Waves Satellite Constellation Design and Analysis

Robert S. Duggan and Chuck Quintero

ABSTRACT

Satellites are excellent platforms for communications, sensing, imaging, and navigation, providing the "high ground" for large-area fields of view and low-loss free-space paths for inter-satellite links. As development and production costs decline, large constellations (upward of thousands of satellites) are planned for near-future launches by both private and public entities. Designing these constellations is challenging because of the large trade space that includes altitude, inclination, total number of satellites, distribution of satellites in planes, and phasing between satellite planes. In this article, we discuss a new constellation design (patent pending), which we call a Waves constellation, developed by the Johns Hopkins University Applied Physics Laboratory (APL) to provide optimal coverage in a given latitude band. Further, we discuss our work to speed up the analysis of satellite constellation coverage, which can be used with the Waves geometry or any arbitrary constellation geometry.

INTRODUCTION TO CONSTELLATION DESIGN CONCEPTS CONSIDERED

Satellite networks are the backbone for a number of current technologies. They are commonly used for navigation (e.g., the Global Positioning System, or GPS) but are becoming increasingly important for communications and Earth monitoring. A single satellite can provide coverage of an area of interest and cross-link communication between satellites in a network. For communications in particular, placing satellites in low Earth orbit reduces latency and the per-unit platform and launch cost. Compared with geostationary orbits (~35,800 km altitude), the low Earth orbit regime (~250–2,000 km) can be exploited with much smaller satellites, as the required transmitter power scales as the inverse square of the distance to the ground station. A number of mega-constellations (hundreds to thousands of satellites) are in the development or planning stages, including SpaceX's Starlink (as many as 42,000 satellites planned) and Amazon's Project Kuiper (more than 3,000 satellites planned).[2] Given the large number of satellites in these networks, improvements in constellation designs that can reduce the number of satellites by even 10% bring significant

Note: Some of the concepts discussed in this article were presented at AMOS 2021.[1]

value. Many communications constellation designs use 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 the satellites be in near-polar orbits. This type of constellation is falling out of favor, since there is a "seam" between the two halves of the constellation that makes routing communications traffic between them particularly difficult.

In this article, we discuss a new concept for constellation design, called a Waves constellation. In this APL design, the true anomaly positions among the planes are synchronized, such that they cover the maximum and minimum latitudes in unison. This is in contrast with traditional Walker-Delta designs, which often provide favorable coverage at lower latitudes but are poorly synched at higher latitudes. Further, the Waves geometry naturally supports easy data links both within a plane and across planes among a wave.

This new constellation design can also be applied to communications networks with diverse latitude requirements. Since the new constellation design can be layered, with optimized latitudes stacked with different inclinations, a wide latitude band can be provided with the same increased/assured access and reduced or eliminated gaps.

IMPORTANT CONCEPTS FOR UNDERSTANDING WAVES CONSTELLATIONS

To understand this new approach to constellation design, it is important to differentiate between the in-plane satellite positions and the phasing between satellites in different planes. The term *wave* identifies the unique phasing relationship between cross-plane satellites as the distinguishing feature between the Waves constellation and typical Walker-Delta constellation designs. *Wave* refers to the set of satellites that cross the equator together, all in ascending or descending motion. To understand why this coordinated wave design optimizes coverage, it is important to understand the coverage of an inclined orbit versus latitude. At higher latitudes, as longitude lines compress, fewer satellites are needed in each wave to provide complete coverage. The coverage over these inclinations is further increased because at the top and bottom of the orbits, the satellite slows and reverses its latitude rate, like a sinusoid having the smallest derivative at its maximum and minimum points. These factors increase the access time over the optimized design latitudes, as compared to the equator. The constellation design is optimized by spacing adjacent planes in RAAN so that, as one satellite in a wave moves west to east and loses coverage for a given longitude, a satellite behind it in RAAN moves into place and continues the coverage. Then, as one wave descends below the design latitude, the subsequent wave ascends and takes over coverage.

