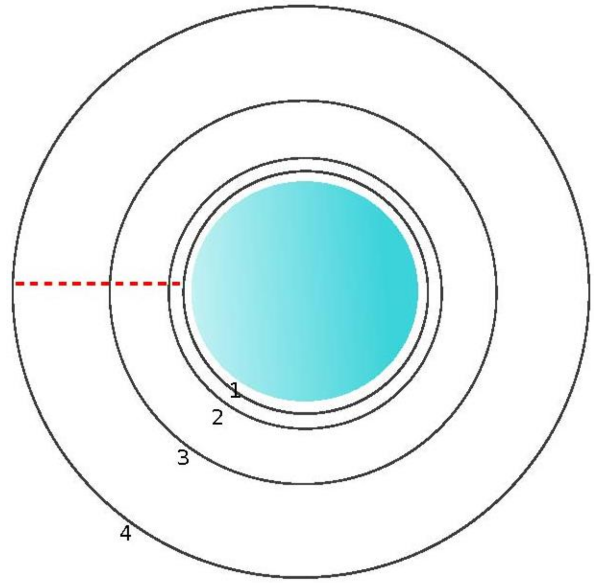


Figure 9. An example altitude configuration of four satellites, the highest in the initial and lowest in the final orbit of 450 km altitude.

In the case of four satellites' differential orbit natural precession seen in Figure 9, the target difference between each satellite to achieve a 450 km Walker delta is 360°/N = 90°, where N is four satellites. According to Wakker (2007) and Vallado (2007), the secular RAAN change experienced during one orbit with respect to a chosen inertial reference frame is

$$\dot{\Omega} = -\frac{3}{2} J_2 R_e^2 \sqrt{\frac{\mu}{r^7}} \cos(i) \rightarrow \Delta\Omega_{J2tot} = \dot{\Omega}\,\Delta t \quad (6)$$

where R_e is the Earth's average radius; J_2, Earth's first zonal harmonic; and r is the satellite orbit instantaneous radius, which is simply the orbit semi-major axis a for a circular orbit. Thus, the total RAAN change in a certain time period Δt is $\Delta\Omega_{2\pi}$. Assuming the time taken for the change of altitude is small, it takes time Δt for a satellite with an orbit semi-major axis a to change its RAAN by $\Delta\Omega_{J2tot}$.

Figure 10 shows the time Δt taken for the constellation to deploy from a range of initial (represented by satellite 4 in Figure 9) altitudes. The amount of satellites in the constellation does not in the end affect much the time taken for the formation of the constellation, as it is measured between the highest and the

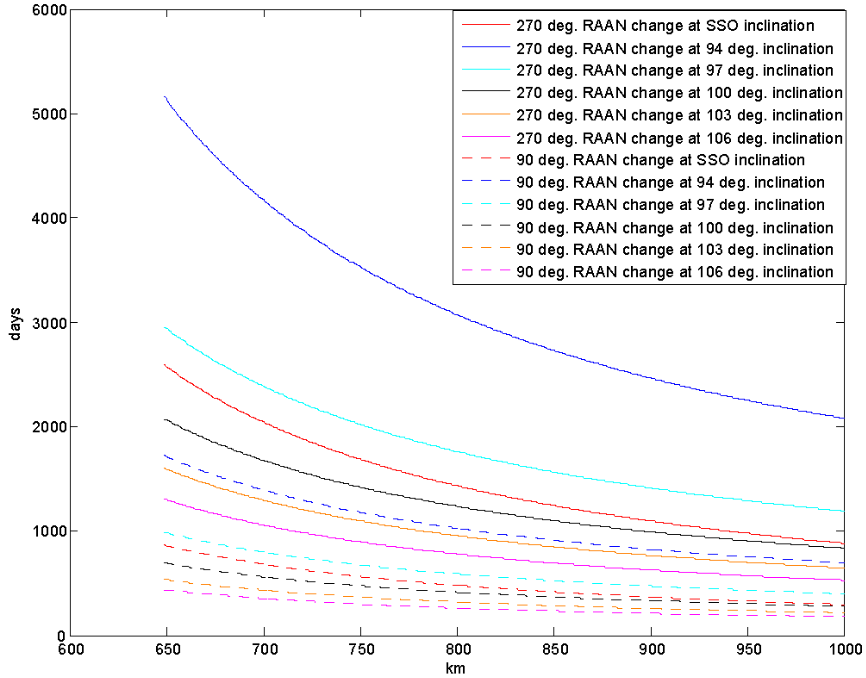


Figure 10. Days taken for the last and first satellite in Figure 9 to precess from an initial circular orbit ranging from 650 to 1000 km altitude (any lower initial orbits would have started to take a prohibitively long time). The cases of RAAN precession up to 270° and 90°, with 94, 97, 100, 103, and 106 inclination and initial orbit SSO inclinations for all satellites, is presented.

lowest satellite, and so depends on how much RAAN precession is required by the lowest satellite relative to the highest. If the inclination range of 94, 97, 100, 103 and 106 degrees is again assumed, the needed 270° RAAN relative change for the 4-satellite constellation to form will take a bit less than two years when the highest satellite is at 1000 km. However, if only two satellites of the constellation are launched at one time and their relative RAAN precession is 90°, they will be in place in just over half a year. So the precession time and the number of launches used can be traded off in a bid to minimize the total time taken for constructing the constellation. The precession time is also sensitive to the inclinations of the satellites, so simply keeping them at their initial orbit SSO inclination adds significantly to the precession time. This also argues for performing any inclination changes before maneuvering into the precession configuration.

Once each satellite assumes its correct RAAN with respect to the aimed constellation geometry, represented by satellite 1 in Figure 9, it drops its altitude to the final constellation altitude, thus freezing their RAAN parameter with respect to satellite 1. Deployment with natural RAAN precession can also be sped up; however, if a Δt of 5 month for the 450 km 270° constellation deployment example is wanted, for instance, the highest satellite would have to be at an altitude of more than 10,000 km, significantly changing the altitude the satellite has to get to and environment it needs to withstand.

4. Conclusions

By applying several small satellites in a specific constellation geometry, it is possible to concentrate its coverage in certain narrow target areas, such as Earth's poles, increasing several-fold the refresh rate in that area. The constellation geometry itself with which this can be done can be as simple as a Walker delta, but when combined with small satellites, becomes a feasible remote sensing constellation for operational uses in the regions. By using satellites under 100 kg that have identical interfaces and a small volume, and so offer more launch opportunities as secondary payloads or along with other small satellites, a relatively cheap yet effective remote sensing constellation can be constructed.

The higher the orbit altitude of the constellation is, the fewer satellites are needed to sufficiently cover the polar regions, but the more demanding it will be for the onboard imaging instrument, considering the constraint resources and environment small satellites under 100 kg offer.

One of the main challenges in lower orbit altitudes is that the satellites will require a propulsion system of their own, to be able to achieve optimal orbit parameters with respect to the rest of the constellation, and depending on the orbit in which the satellite is left by the launcher and the final inclination desired, might need several hundred meters per second ΔV. Natural precession can be used to alleviate propulsion requirements, but will in turn require months or even years to deploy the constellation.

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