Orbital diversity and inclination optimization for large count LEO constellations in non-polar orbits

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1 INTRODUCTION TO CONSTELLATION DESIGN CONCEPTS CONSIDERED

This paper describes and explains the underlying concept and design principles for a new constellation design called the Waves constellation. This constellation design phase shifts true anomaly positions with respect to conventional Walker-Delta true anomaly positions in order to optimize high latitude coverage. We propose a novel method to synchronize the true anomaly positions, so that the satellites at the top and bottom of their orbits fly in a coordinated manner over the maximum and minimum latitudes, and therefore provide maximum coverage at that designed latitude. In addition, there are relevant positional advantages of the satellites in these latitudes which provide for both in-plane and cross-plane datalinks simultaneously.

This new constellation design is particularly relevant to communications networks using large numbers of satellites (colloquially called mega-constellations). Since the new constellation design can also be layered, with optimized latitudes stacked with different inclinations, a wide latitude band can also be provided, with the same increased/assured access, and reduced/eliminated gaps.

Licensing opportunities for this new constellation design are available by contacting the authors at the Johns Hopkins University – Applied Physics Laboratory.

2 MOTIVATION FOR LARGE CONSTELLATION DESIGNS

Mega-constellations in low earth orbits (LEOs) are planned, operated by either private companies or nations. From the largest to the smallest systems, the list includes: SpaceX's Starlink (4,108), OneWeb (6,372), Samsung (4,700), Amazon's Project Kuiper (3,236 satellites planned), Boeing (3,116), Sat Revolution (1,024), China's Hongwan (864), RosCosmos's Sfera (640), India's Astro Tech (600), Canada's Telesat (512), and more than 2,000 others. If we include other recent proposals the total number increases to over 100,000 new satellites in orbit. More than 18,000 of this total have been proposed for launch in the next 5 years. [1] (O'Callaghan, 2019)

Current communications constellation designs require Polar-Star orbits (exemplified by Iridium) which divide the ascending nodes of their orbital planes over 180° of right ascension (RAAN). This approach, cuts the number of satellite planes in half, but requires that all of the satellites are in near polar orbits. The deployment of proposed mega-constellations utilizing traditional orbital configurations Polar-Star orbits present an increasing risk of satellite conjunction in polar-regions.

In addition, Walker-Delta constellations provide good Earth coverage, but near-neighbors in adjacent planes are constantly changing geometries and have widely varying Doppler shifts which can make it difficult to maintain a cross-plane datalink.

3 IMPORTANT CONCEPTS FOR UNDERSTANDING WAVES CONSTELLATIONS

In order to differentiate between coordinated satellite positions among all orbital planes in a constellation, and the phasing between satellites in different planes, the term "waves" is introduced. By wave, it is meant the set of satellites that cross the equator together, all in ascending or descending motion. Important to understanding why this coordinated wave design provides optimized coverage is development of understanding the coverage of an inclined orbit versus latitude. At the Northernmost and Southernmost parts of the inclined orbit, the non-polar satellite is flying mostly West to East. This eastward movement reduces the ground velocity of the satellite, since the earth is rotating in the same direction that the spacecraft is traveling. In addition to increasing the access time over these

latitudes, as compared with the equator, the eastward movement allows adjacent planes to be spaced behind in Right Ascension of the Ascending Node (RAAN), so that as one satellite loses access to a ground location at the designed latitude, a satellite behind it in RAAN picks it up, and continues the coverage. Because the satellites in all of the planes are synchronized, the latitude segment remains in coverage for a substantial portion of the orbital period, from 25% at low latitudes to 15% at higher latitudes of interest. As shown in Figure 1, a ground location will enter a wave from the East, and transition across access provided by 3-4 satellites in the same wave, before the wave hands off to the replacement wave.