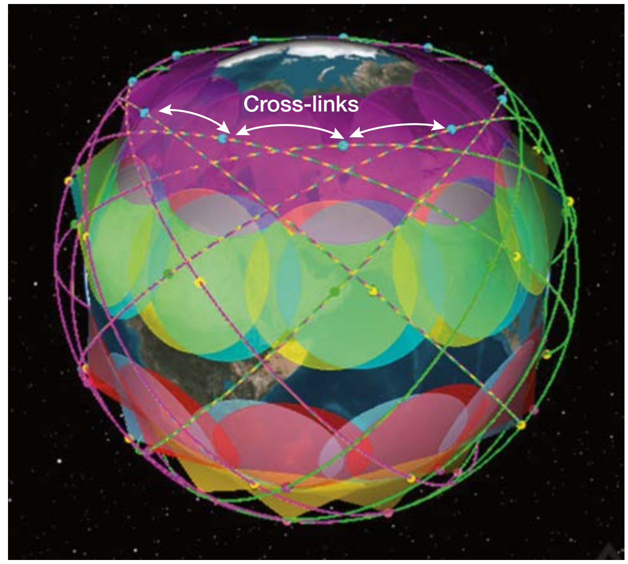

Figure 1. Visual depiction of the Waves constellation. Each satellite coverage cone is color-coded to a single wave. As the satellites progress in their orbits, the waves hand off coverage of latitude bands. The spacing is designed to provide persistent coverage near the design latitudes, which are near the northern/southernmost latitudes of the orbit. (Adapted from Quintero and Duggan.[1])

As discussed later, this improvement in high-latitude performance does come with a price. For a traditional Walker-Delta constellation, the satellites in adjacent planes have a phasing to form a consistent diamond shape near the equator, which results in more consistent coverage at lower latitudes but suboptimal coverage at higher latitudes. The fractional coverage the Waves constellation experiences dips lower than Walker-Delta constellations at lower latitudes. This effect is visible in Figure 1, where the waves transiting the equatorial region of Earth show gaps, because they are moving quickly to support improved coverage and handoff with the next descending wave at the design latitude. In Figure 2, gray, cyan, and purple waves are descending, while light yellow, red, and dark yellow waves are ascending. Figure 3 shows the progression of the satellites at various time steps, where the different waves exchange coverage of various latitude bands.

INCLINATION SELECTION AND THE REQUIRED CONSTELLATION DESIGN

Constellation design is generally an iterative process, but the geometry of the Waves constellation lends itself to an analytic starting point. The design process starts with a determination of the latitude of desired

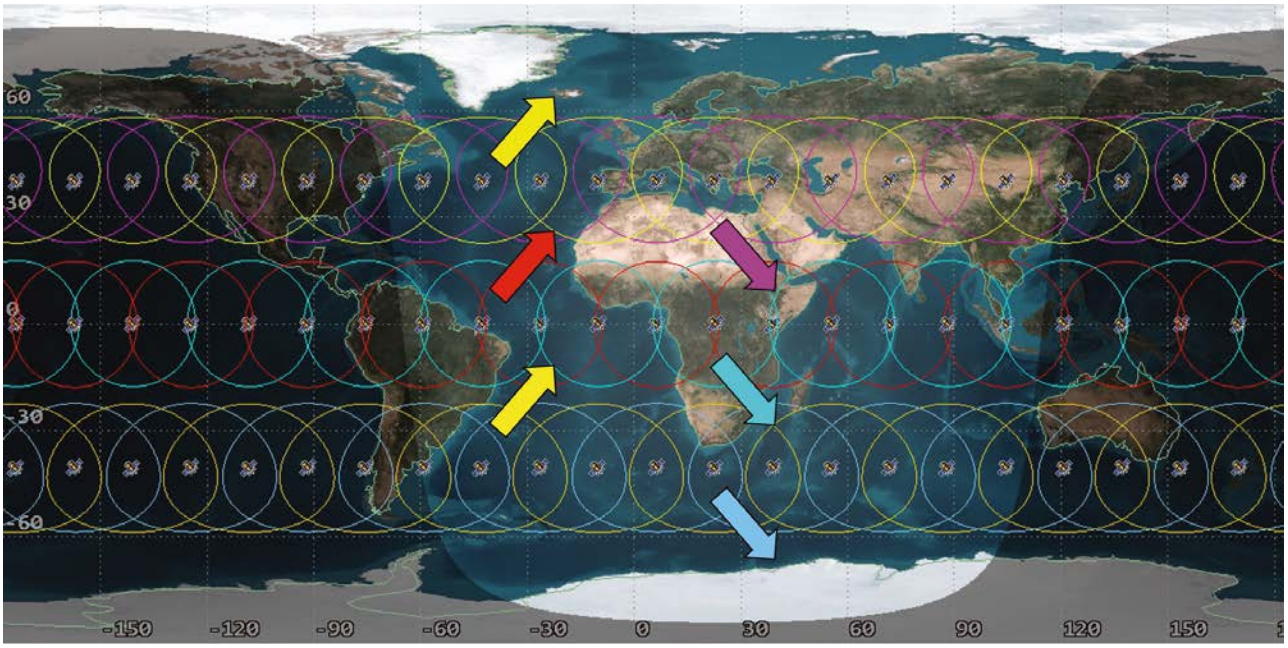

Figure 2. Color-coded satellite coverages illustrating handoffs between access times. Gray, cyan, and purple waves are descending, while light yellow, red, and dark yellow waves are ascending. (Adapted from Quintero and Duggan.[1])

coverage. We focus on the Northern Hemisphere, but all the constellations are symmetric about the equator. A satellite's coverage extends north of its inclination, with coverage extended by higher altitudes and the ability of the satellite to steer pointing from nadir. The slant range can be calculated from these two quantities. It is then possible to solve for the ground range and the inclination from the desired overlap of the coverages within the wave.

Next, the number of planes is determined by the rounded-up number of overlapped coverages that evenly space around Earth. For example, if each satellite provides 45° of longitude coverage at the design latitude, then eight planes are required.

The determination of the optimal number of waves in the constellation is an iterative process, based on the desired latitude band requiring access. 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 criterion is then rounded down, so that the waves are evenly spaced about the plane.

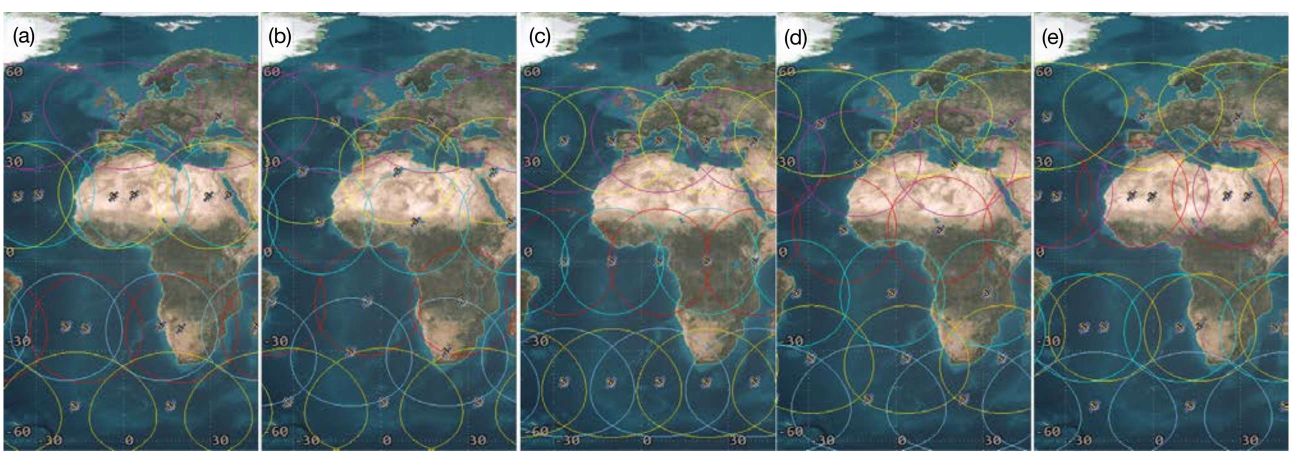

Figure 3. Time snapshots of the coverage map for a Waves Constellation designed to cover latitudes around 40° (time progressing left to right). The purple satellite wave starts with coverage of the northern design latitude and hands off coverage to the green wave. Also note the coverage gaps at the equator (a and e) and at ~20° latitude (c). Note this constellation is overdesigned for coverage at the highest latitude (significant overlap of the coverage cones).