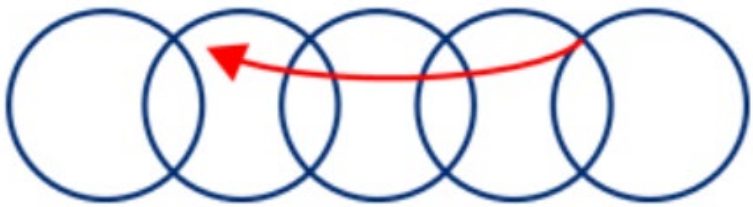

Fig. 1. Movement of coverage wave over a designated ground station latitude

Because every plane is synchronized, the entire latitude band is covered by a number of satellites equal to the number of planes. Since those satellites persist over that latitude for 15-25% of the orbital period, the total number of satellites required is between 4 and 6 times the number of planes. In the specific example shown in Figure 2, the purple wave of satellites is providing access for the designed latitude. The blue wave of satellites is leaving the designed latitude access band, and the yellow wave is ascending into position to replace the purple wave, when it completes its coverage of the designed access band.

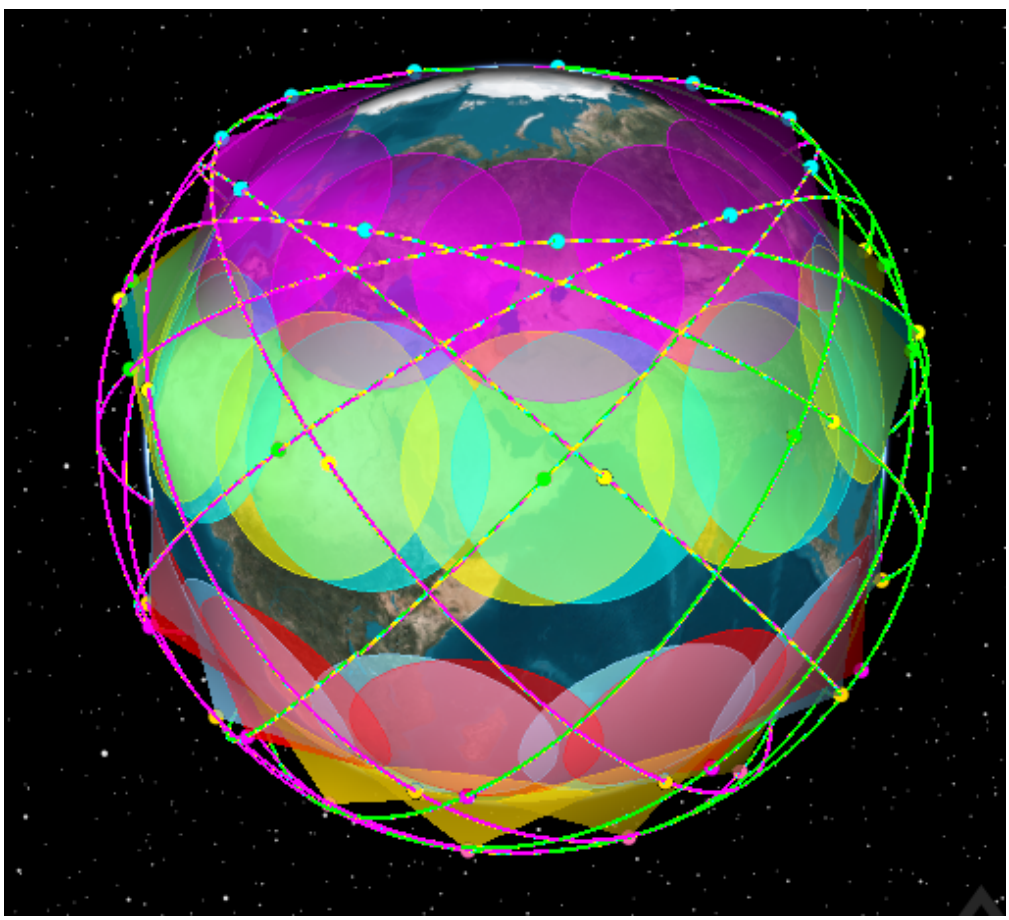

Fig. 2. Color coded satellite coverages illustrating hand-offs between access times