GRAPHICAL USER INTERFACE PROCESS FOR GENERATING COVERAGE DATA

The preceding section briefly describes the process for calculating the constellation design that provides coverage at a given design latitude, which is laid out in the flowchart in Figure 4. Generally we are interested in knowing the coverage for a range of latitudes and might increase or decrease the number of satellites based on priorities. Systems Took Kit (STK), developed by AGI, provides a time-domain simulation of satellite trajectories to gather this data with precision.[3] The STK graphical user interface (GUI) has a low barrier to entry for inputting satellites in specific orbits, but it becomes tedious to use when populating an entire constellation of tens to hundreds of satellites. STK can read two-line element (TLE) files for the satellite orbits, so we wrote a separate software package for creating TLEs for a given constellation design. The native GUI can also be used for saving STK-generated reports, but again requires a few user clicks for each ground location of interest. These reports contain time-domain data, which must be processed with a tool such as MATLAB to generate statistics; an additional script is needed to import the data to MATLAB. With these results, the user can then feed back an updated design to the process and continue until a satisfactory result is found. Beyond writing the MATLAB code for data import and processing, managing the STK GUI can take tens of minutes or even hours for the analysis of one constellation. To explore proliferated low Earth orbit constellations with hundreds of satellites, the process can be a major time sink.

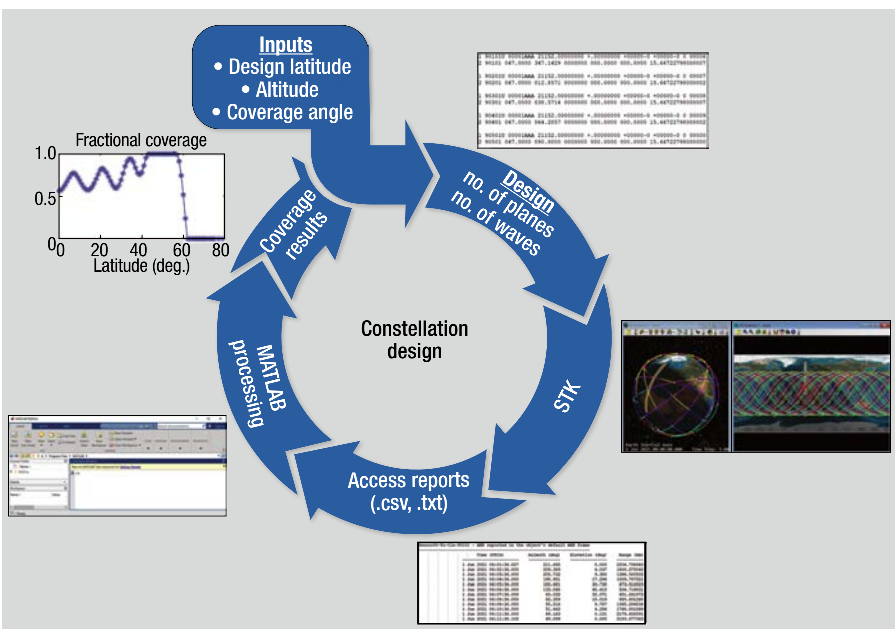

Figure 4. Flowchart for designing satellite constellations with STK. For a given mission, one needs to create a constellation design to load into STK (one by one through the GUI or with TLE files), work through the STK GUI to set up and run the scenario and export reports, and process the data in an external program.

DATA GENERATION WITH STK AND MATLAB

We have developed a set of MATLAB tools to integrate with STK for generating and analyzing constellation performance. These tools bypass some of the sticking points in the previous process. The tools perform multiple functions:

1. Allow the user to define one or multiple constellations to study (including using the Waves design rules if so desired).
2. Define Earth locations of interest for which to generate coverage data.
3. Given a list of satellites and locations, create a list of commands for STK to generate satellites/sensors and create the necessary reports of altitude/elevation/range for sensors in view from each ground location.
4. Parse these reports to bring data into MATLAB.
5. Calculate statistics for satellite coverage (e.g., the fraction of time with a satellite link available at each Earth location, the average number of satellites in view, the average coverage gap duration).

These tools are quite versatile and can be used for analyzing a single constellation or automating hundreds of runs at a time to support parameter sweeps or other designs of experiments. The current scheme, while still often requiring large run times for STK and MATLAB processing, especially with large data sets, executes the run sets automatically. Significant amounts of data can be generated without user supervision.

By using this toolbox, we are able to perform more detailed analysis of given constellations. For example, we are able to quickly produce plots, such as those in Figure 5, that not only confirm persistent coverage at the design latitude but also show the latitude band of persistent coverage. We are also able to account for the fact that sensors generally work only to some angle above the horizon, and we can recalculate the coverage statistics based on what

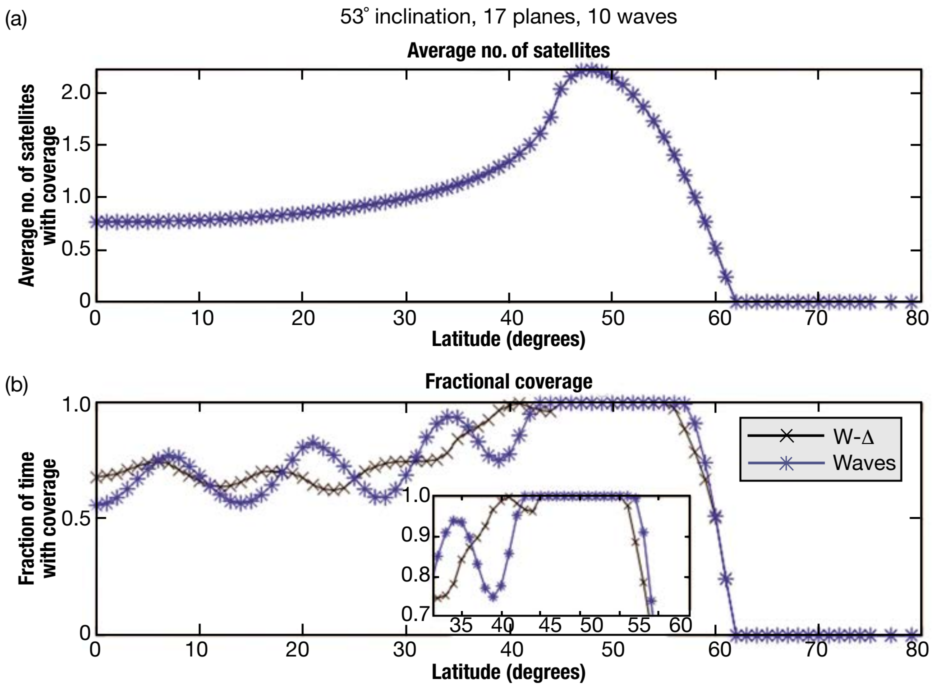

Figure 5. Mean number of satellites in view at a given time and the fraction of time with a satellite accessible at varying latitudes for the two constellations. Our tool provides the coverage results for the Waves constellation, and we have added the Walker-Delta results from a separate, modified version of the tool. The inset shows a close-up view of latitude band of persistent coverage.

this grazing angle might be (given satellite altitude, this angle has 1:1 correspondence with both slant range and opening angle from nadir from the satellite's perspective).

Within this framework, it is easy to modify our tools to gather additional types of data. For example, we can add an additional postprocessing step to analyze the statistics for range from satellite to ground station if we are calculating link budgets. We could also save additional metrics generated within STK if needed.

RESULTS OF COMPARISON BETWEEN WAVE AND WALKER-DELTA DESIGNS

For comparison with the Waves constellation, we used a Walker-Delta constellation[4] with the same number of planes and the same number of satellites per plane as a basis. 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 the planes are phased. Specifically, Walker-Delta planes are phased such that the nearest neighbor satellites are hexagonally close-packed as the satellites pass the equator, and Waves planes are phased such that each of the nearest satellites in neighboring planes is at the same true anomaly. This forms a wave of satellites in all planes that rise and fall together. In this work we largely focus on the metric of fractional coverage (the percentage of time with at least one satellite in view). A communications network should optimally provide customers with service 100% of the time. For this analysis, we used parameters similar to those for the SpaceX Starlink communications constellation: 550 km satellite altitudes, 53° inclination, and "coverage" defined as a satellite being in view at elevation angles greater than 25° above the horizon. This is equivalent to the slant range from the ground station to the satellite being within about 1,300 km. In this comparison, we used 17 planes and 10 satellites per plane.