4 INCLINATION SELECTION AND THE REQUIRED NUMBER OF PLANES

Since coverage extends well to the North of the inclination of the satellite constellation, the required inclination for a latitude design requirement is reduced by higher altitudes (a) and larger nadir pointing angles (ϕ) in the satellite communications (comms) systems. The resulting slant range is:

$$R_{slant} = 2 \cdot (r_e + a) \cdot \cos(\phi) - \sqrt{4 \cdot (r_e + a)^2 \cdot cos^2(\phi) - 4 \cdot r_e \cdot a - 2 \cdot a^2}$$

Using the Law of Sines, it is then possible to solve for the ground range, and the inclination from the desired overlap of the coverages within the wave.

$$\frac{R_{slant}}{\sin\left({R_{gnd}}/{r_{earth}}\right)} = \frac{r_e}{\sin(\phi)}, \; R_{gnd} = r_{earth} \cdot \sin^{-1}\left(\frac{R_{slant} \cdot \sin(\phi)}{r_e}\right)$$

$$\theta_{Inclin} = \theta_{lat} - (1 - overlap)\frac{R_{gnd}}{r_{earth}}$$

This same calculation for inclination is used to provide a the number of planes. The number of planes is simply the rounded up number of overlapped coverages that evenly space around the earth. If each 2θ overlapped cone provides 30° of coverage, then 12 planes are required.

5 DETERMINATION OF NUMBER OF WAVES REQUIRED IN EACH PLANE

The determination of the number of waves is an iterative process, based on the desired latitude band requiring access. Better success has been achieved with even numbers of waves in the constellation, which creates an exact mirror of access behavior in the Southern latitude band as the Northern latitude band. For a given inclination, the following wave is spaced, so that it reaches the design latitude as the previous waves leaves that latitude. The spacing found using that criteria is then rounded down, so that the waves are evenly spaced about the plane.

6 EXAMPLE RESULTS FOR LEO CONSTELLLATIONS – COVERAGE & GAPS

A 20 x 20 grid over the US (similar to the down-sampled 5 x 5 sampling grid in Figure 3) was used to evaluate a Waves constellation. A Walker-Delta constellation with identical number of planes and number of satellites per plane was used as a basis for comparison. The only different between the two constellations, was that the Waves constellation satellites were phased, so that the satellites in each plane cross the equator at the same time as its cross plane neighbors.

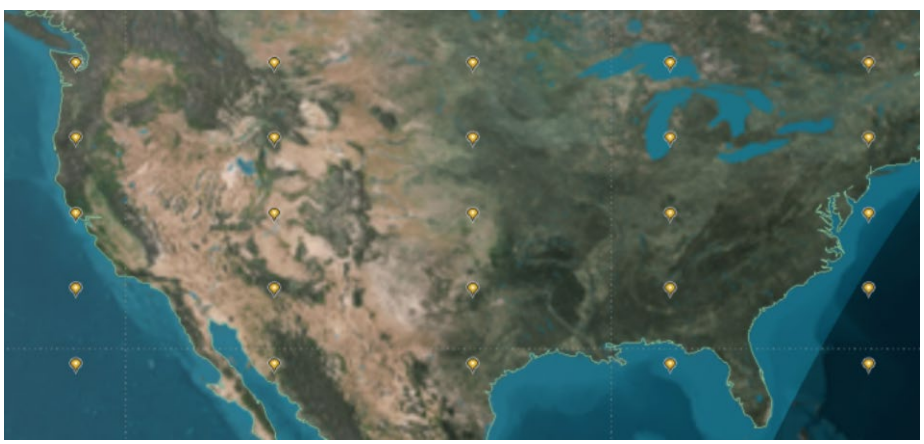

Fig. 3. Example of gridding used for access calculations

7 RESULTS OF COMPARISON BETWEEN WAVE AND WALKER-DELTA DESIGNS

Both constellations were set up with the same number of planes, and the same number of satellites per plane, so the difference is in how they are phased, specifically: Walker-Delta planes are phased such that nearest neighbor satellites are hexagonally close packed as the satellites pass the equator, and Waves planes are phased such that each the nearest satellite in neighboring planes are at the same true anomaly. This forms a wave of satellites in all planes that rise and fall together.