To compare Walker-Delta and Waves constellation designs fairly, the baseline configuration of each plane of satellites is the same (inclination and number of satellites in each plane). The average number of satellites visible from the latitudes sampled is identical, as shown in the top plot of Figure 5. However, the phasing determines whether the satellites bunch and spread apart or remain more evenly spaced at the desired latitudes. The co-phasing used in the Waves constellation better utilizes the available coverage. A single Waves design provides a roughly 4° improvement in access latitudes with fractional coverage of 100% compared with a Walker-Delta of exactly the same size.

EXTENDED COVERAGE BAND WITH MORE SATELLITES

By adding satellites to the constellation, a wider latitude band of continuous coverage can be created. Since a significant proportion of Earth's population live in 20°–50° latitudes (see Figure 6 for a breakdown of population versus latitude), mostly in the Northern Hemisphere, that was chosen as our preliminary design requirement. Latitudes of 20°–60° extend the coverage to the northern tip of the United Kingdom.

Taking the same altitude and inclination as the previous constellation, by increasing the number of satellites to 19 planes, 18 Waves (doubling the size compared with the previous constellation), we find continuous coverage within the 20°–60° band. Even near the equator, coverage is available >90% of the time (Figure 7).

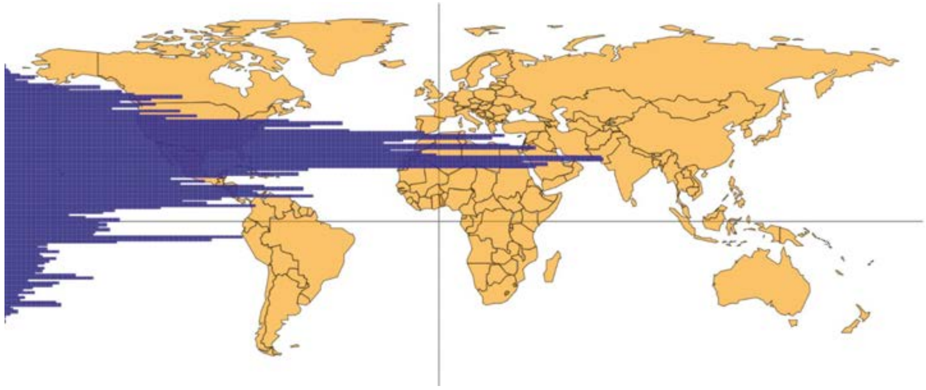

Figure 6. Earth population by latitude. To optimize the coverage relative to cost, a constellation can prioritize coverage at latitudes with larger populations. (Reprinted with permission from engaging-data.com, https://engaging-data.com/.[5])

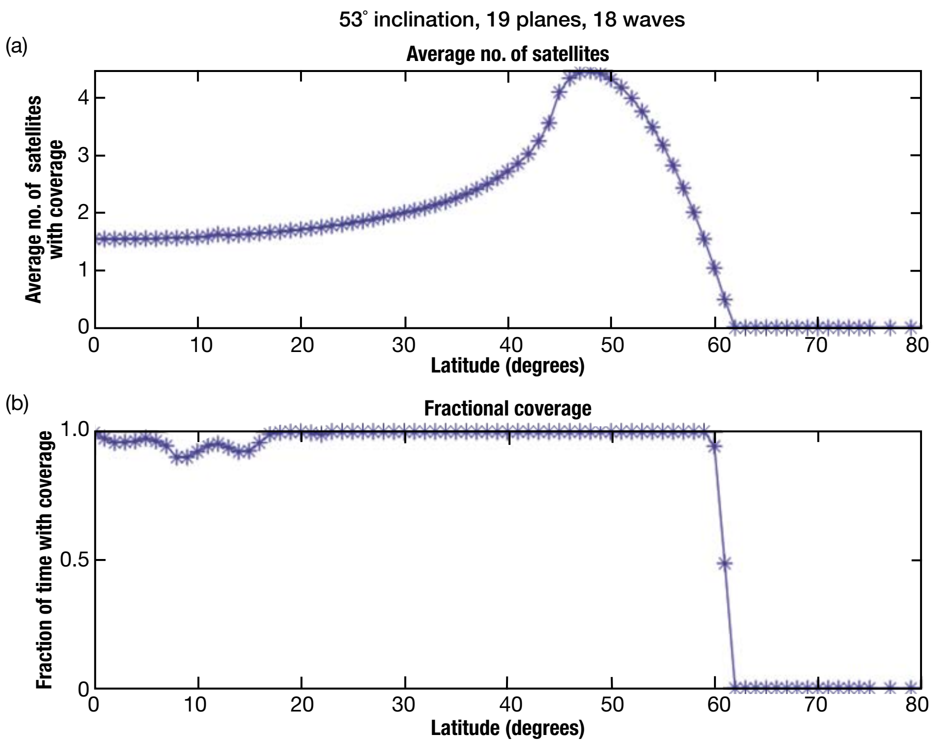

Figure 7. Coverage with denser Waves constellation. There are roughly twice the satellites in this constellation compared with that in Figure 5, so there is a much wider band of latitudes with persistent coverage.

STACKING MULTIPLE WAVES CONSTELLATIONS

One thing to note with the coverage in Figure 7 is that satellites tend to be visible for more time at the higher latitudes (~2 times the average number of satellites in view at 50° latitude compared with 30°). It is desirable to even this out over the coverage band. One way to accomplish this is to have multiple Waves constellations, each at different inclinations, to provide coverage over separate latitude bands. The "peak" in the average number of satellites in view from the lower-inclination sub-constellation means there are more connections available for a single ground location compared with a single constellation. When the sub-constellations have the same number of planes or waves, their phasing relative to each other will change the coverage. In Figure 8, b–d, we show the effect of progressing the starting position of the waves in the lower sub-constellation by 0%, 25%, and 50% of the in-plane true anomaly spacing, respectively. That is, we

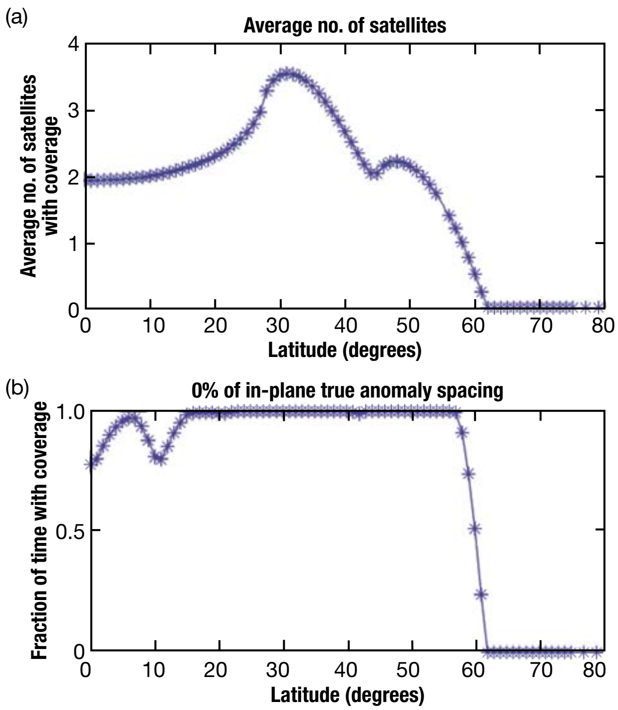

Figure 8. Coverage with two Waves constellations at different inclinations. The sub-constellation parameters are 53° inclination, 17 planes, 10 waves, and 37° inclination, 19 planes, 10 waves. (a) Compared with the constellation in Figure 7, there are more satellites on average in the mid/low latitudes of the coverage band (30°–40°). (b–d) The coverage for different relative start phases of each wave for the lower-inclination sub-constellation as compared with the higher.

change when the waves in each constellation cross the equator relative to each other. Note that panel b shows about ~5° extra of persistent coverage but then drops to poorer coverage near the equator as compared with panel c or d. This reduced coverage at the equator in panel b is because the two sub-constellations have waves that cross the equator at the same time, and thus have gaps at the same time. By nature of the same geometric relationship, the waves from each sub-constellation provide complementary coverage in the ~15°–20° latitude band. Note that satellites at different inclinations have different precession rates,[6] and that the two sub-constellations will likely be slightly shifted in altitude to avoid collisions. Thus, over time they will drive relative to each other, and the "instantaneous" fractional coverage (on the time scale of roughly a day) will shift among the representative curves in Figure 8 (b–d).