Because the plane configurations are identical, the average number of satellites visible from the latitudes sampled are identical, as shown in top plot of Figure 4. The co-phasing used in the Waves constellation better utilizes the available coverage, and has a fractional coverage (defined as the percentage time that a satellite is in the field of view (FOV). For this analysis, the FOV was limited to elevation angles above 26°. Both constellations had 650 km altitude, 43° inclination, 17 planes and 8 satellites per plane. The approximately 5° improvement in access latitude is perhaps not as important as the fact that in the improved coverage, the fractional coverage is 100%. For the same number of satellites, access is always available. Communications customers never want gaps in their coverage.

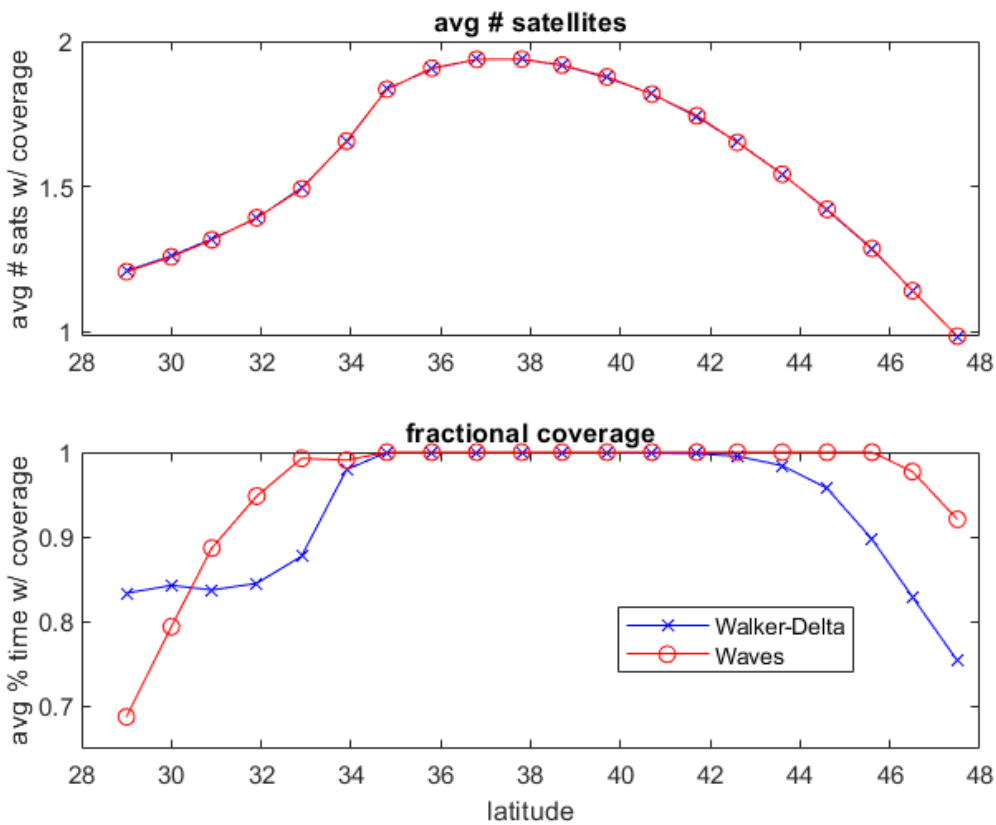

Fig. 4. Coverage per plane compared with coverage by the 2 constellations

This improvement in high latitude performance does come with a price. The fractional coverage for the Waves constellation is 10% lower than Walker-Delta constellations at 20° latitude. This effect was easily visible previously in Figure 2, where the waves transiting the equatorial region of the earth are quickly moving to support the design latitude.

In further example, shown in Figure 5: grey, cyan, and purple waves are ascending, while the yellow, red, and dark yellow waves are descending.