CROSS-LINKS DURING WEST-TO-EAST TRANSIT

A typical required function of a large constellation is routing information between the satellites to get to a desired downlink location. In general, the relative positions of satellites are always changing, so the optimal routing is a complex, time-dependent problem. Further, one has to point the cross-link communication beam (often optical) to the adjacent satellites. The Waves constellation offers a number of inherent benefits on this front. Like other Walker-Deltas, there is a consistent relationship to the satellites leading/lagging within the plane. Within a wave, because of the co-phasing, there is also always a satellite directly east and west of the transmitting satellite. Additionally, during the access time period, where the satellites are at the design latitude, the cross-link connections are at their minimum separation and thus easier to close. With all these factors, the new approach requires greatly reduced steering (pointing) of cross-link communications systems. Message traffic can travel to any longitude along the wave and then traverse up/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 relatively simple antenna system with fixed pointing and reduced routing complexity/fragility to achieve a time-optimal downlink.

CONCLUSIONS

In summary, we developed and applied for a patent for a new constellation design for a co-phased satellite constellation with assured access (100%) for extremely useful latitude bands. The new constellation requires reduced steering (pointing) at cross-link areas for the latitudes of interest.

For deeper analysis, we developed tools for the integration of STK's satellite propagator with MATLAB's processing capabilities. We generated large amounts of data to jump-start future designs. While we focused specifically on fractional coverage in this work, other performance metrics can be evaluated with this same framework.

Together, these advancements will aid in the design and analysis process of systems that use satellite networks. Our ideas are useful for a number of applications. One example is positioning, navigation, and timing, where our design and analysis tools could be used for constellations that, for example, ensure a persistent view of three satellites for triangulation. We envision extending the processing algorithms to have more of these application-specific metrics.

REFERENCES

[1]C. Quintero and R. S. Duggan, "Orbital diversity and inclination optimization for large count LEO constellations in non-polar orbits," paper presented at *Adv. Maui Optical and Space Surveillance Technol. Conf. (AMOS)*, Maui, HI, Sep. 2021.

[2]J. O'Callaghan, "The risky rush for mega constellations," *Sci. Amer.*, Oct. 31, 2019, https://www.scientificamerican.com/article/the-risky-rush-for-mega-constellations/.

[3]"Systems Tool Kit (STK)" Product Page, Analytical Graphics, Inc., https://www.agi.com/products/stk (accessed Oct. 9, 2021).

[4]J. G. Walker, "Continuous whole-Earth coverage by circular-orbit satellite patterns," Royal Aircraft Establishment Technical Report, Mar. 24, 1977.

[5]"World population distribution by latitude and longitude," Engaging Data, https://engaging-data.com/population-latitude-longitude/ (accessed Oct. 9, 2021).

[6]C. D. Brown, *Elements of Spacecraft Design*. Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 2002.

Robert S. Duggan, Research and Exploratory Development Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Robert S. Duggan is a member of the Discovery Program 2021 cohort. He completed his BS in engineering physics at Cornell University and his MS and PhD in electrical and computer engineering at the University of Texas at Austin. His graduate research focused on the study of time-varying and active electromagnetic systems, particularly for nonreciprocity and sensing. He joined APL's Discovery Program in the summer of 2021, with his first rotation in the Force Projection Sector's Strike Guidance Navigation Control and Seekers Group, where he worked on the analysis of satellite systems for numerous applications. His email address is robert.duggan@jhuapl.edu.

Chuck Quintero, Force Projection Sector, Johns Hopkins University Applied Physics Laboratory, Laurel, MD

Chuck Quintero is a senior radio frequency (RF) systems engineer with the Strike Guidance Navigation Control and Seekers Group at APL. He has an MSEE from the University of Pennsylvania and an SB from MIT and is currently pursuing a DEng from the Johns Hopkins University. During his 40-year career, he has worked on space-based, airborne, and surface-based RF systems for remote sensing, electronic warfare, and communications at APL, Leidos, SRI International, Northrop Grumman, ITT Harris, and Lockheed Martin. Chuck is an avid astronomer, a STEM lecturer for NASA's Jet Propulsion Laboratory, and an electronic warfare (EW) Certification chair for the Association of Old Crows. Chuck has published and presented papers on satellite constellation design, space surveillance, multichannel high bandwidth RF systems, and radar. His email address is chuck.quintero@jhuapl.edu.