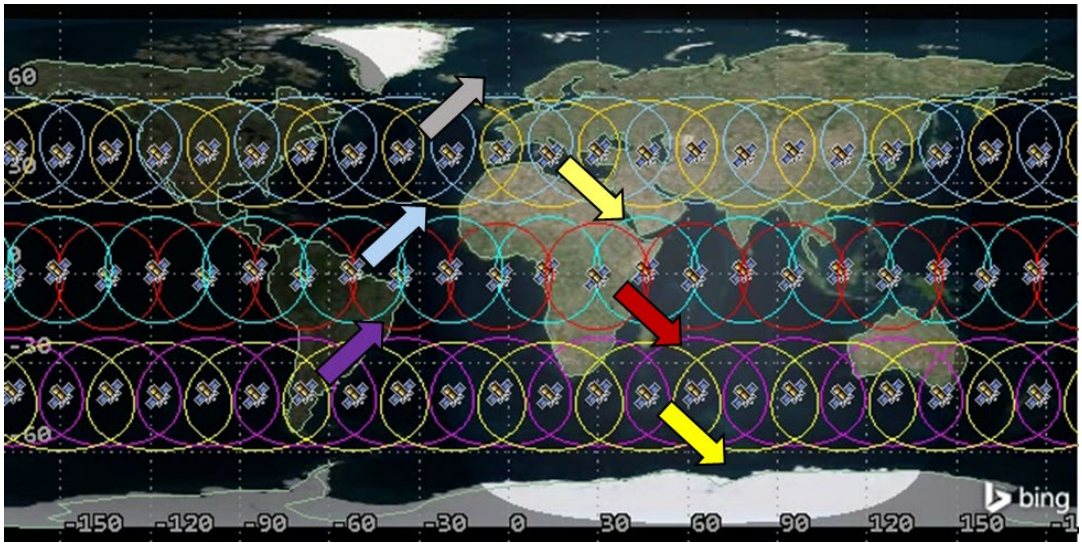

Fig. 5. Waves constellation with 774 km altitude, 50 inclination, 11 plane, 8 satellites per plane

As shown in Figure 6, the higher inclination of this Waves constellation provides even more coverage improvement over the equivalent Walker-Delta.

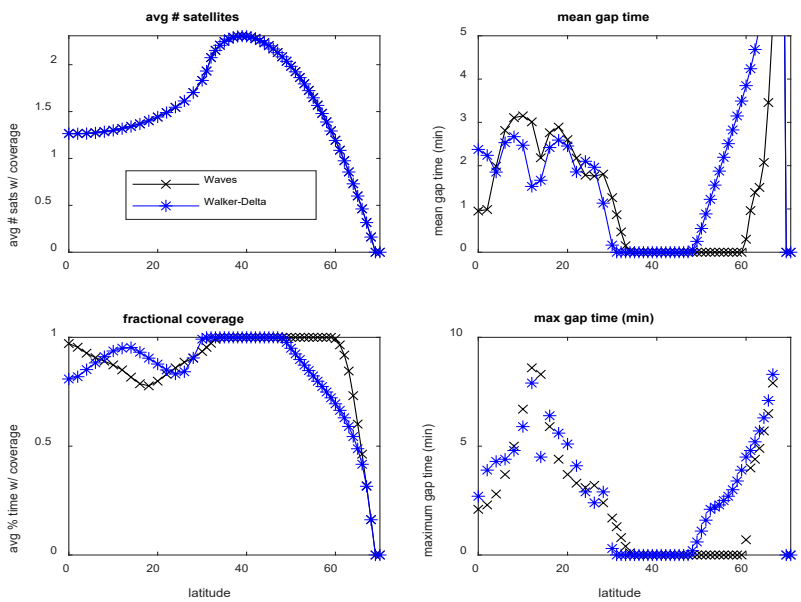

Fig. 6. Gap time results for 50° inclination design shows significant high latitude performance

8 CROSS-LINKS DURING WEST TO EAST TRANSIT

It should be noted at this point that during the access time period, where the satellites are at the design latitude, the neighboring planes are in-line with the co-planar satellites. The cross-link connections are actually shorter and easier to close than the in-plane lengths. Because all of the satellites in a wave are in the same latitude slice and all the satellites in the wave are oriented West to East, the new approach requires greatly reduced steering (pointing). Message traffic can travel to any longitude along the wave, and then traverse down the orbital plane to arrive at the desired destination. These cross-links between satellites for data transfer between planes and coordination can likely be achieved with a single antenna system with fixed pointing forward and aft.

9 ORBITAL DIVERSITY USING SECONDARY WAVES CONSTELLATION

The natural question after seeing the significant improvements at high latitudes is to ask if a second, lower latitude Waves constellation can fill in the gaps. Figure 7 shows the fractional coverage and gap time for a combined 20° and 50° inclined Waves constellation at 774 km. This dual Waves constellation model was also configured to include a link budget limitations, such that the slant range allowed was always less than 1000 km. This range limitation is effectively a reduction in the nadir pointing angles (ϕ=50°). Even with this extreme limitation on range, the required number of satellites for assured access is still less than 600 satellites.

Although this question has not been examined deeply at this point in our research, initial results indicate that the second constellation set will likely have very different parameters than the higher inclination set. The 50% reduction in satellites required to maintain 100% access at low latitudes is not fully confirmed, but is trending in our preliminary results.

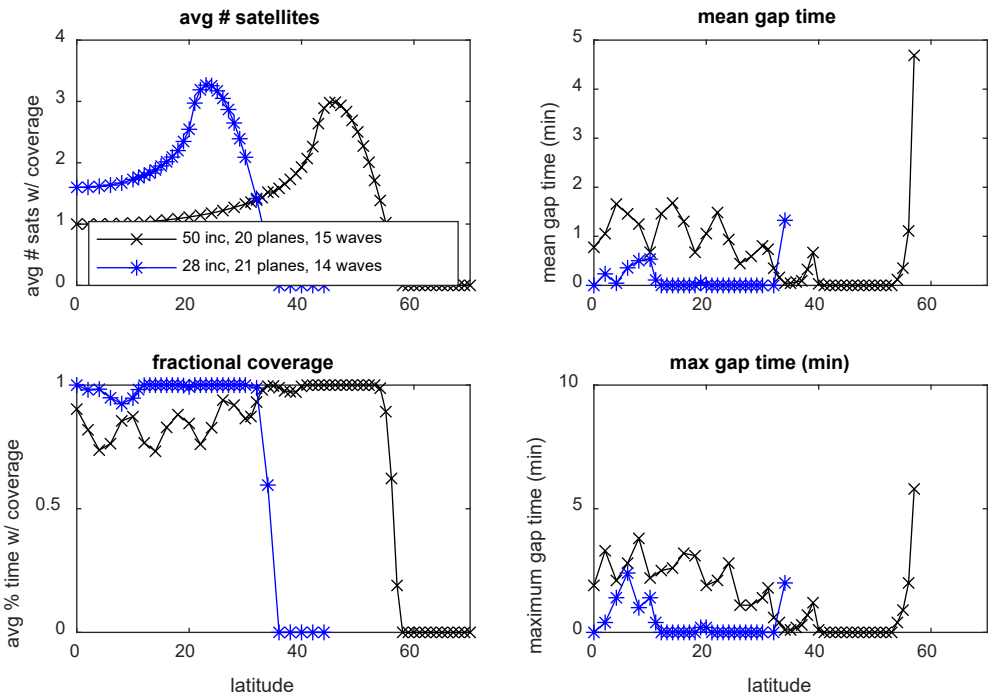

Fig. 7. Coverage and gap time improvements through the addition of a 2nd Wave constellation

10 SUMMARY OF PRESENTATION

In summary, the new approach for co-phasing satellites in a satellite constellation, provides assured access (100%) for extremely useful latitude bands. The new approach requires reduced steering (pointing) at cross-link areas at the latitudes access is already being provided. These cross-links between satellites for data transfer between planes and coordination can likely be achieved with a single antenna system with fixed pointing forward and aft.

11 REFERENCES

[1] The Risky Rush for Mega Constellations, Jonathan O'Callaghan, Scientific American, October 31, 2019, https://www.scientificamerican.com/article/the-risky-rush-for-mega-constellations/